# The Agulhas Current During the Late Pleistocene: Analysis of Modern Faunal Analogs

Abstract. *Analysis of micropaleontologic evidence in a deep-sea core in the southwest Indian Ocean indicates that the Agulhas Current was not a dominant feature of this region during glacial intervals. Interpretation of the fossil record, based on the analysis of modern faunal analogs, indicates that during glacial intervals the Agulhas Current was not the strong, year-round current that it is today. Evidence shows that during summer months a weak tropical current was present. During winter months the current was replaced by cool, high-salinity waters. This interpretation suggests that seasonal changes in circulation may have been more pronounced in the southwest Indian Ocean during glacial intervals than today.*

The purpose of this report is to describe how circulation patterns in the southwest Indian Ocean may have changed during the last glacial maximum. This description is based on an analysis of the fossil remains of planktonic foraminifera within deep-sea core RC 17-69, from the southwest Indian Ocean (Fig. 1). I have compared each sample within the core to modern samples, which are used to estimate past sea-surface temperatures and salinities, and I have used these comparisons to reconstruct probable circulation patterns.

The Agulhas Current is part of a complex current system in the southwest Indian Ocean which transports low-salinity, tropical waters southward through the region (Fig. 1). The South Equatorial Current bifurcates at the northeastern tip of Madagascar, feeding tropical waters into the Madagascar and Mozambique currents. These currents feed into the Agulhas Current and finally into the West Wind Drift (*1*). Occasionally, water from the Agulhas Current flows into the South Atlantic (*2*). The Agulhas Current is a dominant feature of the southwest Indian Ocean throughout the year, although the flow is about 30 percent stronger during winter months (*1*).

Water within the Agulhas Current may be distinguished from surrounding waters by its characteristic temperatures and salinities (*2–4*) (Table 1). The distribution of assemblages of planktonic foraminifera in recent sediments reflects these major water mass features (*5–7*) (Table 1). For example, an assemblage of tropical species including *Globigerinoides ruber*, *G. sacculifer*, and *Globigerinita glutinata* is associated with tropical water (including waters within the Agulhas Current). A second faunal assemblage, including *Globorotalia inflata* and *G. truncatulinoides* (right-coiling variety), characterizes high-salinity subtropical water (STW). A third assemblage, including *Globigerina bulloides*, *Globorotalia truncatulinoides* (left-coiling variety), and *Globigerina pachyderma* (right-coiling variety), is associated with subantarctic water (SAW). The boundary between the second and third faunal assemblages corresponds closely with the location of the Subtropical Convergence (STC) (*7, 8*) (Table 1); the subtropical assemblage is dominant north of the STC, whereas south of the STC, the subpolar assemblage is dominant.

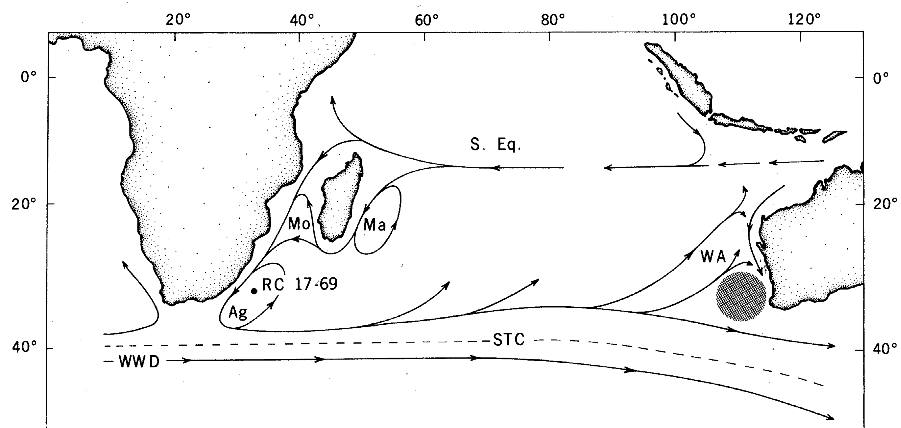


Fig. 1. Schematic diagram of circulation patterns in the southern Indian Ocean. Abbreviations: *S. Eq.*, South Equatorial Current; *Ma*, Madagascar Current; *Mo*, Mozambique Current; *Ag*, Agulhas Current; *WWD*, West Wind Drift; *STC*, Subtropical Convergence; and *WA*, West Australian Current. The location of core RC 17-69, off the southwest coast of Africa, is indicated. The stippled area off the west coast of Australia indicates the region of modern faunal analogs for glacial faunas in core RC 17-69.

In this report I use the above oceanographic and faunal criteria to interpret past water mass conditions in the region of core RC 17-69.

In an earlier analysis of this core, Bé and Duplessy (*9*) examined morphologic variations of the species *Orbulina universa*. They suggested that an average diameter of 450 $\mu$m could be used to indicate the location of the STC in the past. On the basis of this hypothesis and an analysis of *O. universa* within the core, they inferred that the STC was located to the north of RC 17-69 throughout much of the Late Pleistocene. Since the STC in this region today marks the confluence of the Agulhas Current and the West Wind Drift (*1, 3*), their interpretations suggest that the Agulhas Current could not have flowed southward across this region at these times and that SAW (today found south of the STC) must have occurred at this location.

What happened to the Agulhas Current during the Late Pleistocene? I have reexamined the top meter of core RC 17-69 because it includes the present interglacial and the last glacial maximum and thus is representative of climatic extremes within the entire core. My interpretations are based on a total faunal analysis of the top section, carried out with a "modern analog" technique as described below.

The following method may be used to quantify faunal changes within a deep-sea core in terms of modern oceanographic conditions. An index of faunal similarity (*10*) may be used to compare the fauna from each level to modern core-top samples in the Indian Ocean in order to identify a subset of modern faunal analogs (samples that are most similar to the downcore samples). These modern samples are important because they also may be interpreted as oceanographic analogs. In other words, oceanographic conditions which produce a particular faunal assemblage on the sea floor today may be quite similar to those which produced virtually identical faunas in the past. Thus, environmental measurements from regions of the modern samples may be used to estimate past sea-surface temperatures and salinities. These estimates are based on an average of measurements for the subset of modern samples, weighted by their similarity index (*11*). The weighting factor gives greater emphasis to those modern samples whose faunas are most similar to those downcore. In addition, the variability of the modern values may be used as a measure of confidence about each estimate (*12*). For example, an estimate could be considered more accurate if it were based on a relatively small range of environmental values within the modern subset than if it were based on a large range (*13*). The above technique differs in methodology from the technique of Imbrie and Kipp (*14*). My technique not only estimates environmental variables but also gives a confidence interval about each estimate and identifies the location of modern faunal analogs which may be useful for interpreting past oceanographic regimes (*15*).

Stratigraphic analyses of core RC 17-69 by $^{14}C$ dating and $\delta^{18}O/^{16}O$ analyses (*9*) indicate that the top meter contains a continuous record of the past 50,000 years. The faunal composition within the top meter of this core is graphically presented in Fig. 2 in terms of the faunal assemblages described above and elsewhere (*7*).

The top 25 cm of the core, representing Holocene conditions, are dominated by a tropical assemblage, an indication that during this interval conditions in the region were much as they are today. Faunal compositions change dramatically at the Pleistocene-Holocene boundary (25 cm). The section below this boundary, which includes the last glacial maximum, is dominated by a subtropical assemblage.

Faunas from the Holocene section of this core were compared with faunas from over 150 modern core-top samples from throughout the Indian Ocean (*7*). The modern samples most similar to the Holocene section are from the southwest Indian Ocean, from the same general region as core RC 17-69. This result indicates that oceanographic conditions during the Holocene were similar to modern oceanographic conditions. Estimated temperatures, however, are slightly higher and estimated salinities are slightly lower than those observed today (compare Tables 1 and 2, and see Fig. 2). These results suggest that the Agulhas Current may have been slightly stronger during the Early Holocene.

In contrast, a comparison between faunas from glacial and modern samples indicates a very different situation. Faunas from modern sediments off the west coast of Australia are nearly identical to faunas in the lower section of core RC 17-69 (see Fig. 1). These results suggest that the region off the Australian coast may be a modern oceanographic analog of the southwest Indian Ocean during the last glacial maximum. Today the region off the Australian coast is characterized by a subtropical current which carries cool (< 17°C), high-salinity (> 35.50 per mil) waters northeastward and a seasonally variable tropical current which carries warm, low-salinity water southward (*16*). By analogy, similar conditions may have occurred in the southwest Indian Ocean during the last glacial period, producing virtually identical faunas in the sediments.

Summer temperatures for this interval are estimated at > 20°C (Fig. 2 and Table 2). These temperatures suggest the presence of tropical water in the region which may have been associated with warm Agulhas water. Estimated winter temperatures, however, are less than 17°C, and salinities are greater than 35.5 per mil, an indication that during winter months STW may have occupied this region (Tables 1 and 2).

These data suggest that during the summer months tropical waters may have flowed southward across the region. The waters of this tropical current, however, were more saline than the waters presently within the Agulhas Current. This finding suggests a greater degree of mixing of tropical waters with STW, perhaps within the return Agulhas Current (*17*). During the winter months this tropical water was replaced by high-salinity STW. The source of these waters

Table 1. Table 1. Modern relationship between water mass characteristics in the southwest Indian Ocean and planktonic foraminifera in Recent sediments. Temperature ranges for the Subtropical Convergence are for winter and summer, respectively. Water mass characteristics are from (*2, 3*); fauna are described in the text and in (*7*).

| Water mass | Temperature (°C) | Salinity (per mil) | Dominant faunal group |
|---|---|---|---|
| Tropical waters | | | |
| Warm Agulhas water | > 20° | < 35.5 | Tropical |
| Cold Agulhas water | 17°–20° | < 35.5 | Tropical |
| Subtropical water | < 17° | > 35.5 | Subtropical |
| Subtropical Convergence | 10°–14°, 14°–18° | 35.4–35.6 | Subtropical-subpolar |
| Subantarctic water | 4°–16° | 35.1–35.7 | Subpolar |

Table 2. Table 2. Estimated temperatures, salinities, and probable water masses for the sections of core RC 17-69 corresponding to the Holocene and the glacial maximum. Abbreviations: WAW, warm Agulhas water and STW, subtropical water.

| Core section | February (summer) | | | August (winter) | | |
|---|---|---|---|---|---|---|
| | Temperature (°C) | Salinity (per mil) | Probable water mass | Temperature (°C) | Salinity (per mil) | Probable water mass |
| Holocene | 25.6° ± 1.0° | 35.37 ± 0.14 | WAW | 21.4° ± 1.1° | 35.29 ± 0.15 | WAW |
| Glacial | 20.7° ± 0.6° | 35.59 ± 0.06 | WAW? | 16.2° ± 0.5° | 35.70 ± 0.08 | STW |

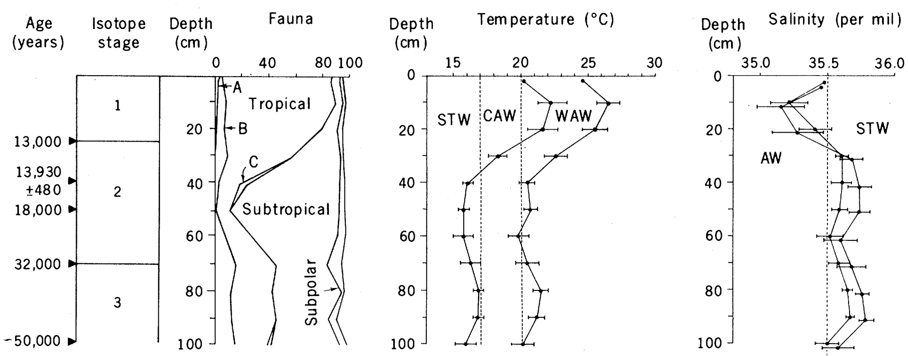


Fig. 2. Paleoenvironmental analysis of the top meter of core RC 17-69. On the left is stratigraphic information from (*9*). The Holocene-Pleistocene boundary occurs at about 25 cm in the core. To the immediate right is a composite diagram showing variations in the percentage composition of faunal assemblages over the last 50,000 years. The tropical, subtropical, and subpolar assemblages are described in the text and in (*7*); A, B, and C are minor faunal components described in (*7*). The graphs in the middle and to the right show estimated surface temperatures and salinities for summer and winter (along with estimated confidence intervals). The topmost samples represent modern conditions. Plotted in each of these graphs are the estimated surface temperatures and salinities for summer (left) and winter (right) along with the estimated confidence intervals). These figures are separated into zones based on modern water mass characteristics (Table 1). Abbreviations: *STW*, subtropical water; *CAW*, cold Agulhas water; *WAW*, WAW, warm Agulhas water, and STW, subtropical water.

may have been from the west, as a current flowing eastward around the Cape of Good Hope (*18*), or through the "surfacing" of STW from below as the Agulhas Current weakened (*19*) or changed its course (*20*).

Why do these interpretations differ from those presented by Bé and Duplessy (*9*)? Analysis of the distribution of modern assemblages (*7, 8*) indicates that the transition between the subtropical and subpolar faunas coincides with the approximate location of the STC (Table 1), with the subpolar assemblage dominant south of the STC. Thus, if Bé and Duplessy's interpretations were correct, the subpolar assemblage should dominate the lower section of the core. Figure 2 shows that this fauna is never dominant. According to these criteria, the STC must have always been south of the core site. Furthermore, according to the criteria listed in Table 1, environmental estimates from both this report and (*9*) indicate the presence of STW, not SAW, during the coldest intervals. The criteria on which Bé and Duplessy's interpretations are based (*Orbulina universa* diameters) may not be as precisely defined as the criteria used in this report (*21*).

Tropical species dominate the fauna in the southwest Indian Ocean today and are associated with the continuous southward flow of the warm, low-salinity water along the African coast. Although tropical species were present during the last glacial maximum, the fauna was dominated by a subtropical assemblage. These faunal changes indicate that advection of tropical water into the region may have been less intense or more variable, or both, during glacial intervals than today. Comparison of these glacial assemblages with modern samples indicates that the region off the west coast of Australia may be a modern analog for the Agulhas region during glacial intervals. On the basis of this analogy, and estimated temperatures and salinities, I conclude that circulation in the Agulhas region during the last glacial period varied seasonally. A warm, southward-flowing current, similar to the Agulhas Current today but characterized by higher salinity, may have flowed southward during the summer months. During the winter months, however, this southward flow either decreased, shifted, or was replaced by a cool, high-salinity current from the south. This increased seasonal variability in current flow does not necessarily indicate an expansion or intensification of monsoon circulation throughout the Indian Ocean. In fact, computer simulations of ice-age climate (*22*) suggest that the southwest monsoon may have been weaker in the northern Indian Ocean. Instead, seasonal weakening or reversal of winds may have occurred within the region and may have affected surface circulation (*23*).

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**References and Notes**

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10. In the present study the cosine of the vector angle between modern and downcore samples is used as a similarity index [J. Imbrie and E. Purdy, *Mem. Am. Assoc. Pet. Geol. 1* (1962), p. 253]. This metric may be calculated by first normalizing each sample to unit length (that is, setting the sums of the squares equal to unity) and then calculating the cross product.
11. The environmental estimate, $E$, for a downcore sample is given by

$$\hat{E} = \frac{\sum_{i=1}^{ns} s_i \cdot e_i}{\sum_{i=1}^{ns} s_i}$$

where $s_i$ is the faunal similarity between the downcore sample and the core-top sample $i$, $e_i$ is the environmental value for sample $i$, and $ns$ is the number of analogous modern samples used in the estimation. Tests based on the use of a modern set of core-top samples from the Indian Ocean (*7*) give the following standard errors for 152 estimates, based on the ten most similar analogs for each sample (that is, $ns = 10$): August sea-surface temperature, ± 1.34°C; February sea-surface temperature, ± 1.17°C; August sea-surface salinity, ± 0.47 per mil; and February sea-surface salinity, ± 0.42 per mil.
12. In tests carried out with the modern set of 152 core-top samples, confidence intervals were of the same order of magnitude as the residuals and positively correlated to the absolute value of the residuals ($P < .001$).
13. In addition, numerical experiments parallel to those outlined by W. Hutson [*Quat. Res. (N.Y.)* **8**, 355 (1977)] indicate that, if there are no modern analogs for a downcore sample, low-similarity indices or large confidence intervals, or both, would indicate that the resulting estimate may be erroneous.
14. J. Imbrie and N. Kipp, in *The Late Cenozoic Glacial Ages*, K. Turekian, Ed. (Yale Univ. Press, New Haven, 1971), p. 71. See also (*5, 7*).
15. Numerical comparisons, however, indicate that both techniques yield virtually identical estimates ($P < .001$).
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17. High-salinity estimates for glacial intervals may also reflect the effect of large continental ice sheets on global salinity.
18. Faunal data from a core (RC 11-86) off Cape Town, South Africa, indicates that subtropical conditions may have existed in the region during the last glacial maximum.
19. Darbyshire (*2*) reported that Agulhas waters often overlie subtropical waters, which may "surface" when flow in the Agulhas Current weakens.
20. On the basis of theoretical studies, G. Veronis [*J. Mar. Res.* **31**, 228 (1973)] suggests that increased wind stress could cause a western boundary current such as the Agulhas Current to become "detached" from the coast.
21. Examination of the data on which Bé and Duplessy based their interpretations [figure 2 of (*9*)] shows that the STC lies within a region where the average diameters are between 400 and 450 μm. At no time are the diameters less than 400 μm.
22. J. Williams, R. G. Barry, W. M. Washington, *J. Appl. Meteorol.* **13**, 305 (1974); W. Gates, *J. Atmos. Sci.* **33**, 1844 (1976); S. Manabe and D. Hahn, *J. Geophys. Res.* **82**, 3889 (1977).
23. For example, the ice-age simulation by Manabe and Hahn (*22*) indicates a change in both the direction and the intensity of the winds in the southwest Indian Ocean during the austral winter. These changes in the wind regime may have altered the wind stress over the Agulhas Current enough to cause the current to separate from the coast, as theorized by Veronis (*20*).
24. I thank A. Bé and his staff for their generous contribution of faunal data from core RC 17-69; I thank A. Bé, J.-C. Duplessy, W. Prell, and D. Williams for their useful comments and suggestions. I am grateful to D. McEwan for computational assistance, P. Lawrence for drafting, and G. Davis for typing services. This research was supported by NSF (International Decade of Oceanographic Exploration) grants DES 76-02202 and OCE 77-23162.

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## Dislocations in Spinel and Garnet High-Pressure Polymorphs of Olivine and Pyroxene: Implications for Mantle Rheology

Abstract. *The meteorite Tenham was observed by transmission electron microscopy and ringwoodite and majorite, the high-pressure polymorphs of olivine and pyroxene, were identified. Ringwoodite contains antiphase boundaries and straight dislocations that are probably dissociated. Mantle flow of spinel might proceed by pure climb, and whole-mantle convection may be possible if the grain size is small enough.*

High-pressure syntheses have confirmed that olivine and pyroxene transform, respectively, to spinel and garnet structures (*1*). This transformation is compatible with seismic data and is thought to account for the 400-km discontinuity in the earth's mantle (*2*). Inasmuch as dislocations and stacking faults control the plastic flow properties of crystals (*3*), we began an investigation of the nature and structure of these defects in ringwoodite and majorite. Our purpose was to obtain a qualitative description of the rheology of high-pressure silicate phases and assess the possibility of deep-mantle convection.

We report here transmission electron microscopic observations of dislocations and extended defects in ringwoodite and majorite crystals. Ringwoodite is the high-pressure $\gamma$ spinel polymorph of olivine, and majorite is the high-pressure

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