Assessing the role of the Subtropical Front in regulating Agulhas Leakage at the Last Glacial Termination

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Paleoceanographic variability of Agulhas Leakage

Many paleoceanographic studies have found significant glacial-interglacial variability in the Agulhas Leakage, with cold glacial periods tending to have less leakage, and maximum leakage occurring during, or just prior to glacial terminations. One example is shown below.

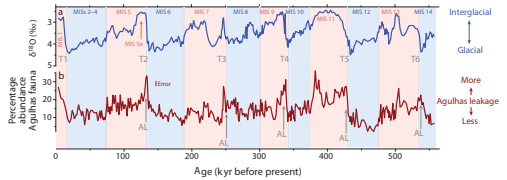

Figure 1. A palaeoceanographic time series from the Agulhas leakage corridor spanning the last 570 kyr. (Figure reproduced from Beal et al. 2011; data from Peeters et al. 2004) a) $\delta^{18}O$ of benthic foraminifera from a sediment record in the Cape Basin represents a proxy for glacial–interglacial variations in global climate (highlighted by vertical blue/red shading). T1–T6 mark terminations of the past six glacial periods. B) Abundance of tropical planktonic foraminiferal marker species from the same sediment record indicate maximum Agulhas leakage (AL) during glacial terminations T2–T6. Standard error (1.73%) is illustrated.

Proposed mechanisms for reduced Agulhas Leakage during glacial periods:

1. *Stronger* Agulhas Current caused a more upstream (eastward) Retroflection, and *less* Leakage

   An *inverse* relationship between Agulhas Current flux and Agulhas Leakage is supported by:
   - Simple, idealized models (e.g. Ou and de Ruijter, 1986)
   - Langrangian drifter models (van Sebille et al. 2009)
   - Modern observations (de Ruijter et al. 2004)
2. More *northward* Subtropical Front (STF) restricted the Agulhas Retroflection, causing *less* Leakage

   A direct relationship between STF latitude and Agulhas Leakage is supported by various models (e.g. de Ruijter and Boudra, 1985, Matano, 1996)

Results from the Provenance and Flux of Terrigenous Sediments

Strontium isotope ratios ($^{87}Sr/^{86}Sr$) of the terrigenous sediment deposited in the deep sea provide a good indicator of its provenance. In general, low $^{87}Sr/^{86}Sr$ indicate a relatively young continental source, while very high $^{87}Sr/^{86}Sr$ indicate that the provenance contains very old terrains, such as those exposed on the eastern coast of South Africa (Fig. 2). Terrigenous $^{87}Sr/^{86}Sr$ of modern sediments in the South Atlantic show a pattern resembling the surface ocean circulation, with sediments underlying the Agulhas Current and the Agulhas Return Current having significantly higher $^{87}Sr/^{86}Sr$ than surrounding sediments (Fig. 2). It is for this reason that we can use terrigenous $^{87}Sr/^{86}Sr$ as an Agulhas Current proxy.

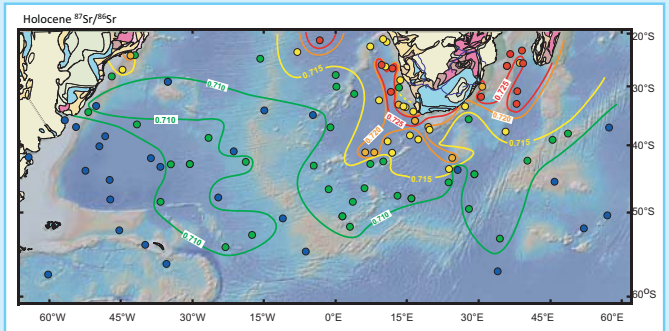

Figure 2. Terrigenous $^{87}Sr/^{86}Sr$ for Holocene sediments for the region from 40°W-60°E and 20°S-60°S (Franzese et al. 2006). Symbols marking core locations, $^{87}Sr/^{86}Sr$ contours and the ages of exposed land surfaces are color coded following the scales shown below.

$^{87}Sr/^{86}Sr$: < 0.710 | 0.710 - 0.715 | 0.715 - 0.720 | 0.720 - 0.725 | > 0.725

Cenozoic	Mesozoic	Palaeozoic	Proterozoic (Late)	Proterozoic (Middle)	Proterozoic (Early)	Archean	Precambrian (Undivided)

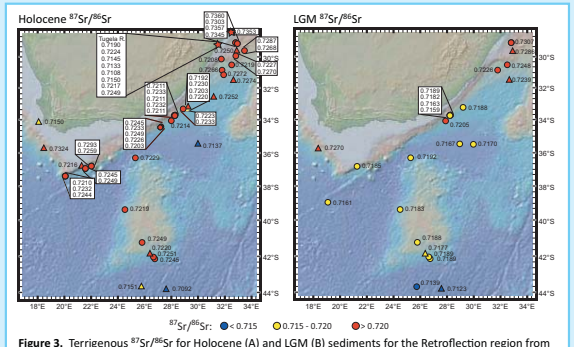

Figure 3. Terrigenous $^{87}Sr/^{86}Sr$ for Holocene (A) and LGM (B) sediments for the Retroflection region from 17-34°E and 28-44°S. Sediment core data from this study are shown in circles and triangles; stars show the locations of the river mouth. (Franzese et al. 2009)

Provenance Results

Provenance and flux data for sediments deposited in this region during the Last Glacial Maximum (LGM, ~20,000 years ago) are consistent with reduced Agulhas Leakage, but also indicate that the Agulhas Current was significantly *weaker* than during the Holocene (recent 10,000 years) (Franzese et al. 2006).

Based on the relatively low LGM $^{87}Sr/^{86}Sr$ in cores northeast of the Agulhas Plateau (0.717), there is no compelling evidence that the Agulhas Retroflection was east of the Agulhas Plateau during the LGM (Fig. 3b). In addition, the homogeneity of LGM $^{87}Sr/^{86}Sr$ with water depth (Fig. 4) most likely reflects a surface water source that is common to all sites. This could only be true if during the LGM, the Agulhas Retroflection was positioned west of the Agulhas Plateau, close to its modern position.

Based on all available data, the most plausible scenario for the LGM circulation is no change from the modern flow path of the Agulhas Current or the location of Retroflection. The glacial pattern of $^{87}Sr/^{86}Sr$ is very similar to the modern, but the absolute values are generally lower than in the Holocene (Fig. 3). This implies that during the LGM, the Agulhas Current flowed along its modern trajectory, but was depositing less material with very high $^{87}Sr/^{86}Sr$. Since there is no evidence for a LGM to Holocene change in the end-member sediment composition (Franzese et al. 2006), this means that the Agulhas Current delivered less particles to these sediments during the LGM. We infer that the reason for this was a smaller sediment transport capacity, i.e. a weaker Agulhas Current flow.

In summary, the best paleoceanographic evidence suggests that during the LGM, the *Agulhas Current was weaker* and there was *less Agulhas Leakage*. This is inconsistent with hypothesis #1 above. In addition, the Agulhas Retroflection does not appear to have been displaced during the LGM, which is inconsistent with hypothesis #2 above. **We therefore posited another hypothesis:**

3. **Stronger Agulhas Current may lead to *more* Leakage**

   A *positive* relationship between Agulhas Current flux and Agulhas Leakage is supported by a regional ocean model known as The Southern Africa Experiment (SAfE), forced by the increased Agulhas Current strength due to recent global warming (Rouault et al. 2009)

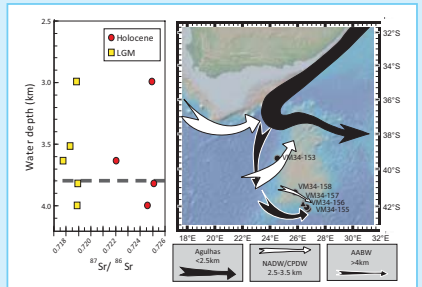

Figure 4. Terrigenous $^{87}Sr/^{86}Sr$ for cores from the Agulhas Plateau with water depth (Franzese et al. 2009). The dashed line at 3.8 km to shows the approximate interface between AABW and CPDW.

Re-evaluating Hypothesis #2

In spite of compelling evidence that the Agulhas Retroflection occupied its modern flow path during the LGM (see: Provenance Results), the idea that north-south migrations of the STF play an important role in regulating the amount of Agulhas Leakage persists (e.g. Bard and Rickaby, 2009, De Dekker et al. 2012). We therefore feel that it's necessary to accurately reconstruct the location of the STF south of Africa. The STF is a zone of high meridional sea surface temperature (SST) and sea surface salinity (SSS) gradients, so changes in the location of the STF can be most accurately addressed by measuring proxies for SST and SSS in a meridional transect of deep sea cores (Fig. 5).

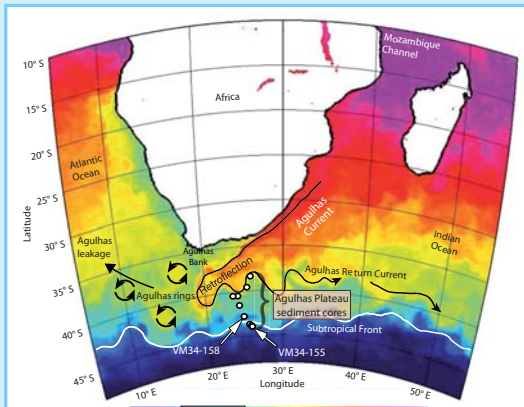

Figure 5 (modified from Figure 3 of Beal et al. 2011). The major features of the Agulhas Current System (black arrows), the southern boundary of the modern STF (white line) and core locations for the proposed study (circles). Background color shows SST for 23 May 2009; SST data are from the NAVOCEANO K10 analysis with combined satellite infrared and microwave measurements, made available through the GHRSST project (Donlon et al. 2007). North–south migrations of the STF (related to wind curl changes) and/or the retroflection loop (related to varying Agulhas strength) can choke or open the "leakage gap" between Africa and the STF.

Our project fills in a significant geographical gap in glacial reconstructions of the STF by using a meridional transect of cores from the western flanks of the Agulhas Plateau, between the latitudes of 38°S and 42°S. We are using paired measurements of planktonic Mg/Ca and $\delta^{18}O$ as proxies for SST and SSS, to explicitly reconstruct the position of the STF over the past 25,000 years, covering the time period of the Last Glacial Termination, and we plan to combine these with measurements of proxy tracers of particles and water mass. We will produce high temporal resolution records of the SST and SSS gradients associated with the STF immediately south of the Agulhas Retroflection over the last 25,000 years. In the figures below, we present the initial results of our study, focusing on two of the southernmost cores in the transect, near the modern location of the STF.

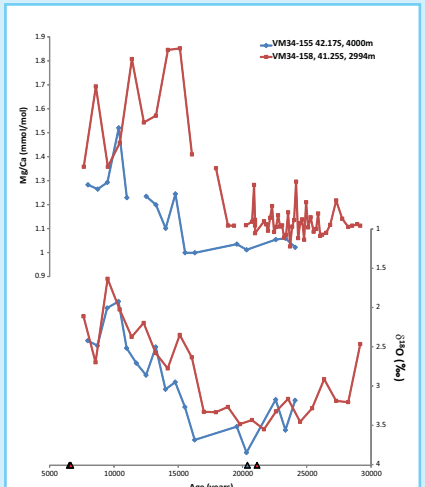

Figure 6. Mg/Ca (top) and $\delta^{18}O$ (bottom) of *G. bulloides* from VM34-158 and VM34-155. Calibrated ^{14}C ages of *G. bulloides* VM34-158 (red carrot) and VM34-155 (blue carrot) are also shown for reference.

- Mg/Ca and $\delta^{18}O$ both show clear glacial to interglacial gradients, indicating cooler, higher salinity waters during the LGM
- The latitudinal gradient in Mg/Ca appears to be larger than for $\delta^{18}O$, indicating that temperature, as opposed to salinity, dominates the signal
- More high-resolution down-core records and increased resolution records of these cores in the Agulhas Region are necessary to completely constrain the position(s) of the STF over the last deglaciation

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