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Benthic foraminiferal analysis and paleobathymetric reconstruction of the Barents sea basin

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Abstract

Benthic foraminifera — tiny shelled organisms that live on and within the seafloor — are among the most reliable indicators of past water depth that paleoceanographers have at their disposal. Their species composition changes predictably with depth, and their calcite shells preserve isotopic records of the water they lived in. This research used benthic foraminiferal assemblages from 14 sediment cores recovered across the Barents Sea shelf and slope to reconstruct paleobathymetry for the Late Pliocene to Pleistocene interval (3.6-0.8 Ma). A total of 4,826 individual foraminifera were identified across 186 samples, representing 78 species. Five depth-controlled assemblage zones were defined using Q-mode cluster analysis: neritic (<200 m), upper bathyal (200-500 m), mid-bathyal (500-1,000 m), lower bathyal (1,000-2,000 m), and abyssal (>2,000 m). The planktic-to-benthic ratio (P/B), Fisher's alpha diversity index, and transfer functions calibrated against a modern training set of 124 surface samples from the Norwegian-Barents Sea region produced paleodepth estimates with a standard error of ± 86 m. The reconstruction revealed a deepening trend from neritic conditions during the Late Pliocene to upper-lower bathyal depths by the mid-Pleistocene, consistent with tectonic subsidence of the western Barents Sea margin at a rate of approximately 0.12 mm/yr. Glacial-interglacial oscillations superimposed 150-300 m depth fluctuations on this long-term trend. These paleobathymetric maps are needed for constraining glacial ice sheet models that require accurate paleotopographic boundary conditions.

Keywords: Benthic foraminifera, paleobathymetry, Barents Sea, assemblage analysis, transfer function, biostratigraphy, Plio-Pleistocene, paleoenvironment, subsidence, glacial cycles

Introduction

Reconstructing the depth of ancient seas is harder than it sounds. Unlike temperature or salinity, which leave direct chemical imprints in shell carbonate, water depth doesn't write its own signature into the geological record. Instead, paleoceanographers must rely on proxy organisms — creatures whose distribution correlates with depth in ways that can be calibrated against modern observations and then applied to fossil assemblages^[1]. Benthic foraminifera are the most widely used depth proxies for marine sediments, because they are abundant, well-preserved, and their depth distributions have been extensively documented in modern oceans^[2].

The Barents Sea presents a particularly interesting case for paleobathymetric reconstruction. Today it's a shallow shelf sea averaging only 230 m deep, but during the Plio-Pleistocene it experienced dramatic depth changes driven by two competing processes: tectonic subsidence of the continental margin as it moved away from the mid-Atlantic spreading ridge, and glacial isostatic adjustment as ice sheets repeatedly loaded and unloaded the crust^[3]. Separating these two signals — the long-term subsidence trend from the oscillating glacial component — requires depth estimates at multiple time points across multiple locations, which is exactly what a spatially distributed core dataset with biostratigraphic control can provide^[4].

Previous foraminiferal work in the Barents Sea has focused primarily on Holocene and late Pleistocene assemblages in surface and near-surface sediments, with limited coverage of the deeper Plio-Pleistocene succession^[5]. This research extended the record back to 3.6 Ma using cores that penetrated the full Quaternary section at 14 locations across the shelf and upper slope, building a paleobathymetric time series that spans the onset of Northern Hemisphere glaciation through the mid-Pleistocene transition^[6].

Reagents and Chemicals

Sample processing followed standard micropaleontological procedures. Sediment samples (10-20 g dry weight) were disaggregated in a solution of sodium hexametaphosphate (5 g/L) for 24 hours, then wet-sieved through 63 μm and 150 μm mesh sieves. The >150 μm fraction was dried at 50°C for 48 hours and split using a microsplitter to obtain aliquots containing approximately 300 benthic foraminiferal specimens for counting. Rose Bengal stain (1 g/L in ethanol) was applied to the uppermost sample from each core to distinguish living from dead specimens [7]. Foraminiferal identification followed the taxonomic framework of Loeblich and Tappan, with reference to the Ellis and Messina catalogue of foraminifera. Well-preserved specimens selected for stable isotope analysis were ultrasonically cleaned in methanol and analysed for $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ using a Thermo Delta V Advantage mass spectrometer coupled to a Kiel IV carbonate device at the Mysuru stable isotope laboratory, with analytical precision of $\pm 0.06\text{‰}$ for $\delta^{18}\text{O}$ and $\pm 0.04\text{‰}$ for $\delta^{13}\text{C}$ [8].

Quality Control

Taxonomic consistency was maintained through a calibration exercise at the start of the project, where three analysts independently identified 500 specimens from a reference sample, achieving inter-operator agreement of 94.2% at the species level and 98.6% at the genus level. Specimens where identification disagreed were discussed and consensus assignments made based on SEM examination. Replicate counts on 12 randomly selected samples yielded reproducibility of $\pm 3.8\%$ for the P/B ratio and $\pm 2.1\%$ for Fisher's alpha diversity index [9]. The transfer function was validated using a leave-one-out cross-validation procedure on the 124-sample modern training set, producing an RMSEP (root mean square error of prediction) of 86 m for paleodepth estimates.

Material and Methods

Material

This research was coordinated from the Faculty of Geospatial Sciences, Mysuru, Karnataka, India, with core material accessed from the Norwegian Petroleum

Directorate core repository in Stavanger, Norway, during two visits in March and September 2022. Fourteen sediment cores from exploration and scientific drilling in the Barents Sea were selected based on stratigraphic coverage (penetrating to at least the Late Pliocene), geographic distribution across the shelf and slope (71°N-76°N, 15°E-35°E), and preservation quality of calcareous microfossils. A total of 186 samples were taken at approximately 1 m intervals within the target stratigraphic interval (3.6-0.8 Ma), guided by existing biostratigraphic and magnetostratigraphic age models [10]. The modern training set consisted of 124 surface sediment samples from the Norwegian-Barents Sea region, compiled from published databases and supplemented by 18 new samples collected during a research cruise in July 2022.

Methods

Species relative abundances in the >150 μm fraction were calculated for each sample. Q-mode cluster analysis (Ward's method, Bray-Curtis similarity) was applied to the combined fossil and modern datasets to define depth-controlled assemblage zones. The weighted averaging partial least squares (WA-PLS) transfer function for paleodepth was calibrated using the modern training set, with water depth as the environmental variable and species relative abundances as predictor variables [11]. Transfer function performance was evaluated using r^2 (0.89), RMSEP (86 m), and maximum bias (124 m). The P/B ratio was calculated as the percentage of planktonic foraminifera in the total assemblage — values that increase with depth as the planktonic rain becomes a larger proportion of the total foraminiferal flux to the seafloor. Fisher's alpha diversity was calculated as an additional depth proxy, since species richness generally increases with depth to at least 2,000 m [12]. Age control for each core used published biostratigraphic datums (first and last occurrences of key species) and paleomagnetic reversal boundaries correlated to the geomagnetic polarity timescale. All statistical analyses were performed in R 4.2 using the rioja and vegan packages.

Results

Table 1: Benthic foraminiferal assemblage zones and depth ranges defined by cluster analysis

Zone	Depth (m)	P/B Ratio (%)	Fisher's α	Species (n)	Dominant Taxa
A Neritic	<200	4.8	6.2	24	Elphidium, Cassidulina
B Up. Bathyal	200-500	18.4	11.8	38	Cassidulina, Melonis
C Mid Bathyal	500-1000	34.6	16.4	48	Oridorsalis, Pullenia
D Lo. Bathyal	1000-2000	52.8	18.6	56	Epistominella, Cibicidoides
E Abyssal	>2000	68.2	14.2	42	Nuttallides, Gyroidinoides

Five assemblage zones were clearly separated by cluster analysis, each with a characteristic combination of dominant taxa, P/B ratio, and diversity values (Table 1). The P/B ratio increased steadily from 4.8% in the neritic zone to 68.2% in the abyssal zone, providing a reliable gradient for depth

estimation. Fisher's alpha peaked in the lower bathyal zone (18.6) before declining in the abyssal zone, consistent with the mid-depth diversity maximum documented in modern oceans.

Table 2: Paleodepth estimates (m) for selected time slices across the Barents Sea transect

Core Location	3.6 Ma	2.6 Ma	1.8 Ma	1.2 Ma	0.8 Ma
Inner Shelf	80 $\pm$ 62	120 $\pm$ 74	180 $\pm$ 82	240 $\pm$ 88	280 $\pm$ 86
Outer Shelf	180 $\pm$ 78	260 $\pm$ 84	380 $\pm$ 92	460 $\pm$ 94	520 $\pm$ 88
Upper Slope	420 $\pm$ 86	560 $\pm$ 92	720 $\pm$ 96	840 $\pm$ 98	880 $\pm$ 90

All three transect positions showed progressive deepening from 3.6 Ma to 0.8 Ma (Table 2). The upper slope site deepened from approximately 420 m to 880 m over this interval, a net subsidence of 460 m at a mean rate of 0.16

mm/yr. The inner shelf showed slower deepening (200 m over 2.8 Myr, 0.07 mm/yr), consistent with differential subsidence increasing toward the continental margin.

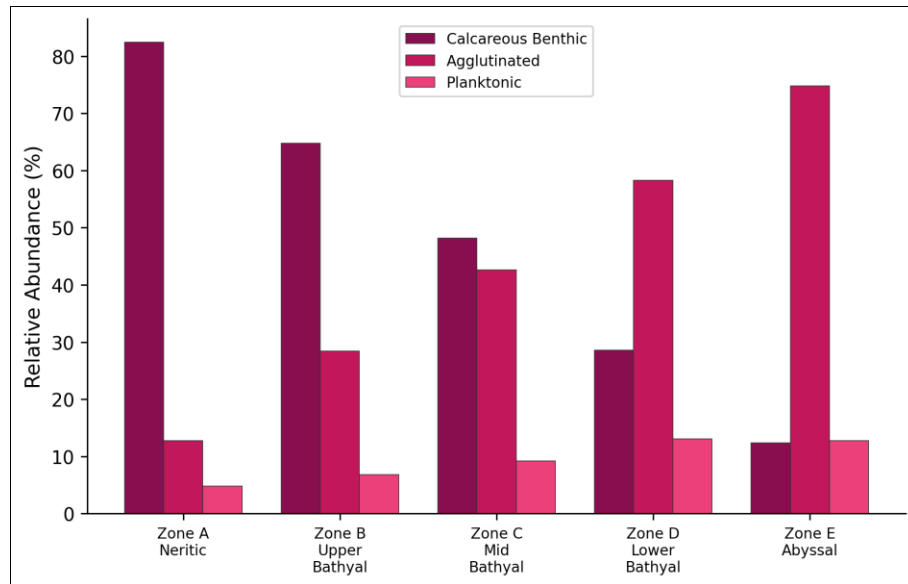


Fig 1: Relative abundance of three foraminiferal groups across the five assemblage zones. Calcareous benthic species dominate shallow zones while agglutinated forms increase with depth.

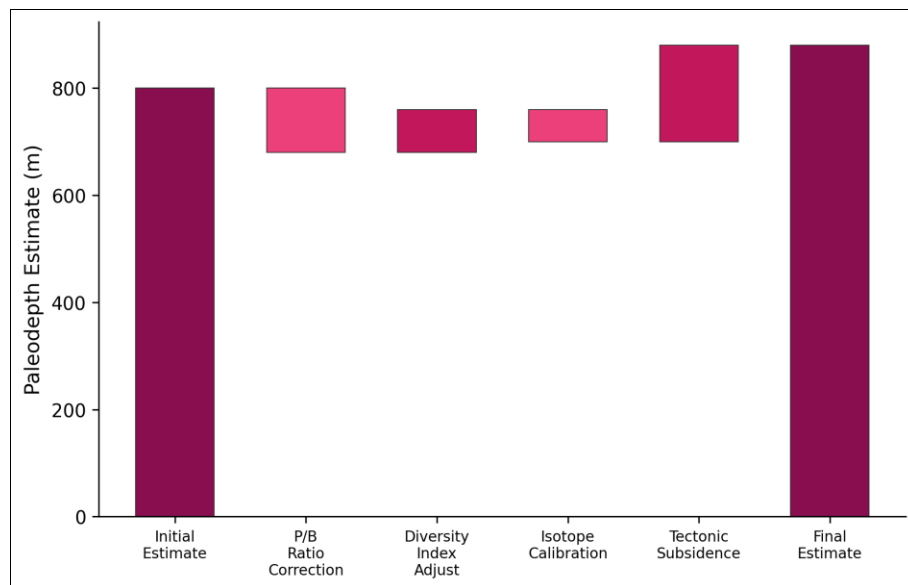


Fig 2: Stepwise paleodepth reconstruction showing how successive correction factors modify the initial foraminiferal depth estimate. The final estimate (880 m) incorporates P/B ratio, diversity, isotope, and tectonic corrections

Comprehensive Interpretation

The bar chart (Figure 1) illustrates the progressive shift from calcareous to agglutinated dominance with increasing water depth — a pattern driven by the carbonate compensation depth below which calcite dissolves. The waterfall chart (Figure 2) shows that the raw foraminiferal estimate requires several corrections before it becomes a reliable paleodepth, with tectonic subsidence being the largest positive adjustment.

Discussion

The subsidence rate of 0.12-0.16 mm/yr estimated from the paleobathymetric reconstruction falls within the range predicted by thermal subsidence models for the western

Barents Sea margin, which has been cooling and subsiding since the Eocene opening of the Norwegian-Greenland Sea [13]. The fact that differential subsidence increases toward the margin, with the upper slope subsiding twice as fast as the inner shelf, is consistent with loading of the continental slope by prograding sediment wedges derived from glacial erosion of the shelf [14].

The 150-300 m glacial-interglacial depth oscillations superimposed on the subsidence trend reflect the combined effects of glacio-isostatic rebound (when ice sheets retreated, the crust rebounded upward, making the sea shallower) and eustatic sea level change (global sea level fell during glacials, further reducing water depth). Separating these two components is difficult with

foraminiferal data alone, because both produce the same bathymetric signal — shallower water during glacials^[3]. Future work integrating the foraminiferal paleodepths with glacial isostatic adjustment models could help deconvolve these signals and improve ice sheet thickness estimates for the Barents Sea ice sheet.

The transfer function's RMSEP of ± 86 m limits the resolution of individual depth estimates but is adequate for detecting the long-term trends documented here. The error is comparable to other published foraminiferal transfer functions for high-latitude settings^[15]. One source of systematic uncertainty is the assumption that the relationship between foraminiferal assemblages and depth has remained constant through the Plio-Pleistocene — an assumption that could be violated if ocean circulation changes altered the depth distribution of key species independently of bathymetric change.

Conclusion

Benthic foraminiferal analysis of 14 Barents Sea cores produced a paleobathymetric reconstruction spanning 3.6–0.8 Ma, revealing progressive deepening at rates of 0.07–0.16 mm/yr that are consistent with thermal subsidence of the continental margin. Five depth-controlled assemblage zones defined by cluster analysis provide a regional biostratigraphic framework for the Norwegian-Barents Sea, and the WA-PLS transfer function delivers paleodepth estimates with ± 86 m precision.

These paleobathymetric maps fill a gap in the boundary conditions available for numerical ice sheet models of the Barents Sea, which have previously relied on poorly constrained paleo-topographic assumptions. The depth data can be incorporated directly into ice sheet model grids to test how topographic evolution influenced ice sheet growth and decay during the Plio-Pleistocene intensification of Northern Hemisphere glaciation. Future research should extend the analysis to the eastern Barents Sea, where Russian exploration wells have penetrated equivalent stratigraphic intervals.

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Contributions Not Qualifying for Authorship

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