Mapping absolute migration of global mid-ocean ridges since 80 Ma to Present

Desiderius C. P. Masalu

University of Dar Es Salaam, Institute of Marine Sciences, PO Box 668, Zanzibar, Tanzania

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We have computed and mapped the absolute migration of global mid-ocean ridges in the past 80 m.y. and found that ridges have migrated substantially during that period. Presently, the faster-migrating ridges are Pacific-Antarctic, Central Indian, Southeast Indian, Juan de Fuca, Pacific-Nazca, Antarctic-Nazca and Australia-Antarctic ridges which migrate between 3.3 and 5.5 cm/yr. The slower-migrating ridges are Mid-Atlantic and Southwest Indian ridges which migrate between 0.3 and 2.0 cm/yr. Comparing these results with mantle tomography and geochemistry suggests that slower-migrating ridges have deeper depth of origin than faster-migrating ridges, implying a correlation between migration velocity and depth of origin of ridges. The reconstructed Southwestern Indian ridge (near 44°E) between 60 Ma and Present, lies atop reconstructed Central Indian ridge between 80 and 50 Ma, and the present-day Antarctic-Nazca or (Chile) ridge lies atop the reconstructed East Pacific Rise at 70 Ma. Furthermore, the South Mid Atlantic Ridge and the East Pacific Rise near 10°S appear to have been stationary relative to the mantle for the last 80 m.y. These observations suggest that different portions of the mantle have undergone different recycling history, and may explain the origin of mantle heterogeneities.

Key words: Mid-ocean ridge, tectonics, tomography, absolute migration, melt, magnetic lineations.

1. Introduction

Over the past two decades, absolute migration of mid-ocean ridges has been correlated with major observable features of the ridges. For example Stein *et al.* (1977) correlated spreading asymmetry with migration rate, and Davis and Karsten (1986) explained asymmetry in seamount abundance by absolute ridge migration. Ridge migration rate is also thought to be an important factor that influences the diversity of ridge-crest lavas and the compositional uniformity of ridge-crest basalts (Davis and Karsten, 1986). Rapid migration of mid-ocean ridge has been cited as a possible cause of melting asymmetry (Scheirer *et al.*, 1998; Buck, 1999; Evans *et al.*, 1999). Recently, ridge migration has been used to explain depth and geochemical discontinuities between the southern East Pacific Rise and Antarctic ridges (Small and Danyushevsky, 2003), and the variation in ridge morphology that results from melt focusing across discontinuities (Carbotte *et al.*, 2004). In plate tectonics mid-ocean ridges are considered to be passive features the motions of which are governed by the interactions and motions of global plates, a property that makes absolute migration of ridges, a potential recorder of global tectonics. Despite its apparent importance, mapping of historical absolute migration of mid-ocean ridges has not previously been defined and done. We attempt to compute and map the absolute migration of global mid-ocean ridges since 80 Ma.

2. Method and the Data

New seafloor forms at mid-ocean ridges when molten magma passively upwells into the narrow space between two diverging plates (Reynolds and Langmuir, 1997; Dziak *et al.*, 2004; Detrick, 2000). Magnetic minerals in the magma align in the direction of the prevailing geomagnetic field, thus recording the age of the new seafloor. Therefore, if we determine the age of the seafloor and can construct a relevant plate motion model in the hotspot reference frame, we can locate the ridge when the seafloor formed. A digital age grid for the world's seafloor with a grid node interval of 6 arc minutes is available (Mueller *et al.*, 1997) which was compiled using the geomagnetic time scale of Cande and Kent (1995) for anomalies younger than chron 34 (83 Ma). Using the digital age grid and models for absolute plate motion of Duncan and Clague (1985) and Mueller *et al.* (1993) we reconstructed the paleolocations of global mid-ocean ridges from 80 Ma to present, by rotating seafloor age isochrons at intervals of 10 m.y. from their present to their former locations. For detailed investigation of the migration of the ridges we selected 27 ridge segments, picked their corresponding age isochrons on both sides, and reconstructed their paleolocations using the method outlined above and computed the absolute migration speed for each ridge. Two criteria were considered in determining the segments; first the availability of as many as possible identified magnetic isochrons from Chron 34 to Present on both sides of the segment, and secondly, location of the segment on the ridge. Whenever it was possible segments that were about evenly distributed along or located about the centre of the ridge were selected. The aim was to finally get a better estimation of the absolute migra-

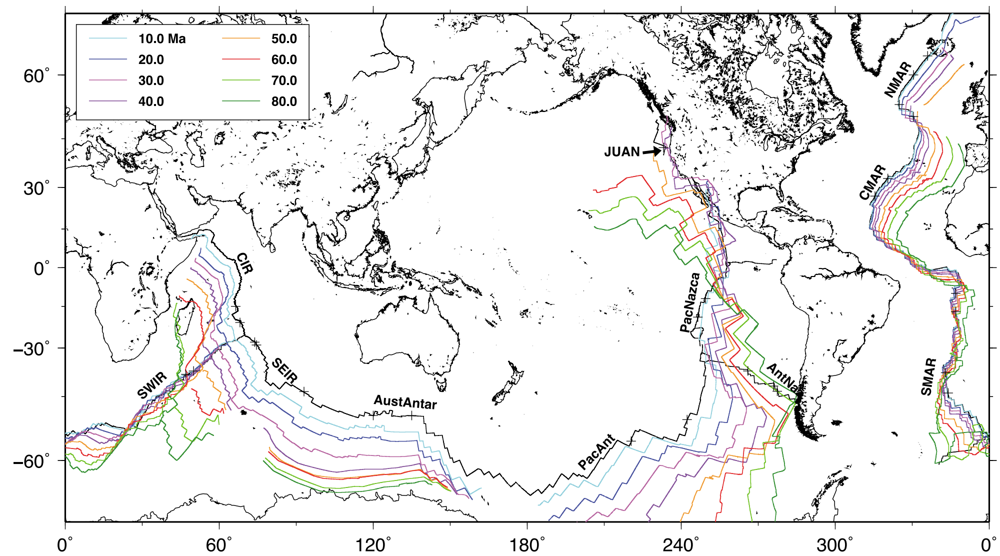

Fig. 1. Absolute migration of global mid-ocean ridges since 80 Ma. Pattern lines are reconstructed past locations of ridges. Numbers in the insert index are years before Present. Crosses show ridge segments used for detailed study and computation of migration speed. Text identifiers are: **JUAN** (Juan de Fuca ridge), **PacAnt** (Pacific-Antarctic ridge), **PacNazca** (Pacific-Nazca ridge), **AntNaz** (Antarctic-Nazca ridge), **SMAR** (South Mid-Atlantic Ridge), **CMAR** (Central Mid-Atlantic Ridge), **NMAR** (North Mid-Atlantic Ridge), **SEIR** (Southeast Indian Ridge), **CIR** (Central Indian Ridge), **SWIR** (Southwest Indian Ridge) and **AustAntar** (Australia-Antarctic ridge). Note: For the purpose of this paper the **SEIR** extends from the Indian Triple Junction to 115°E where it joins with the **AustAntar**.

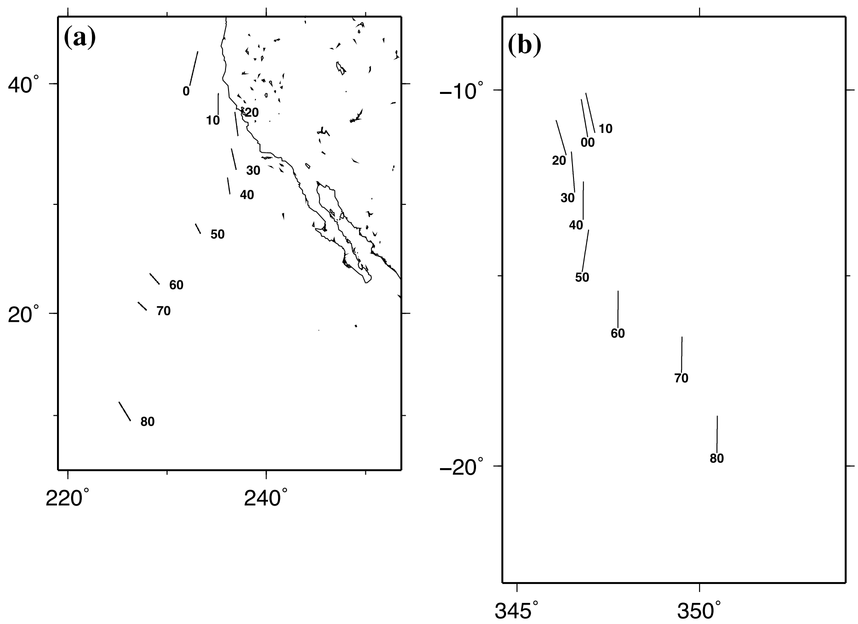

Fig. 2. Absolute migration of some of the selected ridge segments. Solid thick line segments are reconstructed past locations of the ridge segments as indicated by the adjacent number in million years from the present. (a) southernmost segment of the Juan de Fuca ridge, and (b) segment from the SMAR. Other panels as in Fig. 1.

tion speed of the ridge from the stacked absolute migration speed profiles of the segments. This is because absolute migration speed varies at each portion of the ridge. The number of profiles that were stacked for computation of average absolute migration speed and errors for ridges in this study were as follows: Central Indian Ridge—4, Southeast Indian Ridge—6, Southwest Indian Ridge—4, Australia-Antarctica Ridge—4, Pacific–Antarctica Ridge—4, Pacific-Nazca Ridge—4, Juan de Fucca Ridge—1, Antarctica-Nazca Ridge—6, South Mid-Atlantic Ridge—8, Central Mid-Atlantic Ridge—4, and North Mid-Atlantic Ridge—8.

We assume that plates have remained rigid for the past 80 m.y. This is not very true as both inter- and intra-plate deformation exist (Dixon *et al.*, 1996; Kogan *et al.*, 2000; Beavan *et al.*, 2002; Tregoning, 2002; Socquet *et al.*, 2006) due to differing plate rigidity. There are also inherent errors from the use of absolute plate motion models. These models assume that hotspots are fixed or move only very slowly relative to each other. However, the motion between hotspots remains poorly known and the assumption of hotspot fixity is controversial (Molnar and Stock, 1987; Acton and Gordon, 1994; Tarduno and Gee, 1995). It is known that recon-

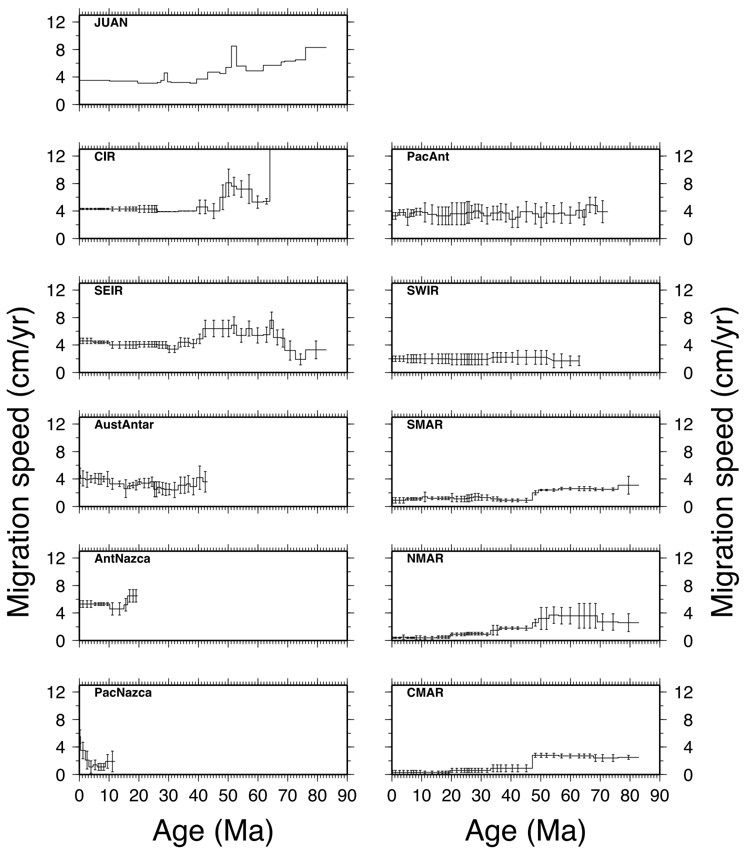

Fig. 3. Stacked profiles of migration speeds of global mid-ocean ridges with errors shown as deviation from the mean. No error bars are shown for JUAN because identified lineations from only one side of the segment were used. Other panels as in Fig. 1.

structions based on the Indo-Atlantic and Pacific hotspots do not agree with each other. This disagreement might indicate that there is a missing plate boundary somewhere, but it could also be that some of the hotspots are moving relative to each other at rates on the order of 20 mm/yr. Results from the latest IODP cruise (Leg 197) to the Emperor Seamounts suggests that the Hawaiian hotspot was moving southwards from ~81–43 Ma at rates of 30–50 mm/yr (Tarduno *et al.*, 2002). Mueller *et al.* (1993) tried to establish an absolute framework for all plates but were unable to include the Pacific plates in their model. For that reason we use Duncan and Clague (1985) model for Pacific ridges and Mueller *et al.* (1993) model for all other ridges. Even considering these sources of errors our results appear to be reasonable, and present the first overview of global motion of mid-ocean ridges.

3. Migration of Global Mid-ocean Ridges

Our results indicate that global mid-ocean ridges have migrated extensively in the past 80 m.y. (Fig. 1). All ridges appear to be migrating but we also note other observations. The East Pacific Rise or EPR (which includes the PacNazca ridge and its northern adjacent Pacific-Cocos ridge) which was probably one ridge with the Juan de Fuca ridge (JUAN) in the past, appears to have rotated clockwise by about 50° in the last 80 m.y. and its central section have not migrated extensively. On the other hand the Southern Mid-Atlantic Ridge (SMAR) displays very small lateral migration. However, reconstructions based on the selected ridge segments

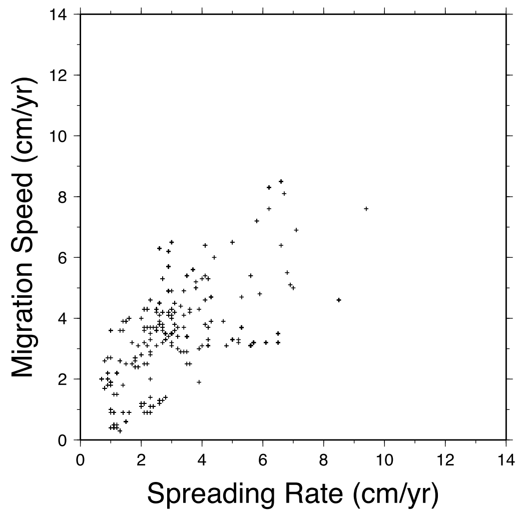

Fig. 4. Absolute migration velocity versus spreading velocity for ridges in this study.

show that the northern EPR and JUAN ridge segments have migrated northward from 80 Ma to Present, and the SMAR appears to be migrating almost northward. The SMAR, during its migratory history ran between several hotspots which may have played a role in limiting lateral migration (Uyeda and Miyashiro, 1974). JUAN appears to be migrating westward since about 20 Ma, which may show the end of clockwise rotation of EPR.

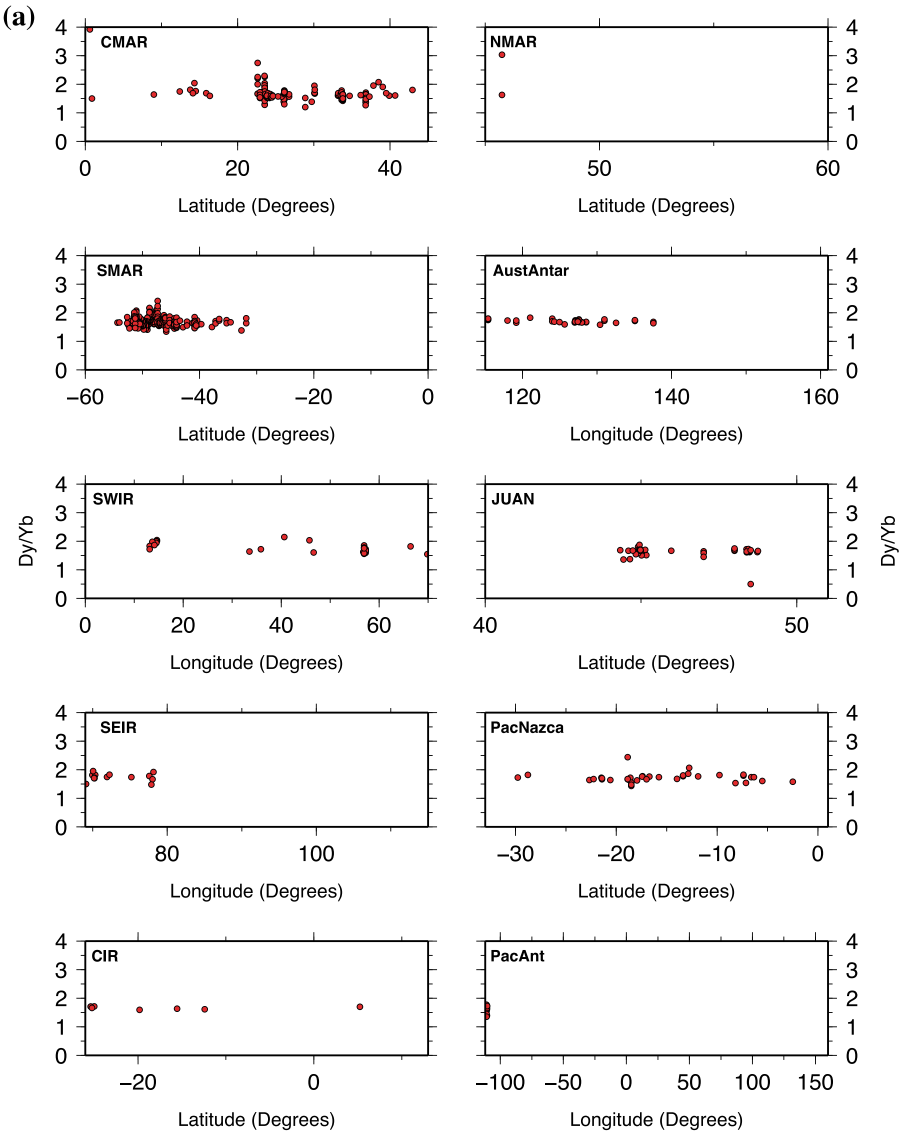

Fig. 5. Dy/Yb ratios of mid-ocean ridges in this study. (a) Along the ridges, and (b) Versus absolute migration speed of ridges. Other panels as defined in Fig. 1. Data from PetDB (http://petdb.ldeo.columbia.edu/petdb).

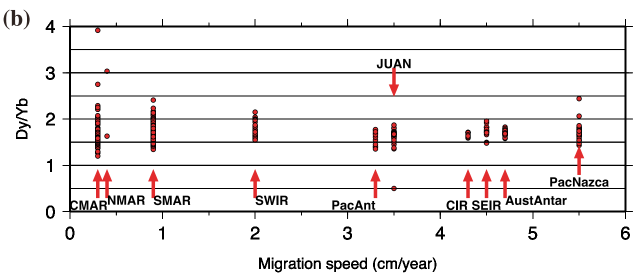

Fig. 5. (continued).

Contrary to SMAR, the Central Mid Atlantic Ridge (CMAR) between the equator and the 40°N latitude, and the Northern Mid Atlantic Ridge (NMAR) north of the 40°N latitude, have been migrating westerly between 80 Ma and Present (Fig. 1), away from SMAR. The implied location of the boundary between SMAR and CMAR is consistent with the Equatorial Atlantic Region (EAR), an area characterized by a dense pattern of mostly medium to large offset fracture zones (Mueller and Smith, 1993). The EAR records a plate boundary between the North and South American plates (Roest and Collette, 1986) that seems has been in existence for the last 80 Ma.

4. Resampling of the Mantle

Figure 1 shows two more important observations. Firstly, the present-day Chile ridge lies atop the reconstructed EPR at 70 Ma, implying that the Chile ridge may be tapping the same portion of the mantle as did the EPR 70 m.y. ago. Similarly, a small section of the reconstructed Southwestern Indian Ridge (SWIR) (near 44°E) between 60 Ma and Present, lies atop the reconstructed Central Indian Ridge (CIR) between 80 and 50 Ma. This implies since 60 Ma to Present, that section of the SWIR may be tapping the same portion of the mantle as did the CIR between 80 and 50 Ma. Secondly, while all ridges appear to be migrating relative to the mantle for the last 80 Ma, the SMAR and EPR near 10°S appear to have been stationary during that period.

This implies that these ridges have been sampling same locations of the mantle for the last 80 Ma. These observations suggest that different portions of the mantle have undergone different recycling history, and may have important thermochemical implications for the mantle. They thus offer a possible mechanism of origin of lateral heterogeneities in the mantle, and variations of the chemistry of global mid-ocean ridges (e.g., Graham *et al.*, 2001). It is important to note here that the exact relative motion between the plates, upper mantle and lower mantle is not known. However, relative to the lower mantle the plates and the upper mantle move in opposite directions, to a large extent cancelling each other out (e.g., Argus and Gross, 2004). The relative motions between plates, upper mantle and lower mantle may thus not greatly affect the above results.

5. Absolute Migration Speed and Mantle Tomography

Absolute migration speed of ridges that were investigated are shown in Fig. 3. The ridges divide into two groups: the slower-migrating ridge group including the CMAR, SMAR, NMAR and SWIR ridges, and the faster-migrating ridge group which includes all other ridges. Presently, the slower-migrating ridges migrate between 0.3 and 2.0 cm/yr whereas the faster-migrating ridges migrate between 3.3 and 5.5 cm/yr.

We compare our results with seismic velocity anomalies beneath global mid-ocean ridges. Su *et al.* (1992) show that seismic velocity anomalies associated with mid-ocean ridges, appear as continuous features to 300 km depth. For the NMAR, SMAR, Pacific-Antarctic ridge (PacAnt), SWIR, and Carlsberg ridges, mantle velocities remain slower than normal on average down to at least 400 km depth, and may persist to 600 km depth. Except for the PacAnt, 'deep-rooted' ridges are the slower migrating (Fig. 3). Although falls in the faster-migrating ridges group, the PacAnt is the slowest in the group. So, the cut-off point between "faster" and "slower" migrating ridges may be $\sim$3.5 cm/yr which seems to be consistent with the velocity found by Small and Sandwell (1994) which distinguishes between mid-ocean ridges that have a ridge-crest versus those that have a median valley. This is supported by the observation that migration velocity of ridges increase proportionally with spreading velocity (Fig. 4). These results imply a possible correlation between absolute migration speed and depth of origin of mid-ocean ridges whereby faster-migrating ridges have shallow depth of origin while slower-migrating ridges have deeper depth of origin. This suggests that slower migrating ridges allow the development of stable and deep rooted mantle convection cells beneath them; whereas faster migrating ridges probably cause some disturbances to mantle convection cells beneath them, thus allow only development of shallow rooted convection cells. Unfortunately, the resolutions of the currently available models of mantle tomography do not allow us to directly quantify this apparent correlation. Furthermore, this study cannot strictly distinguish between the two possibilities, that is, the slower migrating ridges have deeper origins because they are migrating more slowly or, are they migrating more slowly because they have deeper origins.

6. Discussion

One of the most important dynamic processes in the Earth's interior is thermal convection in the mantle. Two methods are used to study temperature variations in the upper mantle: study of trace- and major-element chemistry of basalts erupted at mid-ocean ridges which is directly influenced by the temperature of the mantle beneath (e.g., Klein and Langmuir, 1987; Hellebrand *et al.*, 2001; Humler and Besse, 2002) and seismic velocity studies (e.g., Su *et al.*, 1992; Zhang and Tanimoto, 1992).

Klein and Langmuir (1987, 1989) studied the chemical systematics of global Mid-Ocean Ridge Basalts (MORB) and explained them by variations among different melting columns. In their model, hotter mantle material (from deeper depth) intersects the solidus at greater depth and produces a taller melting column, leading to greater mean pressures and extent of melting whereas cooler mantle material (from shallow depth) intersects the solidus at shallower depth and produces a shorter melting column, leading to lower mean pressures and extent of melting. This model can be combined with our results whereby, faster-migrating ridges correspond to ridges with cooler mantle sources and slower-migrating ridges correspond to ridges with hotter mantle sources. The combined result suggests that the mantle beneath faster-migrating ridges have undergone smaller extents of melting whereas that beneath slower-migrating ridges have undergone greater extents of melting which may influence their chemistry.

Furthermore, during the creation of new Earth crust at mid ocean ridges, melt from the partially melted fertile upper mantle is extracted to the spreading centre, and the residual depleted mantle flows horizontally away (Martinez and Taylor, 2002; Hauri, 1999; Benoit *et al.*, 1999). This model when considered with our results has important implications. Firstly, the observation that the SWIR and present-day AntNazca (also known as Chile ridge) appear to be tapping portions of the mantle as other ridges did in the past suggests that basalts from these ridges may record two or more phases of recycling or the combined effect. They may show greater extents of melting and/or may be more depleted. Secondly, our result show that two sections of the global mid-ocean ridge system, the SMAR and EPR near 10°S, have remained stationary for the last 80 m.y. Because these ridges have been sampling same portions of the mantle for a long time, may be sampling deeper mantle and their chemistry may be different from the rest of the ridges that have been migrating.

We have computed the Dy/Yb ratios of mid-ocean ridges in this study except only for the AntNaz ridge for which data were not available (Fig. 5(a)). Higher Dy/Yb ratios indicate melt originating at greater mantle depths owing to the presence of residual garnet (Carbotte *et al.*, 2004). Disregarding points that are clearly outlier, the Dy/Yb ratio ranges vary as follows: SWIR, 1.55–2.15; SEIR, 1.48–1.96; CIR, 1.59–1.71; AustAntar, 1.58–1.83; NMAR, 1.63 (only two data points available); CMAR, 1.2–2.75; SMAR, 1.34–2.41; PacAnt, 1.35–1.77; PacNaz, 1.43–2.44; and JUAN, 1.36–1.87. The slower-migrating mid-ocean ridges, i.e., the NMAR, CMAR, SMAR and SWIR, and the sections of mid-ocean ridges that have remained stationary at least since 80 Ma, i.e., SMAR and PacNaz (which corresponds to the location where the EPR have remained stationary) have the highest upper ranges of the Dy/Yb ratios indicating they are sampling deeper mantle than the other ridges (Fig. 5(b)).

7. Conclusions

We have computed and mapped the absolute migration of global mid-ocean ridges for the past 80 m.y. Absolute migration speed and depth of origin of ridges appear to correlate whereby slower-migrating ridges have deeper depth of origin than faster-migrating ridges. The cutoff point between "faster" and "slower" migrating ridges is ∼3.5 cm/yr. The SWIR and present-day Chile ridge appear to be tapping portions of mantle as other ridges did in the past, and the SMAR and EPR near 10°S appear to have been stationary relative to the mantle for the last 80 m.y. This suggests that different portions of the mantle have undergone different recycling history.

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D. C. P. Masalu (e-mail: masalu@ims.udsm.ac.tz)