Dynamics of Abyssal Mixing and Interior Transports Experiment
DynAMITE

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The densest waters in the AMOC

— Antarctic Bottom Waters (AABW) and Nordic Seas Overflow Waters (NSOW) — undergo a diapycnal transformation into warmer, lighter density classes – North Atlantic Deep Waters (NADW) — that is remarkable for its amplitude (e.g. 7-8 Sv across the 1.8° isotherm between latitudes 15° - 40°N). This upward transfer of mass and buoyancy gain -- the North Atlantic's **Abyssal Upwelling Cell** (**AUC**) -- is primarily driven by diapycnal mixing along the Mid Atlantic Ridge (MAR) and in the deep Gulf Stream, with secondary contributions from lateral recirculations adjacent to the western boundary. Entrainment of overlying waters warms the bottom layers in the direction of the basin-scale circulation; vortex stretching enhances northward penetration of AABW properties. As the MAR topography steepens, diapycnal flows veer uphill and then westward, boosting DWBC transports by 10-15 Sv near Cape Hatteras and the Bahamas. Mixing weakens the stratification creating massive reservoirs of low potential vorticity waters – an abyssal analog to water masses formed by deep convection and buoyancy loss at high latitudes.

DynAMITE is an investigation of the processes underlying the AUC in the western North Atlantic. It is comprised of 3 components:

1) Analysis of basin-scale PV distributions from climatology
2) A moored transport array of profiling CTDs and current meters to measure the interior flows at depths between 1500 - 6000 m.
3) Microstructure measurements (using the High Resolution Profiler) between Bermuda and the MAR where upwelling is postulated to feed the interior flows

Results from this program underscore the importance of the AUC's contribution to budgets of mass, heat and tracers in the AMOC, and in setting the deep interior layers in motion.

Density and stratification

provide the signatures of strong isopycnal flows and locally enhanced diapycnal mixing that together constitute the cold limb of the AMOC.

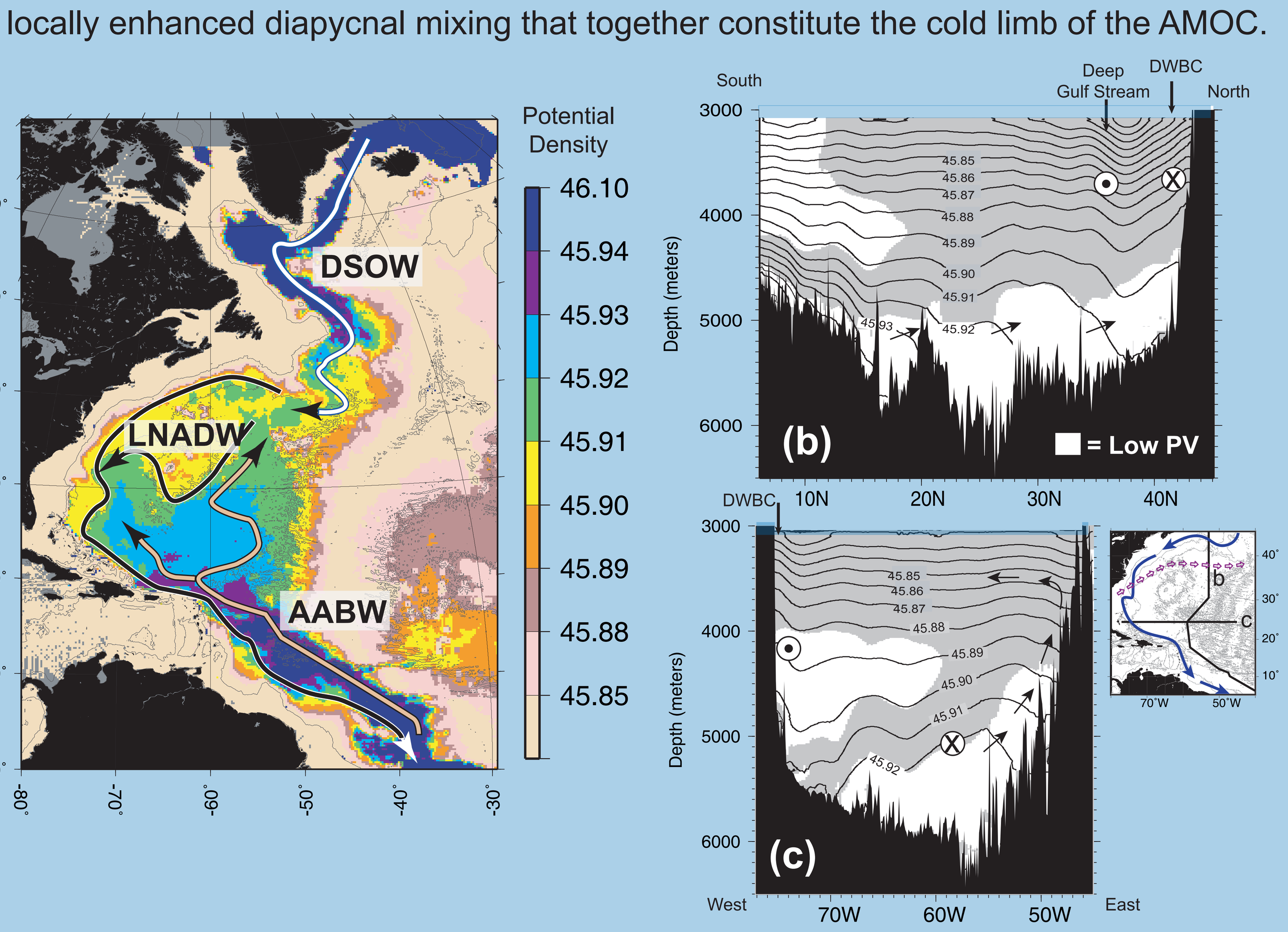

Figure 1.

a) Map of potential density (relative to 4000 db) along the seafloor (color) with schematic flows of AABW, DSOW and LNADW.

b,c) Meridional and zonal sections of potential density sliced through the western basin along the lines depicted on the inset map. White background highlights reservoirs of low potential vorticity (< 2.0e-12 m s^{-1}) where diapycnal mixing has weakened the stratification either locally (isopycnals dipping downward into topography) or upstream of the section. Arrows indicate direction of flows over rugged topography. Circle/crosses and circle/dots indicate geostrophic flow into or out of the plane of the section.

The prevailing view of the cold limb

circulation has emphasized the role of large-scale recirculations to rationalize the observed near-doubling of the DWBC transports between the mid-latitudes and tropics. Aside from 1-2 Sv of locally enhanced upwelling, this picture implies that upward buoyancy flux in the western North Atlantic occurs at background diffusivity rates and timescales associated with advection in these large recirculations.

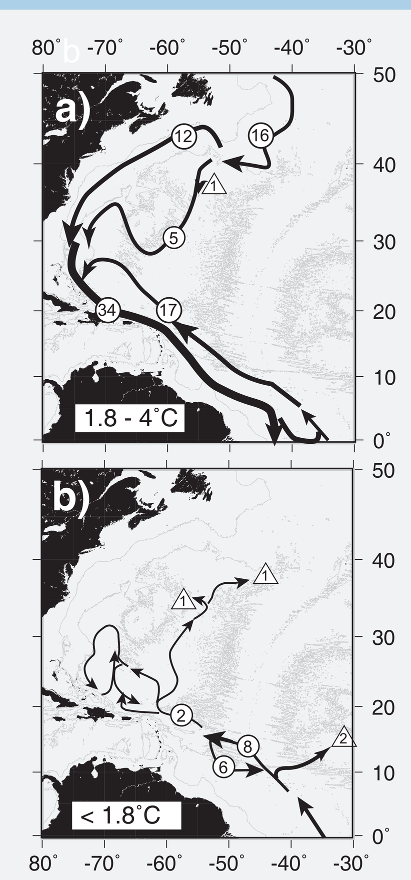

Figure 2.
Adapted from Schmitz & McCartney (1993), circulation cartoons for **a)** deep water (1.8 - 4 deg C) and **b)** bottom water (1.3 - 1.8 deg C). Transports are in Sverdrups, triangles represent upwelling.

Analysis of potential vorticity distributions

in finely divided density layers from the seafloor up to ~1500 meters provides evidence that upwelling and water mass transformation along the MAR are the primary sources of interior flows and the boosted DWBC transport. Maps of layer thickness, H, identify locations of enhanced diapycnal mixing, while f/H contours trace the sources and sinks of the geostrophic interior flows (see separate handout).

In **Fig. 3** (below), composites of the finely divided layers identify 4 basic flow regimes in the cold limb circulation, and their corresponding density / temperature / watermass classes. In **Layer 1**, diapycnal mixing (blue spirals) and vortex stretching inflate the northward penetration of AABW. In **Layer 2**, AABW upwells along the MAR and flanks of Bermuda Rise, AABW and DSOW are mixed in the deep Gulf Stream. In **Layer 3**, mixing along the MAR drives interior flows of LNADW that entrain into the DWBC. Above the crest of the MAR, **Layer 4**, LSW flows equatorward in the DWBC and is modified by advective-diffusive mixing and eddies adjacent to the DWBC and Gulf Stream. Flows from the eastern basin (modified MOW) retroflect back to the northeast without entraining into the DWBC north of 20N.

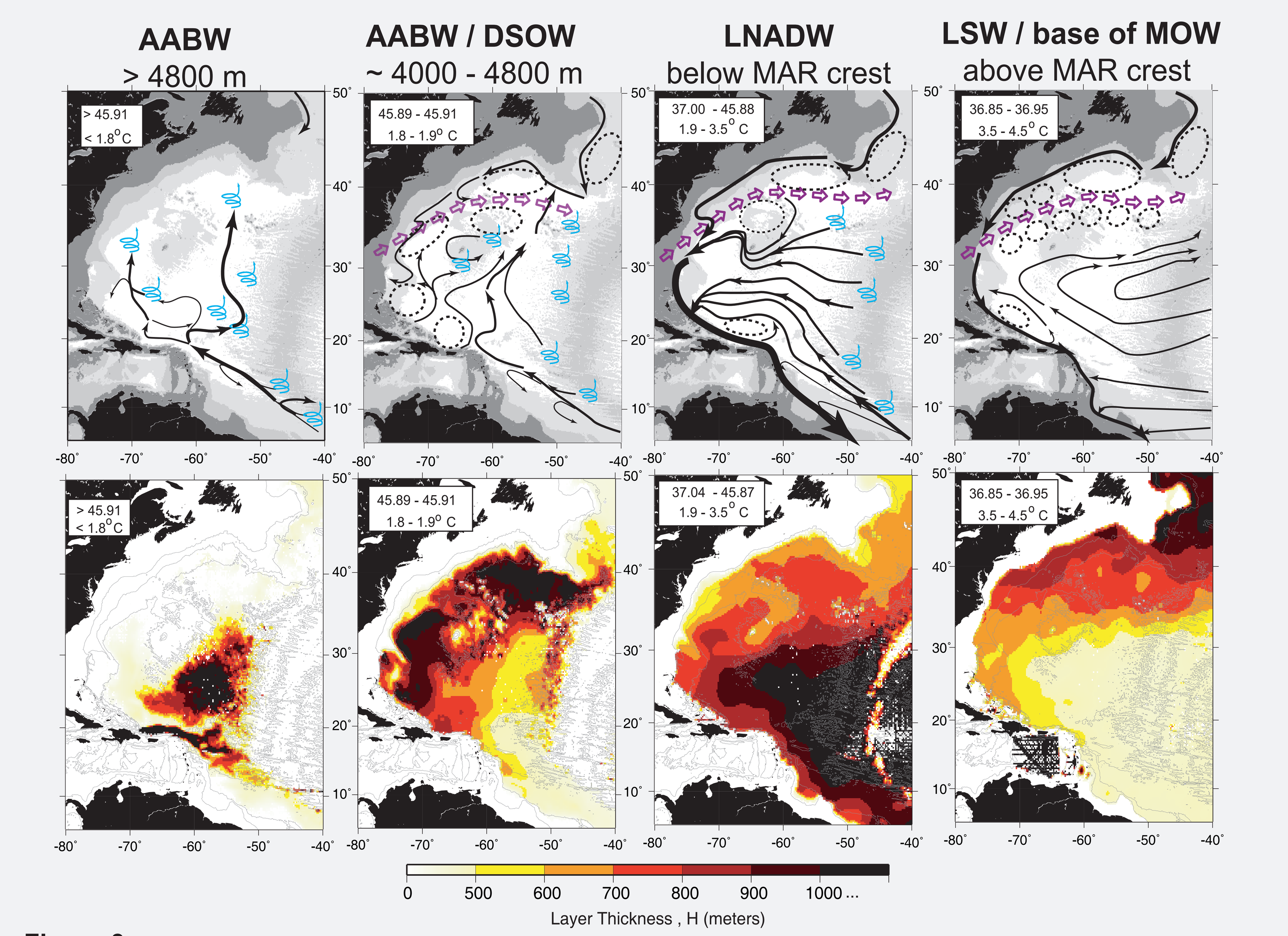

Figure 3.

Top row : schematic diagrams of the mean geostrophic interior flows (solid lines, arrows), recirculations adjacent to boundary currents (dashed ovals), and regions of locally enhanced diapycnal mixing (blue spirals) in 4 layers spanning depths > 1500 m. Purple arrows depict the mean location of the deep Gulf Stream. Potential density bounds, temperature and approximate depth ranges for each layer are labelled. Each layer corresponds to a generalized water mass class:

- **AABW**: Antarctic Bottom Water
- **AABW / DSOW** : mixture of AABW and Denmark Strait Overflow Waters
- **LNADW** : mixture of Nordic Seas Overflows and interior waters (upwelled AABW)
- **LSW / MOW** : Labrador Sea Water and base of the Mediterranean Outflow Waters

Bottom row: vertical thickness of each layer. Thickness maxima correspond to regions of locally enhanced diapycnal mixing: i) over rugged topography of the MAR (Layers 1-3), ii) in the deep Gulf Stream (Layer 2), and iii) in the waters formed by convective mixing in the Labrador Sea (Layer 4)

The field program

was conducted between 20-30N, Bermuda and the MAR.

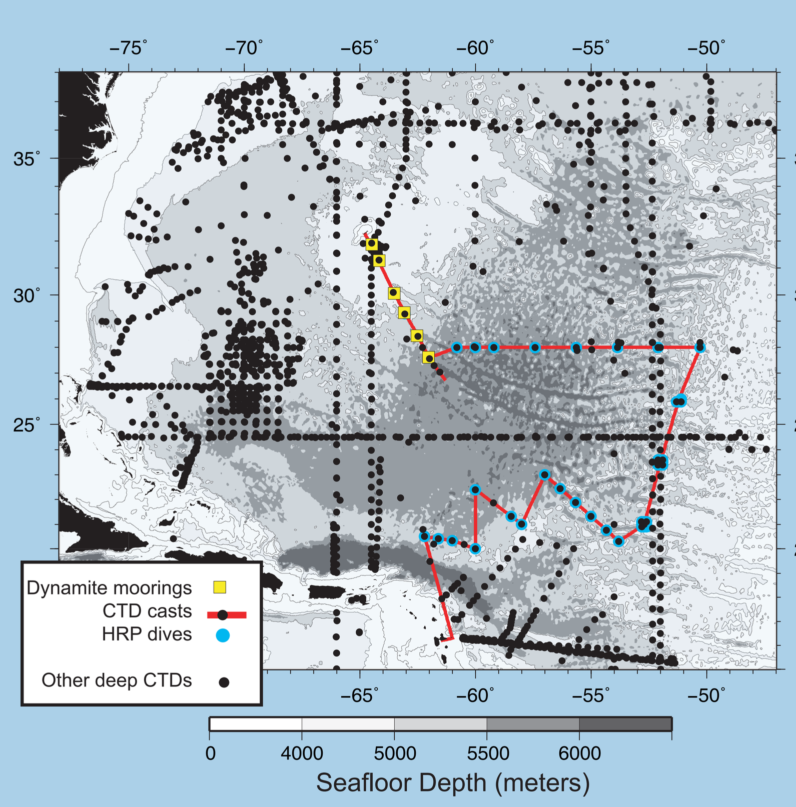

Figure 4. Locations of the DynAMITE moorings (yellow squares) and microstructure survey (red lines) relative to existing full water column profiles (black circles).

1) A moored array of profilers was installed down the southeast flank of Bermuda Rise in September 2010 and recovered in June 2012. These instruments returned profiles of velocity, pressure, temperature and salinity; and are being used to construct estimates of interior transports as a function of density.

2) A microstructure survey was conducted in May / June 2011 aboard R/V Knorr using the High Resolution Profiler (HRP). These measurements have provided estimates of vertical diffusivities across different geographical regimes in the study area. Full water column profiles of P,T,S and velocity filled significant sampling gaps and these have greatly clarified the structure of the regional flow field.

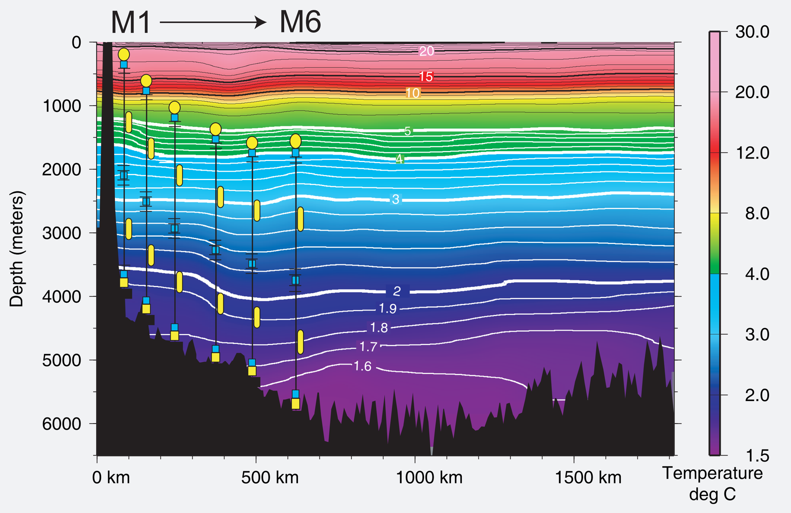

Figure 5.
Diagram of the DynAMITE moored array superimposed on potential temperature. Each mooring was equipped with 2 McLane Moored Profilers (MMP) and 3 sets of fixed point instruments (current meters and CTDs) at the top, middle and bottom of the mooring. Section location is down the mooring line and zonal along 28N to the MAR (see Fig 4). All 6 bottom profilers returned full records over the deployment. Only 3 of the top MMPs (M2,M3,M6) returned usable measurements.

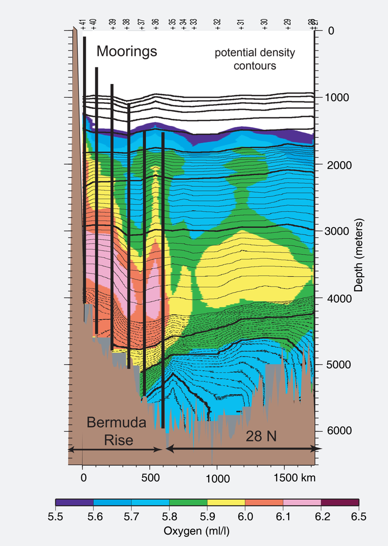

Figure 6.
Same section with oxygen (color) and potential density contours overlain shows these fields relative to the moored array (black vertical lines). Elevated oxygens at the same density are diagnostic of more direct contact with northern sources.

Interior flows along the SE flank of Bermuda Rise

are remarkably strong, averaging 7-10 cm/sec in the core of flow at the base of moorings 1&2.The profiler data are still being processed, but a summary of temperature and velocity records from the VACMs, MicroCat CTDs and the MMPs that have been processed, summarized in Figure 7, give ample evidence of vigorous near-bottom transports. These are primarily directed to the southwest at moorings 1, 2, 3 & 5, but episodically to the northeast at 4 & 6.

Preliminary analysis suggests a close correspondence between the moored measurements and the mean flows predicted by the PV fields.

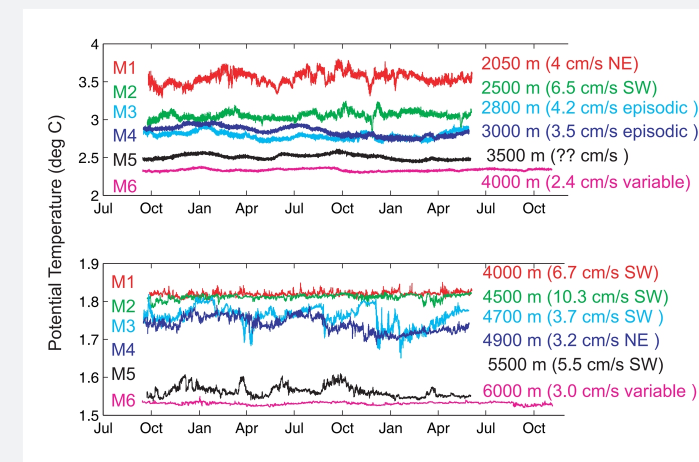

Figure 7.
Potential temperature, average speed and direction of flow from sensors at the bottom and midpoints of each mooring.

Diapycnal mixing is strongest

in the SE corner of the study area, dramatically weakening stratification in the bottom 500 -1000 meters over the MAR. Vertical diffusivities are intensified near the bottom and over the MAR flanks, but result from a relatively constant dissipation being divided by vanishingly small background gradients. Tracers such as silicate (below) reflect the locally enhanced upwelling of bottom waters below the MAR crest.

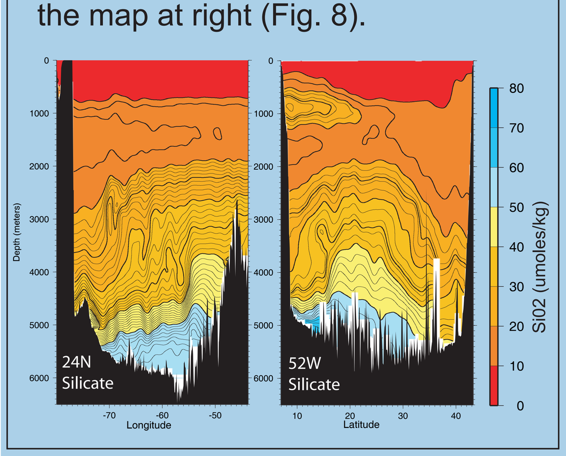

Figure 9.
Sections of silicate along 24N (left) and 52W (right), locations given in the map at right (Fig. 8).

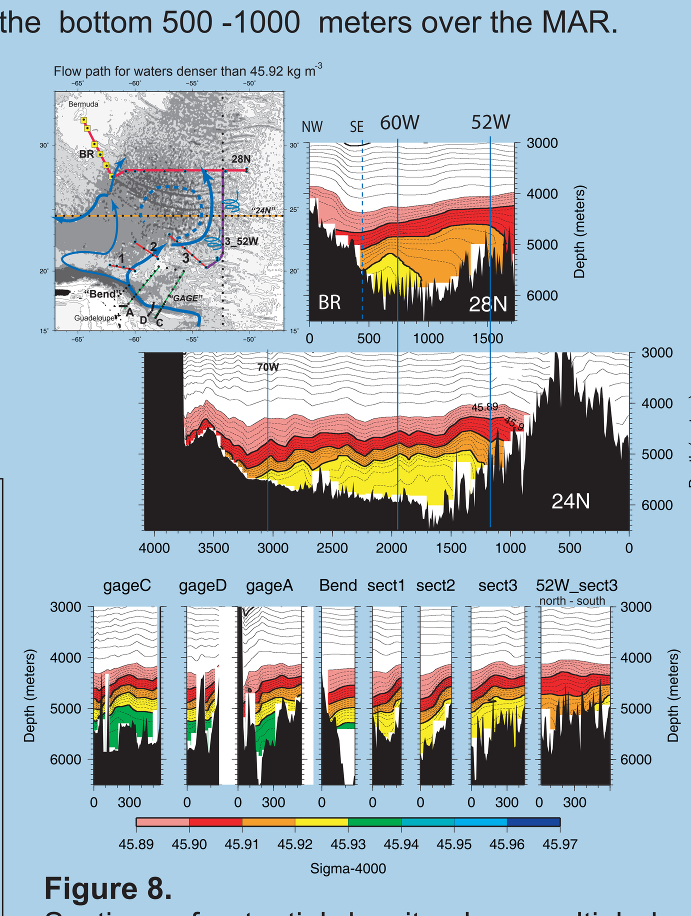

Figure 8.
Sections of potential density along multiple hydrographic lines, locations depicted in the inset map.

The buoyancy forced abyssal circulation

in the western North Atlantic differs fundamentally from that in the Brazil Basin where offset fractures convey dense waters toward the MAR crest and supply the mass required for upwelling. A significant portion of the mean circulation there occurs in canyons below the topographic peaks. Such conduits are largely absent in the DynAMITE study region. Results from the field program suggest that, in this basin, turbulent mixing results in vortex stretching such that beta dynamics govern the mean circulation and supply the mass required for net upwelling and buoyancy gain. Analytic studies (e.g. Spall, JPO, 2001) describe the influence of sloping topography on the deep flows — leading to weak upslope bottom flows and enhanced zonal flows in the layers above the bottom — as in Figs. 1c and 3.

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