The Australian-Antarctic Discordance: Pressurized vs. Non-Pressurized Ridge System

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ABSTRACT

The axial morphology of the Southeast Indian Ridge (SEIR) between Australia and Antarctica changes dramatically along 120°E to 127°E (Fig. 1). At approximately 127°E the ridge changes character along with a difference in water depth of about 1 km. Eastward it changes from a Mid-Atlantic Ridge (MAR) type cross-section to an East-Pacific Rise (EPR) type cross-section (Fig. 2). The MAR profiles a bathymetric low (5- to 20-km wide, 500- to 1500-m-deep rift valley), while the EPR profiles a bathymetric high (10-km-wide, 500-m-high ridge). The MAR type extends westward to approximately 100°E and is called the Australian-Antarctic Discordance (AAD). This geomorphology is unique globally. The MAR is considered a slow-spreading center and like the AAD has similar segmentation characteristics of non-transform (small, <10 km) and transform discontinuous partitions of the ridge at 40 to 60 km. In contrast, the SEIR east of the AAD has segmentation characteristics of a fast-spreading center similar to the EPR. There are no transforms until 138°E, and westward propagating rifts are the only non-transform discontinuities.

INTRODUCTION: SURGE INTERPRETATION

Surge theory (Meyerhoff et al., 1992, 1996) hypothesizes that the primary mantle flow is parallel to ridge strike with Walker-type circulation patterns similar to those of the atmosphere. This is opposed to plate theory Hadley-type circulation, which is the only driving force in plate tectonics. Using surge theory, differences in positive vs. negative bathymetric profiles can be explained by a pressurized vs. non-pressurized mantle conduit beneath the ridge.

A possible reason for a non-pressurized AAD can be found to the north of Australia along the Indonesian Island Arc (IIA) and within the Banda Sea tectonic vortex. A discussion of the Banda Sea tectonic vortex and its possible link to the El Nino phenomena was previously published (Leybourne and Adams, 1999). If the approximate bounding longitude lines, 120°E to 127°E, of the ADD are traced northward parallel to the G12 lineament (Fig. 3), the geographic region encompassed north of Australia includes the Banda Sea tectonic vortex. Plate tectonics hypothesizes northward sheet-, conveyor-, or Hadley-type mantle flow under Australia from the SEIR to the IIA trenches. Assuming axial mantle convergence and downwelling within the AAD, one concludes that northward mantle flow is depressurized by the upwelling tectonic vortex in the Banda Sea. Pressure is relieved along the ADD as it downwells into northward mantle sheet flow which then wraps into eastward mantle stream flow (geostream) under Indonesia. This geostream upwells within the Banda vortex, diverging north and eastward. Mantle streams then migrate in large hemispheric gyres around the North and South Pacific "Rim of Fire." These geostreams then converge on the EPR, explaining not only the depressurized negative anomaly of the ADD, but also the positive bathymetric profile of the EPR as a pressurized ridge system.

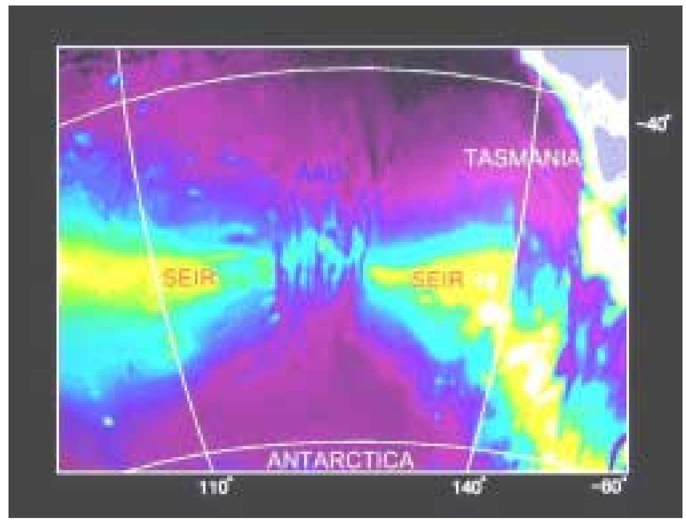

Fig. 1. Bathymetry of the AAD along the SEIR between Australia and Antartica (from NAVOCEANO DBDB-5min by MSRC).

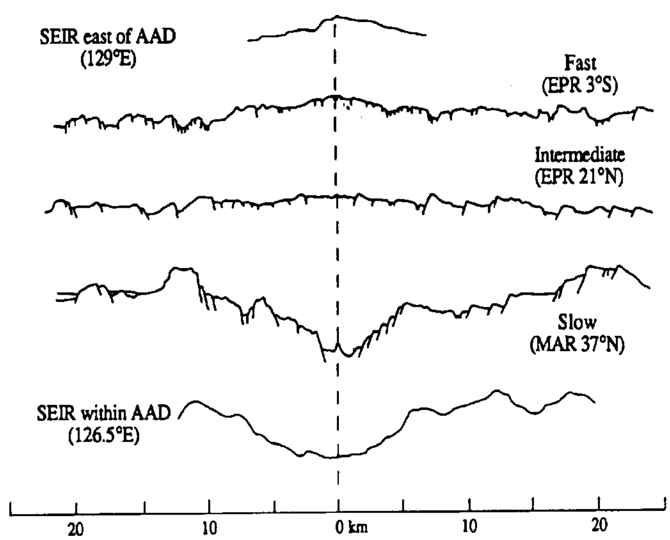

Fig. 2. Bathymetric Ridge Profiles Comparing EPR vs. MAR types, including the SEIR east of the AAD and within the ADD (from West et al., 1994; modified from McDonald, 1982).

The G12 lineament (Fig. 3) and gravity corridor (O'Driscoll, 1986) is a double-bounded, continental-scale fracture zone. It directly ties the AAD vortex to the Banda Sea vortex (Fig. 4). In the southern region, the lineament coincides with a major aeromagnetic basement fault that exceeds 300 km. It is marked by alignment of north/south structural elements and basin margins. The G12 lineament aligns directly with the fracture zone (transform fault) within the AAD that is considered the geochemical boundary between Pacific and Indian Ocean mantle isotopic provinces. Furthermore, it also aligns with the center of the Banda Sea vortex where volcanic arc and shallow mantle outflow are generated. The G5 lineament, also known as the Halls Moblie

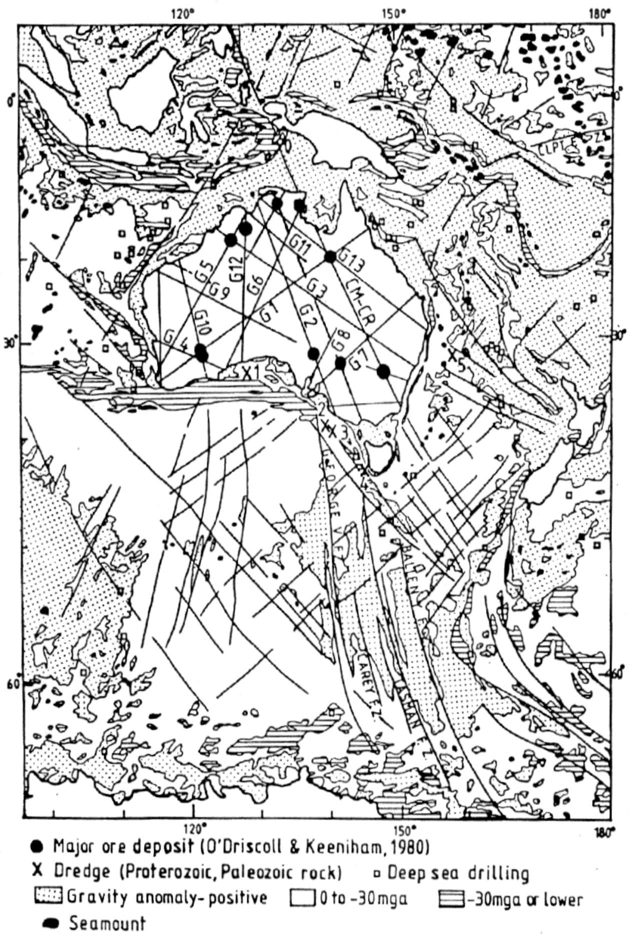

Fig. 3. Australian Continental and Ocean Floor Major Lineaments (from O'Driscoll, 1986; Elliott, 1994; Choi, 1997).

Creek Zone, and the G11lineament align with the leading and trailing edge of the Banda Sea Vortex, respectively. Lineaments reflect basement architecture and form fluid pathways within the lithosphere. These alignments are hypothesized to correspond to deep mantle inflow boundaries from the SEIR and AAD to the Banda region. These lineaments faults behave as a coupled, orthogonal system, faulting rocks as old as the Precambrian (Hills, 1956; O'Driscoll, 1986; Elliott, 1994; and Choi, 1997).

Researchers have advanced several tectonic models to explain the various anomalies discovered in the AAD. Downwelling in the upper mantle is considered as the possible source for the discordance (Hayes and Conolly, 1972; Weissel and Hayes 1974; and Veevers 1982). Hayes also suggested a fixed cold spot hypothesis (Hayes, 1976) and considered a regular pattern of elongated cells oriented perpendicular to the ridge axis, with two downwelling limbs converging beneath the discordance (Hayes, 1988). The AAD appears to be mobile with 15 mm/yr westward drift rate implied by an arcuate-shaped depth anomaly pattern trailing eastward moving away from the ridge. And the anomaly source remains associated with the ridge crest as the ridge migrates northeastward (Marks et al., 1990). Axial asthenospheric or partially molten mantle flows are channeled under the SEIR. The flows originate from the Amsterdam hotspot to the west and the Tasmantid and Balleny hotspots or plumes to the east and converge along the discordance as proposed by Vogt and Johnson (1973) and Vogt (1976). The former paper considers asthenospheric flow, while the latter considers upper mantle flow. Alvarez takes this a step further by suggesting a "world wide return flow system in the upper mantle" in his "continental undertow" model (Alvarez, 1990). More variations on the axial flow model have been put forth (Alvarez, 1982; Vogt et al., 1983; Forsyth et al., 1987; and Klein, 1988). Thus the axial flow model with a westward drift of 15 mm/year of the downwelling region seems to explain the geophysical anomaly patterns within AAD better than any other models put forth. Kuo discusses within the conclusions of his paper the viability of a simple thermal-viscous flow model, that "this flow pattern supports the long envisaged 'pipe' flow hypothesis" (Kuo, 1993).

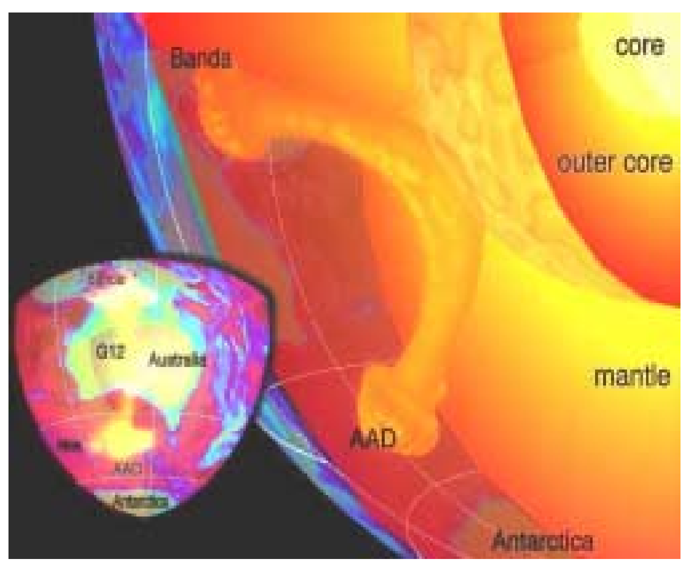

Fig. 4. Preliminary Model Showing Deep Mantle Convection Connection Underlying the G12 Lineament. Downwelling in the AAD and Upwelling in the Banda Sea Drive Northward Mantle Flow Under Australia (by MSRC).

The interesting point to make about the geophysical model of choice for this region is that it is based on a surge tectonic interpretation (Meyerhoff et al., 1992 and 1996) and not a plate model. Axial flow of mantle and asthenosphere along-strike of large-scale tectonic trends such as a mid-ocean ridge are the hallmark of surge tectonic theory. Thus as early as 1973 (Vogt and Johnson, 1973) a surge model was proposed for the interpretation of the geophysical anomalies within the AAD and has remained the most likely explanation to date. Although surge theory was nonexistent when these researchers were modeling the AAD, it is surprising that surge theory was not more readily accepted by modern researchers when first published in 1992, especially considering previous use of its main tenants by many past researchers to explain the anomalous AAD. Most likely this phenomena was considered a local effect. Thus, a global application did not seem self-evident.

GEOPHYSICAL DATA INTERPRETATION

The discordance zone is bounded by large-offset (>100 km) transform faults. Significant changes in depth, ridge morphology, magnetic and gravity anomaly amplitude, seismicity, and geochemistry occur across the eastern bounding transform, while the western transform exhibits less prominent changes.

Many abnormally high topographic regions such as volcanic islands are known and presumably associated with upward-directed asthenosphere convection plumes or hotspots (Heestand and Crough, 1981). However, few major bathymetric depressions other than oceanic trenches are known, and knowledge regarding the locus of return flow in the mantle and the likely response of the lithosphere has been limited. Assuming a downward asthenospheric flow controls bathymetric expression of the AAD, the flow pattern should correspond to the positive depth anomaly contour closure (Hayes, 1988).

Weissel and Hayes' (1974) review of bathymetry data of the SEIR flanks concludes that the processes that produced the depth anomalies along the ridge axis have persisted for at least 30 m.y. The locus of the maximum depth has shifted westward a few degrees with time. Furthermore, based on analysis of sedimentary deposition in Australia and Antarctica, processes responsible for the anomalous bathymetry of the AAD have existed at least since the initial rifting of Australia and Antarctica during the Cretaceous and possibly longer.

The possibility that the residual depth anomalies are not directly related to any underlying pattern of asthenosphere convection implies contrasts in petrology, and associated thermal and mechanical properties of the lithosphere account for the depth anomalies. However, observed depth anomalies associated with the discordance zone are so large that it does not appear that any feasible ranges of thermal and mechanical properties of the lithosphere alone are large enough to account for these anomalies (Hayes, 1988).

A landmark study (McKenzie et al., 1973) determined that free-air gravity associated with convection is dominated by the mass excess or deficiency of the overlying surface deformation. Thus gravity anomalies are generally negative in downwelling regions vs. positive in upwelling regions. A long wavelength negative saddle in both the gravity field and the geoid are coincident with the AAD depth anomaly low (Weissel and Hayes, 1974; and Marsh et al., 1986). An aeromagnetic study of this region (Vogt et al., 1983) identified the presence of two active and two extinct propagating rifts converging on the AAD from the east and west (Klein et al., 1988).

Subsidence and seismic studies portray a cooler than normal upper mantle underlying the AAD (Cochran, 1986; Forsyth, 1992; Forsyth et al., 1987; Kuo, 1993; and Woodhouse and Dziewonski, 1984). A distinct anomaly in mantle shear velocity on the order of 0.35 km/sec in the 20- to 40- km depth range was modeled beneath the AAD (Forsyth et al., 1987). This is anomalous compared to the EPR.

Correlations between Na_2O, FeO, and MgO composition of ridge basalts are believed to be indicators of global variations in upper-mantle temperature (Klein and Langmuir, 1987, 1989). Lavas found in mean water depths of approximately 4500 m with high Na and low Fe characterize the AAD, defining an end member of the global array of mid-ocean ridge basalt compositions. This end member is generally associated with low upper-mantle temperatures and relatively thin crust, which are controlled by deep-seated source-dominant processes. In contrast, to the east, in 2700-m mean depths, lavas are less sodic and more iron-rich, indicating chemical variability is controlled by higher temperature, shallow, crystal fractionation-dominant processes creating a relatively thicker crust (Klein et al., 1991; Pyle, 1994).

Indian Ocean geochemical province isotope compositions of mid-ocean ridge basalts (MORB) are distinct from those of the Atlantic and Pacific. An abrupt eastern boundary between Pb, Sr, and Nd isotope ratios occurs along the AAD between D5 and D7 (Fig. 1 in Klein et al., 1988). The ridge axis is truncated by a single large-offset transform discontinuity at this point. Several researchers (Hayes and Conolly, 1972; and Weissel and Hayes, 1974) suggest the anomalous bathymetric depths may result from downwelling convection flow within the asthenosphere. Thus the AAD may be a "cold spot" or a depression of the mantle. A possible geometry to explain this phenomenon (Klein et al., 1988) involves direct convergence along-ridge strike between the Pacific and Indian Ocean provinces into a mantle sink at the AAD.

DISCUSSION

The Southeast Indian Ocean, between Australia and Antarctica, is one of the best regionally mapped areas in the world, largely due to the circumpolar survey by the USNS *Eltanin* sponsored by the Division of Polar Programs of the National Science Foundation. The depths, sediment thickness, and magnetic lineations have been well mapped, and the results were presented in a special volume on Antarctic oceanology (Hayes, 1972; Hayes and Conolly, 1972; Houtz and Markl, 1972; and Weissel and Hayes, 1972).

Plate theory had just gained prominence during the time this circumpolar survey was completed. And even though plate theory was widely accepted, a main tenant (that of axial flow along-strike) of surge theory (which at the time was nonexistent) was used to explain the anomalies within the AAD. A new global tectonic paradigm based on surge theory incorporates atmospheric Walker Circulation principles into analogous tectonic dynamic concepts of jetstreams/ geostreams, pressure cells/tectonic vortexes, and trade-winds/Hadley cell convection. The surge concept use of Walker circulation patterns and the plate concept use of Hadley circulation patterns, when used together, improve tectonic modeling capabilities. The relationship between the AAD and the Banda Sea can now be realized as high (AAD) and low (Banda) tectonic pressure cells. This shift in perspective creates a global tectonic framework for tectonic interpretations that are not evident with the plate model.

By using an additional analogy between weather fronts and geoid undulations as similar processes in different mediums, a new level of understanding may emerge from tectonic dynamic interpretations. Geoid undulations may be thought of as tectonic fronts or microgravity waves. Thus, tectonic dynamics may be linked to global atmospheric pressure oscillation patterns observed at sea level as pressure teleconnections (Leybourne and Adams, 1999). These sea-level pressure teleconnections are observed across ocean basins and are dynamically linked to the driving force of climate change, such as the El Nino phenomena. If the natural frequencies observed of earth microgravity waves correlate with these climate changes, then a paradigm shift in tectonic interpretation and prediction may be in order.

CONCLUSIONS

The predominant issue arising from a study of the AAD is whether axial flow of mantle and/or asthenosphere along-ridge strike occurs within this region. Convergence of axial flow is the common sense explanation and model of choice by many researchers with obvious implications. If axial flow occurs within the ADD, it is likely axial flow occurs globally along all mid-ocean ridges, considering the ridge system is interconnected. Alvarez advocates this by his statement about a “world wide return flow system in the upper mantle” (Alvarez, 1990). It is also likely axial flow occurs under mountain ranges and island arcs since they also exhibit interconnectivity to mid-ocean ridges, although something about the nature of the flow must be different to manifest such distinct differences in geomorphology.

Pressurized vs. non-pressurized, upwelling vs. downwelling, plus continental vs. oceanic crustal dynamics based on density contrasts are the main parameters influencing differences in geomorphology. A simple explanation for whether a mid-ocean ridge has a positive (EPR-type) or negative (MAR-type) bathymetric expression is based on whether the ridge system is pressurized or not. Fast spreading systems such as the EPR with positive bathymetric expression have convergent inflow pressurizing the ridge. Slow spreading systems such as MAR with negative bathymetric expression at one time were pressurized, but have since lost pressure. The transform fracture pattern observed along most mid-ocean ridge systems is created by a series of downwelling vortexes along the transform offsets when the system was highly pressurized. Spreading and downwelling may still occur along depressurized ridges such as MAR-type, but spreading rates and downwelling along offsets are less dynamic. Thus the axial flow dynamic explaining mid-ocean ridge formation and seafloor spreading is completely opposed at least in the vertical flow direction to the plate theory dynamic of linear upwelling and conveyor-type spreading.

Another note of interest is the north/south vs. east/west relationships of the major mid-ocean ridge systems. The EPR and MAR are oriented north/south and would have north/south converging meridional flow, whereas the SEIR is one of the few mid-ocean ridges oriented east/west and would have zonal flow eastward for the same reasons that jet-streams in the atmosphere flow eastward. This eastward flow converges on a downwelling back-eddy of mantle flow coming south from under New Zealand, creating very anomalous negative geomorphology within the AAD. It appears to be a prime example of the axial convergence phenomena.

Finally, a significant observation of the direct connection between the downwelling AAD vortex and the upwelling Banda Sea vortex along the north/south G12 lineament through continental Australia is noted. The deep connection between these vortices under Australia is likely reflected by shear along this lineament and other associated lineaments such as the G5 and G11, which lead and trail the Banda Sea vortex, respectively. These lineaments are associated with continental fracture zones which behave as a coupled, orthogonal system, faulting rocks as old as the Precambrian. These faults may be associated with complex reactivation events that date back to the earliest Proterozoic (O’Driscoll, 1986; Elliott, 1994; and Choi, 1997).

B. A. Leybourne is an employee of the Naval Oceanographic Office. However, the opinions and assertions contained herein are those of the author, and are not to be considered as official statements of the U.S. Department of the Navy.

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