LEG 187
AUSTRALIAN-ANTARCTIC DISCORDANCE:
MANTLE RESERVOIRS AND MIGRATION ASSOCIATED WITH AUSTRALIAN-ANTARCTIC RIFTING

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ABSTRACT

The Australian-Antarctic Discordance (AAD) is an anomalously deep region centered on the Southeast Indian Ridge (SEIR) between Australia and Antarctica. Among its unique features is an unusually sharp boundary between the ocean-basin scale, upper mantle isotopic domains of the Pacific and Indian Oceans. This boundary has migrated westward into and across the easternmost segment of the AAD at a rate of 25-40 mm/yr during the last 4 m.y., yet the long-term relationship of this important boundary to the AAD, itself, remains unclear. There is limited evidence to suggest that the boundary has been migrating westward for approximately 40 m.y., since the separation of the South Tasman Rise from Antarctica. On the other hand, it seems likely, perhaps even probable, that the isotopic boundary is genetically linked to the mantle processes that have maintained the existence of the AAD for >90 m.y., since Australia and Antarctica first rifted apart.

The long-term configuration and dynamic history of the isotopic boundary can be determined by systematic off-axis sampling, beyond the limit of effective dredging (~7 Ma). During Leg 187, we will extend the sampling program to older crust, between 10 and 30 Ma. An array of 19 drill sites has been designed to determine the configuration of the isotopic boundary and to distinguish among competing hypotheses concerning the nature and extent of mantle migration beneath the SEIR. Approximately 10-12 single-bit holes will sample 20-100 m (ideally about 50 m) into igneous basement. A reactive drilling strategy will allow the selection of later sites within a few hours of core recovery on the basis of trace element data obtained from the earlier sites.

INTRODUCTION

Lavas erupted at Indian Ocean spreading centers are isotopically distinct from those of the Pacific Ocean, reflecting a fundamental difference in the composition of the underlying upper mantle. Along the Southeast Indian Ridge (SEIR), the Indian Ocean and Pacific Ocean isotopic provinces are separated by a uniquely sharp boundary. This boundary has been located to within 25 km along the spreading axis of the SEIR within the Australian-Antarctic Discordance (AAD; Klein et al., 1989; Pyle et al., 1992; Christie et al., in press), and subsequent off-axis sampling has shown that the Pacific mantle has migrated rapidly westward during at least the last 4 m.y. Specifically, Leg 187 investigations will delineate this boundary farther off-axis, allowing us to infer its history over the last 30 m.y.

Because of its proximity to the AAD, this project exploits a unique opportunity to quantify the dynamic behavior and composition of the Earth's upper mantle. In terms of the Ocean Drilling Program (ODP) Long Range Plan, this proposal addresses a fundamental problem in *mantle dynamics*, including relationships among ocean crustal composition, mantle composition, spreading and magma supply rates. It also has strong ties to the U.S. Ridge Interdisciplinary Global Experiments (RIDGE) program and the international InterRidge program.

BACKGROUND

Introduction

The AAD (Fig. 1) is a unique region within the global mid-ocean spreading system. It encompasses the deepest (4-5 km) region of the global mid-oceanic spreading system. Its anomalous depth reflects the presence of both unusually cold underlying mantle and thin crust. Despite a uniform spreading rate, the eastern boundary of the AAD coincides with an abrupt morphologic change from an axial ridge with smooth abyssal topography off-axis (characteristics usually associated with fast-spreading centers) to deep axial valleys with rough off-axis topography (characteristics usually associated with slow spreading). Other anomalous characteristics of the AAD include a pattern of relatively short axial segments separated by long transforms with alternating offset directions, extremely thin oceanic crust, high upper mantle seismic wave velocities, and an intermittent asymmetric spreading history (Weissel and Hayes, 1971, 1974; Forsyth et al., 1987; Marks et al., 1990; Sempéré et al., 1991; Palmer et al., 1993; West et al., 1994, 1997; Christie et al., in press). Multiple episodes of ridge propagation from both east and west toward the AAD suggest that the upper mantle is converging towards this region (Vogt et al., 1984, West and Lin, unpublished data). Indeed, from recent numerical model studies, significant subaxial mantle flow converging on the AAD appears to be an inevitable consequence of gradients in upper mantle temperature around the AAD. Finally, the morphological contrasts across the eastern boundary of the AAD are paralleled by distinct contrasts in the nature and variability of axial lavas, reflecting fundamental differences in magma supply because of strong contrasts in the thermal regime of the spreading center.

Within the easternmost AAD, there is a distinct discontinuity in the Sr, Nd, and Pb isotopic signatures of axial lavas that marks the boundary between Indian Ocean and Pacific Ocean mid-ocean ridge basalt (MORB) mantle provinces (Klein et al., 1988; Pyle et al., 1990; 1992). The boundary itself is remarkably sharp, although within the Pacific region, there is a gradation toward Indian Ocean characteristics within 50-100 km of the boundary (Fig. 2). At zero-age seafloor, the boundary is located within 20-30 km of the ~126°E transform—the western boundary of the easternmost AAD spreading segment. The boundary has migrated westward across this segment during the last 3-4 m.y. (Pyle et al., 1990, 1992; Lanyon et al., 1995, Christie et al., in press) (Figs. 3, 4).

Although such a sharp boundary between ocean-basin-scale upper mantle isotopic domains is unique along the global mid-ocean ridge system, its long-term relationship to the remarkable geophysical, morphological, and petrological features of the AAD is unclear. The AAD is a long-lived major tectonic feature. Its defining characteristic is its unusually deep bathymetry, which stretches across the ocean floor from the Australian to the Antarctic continental margins. The trend of this depth anomaly forms a shallow west-pointing V-shape cutting across the major fracture zones that currently define the eastern AAD segments (Figs. 1, 4). This V-shape implies that the depth anomaly, itself, has migrated westward at a long-term rate of ~15 mm/yr (Marks et al., 1991), which is much slower than the recent migration rate of the isotopic boundary discussed above. The depth anomaly may, in fact, have existed well before continental rifting began ~100 m.y. The presence of restricted sedimentary basins on both continents suggests that precursors of the present AAD may have existed for as long as 300 m.y. (Veevers, 1982; Mutter et al., 1985).

Possible long-term relationships between the isotopic boundary and the morphologically defined AAD fall into two distinct classes, schematically illustrated in Figure 4. Either the recent isotopic boundary migration is simply a localized (~100 km) perturbation of a geochemical feature that has been associated with the eastern boundary of the AAD since the basin opened, or the migration is a long-lived phenomenon that has only recently brought Pacific mantle beneath the AAD. In the first case, the boundary could be related either to the depth anomaly or to the eastern bounding transform, but not to both in the long term. In the second case, the isotopic boundary has only recently arrived beneath the AAD. Although the latter possibility may initially seem fortuitous, it has been independently suggested that Pacific mantle has migrated westward into the region since 40-50 Ma, when separation of the South Tasman Rise from Antarctica first allowed upper mantle flow from the Pacific to the Indian Ocean basin (Alvarez, 1982, 1990). Indian and transitional isotopic signatures from altered ~38 and ~45 Ma basalts dredged to the north and east of the AAD (Lanyon et al., 1995) and from 60- to 69-Ma Deep Sea Drilling Project (DSDP) basalts that were drilled close to Tasmania (Pyle et al., 1992), provide limited support for this hypothesis. Recent off-axis sampling in Zone A (Christie et al., in press) constrains any such boundary to lie within the shaded region of Figure 4 and perhaps requires a hiatus of at least 3 m.y. between the first arrival of Pacific mantle at the eastern boundary of the AAD and its initial penetration into the AAD proper (West and Christie, 1997; Christie et al., in press).

The Nature of the Indian Ocean MORB Mantle Province

The mantle source for Indian Ocean mid-ocean ridge basalts (MORB) is distinct from that of the Pacific Ocean MORB in having distinctly lower $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$, and higher $^{87}Sr/^{86}Sr$, as well as by systematically lower $^{207}Pb/^{204}Pb$ and $^{143}Nd/^{144}Nd$ (Figs. 2, 3). The sharpness of the Indian-Pacific boundary, as expressed in the seafloor lavas, suggests that Indian MORB mantle presently abuts Pacific MORB mantle beneath the AAD, with little or no intermingling. In contrast, along the Southwest Indian Ridge, there is a much more gradational transition from Indian- to Atlantic-type mantle (Mahoney et al., 1992).

The distinctive characteristics of Indian MORB mantle have been variously attributed to the widespread dispersal throughout an otherwise "typical" depleted upper mantle of material with distinctive isotopic characteristics derived from one or more of (1) Indian Ocean hot spot sources, especially the large long-lived Kerguelen mantle plume, (2) lower continental lithosphere derived from the breakup of Gondwanaland, and/or (3) convectively recycled subducted altered oceanic crust (e.g., Subbarao and Hedge, 1973; Hedge et al., 1973; Dupré and Allègre, 1983; Hamelin et al., 1985; Hamelin and Allègre, 1985; Hart, 1984; Michard et al., 1986; Price et al., 1986; Dosso et al., 1988; Klein et al., 1988; Mahoney et al., 1989). The Indian MORB isotopic signature has also been attributed to the interaction of Gondwana continental lithosphere with the Kerguelen mantle plume before India rifted from Australia (Storey et al., 1988; Mahoney et al., 1989; 1992).

Away from the spreading centers, the extent of the Indian MORB mantle is only poorly known. In the region of interest for Leg 187, Pyle et al. (1992) analyzed all available drilled material. They showed that Indian mantle has been present at 110°E, to the east of Kerguelen, since at least 30-40 Ma, and that it may have been present to the east of the AAD before 39 Ma (Pyle et al., 1992; Lanyon et al., 1995). No basalts of Indian affinity have been reported east of the South Tasman Rise at any age, and none younger than 30 Ma are known anywhere east of the AAD. In addition, all samples so far analyzed from recent sampling of the SEIR west of the AAD are clearly of Indian type (L. Hall, J. Mahoney, pers comm., 1998).

The dispersion of Indian mantle and its areal extent may be controlled by one or more of the following:

1. Flattening of the heads of large mantle plumes (~2000 km) (Mahoney et al., 1992).
2. Global-scale upper mantle convection (Hamelin and Allègre, 1985) and, more specifically, advection by temperature gradient-driven mantle flow within the ocean basin (West et al., 1997).
3. Isolation of the upper mantle by the deep roots of the surrounding Gondwana continents (Alvarez, 1982, 1990).
4. Restriction of this upper mantle province to the limits of Archean subcontinental lithosphere beneath the Gondwana continents (Klein et al., 1988).

Regardless of its origin and evolution, the nature and behavior of this isolated reservoir can be better understood through a better definition of the configuration and, hence, the dynamics of its eastern boundary. Because this boundary is so sharply defined, uncontaminated by hot spots or other nearby perturbations, and because the plate motions between Australia and Antarctica are uncomplicated and well known, simple testable predictions can be made for a broad range of hypotheses.

The Origin and Evolution of the Isotopic Boundary

The most direct objective of this proposal is to define, as closely as possible, the off-axis configuration of the Indian-Pacific mantle isotopic boundary. In addition to its importance as a "local" phenomenon, an improved understanding of this boundary is important for a broader understanding of the oceanic mantle in general. In investigating the origins of the AAD and the isotopic boundary, we are also investigating the importance of variations in geochemistry, isotopic makeup, temperature and other physical characteristics of the oceanic upper mantle in general. Improved knowledge of the distribution of these chemical and physical characteristics in space and time will lead to a better understanding of the dynamics of the oceanic mantle and of its interaction with the magmatic processes of the mid-ocean ridge system.

Three possible end-member configurations of the isotopic boundary on the Southern Ocean seafloor are illustrated in Figure 4. In the simplest configuration, the isotopic boundary has always been associated with the eastern boundary of the AAD and therefore follows a flow line oriented approximately north-south. Small scale (~100 km) perturbations in the east-west position of the Indian-Pacific MORB boundary would be consistent with the apparent westward migration of the boundary along segment B5 in the eastern AAD during the last 4 m.y. In the second case, the boundary is associated with the depth anomaly, and follows its trace off-axis. The V-shaped cofiguration of this trace requires that it has moved westward at ~15 mm/yr (Marks et al., 1991); whereas, the recent migration rate of the isotopic boundary is 25-40 mm/yr (Pyle et al., 1992, Christie et al., in press), again requiring small-scale east-west fluctuations in the boundary position to be superimposed on the more gradual (~15 mm/yr) westward motion. In the third case, the isotopic boundary is produced by steady westward migration of Pacific mantle since rifting of the South Tasman Rise. In this case, a reasonable rate for Pacific mantle inflow can be calculated from the assumption that a continental barrier to mantle flow was removed at ~40 Ma, when circum-Antarctic ocean circulation was established south of Tasmania (Royer and Sandwell, 1989; Mutter et al., 1985). This rate is comparable to the recent migration rate of the boundary within the AAD and to the propagation rates (which likely reflect mantle flow; West and Lin, unpublished data) of three westward-propagating rifts along the SEIR east of the AAD. This rate is a long-term average, however, and systematic variations in the along-axis migration rate could be expected with the opening of the ocean basin (West et al., 1997).

SCIENTIFIC OBJECTIVES

During and after drilling of the leg, the primary objective will be to locate the Indian/Pacific isotopic boundary and determine its configuration out to at least 30 Ma. From this information, we will infer the geometry and dynamics of these two mantle reservoirs and their boundary. In addition, there are number of subsidiary objectives. These can be divided into geochemical and geophysical categories for discussion, but we emphasize that these are strongly interrelated and that we will be seeking to thoroughly integrate all the results.

Geochemical Objectives

Geochemical analysis provides the principal tool for locating the isotopic boundary, even if the boundary proves to have a morpho-tectonic expression, as observed within the AAD (Christie et al., in press). However, the geochemical objectives of Leg 187 extend well beyond this simple task, to the problem of defining and understanding the nature and origin of the distinct Pacific and Indian geochemical signatures. Some specific questions that we will address are

- What is the connection between the isotopic boundary and the known "Indian" samples from the DSDP sites near Tasmania and from the Lanyon et al. (1995) dredges northeast of the AAD? If a long-term migrating boundary is identified in Zone A, then these sites might be interpreted as representing Indian mantle that was present throughout the region before the influx of Pacific mantle began. If the boundary is shown not to have migrated across Zone A, then one might conclude that these sites are more influenced by their proximity to the Australian continent than to the Indian Ocean per se. The importance of these questions extends beyond the immediate region. They are relevant to our understanding of the origin of the isotopic signature of Indian Ocean mantle, and they will prove particularly important in considering the origin of recently identified "Indian" samples from western Pacific back-arcs (Hergt and Hawkesworth, 1994) and from the Chile Rise in the eastern Pacific (Klein et al., 1995; Karsten et al., 1996; Sherman et al., 1997).

- The shape of the isotopic boundary can potentially contribute to our understanding of the origin of the AAD. Can it, for example, be traced back to some particular feature of the Australian and Antarctic continents, such as the eastern boundary of the Australian craton?

A secondary objective of the program will be to study the long-term petrologic history of the AAD. Have there been changes in depth and/or extent of melting through time? Can we infer temporal changes in mantle temperature beneath the AAD? Has the underlying cold mantle become warmer or colder through time? Have the petrological contrasts between Zone A and AAD lavas persisted through time?

Geophysical Objectives

Geophysical objectives will primarily focus on understanding the mantle dynamics of the region, and their relation to the anomalous processes within the AAD. As part of the scientific effort associated with the 1996 cruise, West et al. (1997) and West and Christie (1997) have developed a suite of 3-D mantle-flow models specifically tailored to the tectonic history and segmentation characteristic of the eastern SEIR. In addition to integrating cooler than normal mantle temperatures beneath the AAD with along-axis asthenospheric flow toward the AAD, these models have a number of important features significant for this proposal:

- Lateral mantle flow appears to be an inevitable consequence of the separation of the continents and mantle temperature gradients. During initial rifting of the continents, simple divergence is the sole force inducing flow, but as the continents separate, a mantle temperature gradient is required to maintain mantle flow consistent with known limits on the boundary configuration.

- Along-axis asthenospheric flow is confined to a relatively narrow low-viscosity zone beneath the ridge axis (West et al., 1997), and the geometry of the overlying spreading system plays a significant role in channeling the along-axis flow where transforms are included in these models. Confining temperature-gradient driven flow within the low-viscosity zone also results in a temperature inversion in the subaxial mantle that can significantly modify $Na_{8.0}$ and $Fe_{8.0}$ depth correlations.

- Depth gradients in mantle viscosity inevitably lead to a mantle front that is sloping in the direction of flow (West et al., 1997) This can lead to a decoupling of flow-related features that are controlled at different mantle depths. Thus, the isotopic boundary, as mapped at the seafloor, may differ in location and in geometry from a flow-driven propagating rift or from a chain of seamounts that form off-axis. Although no such chains are known east of the AAD, several occur to the west. And, although each of these surface features is a manifestation of mantle migration, none of them necessarily mimics in plan view the actual boundary between the two upper mantle provinces.

At the present state of development, modeling clearly demonstrates that hypothesized long-term mantle migration is consistent with, perhaps even favored by, our current understanding of the Pacific/Indian boundary (West et al., 1997, West and Christie, 1997). If the drilling proposed here allows us to identify the off-axis position of the isotope boundary, these models can be more precisely refined. Increasing refinement of the model will lead to stronger constraints on mantle dynamics of the region, including interactions among physical properties such as mantle temperature gradients, viscosity, flow velocities, and flow patterns. Also planned for continuing work are refinements in the resolution of some of the models. At present, the models are being developed to resolve local segment-scale details of flow, in particular the question of whether and why flow is stopped or impeded by major transform offsets as we have inferred from geochemical observations (West and Christie, 1997; Christie et al., in press). Finally, perturbations in the temperature profile at depth can potentially influence the systematics of mantle melting, and the AAD flow models can be used to predict geochemical features, such as a departure of normalized sodium variations ($Na_{8.0}$; Klein and Langmuir 1987) from predicted trends.

DRILLING STRATEGY

We will drill as many single-bit holes as possible in the allotted time, perhaps as many as 10-12 holes. Each hole should penetrate ~50 m into basaltic basement, recovering sufficient mid-ocean ridge basalt to enable a satisfactory analytical program. Much of the region is devoid of measurable sediment cover and all sites are located on localized sediment pockets. Because these sediments are expected to be reworked and possibly winnowed, they will be recovered only by rotary core barrel (RCB) drilling. A review of recent deep-water legs suggests that at least 10 such short basement penetration holes can reasonably be achieved in a single leg. For example, during Leg 144 20 holes were drilled at 10 sites on guyots in the northwest Pacific. Basaltic basement was recovered in at least one hole at nine of the sites. For Leg 187, the minimum number of holes required for an acceptable definition of the off-axis isotopic boundary is six, but much higher resolution can be obtained with eight or more holes, especially if the program is able to respond to the results of on board geochemical analyses of the recovered basalts. For example, Figure 5 shows the along-axis distribution of Zr/Ba and Rb/Ba ratios across the isotopic boundary, strongly suggesting that these and other ratios can be used off axis to reliably distinguish Pacific from Indian mantle sources.

The best use of the drillship will result from a reactive drilling strategy, predicated on our ability to distinguish "Indian" from "Pacific" mantle using trace element ratios measured on board by inductively coupled plasma (ICP) or direct current plasma (DCP) spectrometry. In the event that adequate onboard analysis is unsuccessful, a worst-case plan will allow for acceptable definition of the boundary by onshore isotopic analysis.

The following discussion describes one example of how such a strategy might proceed. But, there are numerous other possibilities and final decisions have not yet been made. Site numbers are shown in Figure 6.

An initial series of three holes is drilled at Sites 36, 8c, and 22. These sites straddle likely positions of the boundary, other than the most rapid long-term migration. Each of these sites will prove to have basalts that are either derived from Indian (I) or Pacific (P) mantle.

- *Scenario 1*. Basalts at all three sites (I I I) are derived from Indian mantle. This implies rapid migration of the boundary from the east. Sites 14, 13b, and 1b are drilled to establish the location of the I/P boundary, followed by one or more of Sites 4c, 2b, and 29 to locate the boundary farther west.

- *Scenario 2.* Indian-type basalt is at Sites 36 and 8c. Pacific-type basalt is at Site 21 giving an I I P pattern. This implies slower migration, most likely tied to the depth anomaly. Sites 23 and 16 are drilled to better locate the boundary, followed by one or more of Sites 28, 29, and 2b to locate the boundary close to the eastern AAD fracture zone. Finally one or more of Sites 3b, 33, 34, 35, and 27 are drilled to locate the boundary within the AAD.

- *Scenario 3.* Indian-type basalt is at Site 36. Pacific-type basalt is at Sites 8c and 22 (I P P pattern). This implies a long-term assocation of the boundary with the eastern AAD. Working from north to south, the following sites will better define its geometry: Sites 27, 35, 34, 33, 28, 29, and 3b.

ONBOARD ANALYSIS

The chemical analyses required for this leg cannot be reliably caried out by current onboard equipment. It will be necessary to install either a DCP or ICP optical emission spectrometer in the chemistry laboratory. DCP instruments have been successfully used at sea during a number of cruises (e.g., Langmuir et al., 1986). Their requirements in terms of space, power, and ventilation are comparable to those of the atomic absorption instruments already on board. Sample dissolution will require small amounts of hydrofluoric and nitric acids.

LOGGING PLAN

No logging is planned for this leg. Neither the sediment sections nor the basement sections will be deep enough for scientifically meaningful logs to be obtained.

PROPOSED SITES

Details of the 19 approved sites are given in Table 1. The objectives and strategy are the same for all sites—that is, to recover a satisfactory sample of the basaltic basement as efficiently as possible from as many sites as possible.

REFERENCES

Alvarez, W., 1990. Geologic evidence for the plate driving mechanism: The continental undertow hypothesis and the Australian-Antarctic Discordance. *Tectonics*, 9:1213-1220.

Alvarez, W., 1982. Geological evidence for the geographical pattern of mantle return flow and the driving mechanism of plate tectonics. *J. Geophys. Res.*, 87:6697-6710.

Cande, S.C., LaBrecque, J.L., Larson, R.L., Pitmann, W.C., III, Golovchenko, X., and Haxby, W.F., 1989. Magnetic lineations of the world's ocean basins. AAPG Map Ser., 131.

Christie, D.M., West, B.P., Pyle, D.G., and Hanan, B., in press. Chaotic topography, mantle flow and mantle migration in the Australian-Antarctic Discordance: *Nature*.

Dosso, L., Bougault, H., Beuzart, P., Calvez, J.-Y., and Joron, J.-J., 1988. The geochemical structure of the South-East Indian Ridge. *Earth Planet. Sci. Lett.*, 88:47-59.

Dupré, B., and Allègre, C.J., 1983. Pb-Sr isotope variation in Indian Ocean basalts and mixing phenomena. *Nature*, 303:142-146.

Forsyth, D.W., Ehrenbard, R.L., and Chapin, S., 1987. Anomalous upper mantle beneath the Australian-Antarctic Discordance. *Earth Planet. Sci. Lett.*, 84:471-478.

Hamelin, B., and Allègre, C.J., 1985. Large-scale regional units in the depleted upper mantle revealed by an isotope study of the Southwest Indian Ridge. *Nature*, 315:196-199.

Hamelin, B., Dupré, B., and Allègre, C.J., 1985. Pb-Sr-Nd isotopic data of Indian Ocean ridges: New evidence of large-scale mapping of mantle heterogeneities. *Earth Planet. Sci. Lett.*, 76:288-298.

Hart, S.R., 1984. A large-scale isotope anomaly in the southern hemisphere mantle. *Nature*, 309:753-757.

Hedge, C.E., Watkins, R.A., Hildreth, and Doering, W.P., 1973. $^{87}Sr/^{86}Sr$ ratios in basalts from islands in the Indian Ocean. *Earth. Planet. Sci. Lett.*, 21:29-34.

Hergt, J.M., and Hawkesworth, C.J., 1994. Pb, Sr, and Nd isotopic evolution of the Lau Basin: Implications for mantle dynamics during backarc opening. *In* Hawkins, J., Parson, L., Allan, J., et al., *Proc. ODP, Sci. Results*, 135: College Station (Ocean Drilling Program), 505-517.

Karsten, J.L., Klein, E.M., and Sherman, S.B., 1996. Subduction zone geochemical characteristics in ocean ridge basalts from the southern Chile Ridge; implications of modern ridge subduction systems for the Archean. *Lithos*, 37:143-161.

Klein, E.M., and Langmuir, C.H., 1987. Global correlations of ocean ridge basalt chemistry with axial depth and crustal thickness. *J. Geophys. Res.*, 92:8089-8115.

Klein, E.M., Langmuir, C.H., Zindler, A., Staudigel, H., and Hamelin, B., 1988. Isotope evidence of a mantle convection boundary at the Australian-Antarctic discordance. *Nature*, 333:623-629.

Klein, E.M., Langmuir, C.H., and Staudigel, H., 1989. Geochemistry of basalts from the Southeast Indian Ridge, 115°E-138°E. *J. Geophys. Res.*, 96:2089-2107.

Langmuir, C.H., Bender, J.F., and Batiza, R., 1986. Petrological and tectonic segmentation of the East Pacific Rise, 5°30'N-14°30' N. *Nature*, 322:422-429.

Lanyon, R., Crawford, A.J., and Eggins, S., 1995. Westward migration of Pacific Ocean upper mantle into the Southern Ocean region between Australia and Antarctica. *Geology*, 23:511-514.

Mahoney, J.J., Natland, J.H., White, W.M., Poreda, R., Bloomer, S.H., Fisher, R.L., and Baxter, A.N., 1989. Isotopic and geochemical provinces of the western Indian Ocean spreading centers. *J. Geophys. Res.*, 94:4033-4052.

Mahoney, J.J., le Roex, A.P., Peng, Z., Fisher, R.L., and Natland, J.H., 1992. Western limits of the Indian MORB mantle and the origin of low $^{206}Pb/^{204}Pb$ MORB: Isotope systematics of the central Southwest Indian Ridge (17°-50°E). *J. Geophys. Res.*, 97:19,771-19,790.

Marks, K.M., Vogt, P.R., and Hall, S.A., 1990. Residual depth anomalies and the origin of the Australian-Antarctic Discordance Zone. *J. Geophys. Res.*, 95:17,325-17,337.

Marks, K.M., Sandwell, D.T., Vogt, P.R., and Hall, S.A., 1991. Mantle downwelling beneath the Australian-Antarctic Discordance Zone: Evidence from geoid height versus topography. *Earth Planet. Sci. Lett.*, 103:325-338.

Michard, A., Montigny, R., and Schlich, R., 1986. Geochemistry of the mantle beneath the Rodriguez Triple Junction and the Southeast Indian Ridge. *Earth Planet. Sci. Lett.*, 78:104-114.

Mutter, J.C., Hegarty, K.A., Cande, S.C., and Weissel, S.C., 1985. Breakup between Australia and Antarctica: A brief review in the light of new data. *Tectonophysics*, 114:255-279.

Palmer, J., Sempéré, J.-C., Christie, D.M., and Phipps-Morgan, J., 1993. Morphology and tectonic of the Australian-Antarctic Discordance between 123° E and 128° E. *Mar. Geophys. Res.*, 15:121-151.

Price, R.C., Kennedy, A.K., Riggs-Sneeringer, M., and Frey, F.A., 1986. Geochemistry of basalts from the Indian Ocean triple junction: Implications for the generation and evolution of Indian Ocean ridge basalts. *Earth Planet. Sci. Lett.*, 78:379-396.

Pyle, D.G., Christie, D.M., and Mahoney, J.J., 1990. Upper mantle flow in the Australian-Antarctic Discordance (abstr.), *Eos*, AGU fall meeting, 71:1388.

Pyle, D.G., Christie, D.M., and Mahoney, J.J., 1992. Resolving an Isotopic Boundary Within the Australian-Antarctic Discordance. *Earth Planet. Sci. Lett.*, 112:161-178.

Pyle, D.G., Christie, D.M., Mahoney, J.J., and Duncan, R.A., 1995. Geochemistry and geochronology of ancient southeast Indian and southwest Pacific seafloor. *J. Geophys. Res.*, 100:22,261-22,282.

Royer, J.-Y., and Sandwell, D.T., 1989. Evolution of the eastern Indian Ocean since the Late Cretaceous: Constraints from Geosat altimetry. *J. Geophys. Res.*, 94:13,755-13,782.

Sempéré, J.-C., Palmer, J., Phipps-Morgan, J., Christie, D.M., and Shor, A.N., 1991. The Australian-Antarctic Discordance. *Geology*, 19:429-432.

Sherman, S.B., Karsten, J.L., and Klein, E.M., 1997. Petrogenesis of axial lavas from the southern Chile Ridge; major element constraints. *J. Geophys. Res.*, 102:14,963-14,990.

Storey, M., Saunders, A.D., Tarney, J., Gibson, I.L., Norry, M.J., Thirlwall, M.F., Leat, P., Thompson, R.M., and Menzies, M.A., 1988. Contamination of Indian Ocean asthenosphere by the Kerguelen-Heard mantle plume. *Nature*, 338:574-576.

Subbarao, K.V., and Hedge, C.E., 1973. K, Rb, Sr and $^{87}Sr/^{86}Sr$ in rocks from the Mid-Indian Ocean Ridge. *Earth Planet. Sci. Lett.*, 18:223-228.

Veevers, J.J., 1982. Australian-Antarctic depression from the mid-ocean ridge to adjacent continents. *Nature*, 295:315-317.

Vogt, P.R., Cherkis, N.K., and Morgan, G.A., 1984. Project Investigator-1: Evolution of the Australian-Antarctic Discordance from a detailed aeromagnetic study. *In* R.L. Oliver, P.R. James, and Jago, J. (Eds.), *Antarctic Earth Science: Proceedings 4th International Symposium on Antarctic Earth Sciences,* Canberra, Australian Academy of Science.

Weissel, J.K., and Hayes, D.E., 1971. Asymmetric seafloor spreading south of Australia. *Nature*, 231:518-522

Weissel, J.K., and Hayes, D.E., 1974. The Australian-Antarctic Discordance: New results and implications. *J. Geophys. Res.*, 79:2579-2587.

West, B.P., and Christie, D.M., 1997. Diversion of along-axis asthenospheric flow beneath migrating ridge-transform-ridge intersections. *Trans. Amer. Geophys.Union*, Fall Supplement, 78:673.

West, B.P., Sempéré, J.-C., Pyle, D.G., Phipps Morgan, J., and Christie, D.M., 1994. Evidence for variable upper mantle temperature and crustal thickness in and near the Australian-Antarctic Discordance. *Earth Planet. Sci. Lett.*, 128:135-153.

West, B.P., Wilcock, W.S.D., Sempéré, J.-C., and Géli, L., 1997. The Three-Dimensional Structure of Asthenospheric Flow Beneath the Southeast Indian Ridge. *J. Geophys. Res.*, 102:7783-7802.

TABLE 1

PROPOSED SITE INFORMATION AND DRILLING STRATEGY

SITE: AAD-1b	**PRIORITY**:	**POSITION:** 46°20.6'S, 134°59.8'E
WATER DEPTH: 4200 m	**SEDIMENT THICKNESS**: 1-200 m	**TOTAL PENETRATION**: 250 m
SEISMIC COVERAGE:		

Objectives: Recover basement samples for geochemical analysis. Minimum time on site.

Drilling Program: RCB to ~50 m basement

Logging and Downhole Operations: None

Nature of Rock Anticipated: Biogenic ooze, basalt.

SITE: AAD-2b	**PRIORITY**:	**POSITION**: 45°57.4'S, 130°00.0'E
WATER DEPTH: 4500 m	**SEDIMENT THICKNESS**: 0.1-0.15 s	**TOTAL PENETRATION**: 150 m
SEISMIC COVERAGE:		

Objectives: Recover basement samples for geochemical analysis. Minimum time on site.

Drilling Program: RCB to ~50 m basement

Logging and Downhole Operations: None

Nature of Rock Anticipated: Pelagic ooze, basalt.

SITE: AAD-3b	**PRIORITY**:	**POSITION**: 44°25.5'S, 126°54.5'E
WATER DEPTH: 4350 m	**SEDIMENT THICKNESS**: 0.5 s	**TOTAL PENETRATION**: 150 m
SEISMIC COVERAGE:		

Objectives: Recover basement samples for geochemical analysis. Minimum time on site.

Drilling Program: RCB to ~50 m basement

Logging and Downhole Operations: None

Nature of Rock Anticipated: Pelagic ooze, basalt.

SITE: AAD-4c	**PRIORITY**:	**POSITION**: 47°32.7'S, 130°00.'E
WATER DEPTH: 4050 m	**SEDIMENT THICKNESS**: 0.1 s	**TOTAL PENETRATION**: 150 m
SEISMIC COVERAGE:		

Objectives: Recover basement samples for geochemical analysis. Minimum time on site.

Drilling Program: RCB to ~50 m basement

Logging and Downhole Operations: None

Nature of Rock Anticipated: Pelagic ooze, basalt.

SITE: AAD-8c	**PRIORITY:**	**POSITION**: 41°16.3'S, 129°48.9'E
WATER DEPTH: 5550 m	**SEDIMENT THICKNESS**: 0.15-0.3 s	**TOTAL PENETRATION**: 150 m
SEISMIC COVERAGE:		

Objectives: Recover basement samples for geochemical analysis. Minimum time on site.

Drilling Program: RCB to ~50 m basement

Logging and Downhole Operations: None

Nature of Rock Anticipated: Pelagic ooze, basalt.

SITE: AAD-13b	**PRIORITY**:	**POSITION**: 45°01.2'S, 135°00.2'E
WATER DEPTH: 4575 m	**SEDIMENT THICKNESS**: 0.1 s	**TOTAL PENETRATION**: 250 m
SEISMIC COVERAGE:		

Objectives: Recover basement samples for geochemical analysis. Minimum time on site.

Drilling Program: RCB to ~50 m basement

Logging and Downhole Operations: None

Nature of Rock Anticipated: Pelagic ooze, basalt.

SITE: AAD-14c	**PRIORITY**:	**POSITION**: 44°01.3'S, 134°59.9'E
WATER DEPTH: 4700 m	**SEDIMENT THICKNESS**: 0.2-0.3 s	**TOTAL PENETRATION**: 150 m
SEISMIC COVERAGE:		

Objectives: Recover basement samples for geochemical analysis. Minimum time on site.

Drilling Program: RCB to ~50 m basement

Logging and Downhole Operations: None

Nature of Rock Anticipated: Pelagic ooze, basalt.

SITE: AAD-16	**PRIORITY**:	**POSITION**: 41°28.4'S, 131°19.5'E
WATER DEPTH: 5700 m	**SEDIMENT THICKNESS**: 0.2 s	**TOTAL PENETRATION**: 250 m
SEISMIC COVERAGE:		

Objectives: Recover basement samples for geochemical analysis. Minimum time on site.

Drilling Program: RCB to ~50 m basement

Logging and Downhole Operations: None

Nature of Rock Anticipated: Pelagic ooze, basalt.

SITE: AAD-20	**PRIORITY**:	**POSITION**: 45°45.2'S, 134°59.9'E
WATER DEPTH: 4275 m	**SEDIMENT THICKNESS**: 0.2 s	**TOTAL PENETRATION**: 250 m
SEISMIC COVERAGE:		

Objectives: Recover basement samples for geochemical analysis. Minimum time on site.

Drilling Program: RCB to ~50 m basement

Logging and Downhole Operations: None

Nature of Rock Anticipated: Pelagic ooze, basalt.

SITE: AAD-21	**PRIORITY**:	**POSITION**: 44°27.9'S, 134°59.9'E
WATER DEPTH: 4575 m	**SEDIMENT THICKNESS**: 0.1 s	**TOTAL PENETRATION**: 250 m
SEISMIC COVERAGE:		

Objectives: Recover basement samples for geochemical analysis. Minimum time on site.

Drilling Program: RCB to ~50 m basement

Logging and Downhole Operations: None

Nature of Rock Anticipated: Pelagic ooze, basalt.

SITE: AAD-23	**PRIORITY**:	**POSITION**: 42°3319'S, 135°00.1'E
WATER DEPTH: 4950 m	**SEDIMENT THICKNESS**: 0.15 s	**TOTAL PENETRATION**: 250 m
SEISMIC COVERAGE:		

Objectives: Recover basement samples for geochemical analysis. Minimum time on site.

Drilling Program: RCB to ~50 m basement

Logging and Downhole Operations: None

Nature of Rock Anticipated: Pelagic ooze, basalt.

SITE: AAD-27	**PRIORITY**:	**POSITION**: 41°18.6'S, 127°57.1'E
WATER DEPTH: 5100 m	**SEDIMENT THICKNESS**: 0.1 s	**TOTAL PENETRATION**: 250 m
SEISMIC COVERAGE:		

Objectives: Recover basement samples for geochemical analysis. Minimum time on site.

Drilling Program: RCB to ~50 m basement

Logging and Downhole Operations: None

Nature of Rock Anticipated: Pelagic ooze, basalt.

SITE: AAD-28	**PRIORITY**:	**POSITION**: 43°15.3'S, 128°52.1'E
WATER DEPTH: 5100 m	**SEDIMENT THICKNESS**: 0.2-0.3 s	**TOTAL PENETRATION**: 250 m
SEISMIC COVERAGE:		

Objectives: Recover basement samples for geochemical analysis. Minimum time on site.

Drilling Program: RCB to ~50 m basement

Logging and Downhole Operations: None

Nature of Rock Anticipated: Pelagic ooze, basalt.

SITE: AAD-29	**PRIORITY**:	**POSITION**: 43°56.9'S, 128°49.7'E
WATER DEPTH: 5100 m	**SEDIMENT THICKNESS**: 0.2-0.3 s	**TOTAL PENETRATION**: 250 m
SEISMIC COVERAGE:		

Objectives: Recover basement samples for geochemical analysis. Minimum time on site.

Drilling Program: RCB to ~50 m basement

Logging and Downhole Operations: None

Nature of Rock Anticipated: Pelagic ooze, basalt.

SITE: AAD-33	**PRIORITY**:	**POSITION**: 43°44.9'S, 127°44.9'E
WATER DEPTH: 4800 m	**SEDIMENT THICKNESS**: 0.2 s	**TOTAL PENETRATION:** 250 m
SEISMIC COVERAGE:		

Objectives: Recover basement samples for geochemical analysis. Minimum time on site.

Drilling Program: RCB to ~50 m basement

Logging and Downhole Operations: None

Nature of Rock Anticipated: Pelagic ooze, basalt.

SITE: AAD-34	**PRIORITY**:	**POSITION**: 42°44.2'S, 127°53.2'E
WATER DEPTH: 4875 m	**SEDIMENT THICKNESS**: 0.2 s	**TOTAL PENETRATION**: 250 m
SEISMIC COVERAGE:		

Objectives: Recover basement samples for geochemical analysis. Minimum time on site.

Drilling Program: RCB to ~50 m basement

Logging and Downhole Operations: None

Nature of Rock Anticipated: Pelagic ooze, basalt.

SITE: AAD-35	**PRIORITY**:	**POSITION**: 41°57.5'S, 127°59.7'E
WATER DEPTH: 5000 m	**SEDIMENT THICKNESS**: 0.2 s	**TOTAL PENETRATION**: 250 m
SEISMIC COVERAGE:		

Objectives: Recover basement samples for geochemical analysis. Minimum time on site.

Drilling Program: RCB to ~50 m basement

Logging and Downhole Operations: None

Nature of Rock Anticipated: Pelagic ooze, basalt.

SITE: AAD-36	**PRIORITY**:	**POSITION**: 41°52.7'S, 127°00.1'E
WATER DEPTH: 5000 m	**SEDIMENT THICKNESS**: 0.15s	**TOTAL PENETRATION**: 150 m
SEISMIC COVERAGE:		

Objectives: Recover basement samples for geochemical analysis. Minimum time on site.

Drilling Program: RCB to ~50 m basement

Logging and Downhole Operations: None

Nature of Rock Anticipated: Pelagic ooze, basalt.

SITE: AAD-37	**PRIORITY**:	**POSITION**: 44°11.4'S, 126°10.1'E
WATER DEPTH: 5100 m	**SEDIMENT THICKNESS**: <100 m	**TOTAL PENETRATION**: 150 m
SEISMIC COVERAGE:		

Objectives: Recover basement samples for geochemical analysis. Minimum time on site.

Drilling Program: RCB to ~50 m basement

Logging and Downhole Operations: None

Nature of Rock Anticipated: Pelagic ooze, basalt.

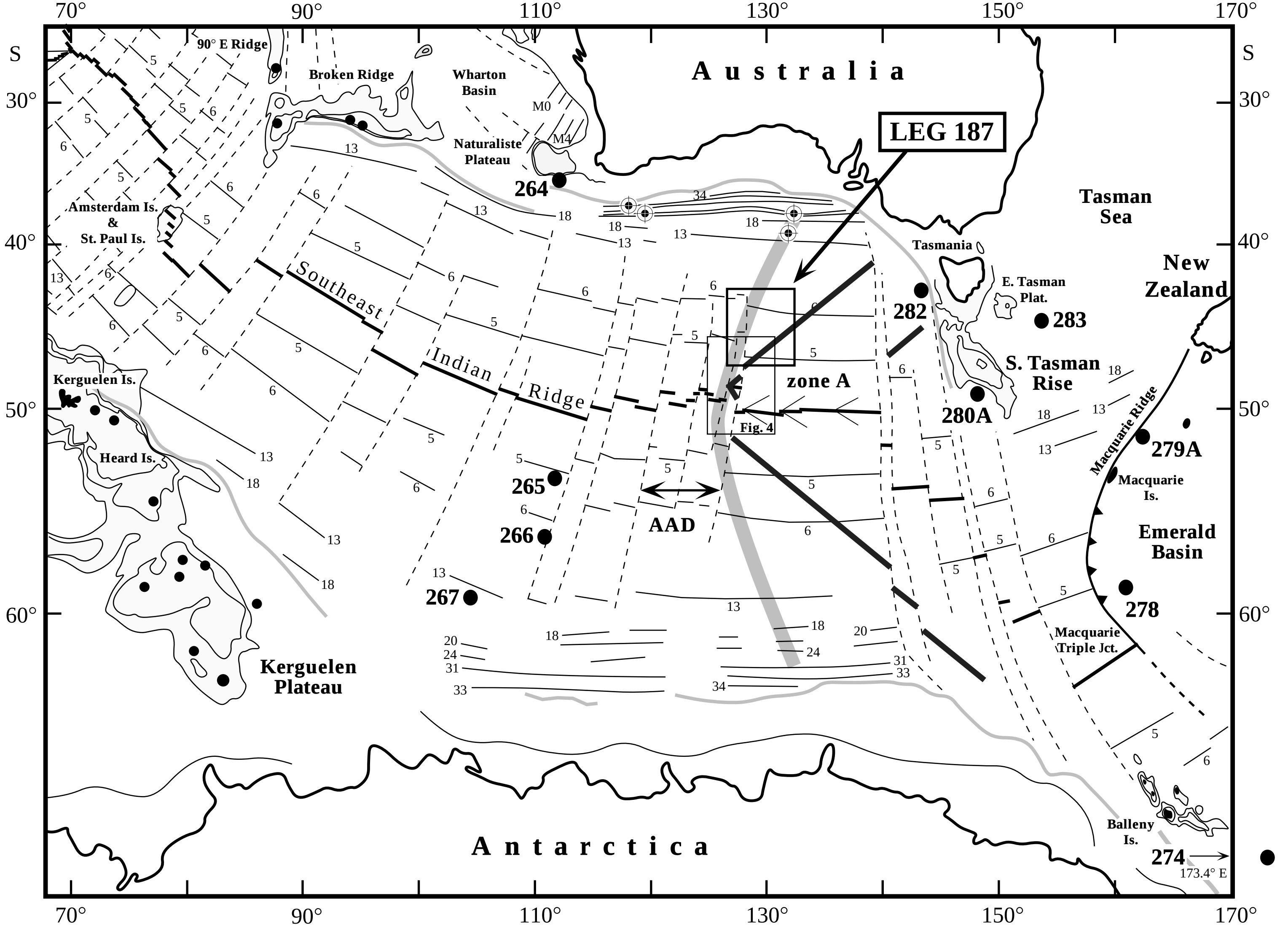

Figure 1. Regional map of the Southeast Indian Ocean showing magnetic lineations (Cande et al., 1989), the Australian-Antarctic Discordance (AAD), and DSDP sites that sampled basement. Thin dark "V" to the east of the AAD is the inferred trace of the isotopic boundary for a migration rate of ~40 mm/yr. Broader gray "V" is the approximate trace of the regional depth anomaly. (From Pyle et al., 1995). Bulls-eyes south of Australia indicate approximate positions of dredges by Lanyon et al., 1995.

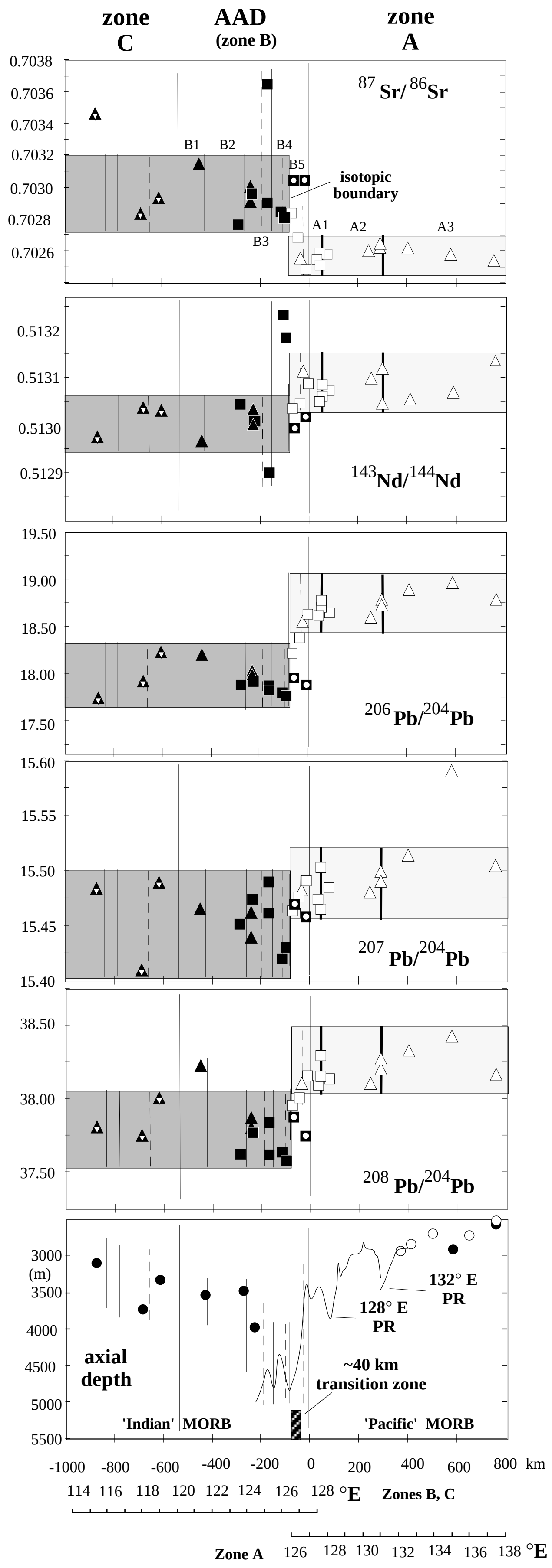

Figure 2. Along-axis profiles of isotopic ratios from the SEIR between 115˚E and 138˚E. Horizontal scale in kilometers from the eastern bounding transform of the AAD. Open symbols and lightly shaded field denote 'Pacific' type MORB. Filled symbols and darker field denote 'Indian' type MORB. From Pyle et al., 1992.

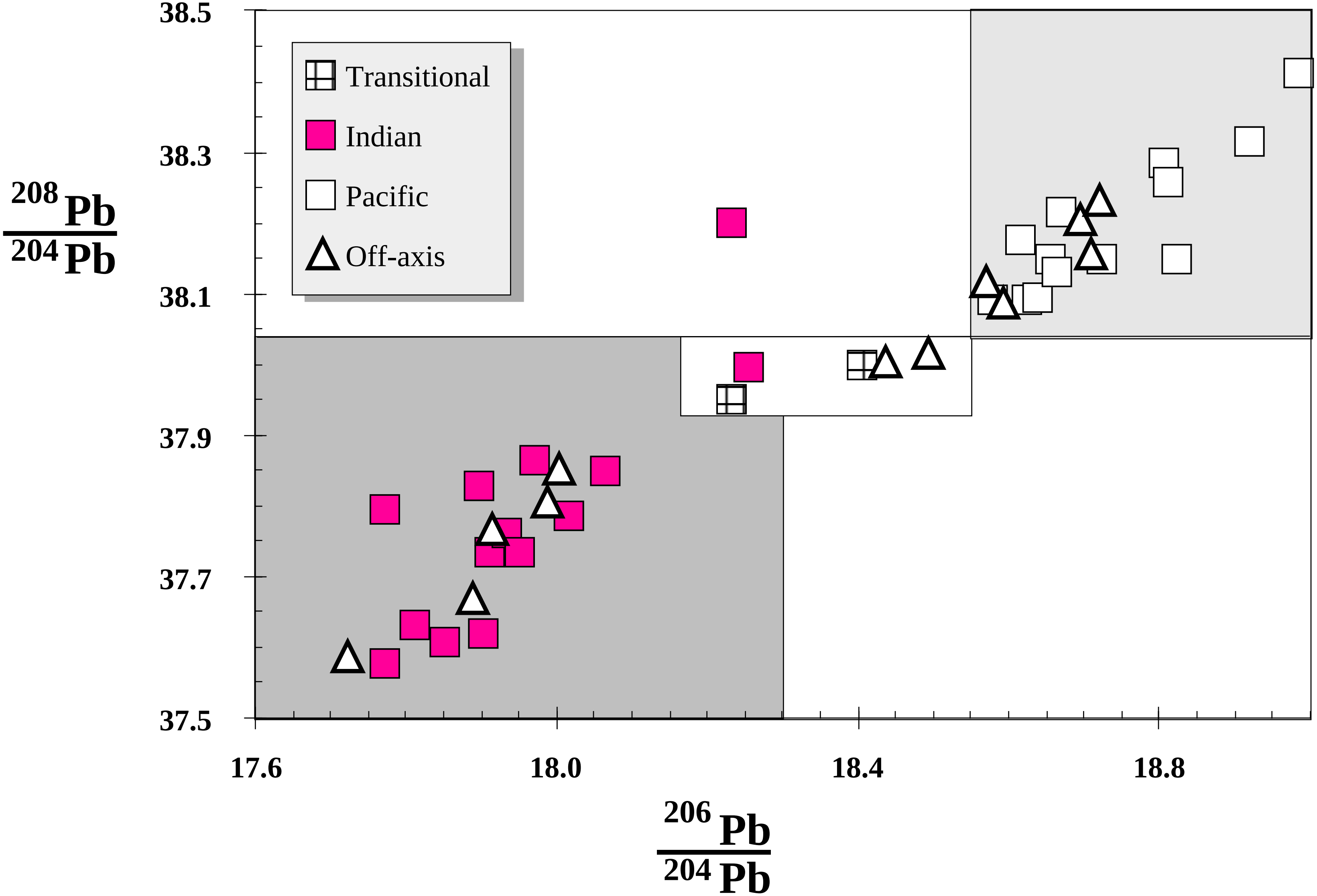

Figure 3. Pb isotopic ratios of axial lavas (squares) showing the Indian and Pacific populations from Figure 2, as well as transitional lavas from Segment B5. Triangles represent off-axis lavas which can be assigned to either the Indian or the Pacific population on the basis of this diagram.

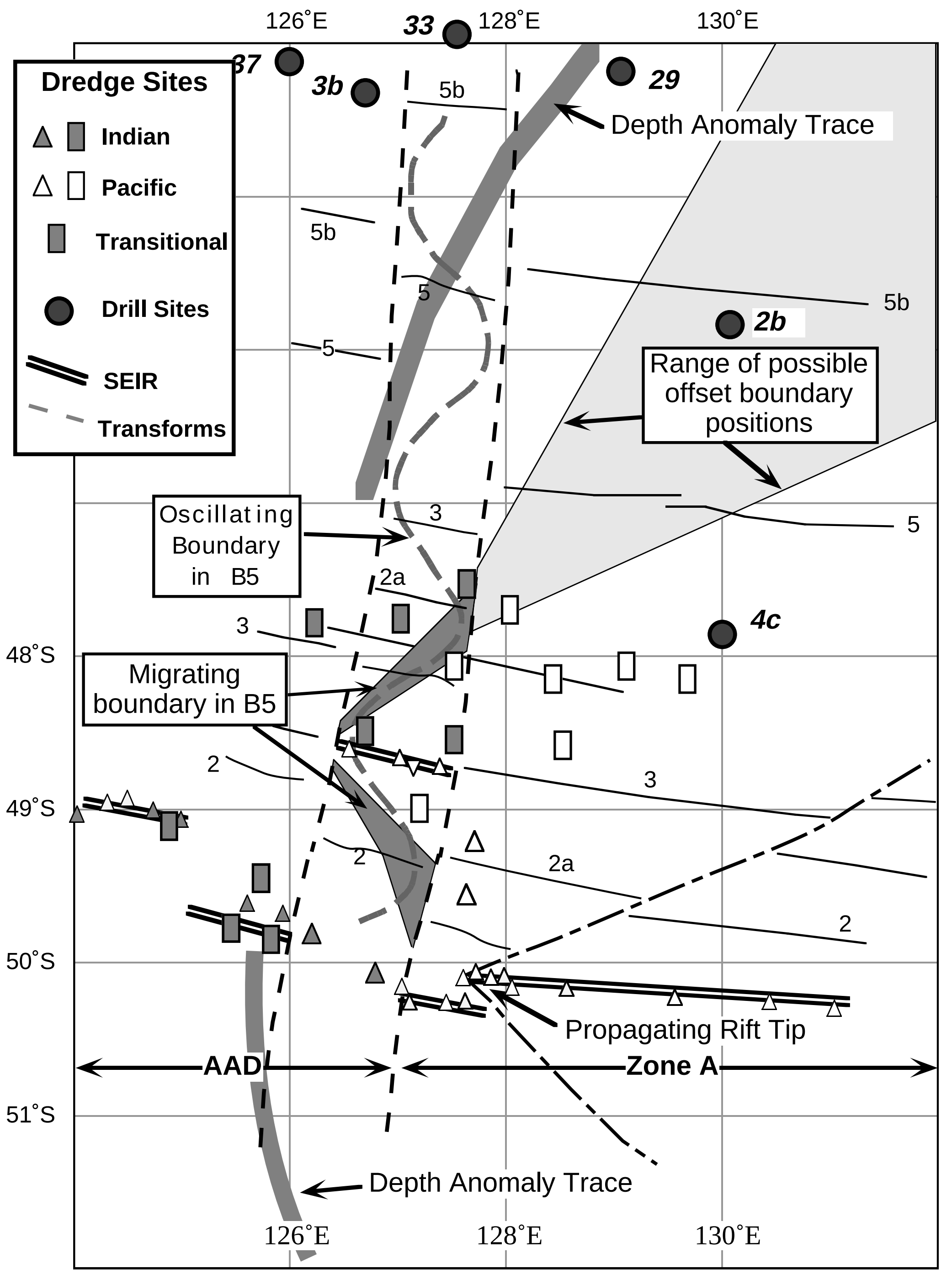

Figure 4. Mantle boundary configurations allowed by current geochemical data from the dredge sites shown. Indian and Pacific populations are the same as in Figure 3. Migration across Segment B5 is confirmed, with the boundary constrained to the vertically ruled area labeled "Migrating boundary in B5." East of the AAD, a boundary produced by long-term westward migration is constrained to the medium gray shaded region in the upper right quadrant. Alternate boundary configurations are associated with the curving trace of the depth anomaly or oscillating between the easternmost AAD transforms. The more southerly Leg 187 drill sites are shown as dark gray filled circles. The remaining sites lie to the north and east of this map. Magnetic anomalies are numbered 2 through 5B.

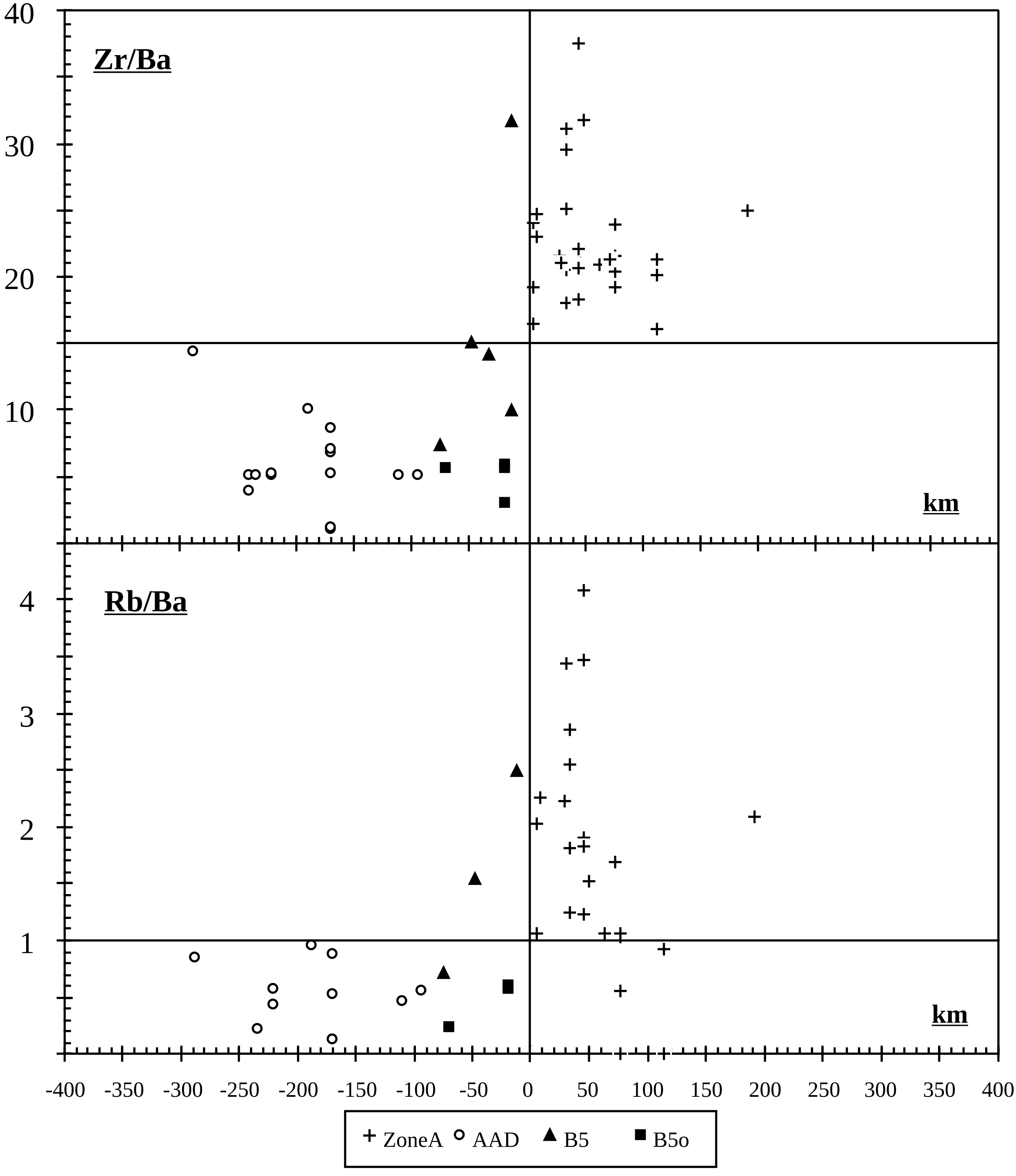

Figure 5. Rb/Ba and Zr/Ba for axial samples plotted against distance along axis from the eastern boundary of the AAD. These and similar ratios will be used during the drilling leg to guide site selection. Note that samples from Segment B5, immediately to the east of the isotopic boundary are transitional in many characteristics. Black squares are off-axis B5 samples dredged in 1988.

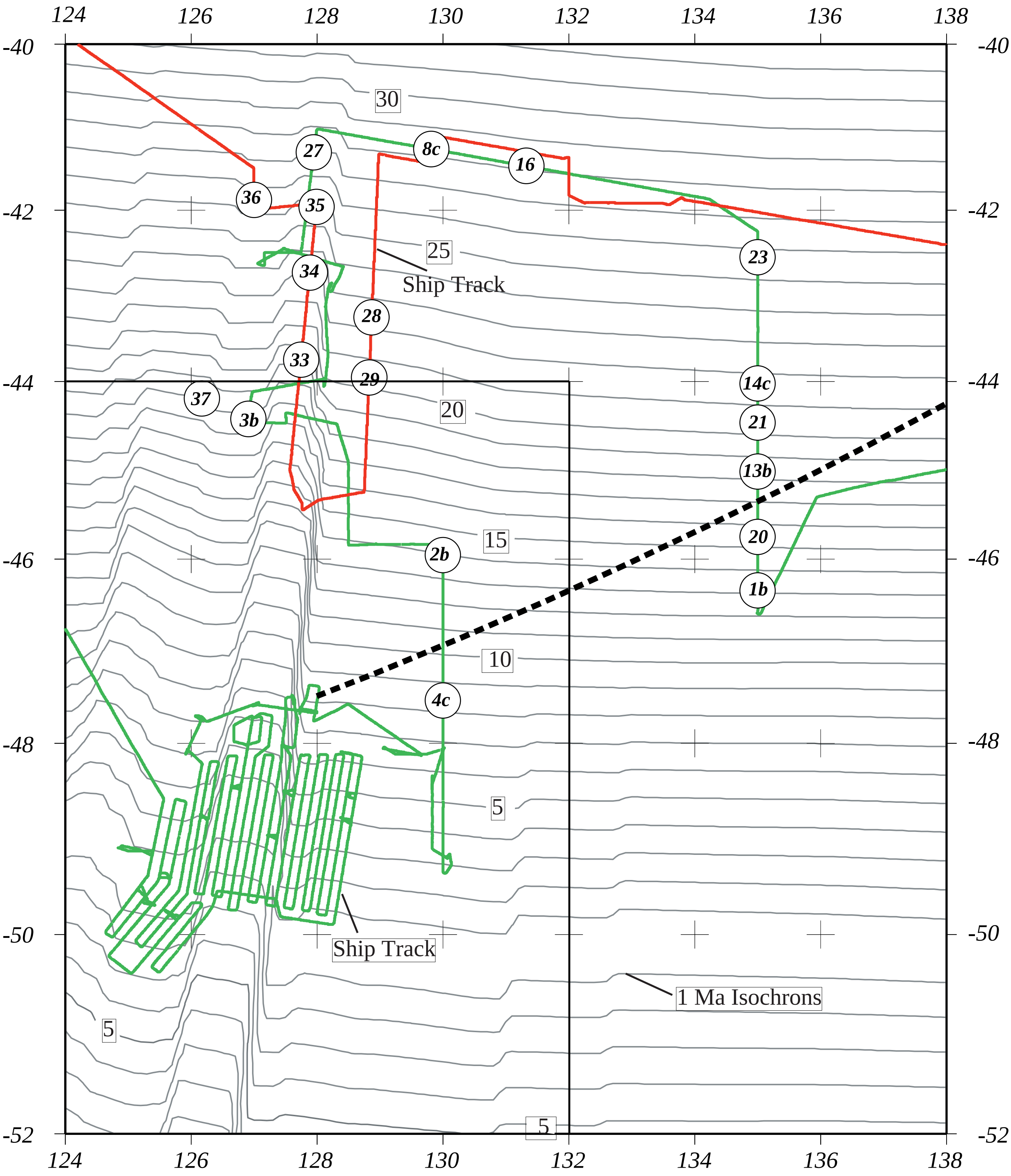

Figure 6. Proposed drill sites in relation to 1 Ma isochrons and to site survey ship tracks. Transforms appear as deflections of the isochrons. Spreading axis (zero isochron) is not plotted. Dashed line marks the predicted southernmost limit for possible locations of the isotopic boundary based on sampling of 0-7 Ma seafloor (Christie et al., in press).