Assessing the HMS Challenger collection as a late 19 th Century physicochemical surface ocean indicator using computed X-ray microtomography

Stergios D. Zarkogiannis[1*], Thomas Wood[1*], Giles Miller[2], Stephen Stukins[2], Brett Clark[2]

[1]University of Oxford, United Kingdom, [2]Natural History Museum (United Kingdom), United Kingdom

Submitted to Journal:
Frontiers in Marine Science

Specialty Section:
Global Change and the Future Ocean

Article type:
Original Research Article

Manuscript ID:
1454260

Received on:
24 Jun 2024

Revised on:
12 Sep 2024

Journal website link:
www.frontiersin.org

Scope Statement

Previous comparisons of HMS Challenger expedition (1872-1876) material to modern plankton samples raise questions about their representation of the late Holocene ocean state. This study utilizes X-ray micro-computed tomography (µCT) to examine 21 samples from the Natural History Museum, London. Most samples contain benthic foraminifera shells, foraminiferal fragments, and detrital quartz grains, while others lack calcareous microfossils. We find that these samples, taken from tow-nets at deeper parts of trawl and dredge lines, capture resuspended bottom sediments from the late Holocene, not just pelagic conditions of the 1870s. µCT proves effective for non-destructive sediment analysis, avoiding the need for washing and wet sieving.

Conflict of interest statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest

Credit Author Statement

Brett Clark: Data curation, Resources, Writing – review & editing. Giles Miller: Investigation, Methodology, Project administration, Resources, Writing – review & editing. Stephen Stukins: Resources, Validation, Writing – review & editing. Stergios D. Zarkogiannis: Conceptualization, Funding acquisition, Investigation, Methodology, Visualization, Writing – original draft. Thomas Wood: Formal Analysis, Investigation, Visualization, Writing – original draft.

Keywords

HMS challenger, early-industrial, tow-net sediment, contamination, deep water deposits, X-ray micro-computed tomography

Abstract

Word count: 218

Plankton tow samples that were collected during the HMS Challenger expedition between 1872 and 1876 have the potential to provide a unique window to the physicochemical conditions of the water column during the late 19 th century. Challenger sediment collections have previously been assessed and compared to modern plankton collections but questions remain as to whether some of the samples possibly represent the state of the late Holocene ocean. In the present study we use X-ray micro-computed tomography (µCT) to examine all 21 available samples from the global ocean that were labelled as 'tow-net at dredge', 'weights' or 'trawl' in the Ocean Bottom Deposits (OBD) collection at the Natural History Museum, London. We find in most of the samples the presence of benthic foraminifera shells, and high concentrations of foraminiferal fragments and detrital quartz grains; while the rest of the samples are sedimentary material barren of calcareous microfossils. We confirm that these samples are from tow-nets at the deeper parts of the sampling lines that were attached to the trawl and dredge; they are a capture of resuspended bottom sediments incorporating specimens of possible late Holocene age and may not solely reflect pelagic conditions during the 1870s. This study highlights the use µCT in the non-destructive analysis of sediment collections without the need for washing and wet sieving.

Funding information

This research was supported by UK Research and Innovation Grant (SODIOM) EP/Y004221/1.

Funding statement

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article.

Ethics statements

Studies involving animal subjects
Generated Statement: No animal studies are presented in this manuscript.

Studies involving human subjects
Generated Statement: No human studies are presented in the manuscript.

Inclusion of identifiable human data
Generated Statement: No potentially identifiable images or data are presented in this study.

Data availability statement

Generated Statement: The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/supplementary material.

Assessing the HMS *Challenger* collection as a late 19th Century physicochemical surface ocean indicator using computed X-ray microtomography

Stergios Zarkogiannis[1†*], Thomas Wood[1†*], C. Giles Miller[2], Stephen Stukins[2], Brett Clark[2]

[1]Department of Earth Sciences, University of Oxford, Oxford, United Kingdom

[2]The Natural History Museum, London, United Kingdom

[†] These authors contributed equally to this work and share first authorship

*** Correspondence:**
Corresponding Authors
stergios.zarkogiannis@earth.ox.ac.uk; thomas.wood@st-annes.ox.ac.uk

Keywords: HMS *Challenger*, early-industrial, tow-net sediment, contamination, deep water deposits, X-ray micro-computed tomography

Abstract

Plankton tow samples that were collected during the HMS *Challenger* expedition between 1872 and 1876 have the potential to provide a unique window to the physicochemical conditions of the water column during the late 19th century. *Challenger* sediment collections have previously been assessed and compared to modern plankton collections but questions remain as to whether some of the samples possibly represent the state of the late Holocene ocean. In the present study we use X-ray micro-computed tomography (μCT) to examine all 21 available samples from the global ocean that were labelled as 'tow-net at dredge', 'weights' or 'trawl' in the Ocean Bottom Deposits (OBD) collection at the Natural History Museum, London. We find in most of the samples the presence of benthic foraminifera shells, and high concentrations of foraminiferal fragments and detrital quartz grains; while the rest of the samples are sedimentary material barren of calcareous microfossils. We confirm that these samples are from tow-nets at the deeper parts of the sampling lines that were attached to the trawl and dredge; they are a capture of resuspended bottom sediments incorporating specimens of possible late Holocene age and may not solely reflect pelagic conditions during the 1870s. This study highlights the use μCT in the non-destructive analysis of sediment collections without the need for washing and wet sieving.

1 Introduction

The HMS *Challenger* Expedition was a pioneering research cruise that took place from 1872 to 1876 and laid much of the foundation of modern oceanographic knowledge. The voyage covered over 68,000 NM (126,000 km) across all the world's oceans, with an array of scientific observations made at 362 stations (Linklater, 1972). These included physical measures of temperature and circulation; chemical measures of dissolved acids; and animal, plant and sediment samples taken at all depths. Predominant focus was "devoted to deep-sea research" (Tizard et al., 1885), and so much time was

committed to collecting and observing samples from the ocean bottom by dredging and trawling. However, a conscious effort was made to collect surface and intermediate-depth pelagic samples for comparison with benthic samples, to determine how the nature of the plankton and nekton influenced the composition of the bottom sediment.

While of lesser importance to the *Challenger* Expedition, the physicochemical characteristics of the hard-bodied plankton collected at surface and intermediate depths could provide insight into the physical and chemical nature of the water column during the years 1872-76. While this period post-dates the First Industrial Revolution (1760-1840), it marks the onset of the Second Industrial Revolution (1870-1914) (Landes, 2003) and predates 'The Great Acceleration' of the 1950s (Steffen et al., 2015). This would represent a useful benchmark for comparing contemporary samples, in which any change in biomineralisation intensity may relate to changes in stratification and nutrient supply, or ocean acidification, under the action of increased anthropogenic CO_2 emissions and ocean change.

The Natural History Museum houses many of the natural history specimens collected as part of the *Challenger* Expedition including John Murray's sediment samples which is now part of the Ocean Bottom Deposit (OBD) Collection at the Natural History Museum. Other collections at the museum include preparations of plankton from shallower water settings in the form of diatom preparations or Canada Balsam slides made on the ship to illustrate the micro and meso plankton collected in tow nets at depths of less than 100 m (Figure 1). However, the present study focuses on sediments collected during dredging and trawling that make up part of the OBD. The Murray *Challenger* collection contains sediment from the ocean bottoms that has previously been assessed by Rillo et al. (2019). They compared the foraminiferal content of these bottom sediments with foraminiferal datasets for the Holocene and Last Glacial Maximum and suggested that some but not all of these samples can be used to benchmark the state of the oceans in the 1870s and that there may be older foraminiferal specimens mixed with some of these sediments in some cases.

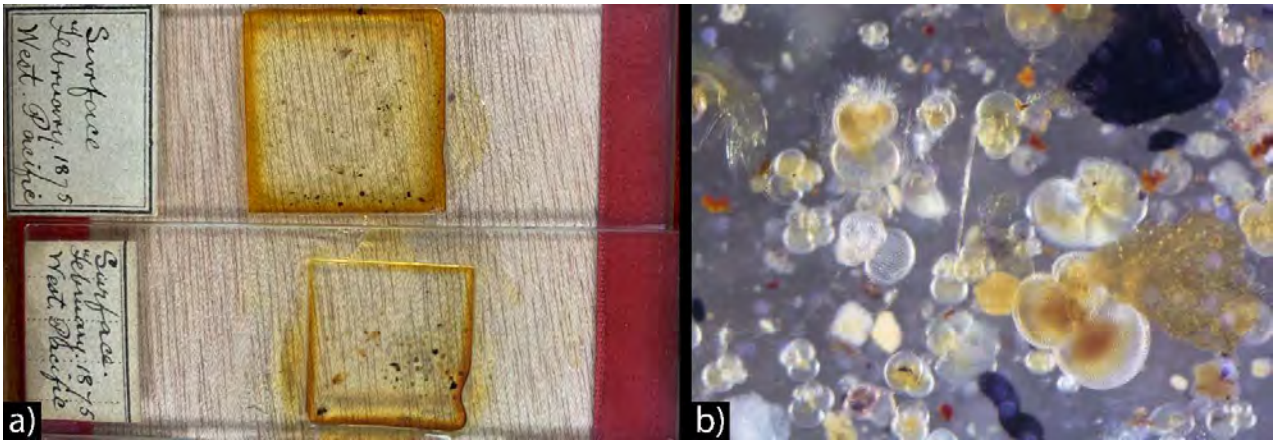

Figure 1: Photographs of a) the original glass slides containing ocean surface plankton collected during the HMS *Challenger* Expedition (1872 - 1876) with plankton nets and fixed with Canada Balsam and b) 60x magnification of the material fixed on the glass slides.

To counteract the possibility that the samples represent older benthic material, Fox et al. (2020) used samples labeled as 'tow net at trawl' or 'tow net at dredge' from the OBD Collection from HMS *Challenger* stations 272 and 299 (Figure 2). These were compared with modern samples collected during the Tara Oceans expeditions (Pesant et al., 2015) to assess the calcification of foraminifera.

The present authors further analyzed these two HMS *Challenger* samples for planktonic foraminiferal shell weight. Following initial washing and coarse fraction sieving, some benthic foraminifera were found in both of theses samples, potentially compromising their representation of ocean conditions in the 1870s. However, as certain species of benthic foraminifera have been identified within modern plankton (Kucera et al., 2017), these benthic occurrences in the HMS *Challenger* samples require further investigation.

This study outlines an X-ray micro-computed tomographic method for assessing these sediments for benthic tracers by scanning all 21 of the samples marked as 'tow net at trawl', 'tow net', 'tow net at dredge' or 'tow net at weights' and one sample marked as 'surface diatoms' from John Murray's Challenger Collection within the Natural History Museum's OBD Collection.

2 Material and Methods

The material examined in this investigation is housed in the Natural History Museum's Ocean-Bottom Deposits Collection and consists of sedimentary residues from 22 sampling stations (Figure 2). The sediments are housed in sealed glass jars that have original sample labels as well as additional labels depicting the 'Murray Collection' (M) number and other collection details. The ocean-bottom deposits of the HMS *Challenger* expedition were chiefly managed by Sir John Murray, who catalogued the collection with his own numbering system, distinct from that of the *Challenger* sounding stations. Additionally, the new labels contained the *Challenger* sounding station number, a brief sample description, date, latitude and longitude, and the depth at which the sample was collected in fathoms. Photographs of some of the original containers are provided in Supplementary Figure 1. Initially sample aliquots (~40 g) from Stations 272 and 299 used in the study of Fox et al. (2020) were washed and the coarse fraction (<63μm) was visually examined under light stereoscope. Both calcareous-walled and agglutinated forms were identified in the samples. Specifically, Station 272 was dominated by the calcareous genera *Cassidulina*, *Bulimina*, and *Oridorsalis*, along with the agglutinated genus *Portatrochammina*. At Station 299, specimens of the genus *Uvigerina* were predominant, with a single specimen of *Pyrgo* observed, along with agglutinated specimens from the genus *Reophax*. After the observation of benthic particles in both samples, the investigation was subsequently extended to the rest of the collection using non-destructive X-ray micro-computed tomography (μCT).

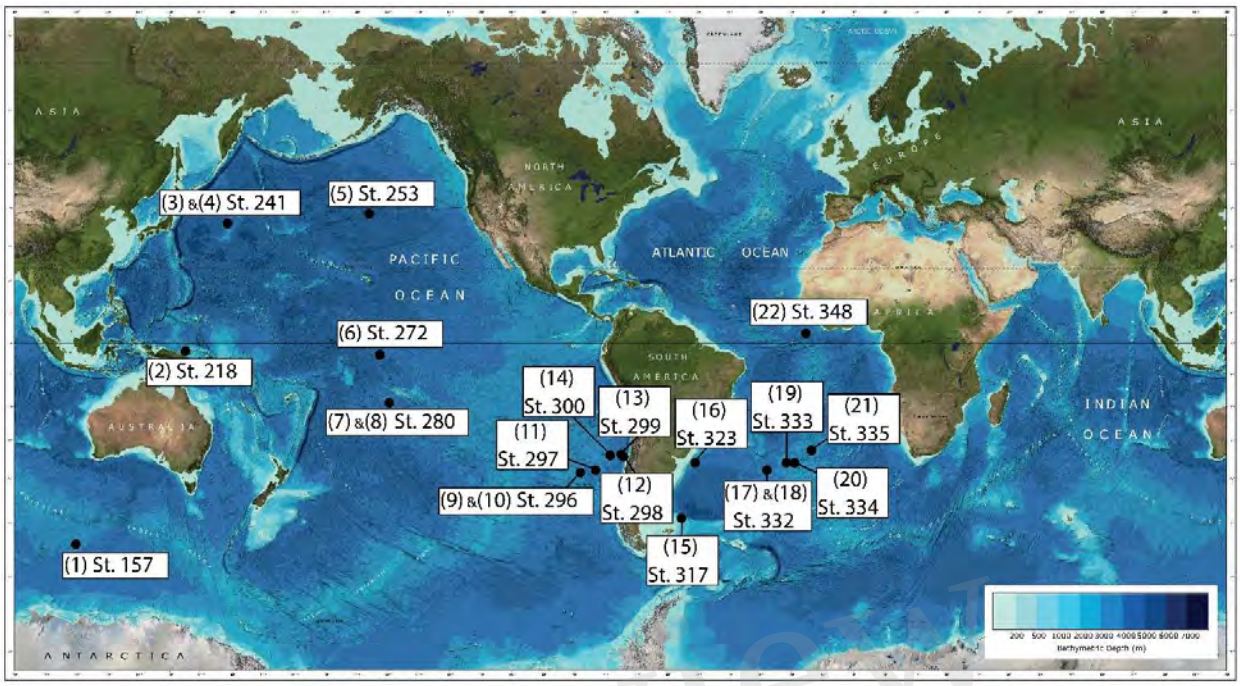

Figure 2: Map showing the location of the HMS Challenger samples analysed in the present study.

2.1 HMS *Challenger* 'tow net' samples in the Ocean-Bottom Deposits collection of the Natural History Museum of London

From the complete set of 20 wooden cabinets containing original *Challenger* sediments, 22 samples were selected (Table 1). All samples with labels that included the words 'tow-net', 'townet' or 'tow net' were chosen and aliquoted for µCT analysis. We identified eight samples from the Atlantic, 13 from the Pacific, and one from the Indian Ocean. For simplicity, we grouped the samples from the Indian and Pacific Oceans into a single Indo-Pacific category. All the sample containers were original and had been air-sealed with cork and adhesive wrap. 14 samples were contained within green, transparent glass "rock bottles" 23 cm in height and 15 cm in diameter (Tizard et al., 1885); six samples were contained within white glass jars 9 cm in height and 5 cm in diameter; and two samples were contained in glass test tubes. One of the glass tubes (Sample 1; Table 1) was labeled 'Surface net – Diatoms' and its appearance was different to the rest. Most of the selected samples exhibited large volumes of loose sediment (see Supplementary Figure 1) or consolidated clumps, whereas Sample 1 was much lower volume and exhibited a whitish, felt-like appearance. Sample 1 was CT scanned but also examined under the light stereoscope.

Table 1: List of HMS *Challenger* material that were tomographically analysed in this study. The original station number is given together with its coordinates converted to decimal degrees (DD) and

the depth converted from fathoms to meters. Collecting method information from the original labels are also included in the table below. For the original labels see Supplementary Figure 1.

Sample Nr	*Challenger* Station	Latitude (DD)	Longitude (DD)	Depth (m)	Ocean Basin	Sample Label collecting method	Collection date
1	157	-53.917	108.583	91	SE Indian	Surface net - Diatoms	03/03/1874
2	218	-2.550	144.067	1,957	N Pacific	Tow-net on trawl	01/03/1875
3	241	35.683	157.700	4,206	N Pacific	Washings - townet	23/06/1875
4	241	35.683	157.700	4,206	N Pacific	From trawl	23/06/1875
5	253	38.150	-156.417	5,715	N Pacific	From tow net dredge	14/07/1875
6	272	-3.800	-152.933	4,755	Eq Pacific	Mud from tow net and trawl	08/09/1875
7	280	-18.667	-149.867	3,548	S Pacific	From tow net at trawl	04/10/1875
8	280	-18.667	-149.867	3,548	S Pacific	Townet	04/10/1875
9	296	-38.100	-88.033	3,338	Chilean Sea (S Pacific)	From tow-net at trawl	09/11/1875
10	296	-38.100	-88.033	3,338	Chilean Sea (S Pacific)	From tow-nets at trawl	09/11/1875
11	297	-37.483	-83.117	3,246	Chilean Sea (S Pacific)	Mud from tow-net at trawl	11/11/1875
12	298	-34.117	-73.933	4,069	Chilean Sea (S Pacific)	Tow net at trawl	17/11/1875
13	299	-33.517	-74.800	3,950	Chilean Sea (S Pacific)	Mud from tow net at trawl	14/12/1875
14	300	-33.700	-78.300	2,515	Chilean Sea (S Pacific)	Trawl, Washing of Trawl, Townet at Trawl	17/12/1875
15	317	-48.617	-55.283	1,893	Argentine Sea (S Atlantic)	From townet at weights	08/02/1876
16	323	-35.650	-50.783	3,475	S Atlantic	Large Washings, Townet & Trawl	28/02/1876
17	332	-37.483	-27.517	4,023	S Atlantic	Mud from townet at trawl	10/03/1876
18	332	-37.483	-27.517	4,023	S Atlantic	From tow-net	10/03/1876
19	333	-35.600	-21.200	3,703	S Atlantic	From tow net at trawl	13/03/1876
20	334	-35.683	-18.517	3,502	S Atlantic	From net at trawl	14/03/1876
21	335	-32.400	-13.083	2,606	S Atlantic	Mud from nets at trawl	16/03/1876
22	348	3.167	-14.850	4,481	N Atlantic	From tow-net at dredge	09/04/1876

2.2 High Resolution X-Ray Computed Microtomography

The µCT analyses were carried out at the *Imaging and Analysis Centre*, Natural History Museum, London, using a Nikon Metrology HMX ST 225 system (Nikon Metrology, Tring, UK), with cone beam projection system. This system is equipped with a 4-megapixel detector panel (2000 × 2000 pixels) with a maximum resolution (voxel size) of 5 µm, a maximum energy of 225 kV for the reflection target, and a maximum current output of 2000 µA. The sediment samples were aliquoted into 50 ml self-standing polypropylene centrifuge tubes. The samples were scanned in batches of 5 after being transferred and secured from moving into a straight-sided polypropylene jar. The scanning took place at a voltage of 120kV and a 200µA current. Specific scanning parameters are detailed in each accompanying data file. The duration of each acquisition lasted approximately an hour and the scanning resolution varied between the different batches from ~30 to 40 µm. The

projections acquired during the scanning process were subsequently reconstructed using the software CT Pro (Nikon Metrology, Tring, UK), which employs a modified version of the Feldkamp et al. (1984) back-projection algorithm. This generated a stack of grayscale TIFF slice images, which were then imported into the Avizo 2019 software for visualization and analysis. In Avizo, the image stack for each sample was visually examined for its contents.

3 Results

Characteristic snapshots that document the existence of benthic particles in each sample were cropped from the produced image stacks and compiled in the figures below. Figure 3 summarizes the tomographs of the Indo-Pacific samples. Sample 1 (Station 157) from the 'Surface net' from the southeast Indian Ocean appears as distinct dense, bright chunks and no benthic material was observed. The examination of this sample under the microscope confirmed that it consisted only of densely packed, fibrous diatomaceous remnants. In contrast, the other samples from the Atlantic and Pacific Oceans that contained carbonate material consistently revealed the presence of benthic foraminiferal shells during the scanning analysis. Sample 5 (Station 253) contained no carbonate material due to its collection below the carbonate compensation depth , where carbonate preservation is not possible (Burton, 1998). In Sample 4 (Station 241) a coral fragment was also observed. The samples contained numerous fragmented foraminiferal shells and quartz grains. Furthermore, Figure 3 shows that the samples consisted of a mixture of larger agglomerates in a matrix of loosely consolidated material. Sample 12 (Station 298) was consolidated more strongly and broke into chunks during sampling. Sample 3 (Station 241), which mentions 'washings' on its label, lacked a matrix of very fine material and had an increased concentration of benthic foraminifera shells and fragments. According to (Murray, 1891) 'washings' refers to when "the ooze or clay was passed through sieves of various sizes" such that "all the larger particles from these sieves were then carefully collected and placed in bottles with spirit, and labelled 'coarse' and 'fine washings'", and likely explains why these tests and fragments were concentrated. This washing related specifically to dredged or trawled material.

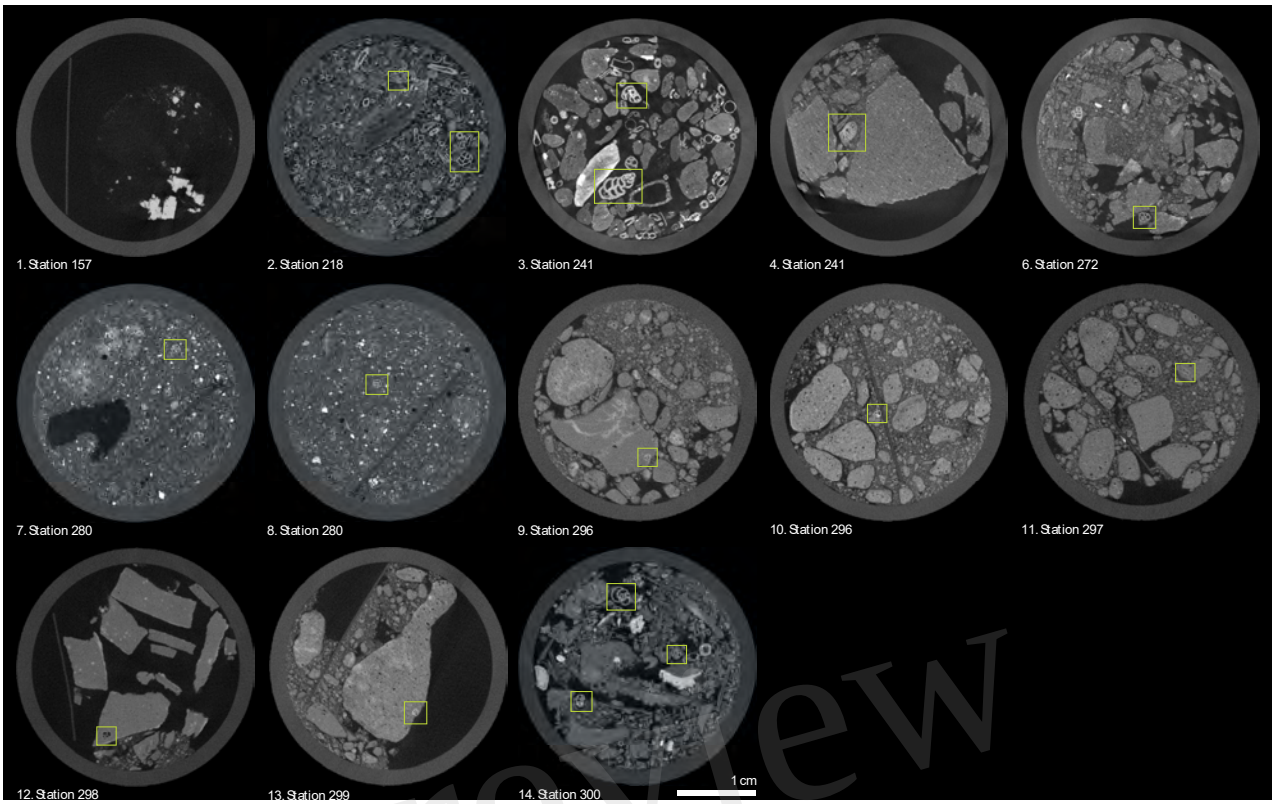

Figure 3: Tomographs of HMS *Challenger* tow net at trawl, dredge, and weights samples from the Indo-Pacific Oceans. The yellow frames highlight characteristic sections of benthic foraminiferal shells in all samples and a coral fragment in 4. Station 241. For exact description of sampling see Table 1. Sample 5. Station 253 is not shown due to lack of carbonate material. A close-up view of the specimens highlighted in the yellow frames is provided in Supplementary Figure 2.

Atlantic samples (Figure 4) also appeared to contain many fragmented foraminifera shells and quartz grains. Most of the samples consisted of a mixture of agglomerates in a matrix of loosely consolidated material. Sample 16 consisted of larger agglomerates and samples 16 to 19 of medium agglomerates, while having only a small number of foraminiferal shells. The rest of the samples were mostly loose material rich in shell and fragments of foraminiferal shells, especially sample 22 from Station 348.

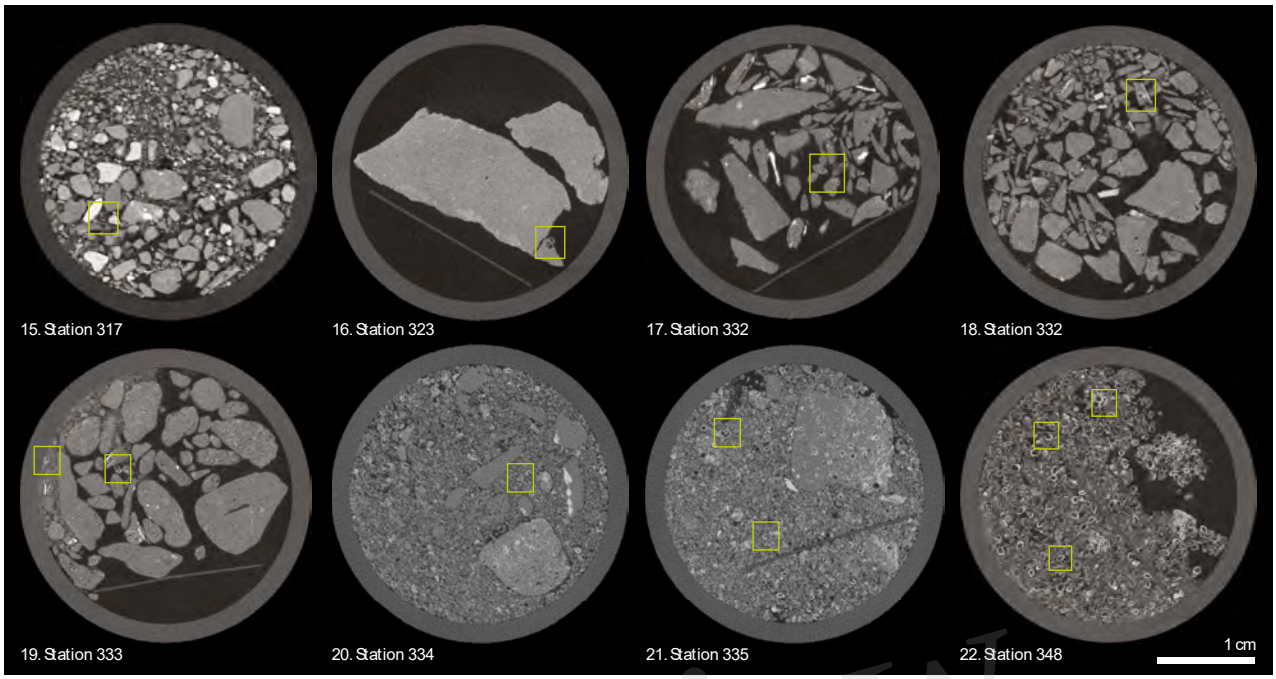

Figure 4: Tomographs of HMS *Challenger* tow net at trawl, dredge, and weights samples from the Atlantic Ocean. The yellow frames highlight some characteristic sections of benthic foraminifera shells in all the samples. For further description of sampling see Table 1. A close-up view of the specimens highlighted in the yellow frames is provided in Supplementary Figure 3.

4 Discussion

All 21 of the HMS *Challenger* samples labeled as 'tow net at trawl', 'dredge' or 'weights', and the one sample labeled 'Surface net', that are housed in the OBD collection at the Natural History Museum, London, were examined during this study. Of all the studied samples, only the 'Surface net' sample was found to consist of purely pelagic material. It was expected that the samples taken by 'tow nets' on the expedition should contain purely pelagic material, to be analysed as a direct representation of the chemical and physical character of the water column on the given dates of sampling. The archival investigation into the written narrative and scientific reports of the expedition (Brady, 1884; Tizard et al., 1885; Murray, 1891) that was performed for the present study suggests that the term 'tow net' in isolation is ambiguous and was used in markedly different applications. Thus, it represents differing sampling techniques, not all of which were likely to collect purely pelagic material.

The Narrative (Tizard et al., 1885) mentions that the pelagic foraminifera were "under almost daily observation during the cruise". Furthermore, the collection of pelagic foraminifera is explicitly noted several times, with species and genus information given in nine of these instances (see Supplementary Table 1). Foraminiferal specimens from surface net samples were mounted on glass slides and are kept in the 'Heron-Allen' Library of the British Museum of Natural History (now: Natural History Museum) (Jones and Brady, 1994). A summary of the archival review key points is given in Supplementary Table 1.

"Surface nets" were "continually in use throughout the cruise" (Tizard et al., 1885) and were deployed predominantly to depths shallower than 100 fathoms (182.9 m). These nets consisted of a coarse cloth net that was held open by an iron hoop up to 18 inches (45.7 cm) in diameter (Figure 5d). Of early use during the expedition, the "dredge" was an iron framework up to five feet (1.52 m) in length that held open a fine cloth bag to be dragged along the seafloor (Figure 5a). This dredge was superseded by a wooden "beam-trawl" (Tizard et al., 1885) that employed a wooden beam up to 17 feet (5.18 m) in length attached to a V-shaped bag, weighted by lead weights to keep the net on the sea floor during trawling (Figure 4b).

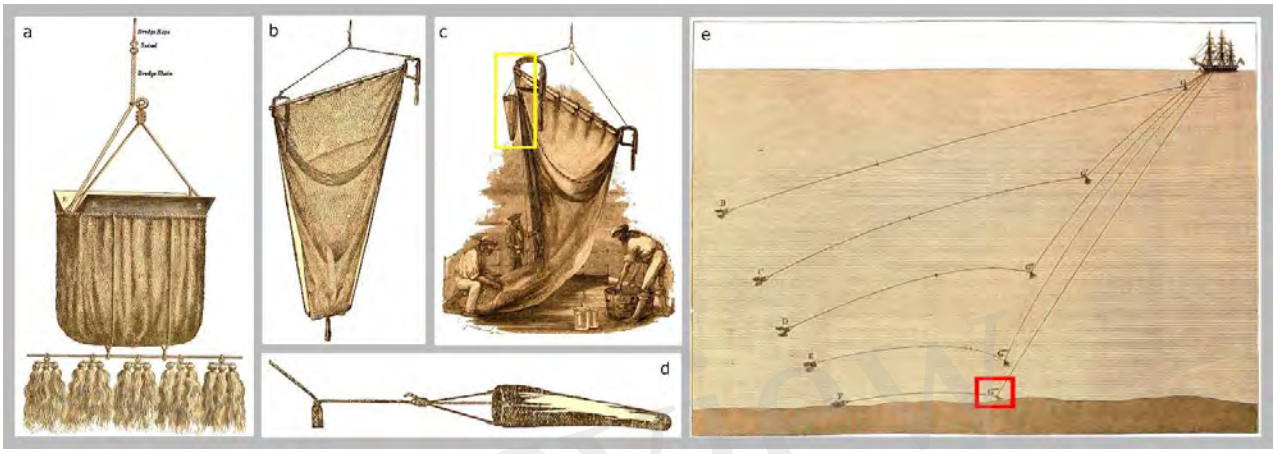

Figure 5: Drawings showing the sampling equipment used on the HMS *Challenger* Expedition. 4a) the "dredge", 4b) the "beam-trawl", 4c) the trawl after use, with a "tow net" attached to the beam (yellow rectangle), notably close to the contact point of the trawl with the seafloor, 4d) the "surface tow net", 4e) the "weights" system used to ensure the trawl remained in contact with the seafloor. A tow net was attached to the weights which made contact with the seafloor at the red rectangle (Tizard et al., 1885).

Murray (1891) explained that the "ordinary surface tow-net was frequently attached to the beam of the trawl and iron frame of the dredge" (Figure 5c); we suggest this sampling method explains the sample labels 'tow net at trawl' (studied Samples 2, 7, 9–12, 14, 16, 17, and 19–21) and 'tow net at dredge' (Samples 5 and 22), as well as other similar wordings associating the 'tow net' with the 'dredge' or 'trawl'. It is likely that this sampling method would not produce purely pelagic material, as these 'tow nets' were in such proximity to the benthic pedoturbation under the action of the 'dredge' or the 'trawl'. Murray (1891) further explains that "a tow-net was in like manner sometimes fixed to the weights that were placed on the trawling line" (Figure 5e) which "occasionally came up filled with mud or ooze". We suggest this defines the sample label 'tow-net at weights' (Sample 15), and Murray's second point implies that this material is also unlikely to be purely pelagic.

The visual examination of the coarse fraction of the aliquots of samples 6 (Station 272) and 13 (Station 299) indicated the existence of many foraminiferal shell fragments and quartz grains indicative of seafloor conditions. Furthermore, the volume of material in the selected samples with 'tow net' present on the labels, contained especially in the rock bottles, was likely too large to be considered a representation of pelagic plankton tows, and thus must be supplemented with bottom sediment. The only pelagic sample of high confidence analysed in this study, sample 1 (Station 157; labeled 'surface net'), was contained within a glass test tube and its material occupied a volume of less than a few cubic centimetres (Supplementary Figure 1). This is a dramatic contrast to other 'tow net' samples that sometimes occupied multiple 23 cm tall rock bottles. All these observations, along

with the presence of seafloor material such as benthic shells or coral fragments (Figure 3.4) revealed by µCT scanning, suggest that the studied samples may have contained resuspended sedimentary material from the seafloor. It should be noted that some benthic foraminifera of the Bolivinitinae lineage have been have both a benthic and a pelagic lifestyle (Kucera et al., 2017), so their presence in these sediments does not necessarily indicate contamination of planktonic nets by benthic material. However, not all observed benthic foraminifera specimens in the tomographs resembled Bolivinitinae. Given the relatively coarse scanning resolution (5µm) used in this study, precise species identification of foraminifera was not possible. The method outlined here is crucial to further assessment of these sediments so that the foraminifera can be identified from each of the samples and interpretations made on the ecological niches of the benthic foraminifera that they contain.

5 Conclusions

X-ray micro-computed tomography scanning has proven to be an efficient, non-destructive method for analyzing sedimentary collections with minimal disturbance. All 21 samples labeled as 'tow net at dredge', 'trawl', or 'weights' from the Murray Challenger Collection within the Ocean Bottom Deposits Collection at the Natural History Museum were found to contain varying concentrations of benthic foraminifera and some coral fragments. The dredge and trawl sampling methods used during the HMS *Challenger* expedition likely introduced resuspended sedimentary particles into the plankton tow nets, along with the planktonic material. The µCT scans enable further analysis of these benthic particles to determine if the species present may also be planktonic. Glass slides prepared on board *Challenger* from plankton tow net material collected from the top 100 meters of the water column may contain foraminifera that serve as better physicochemical surface ocean indicators. These glass slides might offer a more accurate representation of the state of the ocean in the 1870s.

6 Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

7 Author Contributions

Conceptualization S.Z.; methodology and investigation S.Z., G.M., T.W.; software and formal analysis T.W.; resources and data curation G.M. and S.S.; writing—original draft preparation S.Z. and T.W. writing—review and editing G.M., S.S., R.R., S.Z. and T.W.; visualization, S.Z. and T.W. All authors listed, have made substantial, direct, and intellectual contribution to the work, and approved it for publication.

8 Funding

This research was supported by UK Research and Innovation Grant (SODIOM) EP/Y004221/1.

9 Data Availability Statement

The X-ray micro-tomographic datasets generated and analyzed for this study are available at https://data.nhm.ac.uk/dataset/ct-scans-of-h-m-s-challenger-sediments in the NHM Data Portal.

10 References

Brady, H.B. (1884). "Report on the Foraminifera", in: *Report of the Scientific Results of the Voyage of the H.M.S. Challenger During the Years 1873-76.* (London: H.M. Stationary Office).

Burton, E.A. (1998). "Carbonate carbonatescompensation depthcompensation depth," in *Geochemistry*. (Dordrecht: Springer Netherlands), 73-73.

Feldkamp, L.A., Davis, L.C., and Kress, J.W. (1984). Practical cone-beam algorithm. *Journal of the Optical Society of America A* 1(6)**,** 612-619. doi: 10.1364/JOSAA.1.000612.

Fox, L., Stukins, S., Hill, T., and Miller, C.G. (2020). Quantifying the Effect of Anthropogenic Climate Change on Calcifying Plankton. *Scientific Reports* 10(1)**,** 1620. doi: 10.1038/s41598-020-58501-w.

Kucera, M., Silye, L., Weiner, A.K.M., Darling, K., Lübben, B., Holzmann, M., et al. (2017). Caught in the act: anatomy of an ongoing benthic–planktonic transition in a marine protist. *Journal of Plankton Research* 39(3)**,** 436-449. doi: 10.1093/plankt/fbx018 %J Journal of Plankton Research.

Landes, D.S. (2003). *The Unbound Prometheus: Technological Change and Industrial Development in Western Europe from 1750 to the Present.* Cambridge University Press.

Linklater, E. (1972). *The Voyage of the Challenger.* Doubleday.

Murray, J. (1891). "Report on the Deep-Sea Deposits", in: *Report of the Scientific Results of the Voyage of H.M.S. Challenger During the Years 1873-76.* (London: H.M. Stationary Office).

Pesant, S., Not, F., Picheral, M., Kandels-Lewis, S., Le Bescot, N., Gorsky, G., et al. (2015). Open science resources for the discovery and analysis of Tara Oceans data. *Scientific Data* 2(1)**,** 150023. doi: 10.1038/sdata.2015.23.

Rillo, M.C., Kucera, M., Ezard, T.H.G., and Miller, C.G. (2019). Surface Sediment Samples From Early Age of Seafloor Exploration Can Provide a Late 19th Century Baseline of the Marine Environment. 5. doi: 10.3389/fmars.2018.00517.

Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., and Ludwig, C. (2015). The trajectory of the Anthropocene: The Great Acceleration . *The Anthropocene Review* 2(1)**,** 81-98. doi: 10.1177/2053019614564785.

Tizard, T.H., Moseley, H.N., Buchanan, J.Y., and Murray, J. (1885). "Narrative of the Cruise of H.M.S. *Challenger* with a General Account of the Scientific Results of the Expedition", in: *Report of the Scientific Results of the Voyage of H.M.S. Challenger During the Years 1873-76.* (London: H.M. Stationary Office).

Figure 1.JPEG

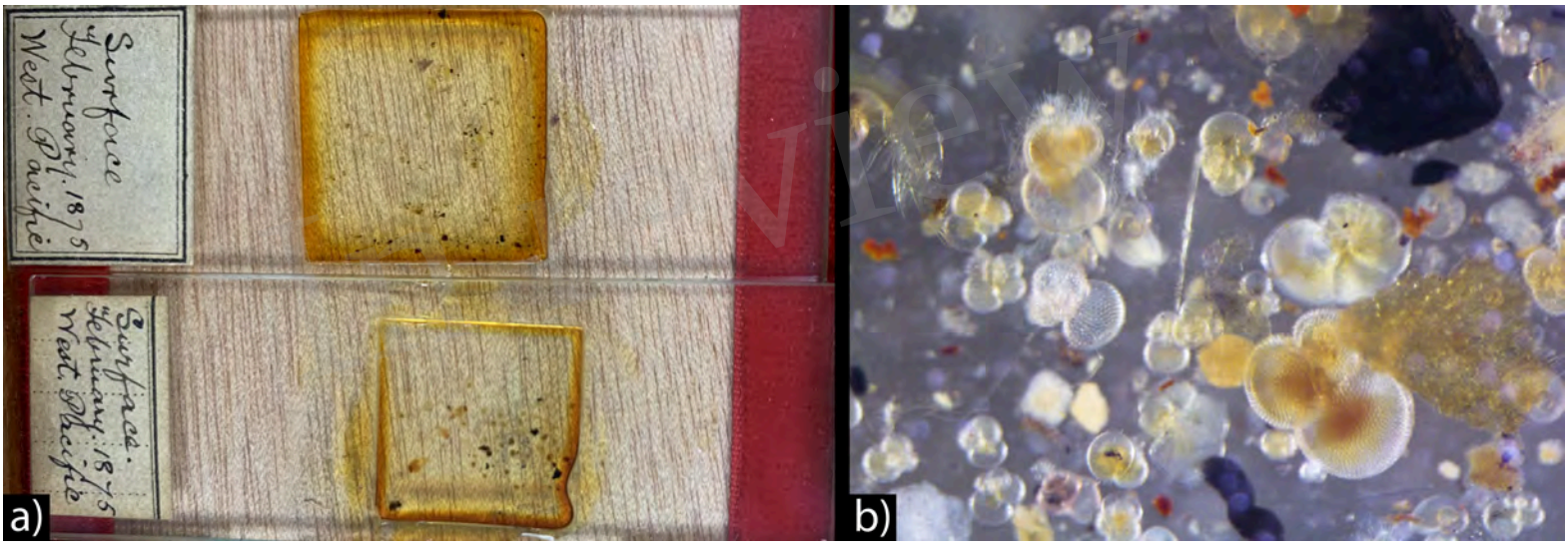

Figure 2.JPEG

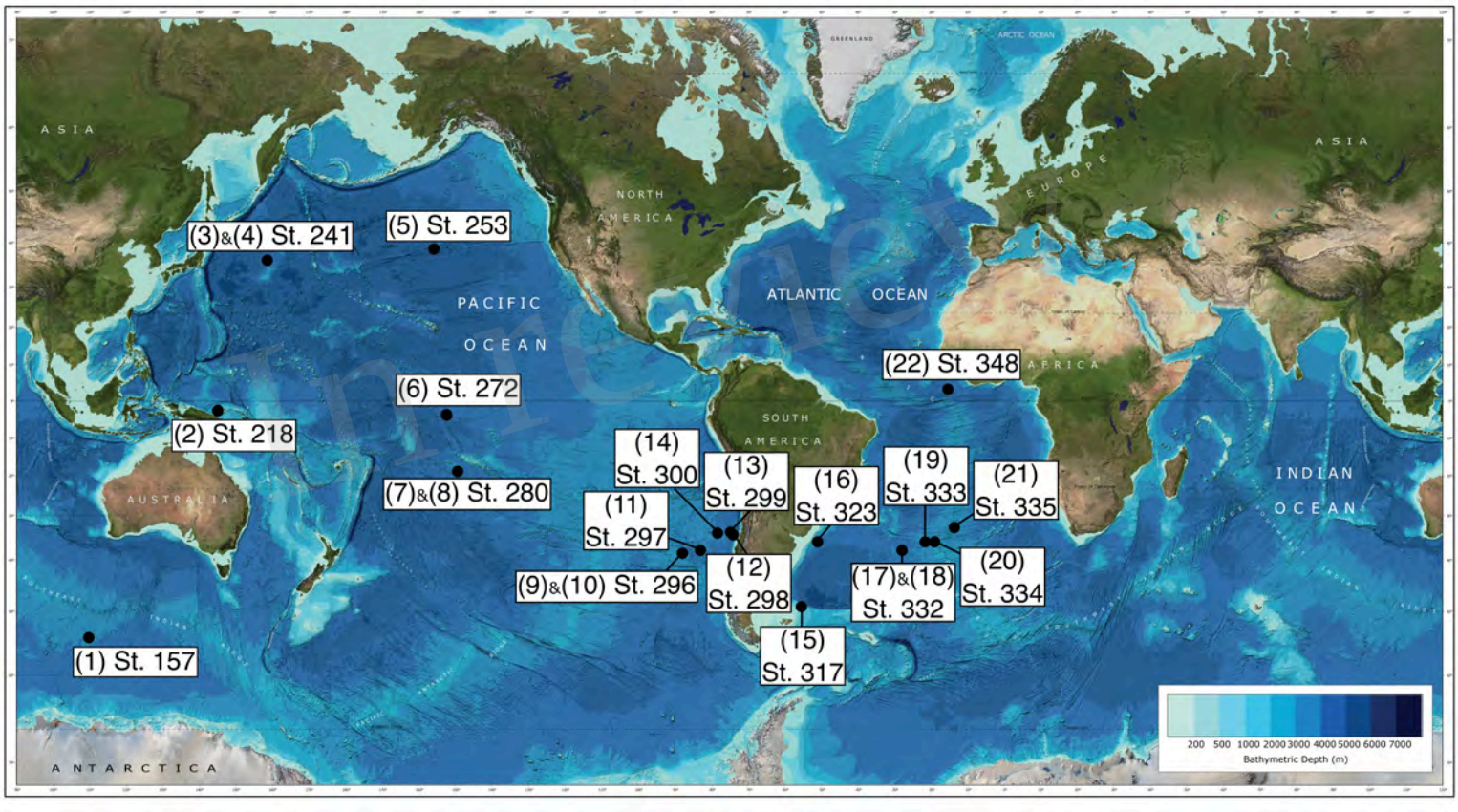

Figure 3.JPEG

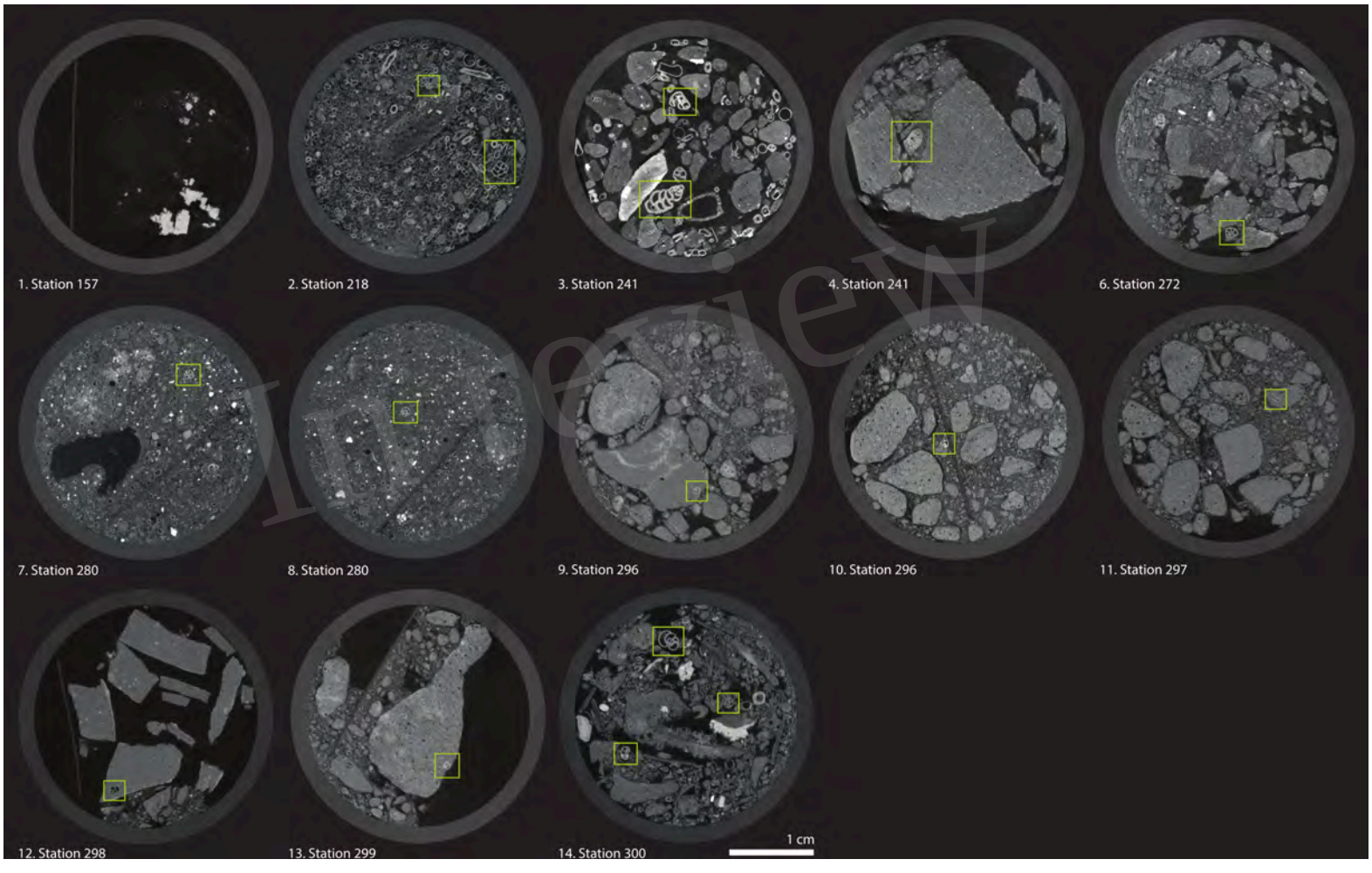

Figure 4.JPEG

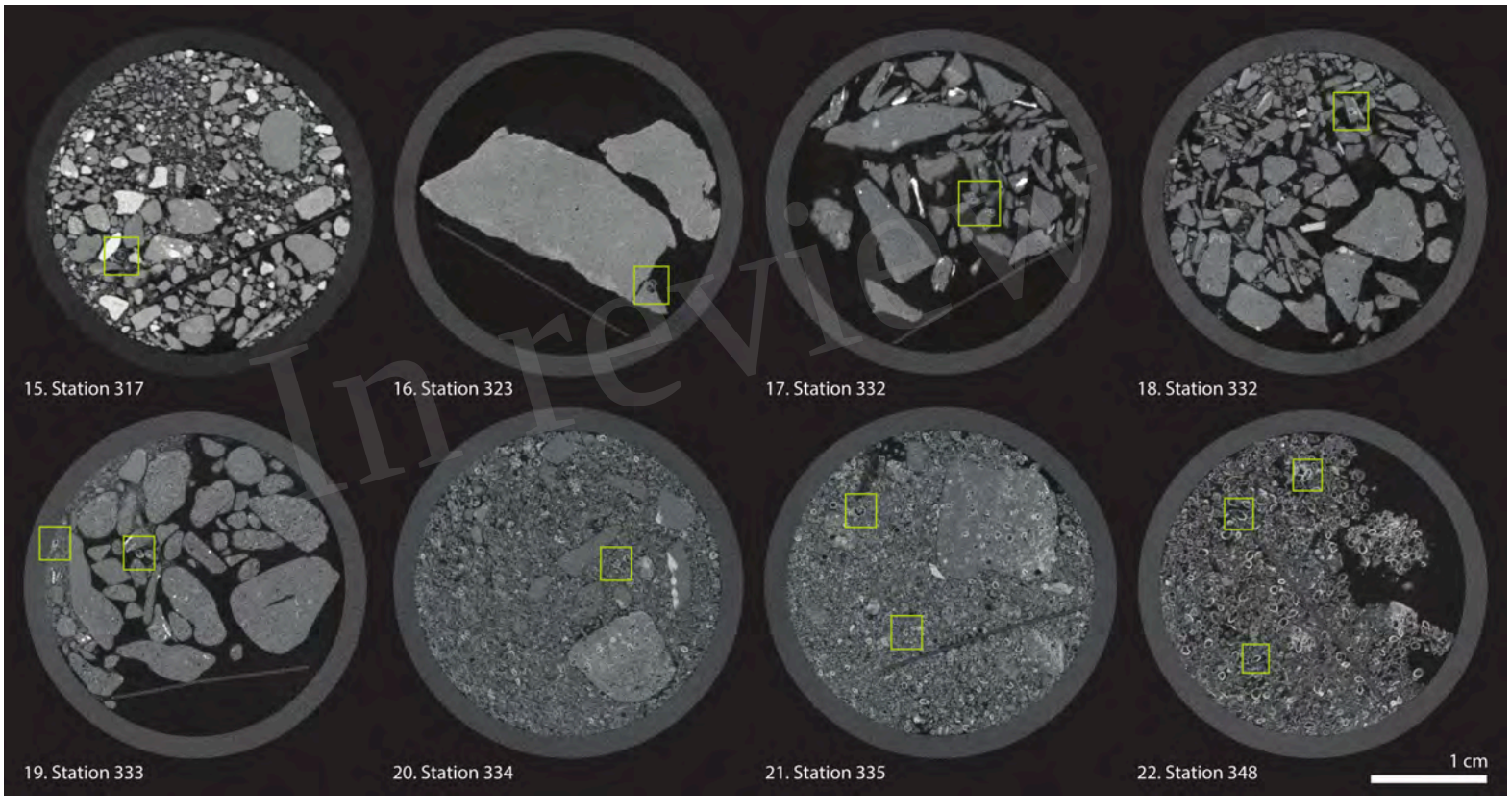

Figure 5.JPEG