Abyssal Canyons and Mixing by Low-Frequency Flow

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Abstract. The role canyons play in abyssal mixing is discussed, with a focus on the issue of low-frequency flow over sills and associated overturning instability as opposed to tidally generated mixing. Flow through several deep canyons on the mid-ocean ridge is reviewed and some global consequences are discussed.

Introduction

Most deep mixing, when defined as diapycnal transport, is associated with a meridional overturning cell of bottom water and deep water. The downwelling part is entrainment into dense plumes from marginal seas and shelves, and the upwelling part is the conversion of the bottom water to deep water, thought to happen predominantly over topography. Mid-ocean ridges bring the effect of near bottom mixing up to mid-depth, hence through several thousand meters of abyssal stratification, and one can distinguish stronger diapycnal upwelling in abyssal layers below the ridge crest in the meridional overturning circulation determined by box inverse models (Fig. 1). In this example (Lumpkin and Speer, 2003), the overflow has been included explicitly in the inversion, and the meridional streamfunction illustrates the dominant diapycnal fluxes due to three effects: surface forcing, overflow, and abyssal upwelling. What box models do not provide is a mechanism for this mixing, though regional calculation of upwelling rates can help to isolate effects, for instance important passages or sills, or areas of upwelling over ridge flanks.

Below the basin scale, topography includes numerous structures determined by geodynamic processes, erosion and sedimentation. Since bottom water follows the deepest path as it fills basins, the morphology of the mid-ocean ridge is expected to have some impact on the conversion of this dense water to deep water, hence on the ocean’s deep thermohaline cell.

Fracture zones and other stress-generated cracks are common in Earth’s crust; the creation of Earth’s crust in the spreading process forms axial valleys that are deep (1000 m or more) on slow spreading ridges like the Mid-Atlantic Ridge and shallow (10’s of meters) on fast spreading ridges like the East Pacific Rise. To identify canyon-like structures that might be important for bottom water flow and mixing we searched bathymetry data (Smith and Sandwell, 1997) for local zonal and meridional depth maxima exceeding 250 m (for details see Thurnherr and Speer, 2003). This reveals the organization of the Mid-Atlantic Ridge flanks into long, nearly zonal canyons and fracture zones (Fig. 2). Some are well known fracture zones that form deep gaps in the ridge, but others are box canyons that do not connect ocean basins. In addition to the Mid-Atlantic Ridge the flanks of the mid-ocean ridges in the Southern Ocean and Indian Oceans are also characterized by a large number of canyons. The meridional depth maxima shown in the figure emphasize quasi-zonal canyons; in the case of zonally trending ridges the ridge-flank canyons are primarily apparent in the distributions of
Figure 2. Zonal-canyon search algorithm results for the tropical and subtropical South Atlantic Ocean (adapted from Thurnherr and Speer, 2003); tectonic-plate boundaries are indicated by solid lines.

Figure 3. Zonal-canyon search algorithm results for the tropical and subtropical eastern South Pacific Ocean; tectonic-plate boundaries are indicated by solid lines.

By contrast, the East Pacific Rise does not show the same raked appearance and is not the center of high canyon density (Fig. 3). Presumably this difference between the ridges is related to spreading rates; the slow-spreading Mid-Atlantic Ridge is associated with stronger relief than the fast-spreading East-Pacific Rise. In regions where there is strong relief on the East-Pacific Rise it appears more random than that on the Mid-Atlantic Ridge and long quasi-linear canyons are much less prevalent. This relationship between spreading rate and canyon incidence appears to hold over most of the global mid-ocean ridge system.

Why should canyons be more important than random topographic roughness for bottom water mixing? What are the key parameters of when canyons are involved? It may be of some use to compare abyssal canyons to coastal canyons (e.g., Hickey, 1995), which have been studied more extensively. Abyssal canyons are typically $10\times$ longer ($O(1000 \text{ km})$), have slopes $10$–$100\times$ weaker ($O(10^{-3})$), and show substantial along-axis depth variations. The latter give rise to multiple sills and sub-basins along the length of the canyon. Coastal canyons span the full water column and along-canyon excursions are therefore more strongly limited by stratification. Abyssal canyons may support flow along their entire length. We proceed under the assumption that density-driven currents dominate the advection of density along the bottom (c.f. Thurnherr and Speer, 2003), and where these currents encounter sills, mixing occurs as stratified water spills over them. This effect is thought to be magnified in canyons which constrict and amplify flow, raising the Froude number. Because of the complexity of bottom water pathways, however, we are unable to offer more than a rough prescription for predicting which canyons ought to have a more important role. Essentially, canyons with weak average bottom slope and more sills will lead to greater mixing and upwelling.

Processes

As water moves through canyons it spills over sills, even as it rises up the flank. This process was documented in the Romanche Fracture Zone (Fig. 4; from Mercier et al., 1994) and the Rift Valley on the Mid-Atlantic Ridge (Fig. 5; from Thurnherr et al., 2002), which show a series of basins and sills surrounding the main (shallowmost) sill. The primary mixing mecha-
nism in both cases is shear-induced overturning with the shear generated by accelerating flow across the sills. The flow may be modulated by oscillations at various time scales (eddies, basin modes, wind-driven barotropic, tidal), but we distinguish this case from a system with tidal forcing alone, driving relatively small (e.g. compared to size of a sill) excursions across the topography. We hypothesize that this “low-frequency” mechanism is generic to long abyssal canyons and important to bottom water transformation in the Atlantic Ocean and elsewhere.

The Chain Fracture Zone is an interesting case because it combines a role as a major conduit with more of a box-canyon form (Fig. 6). Mean flow is strongest 500 m off the bottom, more or less at the exit sill depth near 4050 m (Mercier and Speer, 1998). Although the mean flow decreases with depth into the canyon, both high and low passed (48 hr) variance increases, consistent with observations of flow in other canyons and the notion of enhanced internal wave activity focussed by canyon walls.

Conclusions

The evidence supports the view that mixing in major and minor abyssal canyons is fundamental to bottom water upwelling and the dense thermohaline circulation cell. The question remains of the partition between diapycnal upwelling driven by tidally forced mixing and lower frequency components. This partition likely varies from one density horizon to another, depending on the kind of topography a given layer intersects, and the distribution of sills around a basin. One of the most telling indications of a large-scale difference between the Pacific, where canyon density is lower, and the Atlantic, where it is higher, may be the distribution of large-scale potential vorticity in the near-bottom water (O’Dwyer and Williams, 1997). They find much more horizontally uniform distribution in the Pacific, presumably because there are fewer localized diapycnal sources (as upwelling over topography would be) to these layers.

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References


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