
# New Micropalaeontological Evidence for an Early Pleistocene Existence of the Agulhas Leakage


Thore Friesenhagen*, Michael Knappertsbusch**

*Universität Basel, Bernoullistrasse 32, 4056 Basel, (thore.friesenhagen@unibas.ch)
**Naturhistorisches Museum Basel, Augustinergasse 2, 4001 Basel (michael.knappertsbusch@unibas.ch)

## Introduction

Evolutionary studies about menardiform globorotalids within the western tropical Atlantic and the Caribbean Sea revealed a drastic increase in test size of the planktonic foraminifer *Globorotalia menardii* between 2.5Ma and 2Ma to 1.7Ma, respectively (Knappertsbusch, 2007 & 2016). This time interval coincides with the major phase of the Northern Hemisphere ice growth (Tiedemann et al., 1994). A similar size development was observed in the eastern tropical Atlantic ODP Site 667A (Friesenhagen, in preparation). The question arises, whether this evolution can be explained by a regional high evolutionary rate sensu punctuated gradualism (PG), or by long-distance dispersal of giant forms, that evolved previously in the Indian Ocean. For the mechanism driving such dispersal the Agulhas Leakage (AL) comes into mind. Today, AL transports tropical water masses from the Indian Ocean into the tropical Atlantic Ocean and at least during the Pleistocene it had a major impact on the Northern Hemisphere climate (Beal, 2011). Along with the water masses, Indian Ocean biota are transported into the Atlantic Ocean (Caley et al., 2012, Villar et al., 2015). Caley et al. (2012)used *G. menardii* in Pleistocene samples from the South Atlantic to document the presence of the AL mechanism back until ca. 1.3Ma.
To examine which of these two hypotheses (i.e., PG versus AL) is more likely, we investigate the test size evolution of *G. menardii* in a core from the Mozambique Channel in the Indian Ocean across the Pliocene-Pleistocene boundary and compare it with our observations from the tropical Atlantic (Fig. 1). The lead in occurrence of giant menardiforms in the Indian Ocean compared to the Atlantic Ocean supports the AL hypothesis over the idea of PG. Our new test-size measurements also suggest existence of a "Palaeo-" AL to times earlier than 1.3Ma reported by Caley et al. (2012).

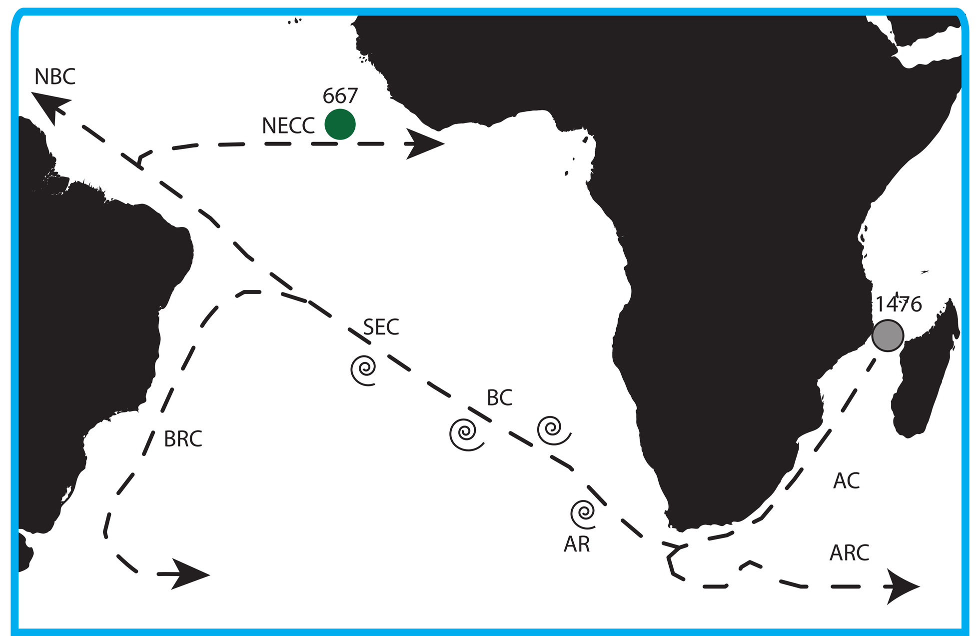


**Fig. 1:** Map showing the site locations as well as the Agulhas Current and the South Atlantic current system following Wefer et al., 1998. AC = Agulhas Current, AR = Agulhas Rings, ARC = Agulhas Return Current, BC = Benguela Current, BRC = Brazil Current, NBC = North Brazil Current, NECC = North Equatorial Counter Current, SEC = South Equatorial Current

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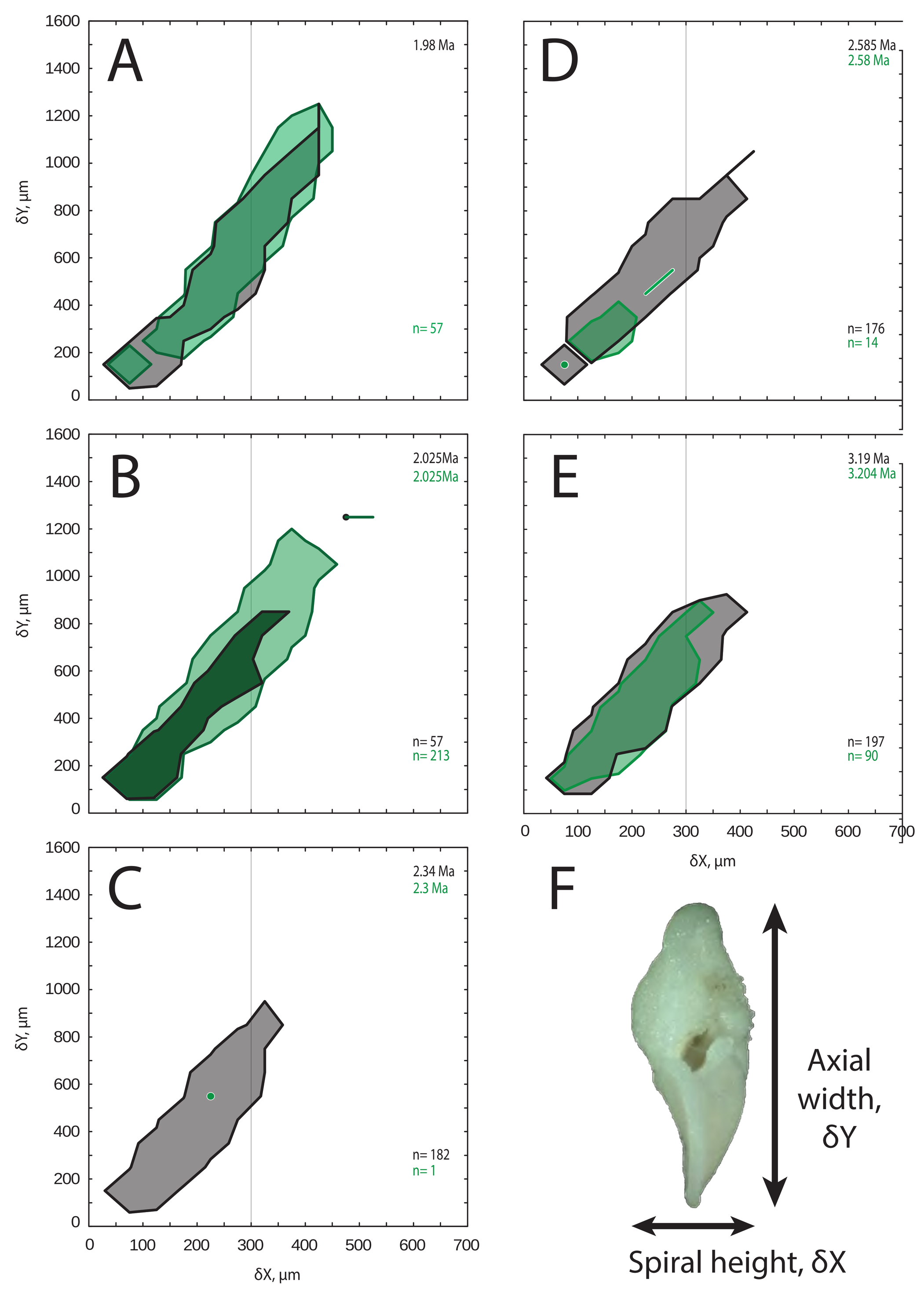


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**Fig.: 2: A-E)** Reduced contour-plots of frequency of δX versus δY of *G. menardii* in keel view at ODP Site 667A (green) and IODP Site U1476A (grey) from 1.98Ma (z-axis value ≈ -0.25) until 3.204Ma (z-axis value ≈ -0.4). The lines illustrate the base-contour of one specimen per grid-cell of 50µm x 100µm and it includes the most extreme, but rare test morphologies. These extremes are believed to represent initial adaptive novelties during test-size evolution. The number in the upper right corner shows the age in million years ago (Ma). The coloured age values correspond to the respective site of the same colour. Information about the construction of these contour plot are explained in Fig. 3. **F)** Image of a *G. menardii* specimen in keel view. **G)** Volume density diagrams (VDD) of the test size generated with 3D PDF software form Visual Technology Services Ltd for the Indian Ocean IODP Site U1476A (grey) and the eastern tropical Atlantic ODP Site 667A (green). The spiral height δX (horizontal X-axis) is plotted against the axial length δY (horizontal Y-axis) and the age (Z-axis, vertical). The axes are normalised: the value "1" represents 700µm on the x-axis and 1600 µm on the y-axis. The z-axis represents the time interval starting by 0Ma (z=0) until 8Ma (z=-1). The iso-surface of the VDDs represent the size of rare forms and interconnect equal outlines of the plane contoured frequency plots from one sample to the next. Thus, VDDs are constructed by stacking contour frequency plots of different ages. The contour frequency plots (Fig. 2A-E) can be recognised within the 3D PDF by generating a cross section parallel to the x-y plain at the corresponding point of time at the z-axis.
Please use your mouse to change your point of view on the VDDs. Via the tool bar, you can select elements of the figure by using "model tree" and create cross sections. If the 3D PDF is not displayed (white surface), please download the poster PDF or open this website in the "Internet Explorer" webbrowser.

## Methods

Twenty samples from IODP Leg 361 Site U1476A, located in the Mozambique Channel, with an age between 0.004Ma and 6.49Ma were washed and sieved using a 63µm net. The fraction >63µm was split and ca. 200 intact menardiform specimens per sample were picked. Images in keel view were taken with the Automated Measurement System for Shell Morphology (AMOR) and were used to analyse several different morphometric parameters, for example the spiral height (δX) and the axial length (δY) (Fig.2F). From the data, contour diagrams (Fig. 2A-E, for further information see Fig. 3) and volume-density diagrams (VDD's) were created (Fig. 2G). The diagrams are not smoothed, which is at cost of a more rough appearance of frequency-iso-surface through time.
Data from Site 667A are applied for comparison because this location shows the earliest occurrence of giant menardiform globorotaliids in our other investigated Atlantic sites (e.g. DSDP Site 502 and ODP Site 925).

## Results

The maximum test size at Site U1476 remains almost stable from the late Pliocene (max δY ≈ 900µm) until the early Pleistocene (max δY ≈ ca. 1250µm) (Fig. 2A-E, 2G). Site 667A shows a decrease in the test size from ~3.2Ma (max δY ≈ 900µm, Fig. 2E) to 2.58Ma (max δY ≈ 550µm, Fig. 2C). From 2.58Ma to ca. 2Ma, the maximum test size more than doubles to an axial length of ca. 1250µm (Fig. 2A, B).
At both sites, the test size observed at ca. 2Ma has never been observed in older samples.

## Discussion and Conclusion

The relatively large and stable maximum test size throughout the Pliocene/-Pleistocene boundary in the Indian Ocean supports the AL hypothesis and indicate a (re-)strengthening of the AL after the Northern Hemisphere Glaciation between 2.3 and 2.05Ma. Thus, the data suggest the existence of the AL at least since 2Ma, i.e. 0.7Ma earlier than proposed by Caley et al. (2012).
The super-large *G. menardii* from 2Ma indicate a surpassing of ecological bounds and is evolutionary seen a novelty for *G. menardii* in those regions. Hence, they may represent a new subspecies of *G. menardii* in both ocean basins. The evaluation of other morphometric parameter, like changes in the predominating coiling direction and the test shape, may provide further evidence for these ideas.

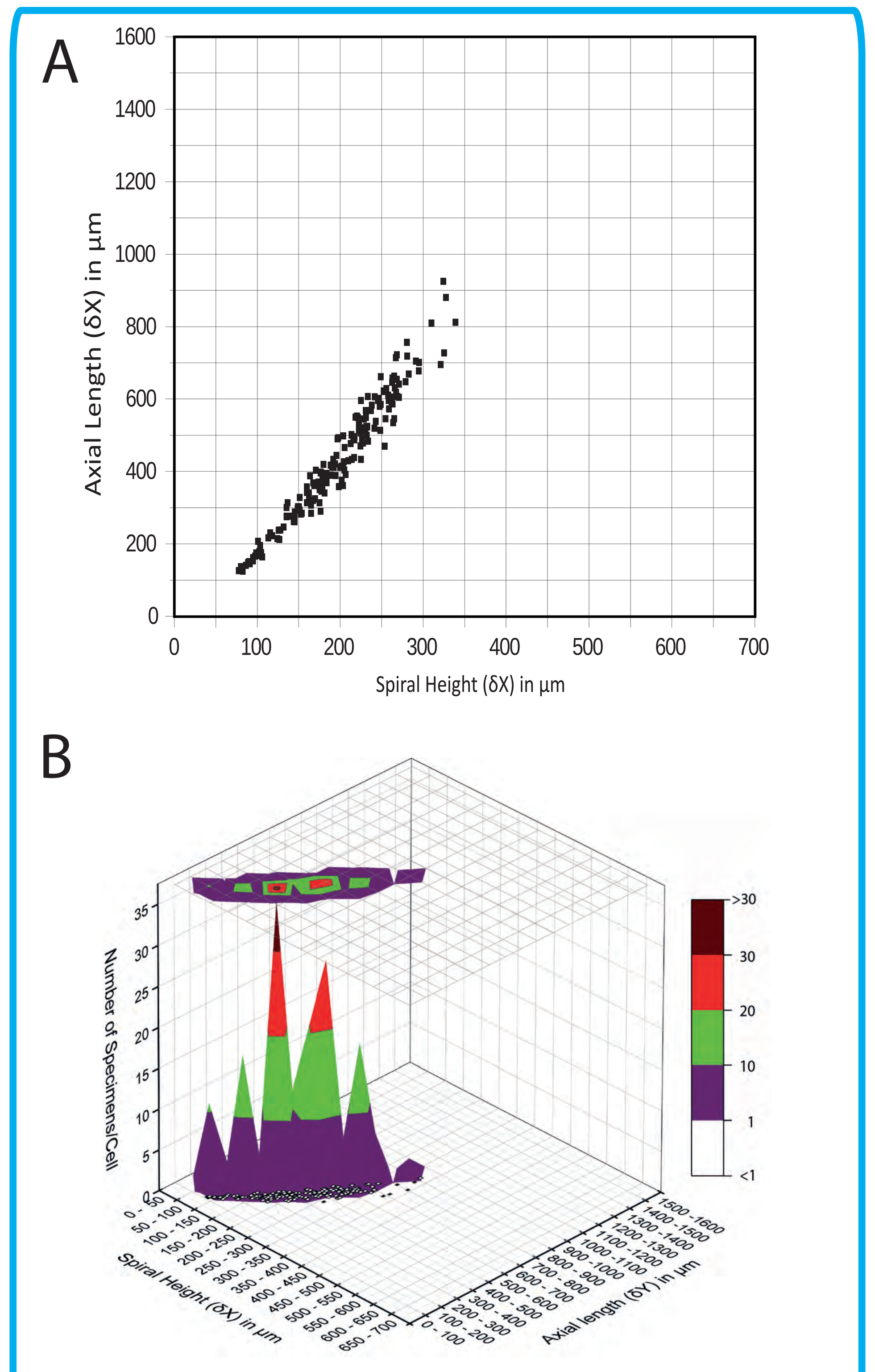


**Fig. 3:** Contour frequency diagrams showing the number of specimens per grid-cell. They are generated by plotting δX and δY values of a sample (here: sample U1476A-7H-3, 32-33cm, age = 2.34Ma, Fig. 2C) in a scatter plot. A grid with the size of 50µm for the x-axis (δX) and 100µm for the x-axis (δY) is superposed to the scatter plot (Fig. 3A) and the frequency per grid cell is counted. According to the grid cell with the highest number of specimens, we choose a contour interval which represents the data best in terms of legibility. In this example, we chose a contour-interval of 10 specimens per grid-cell(Fig. 3B). In order to represent the range in δX and δY best the lowermost contour line representing frequencies of ≥1 specimen per grid-cell is employed as well (such as illustrated in Figures 2A-E). This base-line is thought to be sensitive to adaptive morphological innovation, such as for example unusual extra-large tests.

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