Ostracod and Foraminifer Responses to Late Pleistocene–Holocene Volcanic Activity in Northern Victoria Land as Recorded in Ross Sea (Antarctica) Marine Sediments

Gianguido Salvi [1], Romana Melis [1,*], Paola Del Carlo [2] and Alessio Di Roberto [2]

[1] Dipartimento di Matematica e Geoscienze, Università di Trieste, Via E. Weiss 2, 34127 Trieste, Italy
[2] Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa, Via C. Battisti 53, 56125 Pisa, Italy
* Correspondence: melis@units.it

Abstract: The impacts on ostracods and foraminifers caused by three Late Quaternary ashfalls of different intensities and recovered in the ANTA02-NW2 core sediments (Drygalski Basin, western Ross Sea) were analysed for the first time. Albeit with different timing, both associations demonstrated similar response patterns associated with the deposition of material from volcanic eruptions. In particular, based on the palaeontological evidence, it was possible to divide the cores into four intervals/phases recording the evolution of the ecosystem before and after the deposition events: (1) Pre-extinction phase (high abundance and high diversity values). (2) Extinction phase, characterised by the complete disappearance of ostracod fauna; the foraminiferal assemblage, although not entirely absent, records extremely low values of abundance and diversity (survivor assemblage). (3) Recovery phase (increasing abundance and diversity values), characterised by the recolonisation of some opportunistic taxa; species such as *Australicythere devexa* and *Australicythere polylyca* dominate the ostracod assemblage. (4) Post-extinction phase (high abundance and high diversity values), with the return to an environmental equilibrium characterised by the colonisation of specialised taxa such as *Argilloecia* sp., *Cytheropteron* sp., *Echinocythereis* sp., and *Hemicytherura* spp. Our results may aid in the understanding of how communities (i.e., ostracods and foraminifers) recovered after the impact of direct deposits of volcanic ash into ocean waters. The mechanisms by which disappearance and/or mortality was induced are still not clear. The release of toxic metals during the reaction of the volcanic ash with seawater, the resulting chemical alteration in the seawater, and the change in pH, together with the possible suppression of planktonic organisms, may have caused the two main extinction phases recorded by the ANTA02-NW2 core sediments.

Keywords: ostracods; foraminifers; Drygalski Basin, western Ross Sea shelf; volcanic ashfalls; ecosystem evolution

1. Introduction

Phenomena such as extinction events and other short-term environmental crises have affected evolution on Earth. The aftermath of these events represents an extraordinary phase in evolutionary history, and understanding the nature and timing of biotic recovery is a fundamental challenge, even in light of the effects of pervasive human activities, which have consequences similar to those of major natural disasters [1]. The investigation of how animal communities reacted to rapid and intense past environmental changes, along with post-crisis faunal recovery, requires precise study based on different, abundant, and easily fossilised groups in order to understand origins and the organisation of present-day ecosystems [2]. In this sense, the remote and hostile Southern Ocean can represent a key area, as it hosts a diverse and rich community of life that thrives in an environment that is also dominated by glacial phenomena and strong currents. This is

particularly the case in complex ecosystems such as the Antarctic seas, where many factors—such as glacial and other oceanographic effects—are present in tandem [3]. Marine biological studies in these areas date back to the 19th century, but despite this long history of research, there is a paucity of data regarding the complex interactions between the highly seasonal physical environment and the species that inhabit the Southern Ocean [4]. In addition, results from various studies show that a number of environmental factors, sometimes interacting and operating at different spatial scales, are responsible for the structure of benthic assemblages on the Ross Sea shelf [5,6]. At the same time, the influence of multiple forcing factors operating at different levels has been inferred for Antarctic shelf communities [7–9] and has subsequently been supported by several studies, albeit at slightly different spatial scales [10–12].

Among the abovementioned drivers, volcanic eruptions may play a significant role in changes to the benthic assemblages influencing species' appearances, disappearances, and diversification. In this sense, several studies have analysed the impacts of volcanic eruptions on the environment and biodiversity, as well as the biotic effects of ashfalls and other short-term environmental crises on benthic marine invertebrates, both in recent and past environments [13–22]. In particular, the authors of [13,23] are the only researchers to have dealt with the modern Antarctic environment (Deception Island volcano), but no study has yet addressed older time intervals, where numerous studies have highlighted the abundant presence of marine tephra layers in Late Quaternary sedimentary successions [24–29].

Among the marine invertebrates, one group of tiny crustaceans—the ostracods—has an excellent fossil record and is among the few groups that can be equally (palaeo)environmentally informative in both marine and non-marine realms; as such, they are widely employed as palaeoenvironmental, palaeoclimatic, palaeoceanographic, and biostratigraphic indicators [30–34]. These investigations of modern and recent regional distribution from the shelf, slope, bathyal, and abyssal environments indicate that their distribution is strongly influenced by the physicochemical characteristics of water masses (e.g., temperature, salinity, nutrients, dissolved oxygen, water chemistry, etc.) and by the substrate type and food supply [35–38].

Conversely, less attention has been paid to the responses of ostracods to environmental crises linked to pyroclastic fall deposits, often highlighting the correlation between volcanic episodes, suppliers of nutrient-rich habitats, and the diversification of ostracods [39]. In particular, several studies have analysed the possible correlation between volcanic episodes and the diversification of ostracods in Ordovician sections in North America and Wales [40–42]. Hints et al. [43] demonstrated that the ostracod assemblage underwent a major reorganisation, including the replacement of dominant taxa, a drop in abundance and diversity, and the extinction of several species at the event level. By analysing the effects of submarine volcanism on ostracod fauna from Kagoshima Bay, [44] recorded how volcanic ash appears to favour the development of ostracod populations. Conversely, fumaroles and hot springs decrease the pH values of the water, severely restricting the development of ostracod populations.

The evidence regarding ostracod fauna coming from the analysis of some sedimentary sections of Sandbian age in northwest Estonia shows that significant ashfalls led to the marked rearrangement of assemblages and extinction of some taxa, while less prominent volcanic episodes resulted in only temporary changes in the assemblage structure [45]. More recently, [46] analysed ostracods and foraminifera from the succession of the Late Quaternary La Starza terrace located within the Campi Flegrei caldera, verifying how the abundance and diversity of organisms with calcareous hard parts decrease in the proximity of a hydrothermal vent, where pH and calcium carbonate saturation may be low and pCO_2 high.

Like ostracods, the foraminifers are known for their use in diverse applications, mainly ranging from biostratigraphy, palaeoecology, and palaeoceanographic and ecological studies concerning biomonitoring. They are abundantly present in modern and

ancient brackish water and marine environments. Their distribution is strongly controlled by the physicochemical characteristics of water masses and by the substrate type and food supply, similar to ostracods [47]. As regards palaeoecological studies, foraminifers are very important in the polar areas, where they are used to reconstruct the variations in oceanographic conditions (when using planktonic foraminifers) or to examine the palaeoenvironments (using benthic foraminifers) linked to the variation in the extension of the ice shelves/sheets affecting the continental shelves during the Late Quaternary [48–51].

In this sense, knowledge of the ability of foraminifers to react to extreme (or catastrophic) (palaeo)environmental adversities is important for palaeoecological interpretations. At any rate, the responses of foraminifera to environmental crises linked to volcanic activity have not been thoroughly examined in Antarctica, except for the studies by [13] and [23]. The authors studied the effects of some recent volcanic eruptions on Deception Island (South Shetlands, Antarctica) on the foraminifers, with the results indicating that water turbidity and substratum texture are the major factors affecting their distribution. Comparing data from the 1970s [13] with those from 2000 [23], they found that the foraminiferal community stabilised approximately 6 years after the last volcanic eruption.

The impacts of pyroclastic fall deposits identified in core ANTA02-NW2, composed of Late Pleistocene marine sediments sampled from the northern Drygalski Basin (northwestern Ross Sea continental shelf) [26], allowed us to investigate for the first time the responses of two different benthic taxa in the Ross Sea area (ostracods and foraminifers) to the eruptive activity in the Melbourne Volcanic Province of northern Victoria Land.

In particular, this paper aims to investigate the following:

1. The effects of the deposition of the tephra derived from explosive volcanic eruptions on ostracods and foraminifers;
2. In relation to their response, to demonstrate the dynamics of the diverse phases of the communities in relation to the time of the tephra deposition (i.e., reduction, recolonisation, opportunistic species, and climax phases);
3. To verify similarities or differences, if any, in the behaviour of ostracods and foraminifers in relation to volcanic events.

The Drygalski Basin (DB) is the deepest basin in the Ross Sea, reaching a bathymetry of over 1000 m. It is divided by a threshold into two sectors: the southern basin and the northern basin. In the northern DB, the ice sheet never reached a latitude of 74° N during the last glacial [52,53], but it was influenced by an ice stream, as evidenced by its geomorphological characteristics: mega-scale glacial lineations (MSGLs) and the grounding-zone wedges (GZWs), which highlight the stasis period of the ice stream [53]. This area has been the site of intense and recurrent volcanic activity with large explosive eruptions occurring during the last 150 ka (see [26] and references therein). Volcanic activity has produced abundant and widespread subaerial fallout deposits found in the region's outcrops and embedded in the ice sheets. Records of Late Pleistocene–Holocene subaerial volcanic activity in Victoria Land are also present in marine sediments from the Ross Sea, which contain several tephra layers. Previous studies on Ross Sea marine sediments, including ^{39}Ar-^{40}Ar and radiocarbon dating, suggest that thick marine tephra was emplaced from the Late Pleistocene [26] to historical times [27]. The volcanoes of the Melbourne Volcanic Province are considered to be the most likely sources for these tephra layers on the basis of volcanological, geochemical, and age constraints. In particular, most tephra deposits are derived from eruptions of Mount Melbourne and Mount Rittmann.

2. Materials and Methods

2.1. Sediment Analyses

Core ANTA02-NW2 (73.086° S, 170.918° E, length 300 cm; thereafter NW2) was collected north of Coulman Island in the northern Drygalski Trough at a depth of 588 metres in 2002, during the XVII PNRA cruise, and investigated from the micropalaeontological point of view within the framework of the project "Late quaternary paleoclimatic evolution in Southern Ocean sediments" (Figure 1).
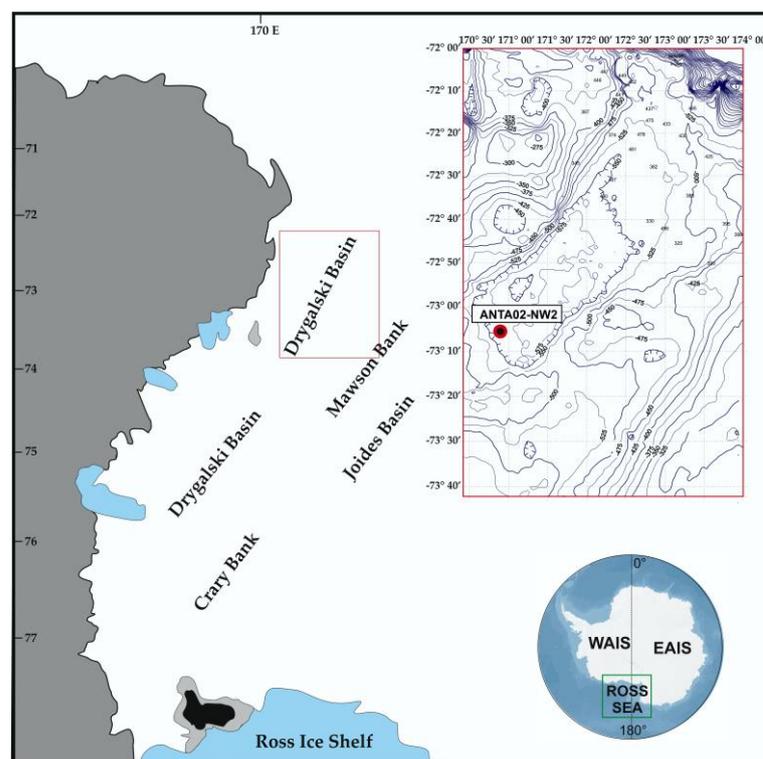

Figure 1. Study area with the location of core ANTA02-NW2 collected in 2002 during the XVII PNRA cruise. The detailed map of the study area is shown in the red inset. Map created using [54] with modified bathymetry. Isobaths every 25 m.

The core was split into two halves, X-rayed, and sampled. Several measurements and analyses were performed on the sediment, including magnetic susceptibility, water content, grain size, and organic C content, as already discussed in [55]. For the purposes of this work, we used only the particle size aspect together with the microfossils.

Three primary pyroclastic fall deposits were identified in core NW2, the elements of which were studied from a compositional, sedimentological, morphological, and chronological point of view in [26]. From the bottom to top of the core, they were as follows:

- Interval 0–13 cm: 13 cm thick, poorly sorted, massive coarse ash–medium lapilli of trachytic composition;
- Interval 213–230 cm: 17 cm thick massive–normally graded bed of well-sorted medium ash of trachytic composition;
- Interval 255–265 cm: 10 cm thick massive lens of poorly sorted coarse ash–lapilli with trachytic–phonolotic composition.

The core was sampled every 10 cm, and the sampling was refined in the proximity of the volcanic intervals recognised by [26] (i.e., core intervals 0–13, 213–230 and 255–265 cm), in order to conduct a more detailed study of the behaviour of ostracods and, subordinately, foraminifers. Fifty-eight (ostracods) and forty (foraminifers) samples, each comprising 1 cm thick core sections, were taken from along the core (Supplementary Tables

S1 and S2). The sediment samples used for ostracod and foraminifer analyses were disaggregated in warm water, gently washed through a 62.5 μm sieve, and subsequently dried and weighed. The >62.5 μm fraction was examined for benthic ostracods. All ostracod specimens were dry-picked, counted, and identified, following the taxonomy of the Antarctic benthic ostracod systematic method [56–69]. The number of specimens refers to both valves and carapaces, i.e., one separated valve is considered to be one specimen and one articulated carapace is one specimen [69]. As described in [70,71], a life assemblage was considered to be an autochthonous thanatocoenosis, and a death assemblage (subjected to postmortem transport and other processes, e.g., [72,73]) was considered to be an allochthonous thanatocoenosis. In this sense, we considered autochthonous ostracod assemblages represented by living specimens or dead ones with left and right valves or complete carapaces of the adults, together with their immature instars, as life assemblages. Conversely, death assemblages (allochthonous thanatocoenosis) were represented by valves from adults without juveniles or juveniles without adults, or by specimens showing evident signs of allochthonous taphocoenosis (e.g., fragmented and/or abraded shells). Only autochthonous assemblages were taken into account. The ostracods and foraminifers discussed in the present paper are archived in the repository of the Department of Mathematics and Geosciences, University of Trieste. Foraminifers were studied using the same samples. When the foraminifers were abundant, the samples were subdivided using a dry splitter until an aliquot containing approximately 300 specimens was obtained. In samples containing fewer than 300 specimens, all benthic and planktonic foraminifers were counted and identified. The species counts were carried out on well-preserved specimens and recorded as the number of specimens of each taxon; these data were subsequently converted into a frequency expressed as a percentage. The identification was mainly as described in [74–76].

2.2. Data Analysis

To characterise the biodiversity of assemblages, three faunal parameters were calculated for both groups at each studied level: (1) species richness (Taxa_S), (2) abundance (specimen/g of observed sand), and (3) the Shannon index (Shannon_H). A cluster analysis of the ostracods was run for the samples (Q-mode). The best results were achieved using Ward's clustering algorithm with the Bray–Curtis distance method. An orthogonally rotated (varimax) Q-mode principal component analysis (PCA) was used to elucidate the distribution of the benthic foraminifers. The relative frequency of the taxa with an occurrence of at least 2% of the total foraminiferal assemblage in at least two samples was used. This procedure left 38 species and 3 genera. The calculated PC scores indicate the contribution of the foraminifer species for each PC; consequently, taxa pertaining to the same PC were considered to have similar palaeoenvironmental conditions. Only the PC loadings that exceeded a value of 0.4 were considered statistically significant, as suggested by [77]. Multivariate analyses (clustering and PCA analyses) on ostracod and foraminiferal assemblages were performed using Addinsoft XLSTAT software (2020), except for the calculation of diversity indices, which was carried out using the PAST (version 4.07) (PAlaeontological STatistic) data analysis package (https://www.nhm.uio.no/english/research/resources/past/) (accessed on 12 December 2022) [78]. Figures were produced using OriginPro, Version 2021b (OriginLab Corporation, Northampton, MA, USA) and CorelDRAW version 17.1.0.572. All ostracod taxa subjected to statistical analysis were previously standardised using the weights of the observed samples.

3. Results

3.1. Ostracods

The ostracod fauna from the analysed levels of core NW2 consisted of 33 species (Table S1), and 6 species were recorded in open nomenclature. The ostracod assemblage was dominated by the well-preserved cytheracean taxa. The most abundant species recovered

were *Australicythere devexa*, *Australicythere polylyca*, *Cativella bensoni*, *Cytheropteron* sp., *Echinocythereis* sp., *Loxoreticulatum fallax*, *Pseudocythere* aff. *P. caudata*, and *Xestoleberis rigusa*; other taxa represented by *Argilloecia antarctica*, *Hemicytherura* spp., *Krithe* spp., *Myrena meridionalis*, *Nodoconcha minuta*, and *Patagonacythere longiducta* showed lesser quantitative values (Table S1). The Shannon_H values ranged between 0 in some precise intervals (i.e., 1.5–10.5 cm, 127.5–141.5 cm, 208.5–239.5 cm, and 243.5–248.5 cm) and 2.31 at 28.5 cm. High values were also recorded from the top to the bottom of the core inside levels 11.5, 38.5, 91.5, and 287.5 cm (Figure 2). The overall Shannon_H value was not particularly high, revealing an ostracod assemblage characterised by low qualitative and quantitative values. Species richness and abundance showed a similar trend, with the highest values recorded in the bottom core levels. The Q-mode cluster analysis performed on the ostracod assemblages of the NW2 core levels identified three groups of samples (Figure 3) characterised by increasing abundance and richness values (from Cluster 1 to Cluster 3, respectively), with the highest values of ostracod fauna recorded in the lower part of the core. Cluster 1 includes all free-species levels. Within Cluster 2, the dominant species were *A. devexa*, *A. polylyca*, *Echinocythereis* sp., and *L. fallax*; in Cluster 3, they were *A. devex*a, *A. polylyca*, *C. bensoni*, *Cytheropteron* sp., *Echinocythereis* sp., *L. fallax*, *Krithe* sp., *P.* aff. *P. caudata*, and *X. rigusa*.
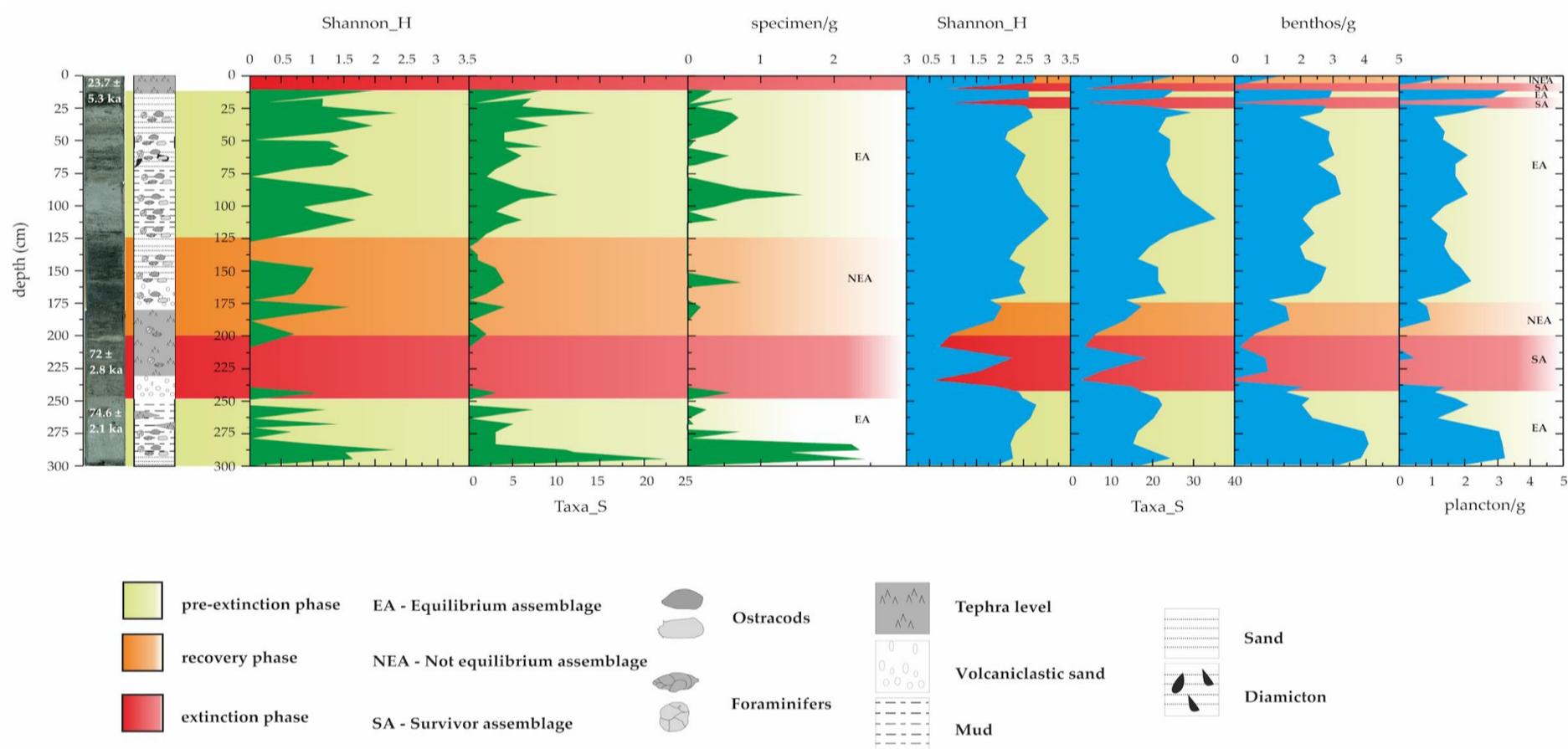
Figure 2. From left to right: down-core of distribution ostracods (in green) and foraminifers (in blue) in terms of Shannon diversity index (Shannon_H), species richness (Taxa_S), and total abundance (>63 μm fraction) in the number of specimens per gram of dry sediment in core ANTA02-NW2. Specimen/g, plankton/g, and benthos/g values are reported in logarithmic values to simplify the reading of the data, because of the high difference in numerical terms from the bottom to the top core levels. The different ecological intervals concerning the ostracod and foraminiferal behaviour in relation to volcanic events are shown (EA = equilibrium association; SA = survivor association; NEA = non-equilibrium association). For details, see the legend in this figure.
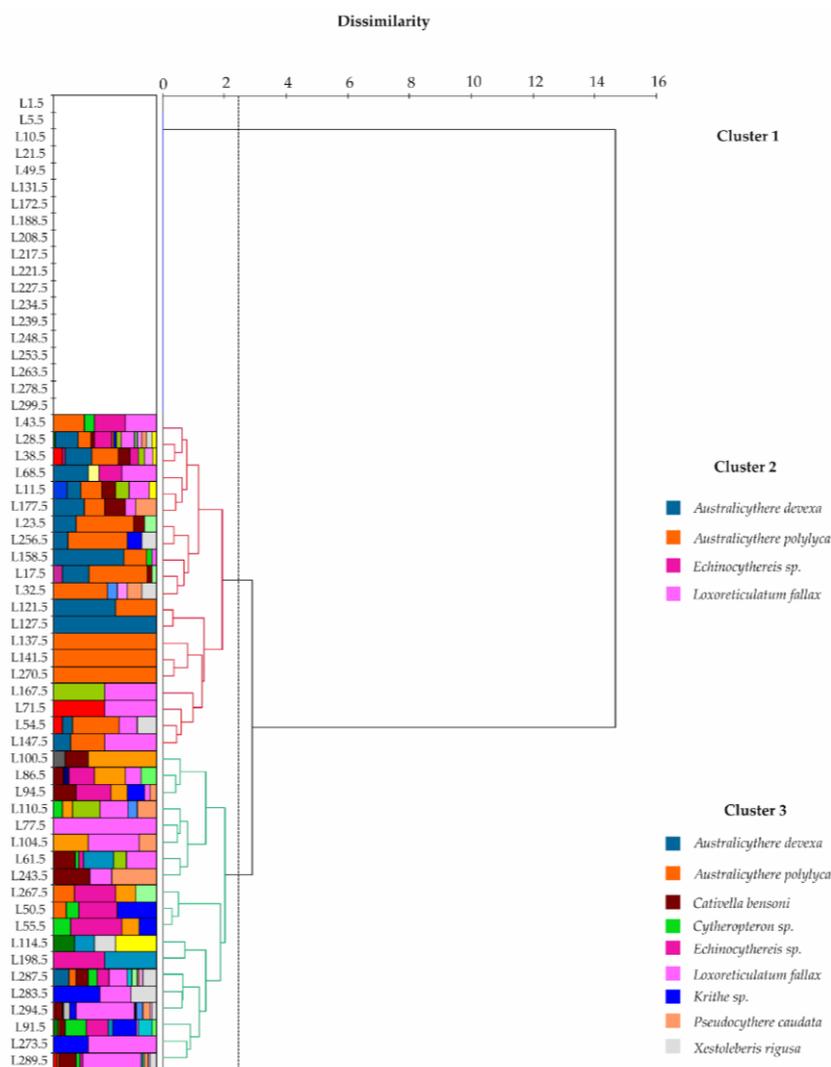
Figure 3. Q-mode cluster analysis (Ward's method; Bray–Curtis algorithm): the dominant species for each cluster are reported. Levels are given in cm.

3.2. Foraminifers

The foraminifers of the studied core consisted of 66 species pertaining to 44 genera (Table S2); species of *Fissurina*, *Fursenkoina*, *Lagena*, and *Oolina* were collectively grouped as species plurimae (spp.). Planktonic foraminifers were exclusively represented by *Neogloboquadrina pachyderma*. Several broken and damaged tests were observed in correspondence with the tephra intervals (fragmentation > 30%), but well-preserved specimens dominated the rest of the studied interval. The benthic foraminifers (abundance varying from 12,162 specimens per studied gram; average 1024 specimens/g) were more abundant than the planktic ones (varying from 0 to 2131 specimens/g, average 223 specimens/g). Although their concentrations were different, they followed the same pattern as the benthic foraminifers throughout the core. Very high foraminifera density was observed at the bottom core, while lower density corresponded to the tephra intervals (Figure 2).

Benthic taxa were present throughout the core; among them, only three species (*Globocassidulina biora*, *G. subglobosa*, and *T. earlandi*) occurred in almost 80% of the studied levels. Among them, the most abundant species, in decreasing order, were *G. biora* (mean value 16.8%), *G. subglobosa* (m.v. 15.4%), *T. earlandi* "*costatae*" (m.v. 12.3%), *Epistominella exigua* (m.v. 8.4%), and *Nonionella bradii* (m.v. 5.9%). Agglutinated taxa, mainly represented by *Miliammina earlandi* and subordinately by *Rhabdammina abyssorum*, prevailed in

the tephra intervals. The Shannon_H values ranged between 0.53 and 3.03. Values over 2.0 were common in the core, while they strongly decreased in the tephra intervals, where the dominance reached higher values (Figure 2).

The four PC scores used in this study explained 79.1% of the total variance in the benthic foraminifers' dataset. These four most significant PCs are referred to here as foraminifer associations (FAs) using the name of the dominant taxon (Supplementary Table S3). They are *Globocassidulina biora* FA, with a high positive *T. earlandi* score, explaining 36.8% of the variance; *G. subglobosa* FA, with a high positive *Cassidulinoides parkerianus* score, explaining 19.7% of the variance; *Epistominella exigua* FA, with high positive *Nonionella* spp. score, explaining 13.1% of the variance; and *T. earlandi* FA, with a high negative *G. biora* score, explaining 9.5% of the variance.

4. Discussion

4.1. Ecological Evolutionary Phases in Sediments from Core NW2

Natural disturbances, such as droughts, fires, hurricanes, or volcanic eruptions, represent key drivers of ecological heterogeneity and ecosystem function. Any of these disturbances could have minor or major pervasive effects on individuals, populations, and communities of vertebrates and invertebrates of all realms, biomes, continents, and ecosystems [79,80]. Their incidence and severity offer unique opportunities for researchers to study and analyse their effects on the ecosystems and organisms therein [81]. In particular, there is still an open debate on the effects derived from the deposition of volcanic ash on the habitats of the fauna living in the water column and within/on the sediments. The ecological impact of its deposition may be relevant not only because of the increased turbidity and sediment accumulation that characterise these events, but also because of the chemical-compositional aspects of the volcanic sediments. Indeed, the surface of airborne volcanic ash particles is often and variably encrusted with highly soluble metal salts (e.g., fluorides, chlorides, and sulphates) and acidic brines derived from magmatic gases (e.g., HF, HCl, and SO_2) contained in the volcanic plumes. These salts rapidly dissolve in seawater and release bioavailable ions, affecting primary productivity and acting as nutrients or pollutants for biomass, depending on their concentration [82]. Ions such as K, P, Mg, and Fe can rapidly fertilise marine ecosystems [82–86]. For example, the Iceland Basin marine region was fertilised due to a significant aerosol input of Fe during the 2010 Eyjafjallajökull volcanic eruption [87]. Conversely, high concentrations of ions dissolved from the surface of volcanic ash, such as Cl, F, Al, As, Cd, Cr, Cu, Pb, Se, and Zn, can provoke short-term chemical alteration in seawater and changes in pH that can be toxic to biomasses [84,88,89].

Finally, account must be taken of the marked environmental changes on the seafloor to small meiofauna (e.g., ostracods and foraminifers) affected by the sudden deposition of the abundant materials of different shape and composition released by volcanic eruptions [90] and by volcanic ash, which lacks oxygen [91] and organic matter [20].

In this sense, for the first time, our findings regarding several volcanic ash deposits in Late Quaternary sediments of core NW2 and the contemporary relationships between volcanic events and the disappearance of ostracods and foraminifera taxa allowed us to summarise over time the different stages and mechanisms of extinction, recovery, and return to pre-crisis conditions. On the basis of the micropalaeontological and statistical analyses, core NW2 was divided into five intervals recording the following ecological evolutionary phases:

Interval 300–257 cm (pre-extinction phase): Except for the basal level of the core, which was barren of ostracod fauna (299–300 cm), this interval showed high diversification of both ostracods and foraminifers in the lower sediments (295–257 cm), with notable values of all biotic parameters (i.e., abundance, species richness, Shannon_H) (Figure 2). Moreover, within this interval, a barren level of ostracods was reported at 279 cm. The ostracod assemblage was characterised mainly by *A. devexa*, *A. polylyca*, *C. bensoni*,

Cytheropteron sp., *Echinocythereis* sp., *L. fallax*, *Krithe* sp., *M. meridionalis*, *P.* aff. *P. caudata*, and *X. rigusa*. As far as foraminifers are concerned, this interval was represented by *E. exigua* FA (Figure 4), significantly accompanied by *Nonionella bradii* and *N. iridea*. Within this interval (255–265 cm), [26] found two lenses of tephra dated 74.6 ± 2.1 ka.
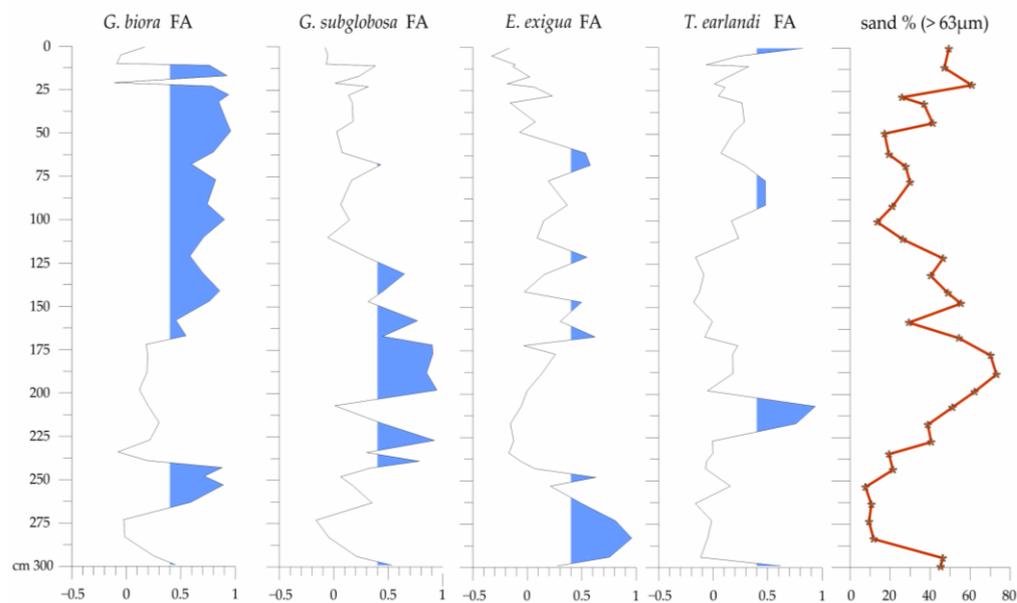

Figure 4. Down-core distribution of the foraminiferal assemblages (FAs) calculated by the principal component analysis (statistically significant loadings as suggested by [77] are shown in blue), together with the percentage of sand in the sediments.

Interval 254–208 cm (extinction phase): This section was characterised by a major crisis period where the ostracod abundance and diversity abruptly decreased, except for the levels 244, 199, and 178 cm, characterised by a few specimens belonging to *A. polylyca*, C. *bensoni*, *L. fallax*, and *P.* aff. *P. caudata*. All other levels were characterised by the absence of ostracod fauna (Figure 2). With some delay compared to ostracods, foraminifers from 234 cm also started to indicate an environmental crisis, evidenced by reductions in the Shannon_H index and density, followed by a fluctuating condition until 199 cm, after which the biotic index and the foraminifers' density both increased. In contrast to ostracods, foraminifers reduced in richness and abundance but did not disappear totally. This interval marks the increased significance of the *G. biora* FA at the base, followed by the *G. subglobosa* and, partially, *T. earlandi* FAs from 240 and 217 cm, respectively (Figure 4), indicating that these species were able to survive this environmental disturbance. Within this interval, from 213 to 230 cm, [26] found a 17 cm thick bed of massive ash dated 72.0 ± 2.8 ka. In correspondence with this volcanic deposition, the foraminifers *Miliammina earlandi* and *M. lata* were the only agglutinate foraminifers present. *M. earlandi* reached its highest relative frequency in this interval.

Interval 198–122 cm (recovery phase): This interval, marking the reappearance of the ostracod fauna, was characterised by a few dominant species, including *A. polylyca*, *C. bensoni*, *L. fallax*, and *P.* aff. *P. caudata*. Abundance, diversity, and Shannon_H showed low values (Figure 2).

Interval 114.5–21.5 cm (post-extinction phase): In the first part of this interval, the levels from 114.5 to 105.5 cm were dominated by the early colonisers *A. polylyca*, *C. bensoni*, *L. fallax*, *and P.* aff. *P. caudata*, likely representing opportunistic taxa that quickly adapted to the new environmental conditions. The next levels showed increasing values in all of the examined biotic parameters, together with the major occurrence of *Argilloecia* sp., *Cytheropteron* sp., *Echinocythereis* sp., *Hemicytherura* spp., *Krithe* sp., *M. meridionalis*, *N. minuta*, *P. longiducta*, and *Xiphichilus gracilis*.

Concerning foraminifers, their increasing presence occurred in tandem with the ostracods (from 168 cm), but unlike ostracods it was faster, since they were newly abundant and diversified until 28 cm. The recovery phase was represented by a decreasing importance of the *G. subglobosa* FA and, consequently, by the increasing significance of the *G. biora* and, subordinately, *E. exigua* FAs (Figure 4). The climax phase was reached at about 110–90 cm, where the maximum values of the Shannon index and richness were reached.

Interval 17.5 top core (new extinction phase): The upper part of the core showed a clear and quick decrease in abundance, richness, and diversity values, with the disappearance of all ostracod species toward the top of the core. The last appearance datum showed an ostracod association dominated mainly by *A. devexa*, *A. polylyca*, *C. bensoni*, and *L. fallax*. This new environmental crisis was also recorded by foraminifers. This interval corresponded to the deposition of the tephra dated 23.7 ± 5.3 ka by [26]. Although the authors recognised a 13 cm thick tephra layer (0–13 cm bsl), the foraminifers were in poor conditions in the levels 21.5 cm bsl and 10 cm bsl. Here, *Globocassidulina* spp. tended to decrease, while *T. earlandi* exceeded 20% in the topmost sediments. The only foraminifera that could survive were the agglutinated ones. In addition to *Miliammina* spp., there were also a few fragments of *Rhabdammina abyssorum* and rare specimens of *Ammodiscus incertus* in these intervals.

4.2. Analysis of the Ostracod and Foraminiferal Assemblages with Respect to the Intervals of Core NW2

The above data allowed us to define the palaeoenvironmental evolution of this area which, in turn, was characterised by the reduction in the abundance of the more sensitive species, the survival of the most resilient species (opportunistic, r-strategist) typical of the crisis phases (i.e., extinction and recovery), and the recovery of the equilibrium fauna characteristics of the pre- and post-extinction phases (Figure 5).
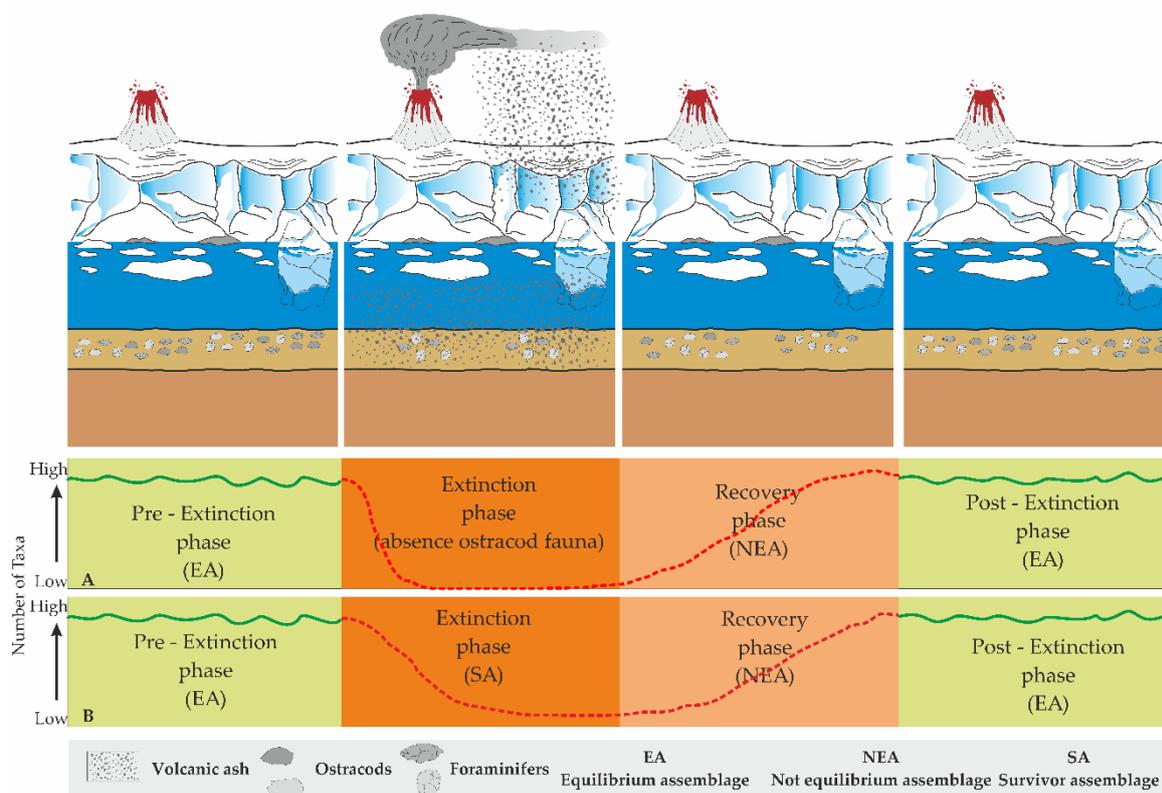

Figure 5. Conceptual scheme, modified from [92], summarising the different stages of extinction, recovery, and return to pre-crisis conditions recorded in the ANTA02-NW2 core sediments. The

lower part of the figure highlights the different reactions to volcanic ash deposition of the ostracod (**A**) and foraminifer (**B**) assemblages. For details, see the legend in this figure.

Research conducted on ostracods in the Southern Ocean is scarce and has mainly investigated how primary productivity in the euphotic zone may influence biodiversity on the seabed at abyssal depths [93]. Numerous authors [69,93–97] have examined the bathymetric and geographic distribution of benthic ostracods in several samples from the Southern Ocean and Antarctica and discussed the factors controlling their distribution by testing the ecological preferences of ostracod genera, as widely used in palaeoceanographic reconstructions [98]. In the Ross Sea area, the study of recent and fossil ostracod associations is even rarer, especially concerning taxonomic contributions [57,99–101]. More recently, the distribution of fossil ostracod and foraminiferal fauna in a sedimentary sequence collected from a northwestern Ross Sea carbonate-rich deposit was analysed for the reconstruction of the palaeoclimatic and oceanographic variations during the Late Quaternary in [50], while for the first time [102] studied the recent ostracod assemblages of the western Ross Sea, correlating abundance and richness values with nutrient distribution and sediment supply, primarily related to the circulation of different oceanographic regimes affecting the floor of the Ross Sea shelf.

In contrast, foraminifers are more extensively studied in Antarctica, especially in the Ross and Weddell Sea environments (e.g., [49,50,76,103–105] and references therein), although current data are still lacking.

The Antarctic shelf benthos is impacted by a wide variety of physical and devastating disturbances, mostly linked to Antarctic ice, but also associated with high wind and wave action, hypoxia, volcanism, etc. [5]. For the first time, an analysis of the volcanic events recorded in core NW2 offers the opportunity to analyse how volcanic events can cause environmental disturbances as a result of the post-eruptive deposition of volcanic ash on benthic ostracods and foraminifers. To this end, the studied core highlighted well-defined intervals defined by (1) a dominant association immediately preceding the pre-extinction and post-extinction recovery phases (non-equilibrium association (NEA), (2) a survivor association (SA) specifically for foraminifers, and (3) a climax association characterising the pre- and post-extinction phases (equilibrium association (EA) (Figure 2). The NEA among the ostracods was mainly characterised by *A. devexa*, *A. polylyca*, *C. bensoni*, *L. fallax*, *P.* aff. *P. caudata*, and *X. rigusa* (Figure A1 in Appendix A). As recently signalled by [102], all of these species are able to live in different shelf environments along an extensive range of water depths. More specifically, *A. polylyca*—an endemic taxon widely recorded in the modern Antarctic region [69,98]—was found at varying depths of the Ross Sea shelf (from 79 to 723 m) [102]. The finding of living specimens of this taxon in the deep areas of the continental shelf and slope shows that this species may be able to migrate vertically throughout the continental margin in a relatively short time [93,96,98]. Similarly, all ostracod species belonging to the NEA indicate (a) their ability to thrive at wide depth, salinity, and temperature ranges by allowing the colonisation of different shelf environments, and (b) the possible close link between the NEA diffusion and the nutrient intakes within the Ross Sea [102]. The NEA among the foraminifers was characterised mainly by a decrease in *E. exigua* and *G. biora* and a relative increase in *Cassidulina porrecta*, *G. subglobosa*, and M. *earlandi*. The SA was specifically defined only for the foraminifers that reduced their richness and diversity during ash accumulation but never disappeared. During these intervals (i.e., 235–199 cm and the topmost 20 cm), species such as *G. subglobosa*, *T. earlandi*, and *M. earlandi* were able to survive. *Globocassidulina subglobosa*, together with *G. biora* and *T. earlandi*, are commonly used to recognise past sub-ice-shelf facies (from proximal to distal) as indicative of a strong glacial influence (e.g., [49,76,104,106]). We believe that the *G. subglobosa* FA characterising this interval represents conditions of elevated or variable sedimentation rates due to the ash accumulation, indicating environmental instability. Noteworthy is the decrease in *G. biora* in these intervals. Although this species is also normally adapted to high rates of terrigenous sedimentation [49,50,76], in this case,

the increased accumulation of sediment of a volcanic nature dissuades its presence. *M. earlandi* is considered to be a residual species, as it is commonly related to an increased corrosivity of water masses [76], often indicative of open marine environments set during the Holocene in the Drygalski and JOIDES basins (e.g., [104]). In the case of core NW2, we argue that its occurrence indicates resilience to the increased corrosivity related to the chemical-compositional aspects of the volcanic sediments or the salts associated with them, which dissolve rapidly in seawater and can release ions that cause pH changes in the environment, as previously highlighted in the first part of this discussion. This is not consistent with the findings of [23], who studied the benthic foraminifers at Deception Island (Antarctica Peninsula), observing that *M. earlandi* (as *M. arenacea*) witnessed periods of long volcanic dormancy.

The EA recorded increasing abundance, diversity, and environmental recolonisation by numerous species that were already present in the pre-extinction period (Figure 2). This association was mainly represented by *Argilloecia* sp., *Cytheropteron* sp., *Echinocythereis* sp., *Hemicytherura* spp., *Krithe* sp., *M. meridionalis*, *N. minuta*, *P. longiducta*, and *X. gracilis* (Figure A2)—the first to fade out during tephra deposition and the last to occur after the post-crisis repopulation phase. All of these species are uncommon in the Ross Sea area [102], as already reported by several authors as endemic ostracod fauna in the Antarctic region [58,67–69,95,107,108].

The EA among the foraminifers was represented by a good diversification between the species, with the presence of *Astrononion* spp., *Cibicides* spp. (mainly *C. refulgens*), *Ehrembergina glabra*, *Fursenkoina* spp., *Nonionella* spp., and miliolids, which were absent or greatly reduced during the other phases. The EA interval recorded the significant occurrence of *E. exigua*, mainly where the sediments were finer (Figure 4); together with *G. biora.*, *E. exigua* is considered to be an opportunistic species that is able to feed on fresh phytodetritus but also adapted to food-limited settings ([109,110] and references therein). *G. biora* normally lives in Antarctic fjords and continental shelf settings from coastal to outer-shelf bathymetry [74,75,105], and in the past it has also been commonly used to recognise the sub-ice-shelf facies from proximal to distal (e.g., [49,76]).

Little is known regarding the ecology of ostracods in the Ross Sea area, except for a small number of studies that reported their presence in sediment cores [50,68] and in western Ross Sea surficial sediments [57,102]. In particular, *M. meridionalis*, *N. minuta*, *P. longiducta*, and *X. gracilis* were mainly found in the western Ross Sea area at the shelf break and near Terra Nova Bay, with constrained depth, salinity, and temperature range values [57,68,102]. These results could confirm and reinforce previous analyses in the western Ross Sea by identifying an opportunistic ostracod association (NEA) able to colonise diverse shelf environments ([102] and references therein). These adaptive traits may be linked to the need to migrate during the last glacial age, surviving within ice-free refugia and/or below the ice shelf [50,111] to pursue the distribution and flux of surface-derived food sources [102,112,113]. In this sense, ostracods and foraminifers could confirm their potential as bioindicators of the health status of marine environments, precisely recording the impacts on the marine ecosystem following volcanic tephra deposition and the dynamics of environmental recovery.

Finally, we observed a certain difference in the behaviours of the two taxonomic groups in response to disturbances due to volcanic sediment accumulation. In fact, foraminifers persist longer in the disturbance phases and still manage to survive with a reduced number of resistant species. Moreover, their recovery to a climax phase is much faster than that of ostracods. This behaviour may reflect both a diverse sensitivity to environmental disturbances and a different way of moving between ostracods and foraminifers; the former, being arthropods, certainly have a greater capacity for movement than foraminifers. In the phases characterised by the most significant disturbances, it is possible to assume that ostracods move to environments that are more favourable.

5. Conclusions

The Antarctic shelf environment is impacted by a wide variety of physical disturbances, the intensity and frequency of which is very variable. Current research is beginning to quantify the frequencies and forces of disturbance, recolonisation, and development of marine biota assemblages over ecological time, but it has yet to be understood exactly how these communities have coped with disturbances on evolutionary scales, or how resilient they will be to anthropogenically induced mutations. In this sense, for the first time in the Ross Sea, Antarctica, the impacts of three Late Quaternary ashfalls of different intensities in core NW2 were studied in order to analyse the recovery patterns of benthic ostracods and foraminifers.

The main results showed that the emplacement of tephra marked temporary changes in both taxa structures, pinpointed by well-defined ecological and evolutionary phases.

1. A pre-extinction phase, characterised by high faunal abundance and diversity values;
2. An extinction phase, marked by the complete disappearance of the ostracods; foraminifers, on the other hand, appear to be less sensitive than ostracods during volcanic episodes, recording extremely low values of abundance and diversity (SA assemblage);
3. A recovery phase, featuring few dominant opportunistic species (NEA assemblage);
4. A post-extinction phase, where the re-emergence (occurrence) of specialised taxa underlines the return to environmental stability (EA assemblage).

As reported by several authors for various taxa [22,114], the mechanisms by which disappearance and/or mortality were induced for ostracods and foraminifers are still not clear. It is not easy to ascertain whether it is the geochemical composition of the tephra that causes the reduction in population or, more likely, an associated effect of this on an increase in the sedimentation rate and turbidity of the water. Moreover, there is some evidence that the release of toxic metals during a reaction of the volcanic ash with seawater, causing chemical alterations in seawater along with the possible suppression of planktonic organisms (e.g., pteropods and planktic foraminifers; key constituents of the food chain) [115], may have caused the two main extinction phases recorded by the NW2 core sediments.

Appendix A

Figure A1. (NEA assemblage)—(**A**)—*Australicythere devexa*, lateral exterior view, right valve. (**B**)—*Australicythere polylyca*, lateral exterior view, left valve. (**C**)—*Cativella bensoni*, lateral exterior view, right valve. (**D**)—*Loxoreticulatum fallax*, lateral exterior view, left valve. (**E**)—*Pseudocythere* aff. *P. caudata*, lateral exterior view, left valve. (**F**)—*Xestoleberis rigusa*, lateral exterior view, right valve.
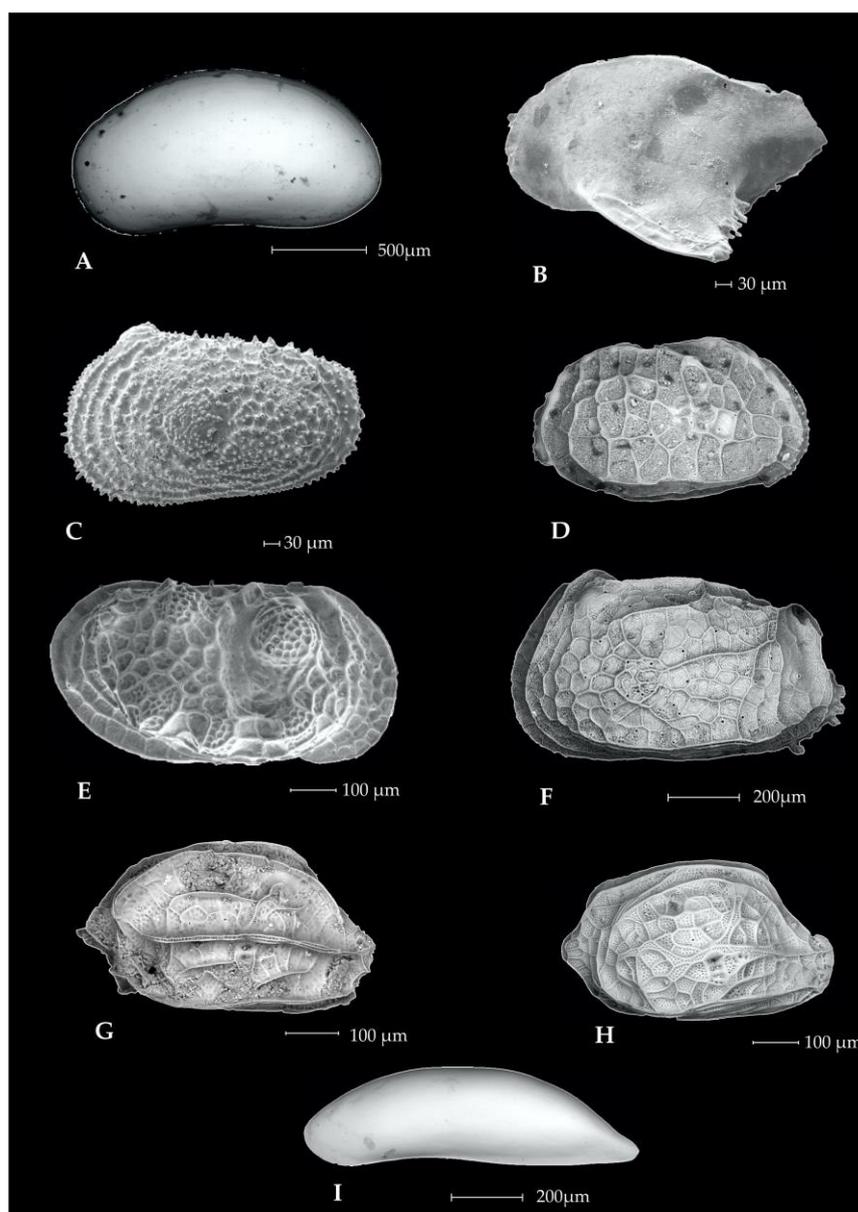
Figure A2. (EA assemblage)—(**A**)—*Argilloecia* sp., lateral exterior view, left valve. (**B**)—*Cytheropteron* sp., lateral exterior view, left valve. (**C**)—*Echinocythereis* sp., lateral exterior view, left valve. (**D**)—*Myrena meridionalis*, lateral exterior view, right valve. (**E**)—*Nodoconcha minuta*, lateral exterior view, right valve. (**F**)—*Patagonacythere longiducta*, lateral exterior view, left valve. (**G**)—*Hemicytherura anomala*, lateral exterior view, right valve. (**H**)—*Hemicytherura irregularis*, lateral exterior view, right valve. (**I**)—*Xiphichilus gracilis*, lateral exterior view, left valve.

References

1. Lowery, C.M.; Bralower, T.J.; Owens, J.D.; Rodríguez-Tovar, F.J.; Jones, H.; Smit, J.; Whalen, M.T.; Claeys, P.; Farley, K.; Gulick, S.P.S.; et al. Rapid recovery of life at ground zero of the end-Cretaceous mass extinction. *Nature* **2018**, *558*, 288–291. https://doi.org/10.1038/s41586-018-0163-6.
2. Hull, P.; Darroch, S.; Erwin, D. Rarity in mass extinctions and the future of ecosystems. *Nature* **2015**, *528*, 345–351. https://doi.org/10.1038/nature16160.
3. Gutt, J.; Bertler, N.; Bracegirdle, T.J.; Buschmann, A.; Comiso, J.; Hosie, G.; Isla, E.; Schloss, I.R.; Smith, C.R.; Tournadre, J.; et al. The Southern Ocean ecosystem under multiple climate stresses—An integrated circumpolar assessment. *Glob. Chang. Biol.* **2015**, *21*, 1434–1453. https://doi.org/10.1111/geb.12794.
4. Griffiths, H.J. Antarctic Marine Biodiversity—What Do We Know About the Distribution of Life in the Southern Ocean? *PLoS ONE* **2010**, *5*, e11683. https://doi.org/10.1371/journal.pone.0011683.
5. Barnes, D.K.A.; Conlan, K.E. Disturbance, colonization and development of Antarctic benthic communities. *Phil. Trans. R. Soc.* **2006**, *362*, 11–38. https://doi.org/10.1098/rstb.2006.1951.

6. Rowden, A.A.; Kröger, K.; Clark, M.R. Compositional patterns of benthic assemblages on the northwestern Ross Sea shelf, Antarctica: Interacting environmental drivers operating at multiple spatial scales. *Hydrobiologia* **2015**, *761*, 211–233. https://doi.org/10.1007/s10750-015-2305-2.

7. Gutt, J. Some "driving forces" structuring communities of the sublittoral Antarctic macrobenthos. *Antarct. Sci.* **2000**, *12*, 297–313. https://doi.org/10.1017/S0954102000000365.

8. Gutt, J.; Sirenko, B.; Smirnov, I.; Arntz, W. How many macrozoobenthic species might inhabit the Antarctic shelf? *Ant. Sc.* **2004**, *16*, 11–16. https://doi.org/10.1017/S0954102004001750.

9. Gutt, J.; Griffiths, H.J.; Jones, C.D.Circumpolar overview and spatial heterogeneity of Antarctic macrobenthic communities. *Mar. Biodivers*. **2013**, *43*, 481–487. https://doi.org/10.1007/s12526-013-0152-9.

10. Barry, J.P.; Grebmeier, J.M.; Smith, J.; Dunbar, R.B. Oceanographic Versus Seafloor-Habitat Control of Benthic Megafaunal Communities in the S.W. Ross Sea, Antarctica. *Biogeochem. Ross Sea Antarct. Res. Ser.* **2003**, *78*, 327–354. https://doi.org/10.1029/078ARS21.

11. Cummings, V.J.; Hewitt, J.E.; Thrush, S.F.; Marriott, P.M.; Halliday, N.J.; Norkko, A.M. Linking Ross Sea coastal benthic ecosystems to environmental conditions: Documenting baselines in a changing world. *Front. Mar. Sci.* **2018**, *5*, 232. https://doi.org/10.3389/fmars.2018.00232.

12. Cummings, V.J.; Bowden, D.A.; Pinkerton, M.H.; Halliday, N.J.; Hewitt, J.E. Ross Sea Benthic Ecosystems: Macro and Mega-faunal Community Patterns From a Multi-environment Survey. *Front. Mar. Sci*. **2021**, *8*, 629787. https://doi.org/10.3389/fmars.2021.629787.

13. Finger, K.L.; Lipps, J.H. Foraminiferal decimation and repopulation in an active volcanic caldera, Deception Island, Antarctica. *Micropaleontology* **1981**, *27*, 111–139.

14. Harper, D.A.T.; Scrutton, C.T.; Williams, D.M. Mass mortalities on an Irish Silurian seafloor. *J. Geol. Soc. Lond.* **1995**, *152*, 917–922.

15. Heikoop, J.M.; Tsujita, C.J.; Heikoop, C.E.; Risk, M.; Dickin, A. Effects of volcanic ashfall recorded in ancient marine benthic communities: Comparison of a near shore and an offshore environment. *Lethaia* **1996**, *29*, 125–139.

16. Hess, S.; Kuhnt, W.; Hill, S.; Kaminski, M.A.; Holbourn, A.; Leon, M. Monitoring the recolonization of the Mt Pinatubo 1991 ash layer by benthic foraminifera. *Mar. Micropal.* **2001**, *43*, 119–142. https://doi.org/10.1016/S0377-8398(01)00025-1.

17. Galeotti, S.; Bellagamba, M.; Kaminski, M.A.; Montanari, A. Deep-sea benthic foraminiferal recolonisation following a volcani-clastic event in the lower Campanian of the Scaglia Rossa Formation (Umbria–Marche Basin, central Italy). *Mar. Micropal*. **2002**, *44*, 57–76.

18. Keller, G. Biotic effects of impacts and volcanism. *Earth Planet. Sci. Lett*. **2003**, *215*, 249–264. https://doi.org/10.1016/S0012-821X(03)00390-X.

19. Kuhnt, W.; Hess, S.; Holbourn, A.; Paulsen, H.; Salomon, B. The impact of the 1991 Mt. Pinatubo eruption on deep-sea foraminiferal communities: A model for the Cretaceous–Tertiary (K/T) boundary? *Palaeogeogr. Palaeoclim. Palaeoecol*. **2005**, *224*, 83–107. https://doi.org/10.1016/j.palaeo.2005.03.042.

20. Wetzel, A. The preservation potential of ash layers in the deep-sea: The example of the 1991-Pinatubo ash in the South China Sea. *Sedimentology* **2009**, *56*, 1992–2009. https://doi.org/10.1111/j.1365-3091.2009.01066.x.

21. Waśkowska, A. Response of Early Eocene deep-water benthic foraminifera to volcanic ash falls in the Polish Outer Carpathians: Palaeoecological implications. *Palaeogeogr. Palaeoclim. Palaeoecol*. **2011**, *305*, 50–64. https://doi.org/10.1016/j.palaeo.2011.02.012.

22. Charquenõ-Celis, F.; Sigala, I.; Zolitschka, B.; Pérez, L.; Christoph Mayr, C.; Massaferro, J. Responses of testate amoebae assemblages (Amoebozoa: Arcellinida) to recent volcanic eruptions, inferred from the sediment record in Laguna Verde, southern Patagonia, Argentina. *J. Paleolimnol*. **2022**, *67*, 115–129. https://doi.org/10.1007/s10933-021-00226-5.

23. Gray, S.C.; Sturz, A.; Bruns, M.D.; Marzan, R.L.; Dougherty, D.; Law, H.B.; Brackett, J.E.; Marcou, M. Composition and distribution of sediments and benthic foraminifera in a submerged caldera after 30 years of volcanic quiescence. *Deep. Sea Res. Part II Top. Stud. Oceanogr.* **2003**, *50*, 1727–1751.

24. Wilch, T.I.; McIntosh, W.C.; Dunbar, N.W. Late Quaternary volcanic activity in Marie Byrd Land: Potential 40 Ar/ 39 Ar-dated time horizons in West Antarctic ice and marine cores. *Bull. Geol. Soc. Am.* **1999**, *111*, 1563–1580.

25. Hillenbrand, C.-D.; Moreton, S.G.; Caburlotto, A.; Pudsey, C.J.; Lucchi, R.G.; Smellie, J.L.; Benetti, S.; Grobe, H.; Hunt, J.B.; Larter, R.D. Volcanic time-markers for Marine Isotopic Stages 6 and 5 in Southern Ocean sediments and Antarctic ice cores: Implications for tephra correlations between palaeoclimatic records. *Quat. Sci. Rev.* **2008**, *27*, 518–540. https://doi.org/10.1016/j.quascirev.2007.11.009.

26. Del Carlo, P.; Di Roberto, A.; Di Vincenzo, G.; Bertagnini, A.; Landi, P.; Pompilio, M.; Colizza, E.; Giordano, G. Late Pleistocene-Holocene volcanic activity in northern Victoria Land recorded in Ross Sea (Antarctica) marine sediments. *Bull. Volcanol.* **2015**, *77*, 36. https://doi.org/10.1007/s00445-015-0924-0.

27. Di Roberto, A.; Colizza, E.; Del Carlo, P.; Petrelli, M.; Finocchiaro, F.; Kuhn, G. First marine cryptotephra in Antarctica found in sediments of the western Ross Sea correlates with englacial tephras and climate records. *Sci. Rep.* **2019**, *9*, 10628. https://doi.org/10.1038/s41598-019-47188-3.

28. Di Roberto, A.; Albert, P.G.; Colizza, E.; Del Carlo, P.; Di Vincenzo, G.; Gallerani, A.; Giglio, F.; Kuhn, G.; Macrì, P.; Manning, C.J.; et al. Evidence for a large-magnitude Holocene eruption of Mount Rittmann (Antarctica): A volcanological reconstruction using the marine tephra record. *Quat. Sci. Rev.* **2020**, *250*, 106629. https://doi.org/10.1016/j.quascirev.2020.106629.

29. Di Roberto, A.; Del Carlo, P.; Pompilio, M. Marine record of Antarctic volcanism from drill cores. In *Geological Society Memoir*; Geological Society of London: London, UK, 2021; pp. 631–647. https://doi.org/10.1144/M55-2018-49.

30. Benson, R.H. Ostracods and Palaeoceanography. Ostracoda in the Earth Sciences. In *Proceedings of the 11th International Symposium on Ostracoda, Warrnambool, Australia, 8–12 July 1991*; De Deckker, P., Colin, J.P., Peypouquet, J.P., Eds.; A.A. Balkema: Rotterdam, The Netherlands, 1988; pp. 1–26.

31. Cronin, T.M.; Holtz, T.R.; Whatley, R.C. Quaternary paleoceanography of the deep Arctic Ocean based on quantitative analysis of Ostracoda. *Mar. Geol.* **1994**, *119*, 305–332.

32. Cronin, T.M.; De Martino, D.M.; Dwyer, G.S.; Rodriguez-Lazaro, J. Deep-sea ostracode species diversity: Response to late Quaternary climate change. *Mar. Micropal.* **1999**, *37*, 231–249.

33. Yasuhara, M.; Cronin, T.M.; Hunt, G.; Hodell, D.A. Deep–sea ostracods from the South Atlantic sector of the Southern Ocean during the Last 370,000 years. *J. Paleontol.* **2009**, *83*, 914–930.

34. Rodriguez-Lazaro, J.; Ruiz-Munõz, F. A General Introduction to Ostracods: Morphology, Distribution, Fossil Record and Applications. In *Developments in Quaternary Sciences*; Elsevier: Amsterdam, The Netherlands, 2012; Volume 17, pp. 1–14. https://doi.org/10.1016/B978-0-444-53636-5.000019.

35. Cronin, T.M.; Raymo, M.E. Orbital forcing of deep-sea benthic species diversity. *Nature* **1997**, *385*, 624–627. https://doi.org/10.1038/385624a0.

36. Cronin, T.; Dwyer, G.; Baker, P.A.; Rodriguez Lazaro, J.; Demartino, D.M. Orbital and suborbital variability in North Atlantic bottom water temperature obtained from deep-sea ostracode Mg/Ca ratios. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **2000**, *162*, 45–57. https://doi.org/10.1016/S0031-0182(00)00104-8.

37. Didié, C.; Bauch, H.A.; Helmke, J.P. Late Quaternary deep-sea ostracodes in the polar and subpolar North Atlantic: Paleoecological and paleoenvironmental implications. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **2002**, *184*, 195–212. https://doi.org/10.1016/S0031-0182(02)00259-6.

38. Cronin, T.M.; Dwyer, G.S.; Farmer, J.; Bauch, H.A.; Spielhagen, R.F.; Jakobsson, M.; Nilsson, J.; Briggs, W.M., Jr.; Stepanova, A. Deep Arctic Ocean warming during the last glacial cycle. *Nat. Geosc.* **2012**, *5*, 631–634. https://doi.org/10.1038/ngeo1557.

39. Swain, F.M. Ostracode speciation following Middle Ordovician extinction events, North-Central United States. *Geol. Soc. Lond. Spec. Publ.* **1996**, *102*, 97–104.

40. Botting, J.P. The ecological effect of volcanic ash-fall in the marine Ordovician of Central Wales. *Acta Univ. Carol.—Geol.* **1999**, *43*, 499–502.

41. Botting, J.P. The role of pyroclastic volcanism in Ordovician diversification. In *Palaeobiogeography and Biodiversity Change: The Ordovician and Mesozoic–Cenozoic Radiations*; Crame, J.A., Owen, A.W., Eds.; Special Publications; Geological Society of London: London, UK, 2002; Volume 194, pp. 99–113.

42. Botting, J.P.; Muir, L.A. Unravelling causal components of the Ordovician Radiation: The Builth Inlier (central Wales) as a case study. *Lethaia* **2008**, *41*, 111–125.

43. Hints, O.; Hints, L.; Meidla, T.; Sohar, K. Biotic effects of the Ordovician Kinnekulle ash-fall recorded in northern Estonia. B*ull. Geol. Soc. Den.* **2003**, *50*, 115–123.

44. Bodergat, A.M.; Ishizaki, K.; Oki, K.; Rio, M. Currents, civilization, or volcanism? Ostracodes as sentinels in a patchy environment: Kagoshima Bay, Japan. *Micropaleontology* **2002**, *48*, 285–299. https://doi.org/10.2113/48.3.285.

45. Perrier, V.; Meidla, T.; Oive, T.; Leho, A. Biotic response to explosive volcanism: Ostracod recovery after Ordovician ash-falls. *Palaeogeogr. Palaeoclim. Palaeoecol.* **2012**, *365*, 166–183. https://doi.org/10.1016/j.palaeo.2012.09.024.

46. Aiello, G.; Barra, D.; Parisi, R.; Isaia, R.; Marturano, A. Holocene benthic foraminiferal and ostracod assemblages in a paleo-hydrothermal vent system of Campi Flegrei (Campania, South Italy). *Palaeont. Electr.* **2018**, *21(3)*, 1–71. https://doi.org/10.26879/835.

47. Murray, J.W. *Ecology and Applications of Benthic Foraminifera*; Cambridge University Press: New York, NY, USA, 2006; p. 426.

48. Smith, J.A.; Graham, A.G.C.; Post, A.L.; Hillebrand, C.-D.; Bart, P.J.; Powell, R.D. The marine geological imprint of Antarctic ice shelves. *Nat. Commun.* **2019**, *10*, 5635. https://doi.org/10.1038/s41467-019-13496-5.

49. Majewski, W.; Prothro, L.O.; Simkins, L.M.; Demianiuk, E.J.; Anderson, J.B. Foraminiferal patterns in deglacial sediment in the western Ross Sea, Antarctica: Life near grounding lines. *Paleoceanogr. Paleoclimatol.* **2020**, *35*, e2019PA003716. https://doi.org/10.1029/2019PA003716.

50. Melis, R.; Salvi, G. Foraminifer and Ostracod Occurrence in a Cool-Water Carbonate Factory of the Cape Adare (Ross Sea, Antarctica): A Key Lecture for the Climatic and Oceanographic Variations in the Last 30,000 Years. *Geosciences* **2020**, *10*, 413. https://doi.org/10.3390/geosciences10100413.

51. Prothro, L.O.; Majewski, W.; Yokoyama, Y.; Simkins, L.M.; Anderson, J.B.; Yamane, M.; Miyairi, Y.; Ohkouchi, N. Timing and pathways of East Antarctic Ice Sheet retreat. *Quat. Sci. Rev.* **2020**, *230*, 106166. https://doi.org/10.1016/j.quascirev.2020.106166, 2020.

52. Bart, P.J.; Sjunneskog, C.; & Chow, J.M. Piston-core based biostratigraphic constraints on Pleistocene oscillations of the West Antarctic Ice Sheet in western Ross Sea between North Basin and AND-1B drill site. *Mar. Geol.* **2011**, *289*, 86–99. https://doi.org/10.1016/j.margeo.2011.09.005.

53. Halberstadt, A.R.W.; Simkins, L.M.; Greenwood, S.L.; Anderson, J.B. Past ice-sheet behaviour: Retreat scenarios and changing controls in the Ross Sea, Antarctica. *Cryosphere* **2016**, *10*, 1003–1020. https://doi.org/10.5194/tc-10-1003-2016, 2016.

54. Davey, F.J. (Ed.) *Ross Sea Bathymetry 1:2,000,000, Version 1.0*; Institute of Geological & Nuclear Sciences Limited: Lower Hutt, New Zealand, 2004.

55. Marigo, S. Foraminiferi e Dinamica della Piattaforma Glaciale del Mare di Ross Occidentale (Antartide): Considerazioni Paleoambientali. Master's Thesis, University of Trieste, Trieste, Italy, 2021.

56. Müller, G. Die Ostracodan der Deutschen Sudpolar-Expedition 1901–1903. Wissenschaftliche Ergebnisse der deutschen Sudpolar expedition. *Zoologie* **1908**, *10*, 51–181.

57. Benson, R.H. Recent Cytheracean Ostracodes from McMurdo Sound and the Ross Sea, Antarctica. *Arthropoda* **1964**, *6*, 1–36.

58. Neale, J.W. An ostracod fauna from Halley Bay, Coats Land, British Antarctic Territory. *Br. Antarct. Surv. Sci. Rep.* **1967**, *58*, 1–50.

59. Hartmann, G. Antarktische benthische Ostracodan III. Auswertung der Reise des FFS "Walther Herwig" 68/1. 3. Teil: Süd-Orkney-Inseln. *Mitt. Aus. Dem. Hambg. Zool. Mus. Und. Institut.* **1988**, *85*, 141–162.

60. Hartmann, G. Antarktische benthische Ostracodan IV. Auswertung der wahrend der Reise von FFS "Walther Herwig" (68/1) bei Sud-Georgien gesammelten Ostracodan. *Mitt. Aus. Dem. Hambg. Zool. Mus. Und. Institut.* **1989**, *86*, 209–230.

61. Hartmann, G. Antarktische benthische Ostracodan, V. Auswertung der Sudwinterreise von FS "Polarstern" (Ps 9/V-1) im Bereich Elephant Island und der Antarktischen Halbinsel. *Mitt. Aus. Dem. Hambg. Zool. Mus. Und. Institut.* **1989**, *86*, 231–288.

62. Hartmann, G. Antarktische benthische Ostracodan VI. Auswertung der Reise der "Polarstern" (Ant. VI-2). (1 Teil, Meiofauna und Zehnerserien sowie Versuch einer vorlaufigen Auswertung aller bislang vorliegenden Daten). *Mitt. Aus. Dem. Hambg. Zool. Mus. Und. Institut.* **1990**, *87*, 191–245.

63. Hartmann, G. Antarktische benthische Ostracodan. VIII. Auswertung der Reise der "Meteor" (Ant. 11/4) in die Gewasser um Elephant Island und der Antarktischen Halbinsel. *Helgoländer Meeresunters.* **1992**, *46*, 405–424.

64. Hartmann, G. Antarktische benthische Ostracodan IX. Ostracodan von der Antarktischen Halbinsel und von der Isla de los Estados (Feuerland/Argentinien). Auswertung der "Polarstern"- Reise PS ANT/X/1b. *Mitt. Aus. Dem. Hambg. Zool. Mus. Institut* **1993**, *90*, 227–237.

65. Hartmann, G. Antarktische benthische Ostracoden X. Bemerkungen zur Gattung Krithe mit Beschreibung einer neuen Untergattung Austrokrithe. *Mitt. Aus. Dem. Hambg. Zool. Mus. Institut* **1994**, *91*, 77–79.

66. Hartmann, G. Antarktische und Subantarktische Podocopa (Ostracoda). In *Antarktische und Subantarktische Podocopa (Ostracoda)*; Koeltz Scientific Books: Koenigstein, Germany, 1997; Volume 7, pp. 1–355.

67. Whatley, R.C.; Moguilevsky, A.; Ramos, M.I.F.; Coxill, D.J. Recent deep and shallow water Ostracoda from the Antarctic Peninsula and the Scotia Sea. *Rev. Esp. Micropal.* **1998**, *30*, 111–135.

68. Dingle, R.V. Ostracoda from CRP–1 and CRP–2/2A, Victoria Land Basin, Antarctica. *Terra Ant.* **2000**, *7*, 479–492.

69. Yasuhara, M.; Kato, M.; Ikeya, N.; Seto, K. Modern benthic ostracodes from Lützow-Holm Bay, East Antarctica: Paleoceanographic, paleobiogeographic, and evolutionary significance. *Micropaleontology* **2007**, *53*, 469–496. https://doi.org/10.2113/gsmicropal.53.6.469.

70. Brenchley, P.J.; Harper, D.A.T. *Palaeoecology: Ecosystems, Environments and Evolution*; Chapman and Hall: London, UK, 1998.

71. Boomer, I.; Horne, D.J.; Slipper, I.J. The Use of Ostracods in Palaeoenvironmental Studies, or What can you do with an Ostracod Shell? In *Bridging the Gap: Trends in the Ostracode Biological and Geological Sciences*; The Paleontological Society Papers: Cambridge, UK, 2003; Volume 9, pp. 153–180. https://doi.org/10.1017/S1089332600002199.

72. Brouwers, E.M. Paleobathymetry on the continental shelf based on examples using ostracods from the Gulf of Alaska. In *Ostracoda in the Earth Sciences*; De Deckker, P., Colin, J.-P., Peypouquet, J.-P., Eds.; Elsevier: Amsterdam, The Netherlands, 1988; pp. 55–76.

73. Brouwers, E.M. Sediment transport detected from the analysis of ostracod population structures: An example from the Alaskan Continental Shelf. In *Ostracoda in the Earth Sciences*; De Deckker, P., Colin, J.-P., Peypouquet, J.-P., Eds.; Elsevier: Amsterdam, The Netherlands, 1988; pp. 231–244.

74. Violanti, D. Taxonomy and distribution of recent benthic foraminifers from Terra Nova Bay (Ross Sea, Antarctica), Oceanographic Campaign 1987/1988. *Palaeont. Ital.* **1996**, *83*, 25–71.

75. Majewski, W. Benthic foraminiferal distribution and ecology in Admiralty Bay, King George Island, West Antarctica. *Pol. Polar Res.* **2005**, *26*, 159–214.

76. Majewski, W.; Bart, P.J.; McGlannan, A.J. Foraminiferal assemblages from ice-proximal paleo-settings in the Whales Deep Basin, Eastern Ross Sea, Antarctica. *Palaeogeogr. Palaeoclim. Palaeoecol.* **2018**, *493*, 64–81. https://doi.org/10.1016/j.palaeo.2017.12.041.

77. Malmgren, B.A.; Haq, B.U. Assessment of quantitative techniques in paleobiogeography. *Mar. Micropal.* **1982**, *7*, 213–236. https://doi.org/10.1016/0377-8398(82)90003-2.

78. Hammer, Ø.; Harper, D.A.T.; Ryan, P.D. PAST: Paleontological Statistics Software Package for Education and Data Analysis. *Palaeontol. Electron.* **2001**, *4*, 9.

79. Sousa, W.P. The role of disturbance in natural communities. *Ann. Rev. Ecol. Syst.* **1984**, *15*, 353–391.

80. Pickett, S.T.A.; White, P.S. *The Ecology of Natural Disturbance and Patch Dynamics*; Academic Press: Orlando, FL, USA, 1985. https://doi.org/10.1016/C2009-0-02952-3.

81. Sergio, F.; Blas, J.; Hiraldo, F. Animal responses to natural disturbance and climate extremes: A review. *Glob. Planet. Chang.* **2018**, *161*, 28–40. https://doi.org/10.1016/j.gloplacha.2017.10.009.

82. Browning, T.J.; Stone, K.; Bouman, H.A.; Mather, T.A.; Pyle, D.M.; Moore, C.M.; Martinez-Vicente, V. Volcanic ash supply to the surface ocean: Remote sensing of biological responses and their wider biogeochemical significance. *Front. Mar. Sci.* **2015**, *2*, 1–22. doi.org/10.3389/fmars.2015.00014.

83. Frogner, P.; Gislason, S.R.; Oskarsson, N. Fertilizing potential of volcanic ash in ocean surface water. *Geology* **2001**, *29*, 487–490. https://doi.org/10.1130/0091-7613(2001)029<0487:FPOVAI>2.0.CO;2.

84. Olgun, N.; Duggen, S.; Croot, P.L.; Delmelle, P.; Dietze, H.; Schacht, U.; Óskarsson, N.; Siebe, C.; Auer, A.; Garbe-Schönberg, D. Surface ocean iron fertilization: The role of airborne volcanic ash from subduction zone and hotspot volcanoes and related iron fluxes into the Pacific Ocean. *Glob. Biogeochem. Cycles* **2011**, *25*. https://doi.org/10.1029/2009GB003761.

85. Durant, A.J.; Villarosa, G.; Rose, W.I.; Delmelle, P.; Prata, A.J.; Viramonte, J.G. Long-range volcanic ash transport and fallout during the 2008 eruption of Chaiten volcano, Chile. *Phys. Chem. Earth* **2012**, *45–46*, 50–64. https://doi.org/10.1016/j.pce.2011.09.004.

86. Lindenthal, A.; Langmann, B.; Paetsch, J.; Lorkowski, I.; Hort, M. The ocean response to volcanic iron fertilisation after the eruption of Kasatochi volcano: A regional scale biogeochemical ocean model study. *Biogeosc. Discuss.* **2012**, *9*, 9233–9257. https://doi.org/10.5194/bgd-9-9233-2012.

87. Achterberg, E.P.; Moore, C.M.; Henson, S.A.; Steigenberger, S.; Stohl, A.; Eckhardt, S.; Avendano, L.C.; Cassidy, M.; Hembury, D.; Klar, J.K.; et al. Natural iron fertilization by the Eyjafjallajokull volcanic eruption. *Geophys. Res. Lett.* **2013**, *40*, 921–926. https://doi.org/10.1002/grl.50221.

88. Morel, F.M.M.; Milligan, A.J.; and Saito, M.A. Marine bioinorganic chemistry: The role of trace metals in the ocean cycles of major nutrients. *Treatise Geochem.* **2003**, *6*, 113–143. https://doi.org/10.1016/B0-08-043751-6/06108-9.

89. Hoffmann, L.J.; Breitbarth, E.; Ardelan, M.V.; Duggen, S.; Olgun, N.; Hassellov, M.; Wängberg, S.-Å. Influence of trace metal release from volcanic ash on growth of *Thalassiosira pseudonana* and *Emiliania huxleyi*. *Mar. Chem.* **2012**, *132*, 28–33. https://doi.org/10.1016/j.marchem.2012.02.003.

90. Mitchell, J.K. *Fundamentals of Soil Behavior*; Wiley and Sons: New York, NY, USA, 1993; pp. 1–437.

91. Haeckel, M.; Beusekom, J.V.; Wiesner, M.G.; König, I. The impact of the 1991 Mount Pinatubo tephra fallout on the geochemical environment of the deep-sea sediments in the South China Sea. *Earth Planet. Sci. Lett.* **2001**, *193*, 151–166. https://doi.org/10.1016/S0012-821X(01)00496-4.

92. Pasotti, F.; Manini, E.; Giovannelli, D.; Wölfl, A.C.; Monien, D.; Verleyen, E.; Braeckman, U.; Abele, D.; Vanreusel, d. Antarctic shallow water benthos in an area of recent rapid glacier retreat. *Mar. Ecol.* **2014**, *36*, 716–733.

93. Brandão, S.N.; Dingle, R.V. *Biogeographic Atlas of the Southern Ocean*; De Broyer, C., Koubbi, P., Griffiths, H.J., Raymond, B., d'Udekem d'Acoz, C., Van de Putte, A.P., Danis, B., David, B., Grant. S., Gutt, J., Eds.; Scientific Committee on Antarctic Research: Cambridge, UK, 2014; pp. 142–148.

94. Ayress, M.; Neil, H.; Passlow, V.; Swanson, K.M. Benthonic ostracods and deep water masses: A qualitative comparison of southwest Pacific, southern and Atlantic Oceans. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **1997**, *131*, 287–302. https://doi.org/10.1016/S0031-0182(97)00007-2.

95. Majewski, W.; Olempska, E. Recent ostracods from Admiralty Bay, King George Island, West Antarctica. *Pol. Polar Res.* **2005**, *26*, 13–36.

96. Brandt, A.; Gooday, A.; Brandão, S.; Brix, S.; Brökeland, W.; Cedhagen, T.; Choudhury, M.; Cornelius, N.; Danis, B.; De Mesel, I.; et al. First insights into the biodiversity and biogeography of the Southern Ocean deep sea. *Nature* **2007**, *447*, 231–114. https://doi.org/10.1038/nature05827.

97. Brandão, S.N.; Horne, D.V. The Platycopid Signal of oxygen depletion in the ocean: A critical evaluation of the evidence from modern ostracod biology, ecology and depth distribution. *Paleogeogr. Paleoclimatol. Paleoecol*. **2009**, *283*, 126–133. https://doi.org/10.1016/j.palaeo.2009.09.007.

98. Brandão, S.N.; Saeedi, H.; Brandt, A. Macroecology of Southern Ocean benthic Ostracoda (Crustacea) from the continental margin and abyss. *Zool. J. Linn. Soc.* **2022**, *194*, 226–255. https://doi.org/10.1093/zoolinnean/zlab078.

99. Chapmann, F. Ostracoda from elevated deposits on the slopes of Mount Erebus, between Cape Royds and Cape Barne. British Antarctic Expedition 1907–1909 under the command of Sir E. H. Shackleton. *Rep. Sci. Investig. Geol.* **1916**, *2*, 49–52.

100. Chapmann, F. Ostracoda from up thrust mud above the Drygalski Glacier, southeast of Mount Larsen. British Antarctic Expedition 1907–1909 under the command of Sir E. H. Shackleton. *Rep. Sci. Investig. Geol.* **1916**, *2*, 37–40.

101. Chapmann, F. Report on the Foraminifera and Ostracoda: Out of marine muds from soundings in the Ross Sea. British Antarctic Expedition 1907–1909 under the command of Sir E. H. Shackleton. *Rep. Sci. Investig. Geol.* **1916**, *2*, 53–80.

102. Salvi, G.; Anderson, J.B.; Bertoli, M.; Castagno, P.; Falco, P.; Fernetti, M.; Montagna, P.; Taviani, M. Recent Ostracod Fauna of the Western Ross Sea (Antarctica): A Poorly Known Ingredient of Polar Carbonate Factories. *Minerals* **2022**, *12*, 937. https://doi.org/10.3390/min12080937.

103. Ishman, S.E.; Szymcek, P. Foraminiferal distributions in the former Laresen-A ice shelf and Prince Gustav channel region, eastern Antarctic Peninsula margin: A baseline for Holocene paleoenvironmental change. *Antar. Res. Ser.* **2003**, *79*, 239–260. https://doi.org/10.1029/AR079p0239.

104. Melis, R.; Salvi, G. Late Quaternary foraminiferal assemblages from western Ross Sea (Antarctica) in relation to the main glacial and marine lithofacies. *Mar. Micropal.* **2009**, *70*, 39–53. https://doi.org/10.1016/j.marmicro.2008.10.003.

105. Capotondi, L.; Bonomo, S.; Budillon, G.; Giordano, P.; Langone, L. Living and dead benthic foraminiferal distribution in two areas of the Ross Sea (Antarctica). *Rend. Lincei Sci. Fis. Nat.* **2020**, *31*, 1037–1053. https://doi.org/10.1007/s12210-020-00949-z.

106. Bart, P.J.; Coquereau, L.; Warny, S.; Majewski, W. In situ foraminifera in grounding zone diamict: A working hypothesis. *Antarct. Sci.* **2016**, *28*, 313–321. https://doi.org/10.1017/S0954102016000055.

107. Briggs, W.M. Ostracoda from the Pleistocene Taylor Formation, Ross Island, and the Recent of the Ross Sea and McMurdo Sound region, Antarctica. *Antarct. J. United States* **1978**, *14*, 27–29.

108. Szczechura, J.; Blaszyk, J. Ostracods from the Pecten conglomerate (Pliocene) of Cockburn Island, Antarctic peninsula. *Palaeontol. Pol.* **1996**, *68*, 175–186.

109. Gooday, A.J. Epifaunal and shallow infaunal foraminiferal communities at three abyssal NE Atlantic sites subject to differing phytodetritus input regimes. *Deep-Sea Res.* **1996**, *43*, 1395–1421.

110. Melis, R.; Capotondi, L.; Torricella, F.; Ferretti, P.; Geniram, A.; Hong, J.K.; Kuhn, G.; Khim, B.-K.; Kim, S.; Malinverno, E.; et al. Last Glacial Maximum to Holocene paleoceanography of the northwestern Ross Sea inferred from sediment core geochemistry and micropaleontology at Hallett Ridge. *J. Micropal.* **2021**, *40*, 15–35.

111. Griffiths, H.J.; Anker, P.; Linse, K.; Maxwell, J.; Post, A.L.; Stevens, C.; Tulaczyk, S.; Smith, J.A. Breaking All the Rules: The First Recorded Hard Substrate Sessile Benthic Community Far Beneath an Antarctic Ice Shelf. *Front. Mar. Sci.* **2021**, *8*, 642040. https://doi.org/10.3389/fmars.2021.642040.

112. Fabiano, M.; Danovaro, R. Meiofauna distribution and mesoscale variability in two sites of the Ross Sea (Antarctica) with contrasting food supply. *Polar Biol.* **1999**, *22*, 115–123. https://doi.org/10.1007/s003000050398.

113. Jansen, J.; Hill, N.; Dunstan, P.; McKinlay, J.; Sumner, M.; Post, A.; Eléaume, M.; Armand, L.;Warnock, J.; Galton-Fenzi, B.; et al. Abundance and richness of key Antarctic seafloor fauna correlates with modelled food availability. *Nat. Ecol. Evol.* **2018**, *2*, 71–80. https://doi.org/10.1038/s41559-017-0392-3.

114. Wall-Palmer, D.; Jones, M.T.; Hart, M.B.; Fisher, J.K.; Smart, C.W.; Hembury, D.J.; Palmer, M.R.; Fones, G.R. Explosive volcanism as a cause for mass mortality of pteropods. *Mar. Geol.* **2011**, *282*, 231–239. https://doi.org/10.1016/j.margeo.2011.03.001.

115. Hunt, E.A.; Pakhomov, G.W.; Hosie, V.; Siegel, P.; Ward, K.B. Pteropods in Southern Ocean ecosystems. *Prog. Oceanogr.* **2008**, *78*, 193–221. https://doi.org/10.1016/j.pocean.2008.06.001.