Earth and Planetary Science Letters 424 (2015) 179–190

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Age distribution of Ocean Drill sites across the Central Walvis Ridge indicates plate boundary control of plume volcanism in the South Atlantic

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ARTICLE INFO

Article history:
Received 25 February 2015
Received in revised form 9 May 2015
Accepted 12 May 2015
Available online 2 June 2015
Editor: A. Yin

Keywords:
South Atlantic
mantle plumes, hotspots
Ocean Drilling
mid-ocean ridges
geochronology

ABSTRACT

The Tristan–Gough hotspot trail on the African plate consists of the Walvis Ridge and a younger province of seamounts and islands. In order to determine the relative motion between the African plate and the Tristan–Gough hotspot it is essential to resolve changes in the age and morphology of the Walvis Ridge. A significant problem is, however, to establish how the vigor and flow of hotspot material to the mid-ocean ridge constructed the Walvis Ridge. We have addressed this issue by measuring an $^{40}Ar/^{39}Ar$ stratigraphy at three sites across the central Walvis Ridge sampled by Ocean Drilling (DSDP Leg 74). The age–distance relation of volcanism, together with geophysical, geochemical and paleodepth information, suggests collectively that hotspot volcanism was occurring locally c. 72 Ma on an elevated segment of the mid-ocean ridge located close to the Tristan–Gough hotspot. As the mid-ocean ridge migrated away from the hotspot (c. 36 km/Ma) between c. 72 Ma and 68 Ma, hotspot material continued flowing to the mid-ocean ridge and the Walvis Ridge shoaled rapidly (c. 500 m/Ma) to the west, on seafloor that might have been subsiding at a rate consistent with normal crustal cooling. This apparent correlation points to the possibility of an inverse relation between the volume flux of hotspot volcanism and the distance between the mid-ocean ridge and the Tristan–Gough hotspot. We infer that since c. 93 Ma the geometry and motion of the mid-ocean ridge determined where the hotspot material that built the Walvis Ridge was channeled to the plate surface. Furthermore, interplay between hotspot flow, and the changing geometry of the mid-ocean ridge as it migrated relative to the Tristan–Gough hotspot, might explain the age and morphology of the Walvis Ridge. Our finding provides further evidence that the distribution of hotspot volcanism in the southeast Atlantic expresses interaction between deep mantle (plume) and shallow plate tectonic and asthenosphere processes.

1. Introduction

The South Atlantic region offers important opportunities to discover if the interaction of hotspot melting anomalies with continental breakup and mid ocean spreading ridges during the past ~130 Ma is related to deep or shallow processes in the mantle. The record of these processes is preserved as chains of massive volcanic ridges (e.g. Walvis Ridge and Rio Grande Rise), and various dispersed clusters of seamounts and smaller volcanic ridges (e.g. Discovery, Shona, Bouvet) scattered across a c. 2000 km-wide region of anomalously shallow seafloor in the southeast Atlantic (Nyblade and Robinson, 1994; O'Connor et al., 2012).

The Walvis Ridge (Fig. 1) is important because it is one of few hotspot tracks that initiated with continental flood basalts in a continental rifting setting, and ends at young/active ocean islands (Tristan da Cunha and Gough) (Morgan, 1981; O'Connor and Duncan, 1990; Duncan and Richards, 1991). The usual explanation for the Walvis Ridge is that it is caused by plate motion relative to a hotspot that is connected to a narrow thermal column (plume 'tail' or 'conduit') extending deep in the mantle (Wilson, 1963; Morgan, 1971). Hotspots are sites of active volcanism than can exist at the same time above a plume orifice and on a mid-ocean ridge located some distance away (Sleep, 2002). But the existence of mantle plumes is still in question, especially the notion of narrow conduits extending as far as the core mantle bound-

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http://dx.doi.org/10.1016/j.epsl.2015.05.021
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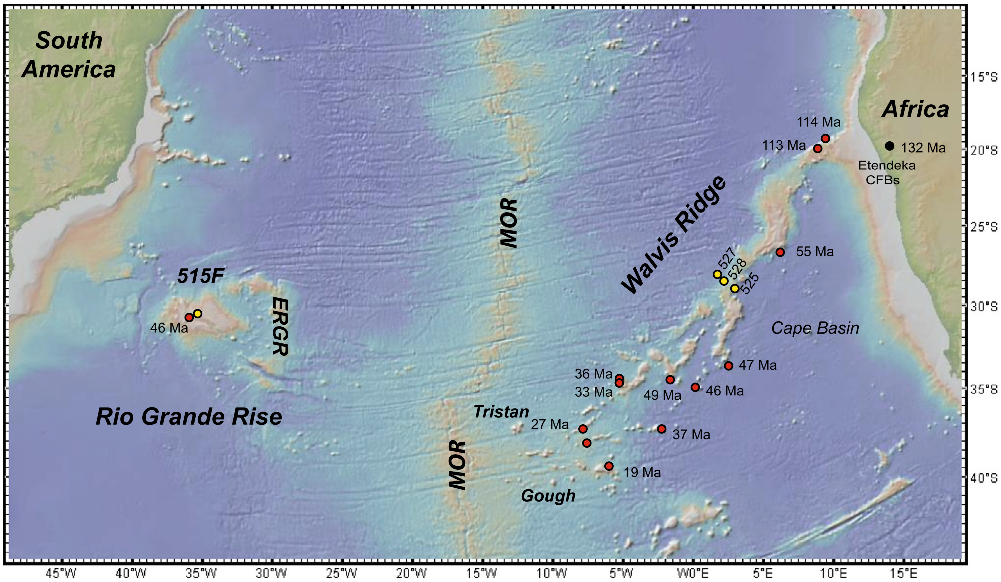

Fig. 1. Topographic map of the South Atlantic showing the Walvis Ridge and Rio Grande Rise and Ocean Drilling sites (yellow dots). Red dots are for locations of samples with existing $^{40}Ar/^{39}Ar$ ages (Rohde et al., 2012; O'Connor and le Roex, 1992; Renne, 2011). ERGR = East Rio Grande Rise; MOR = mid-ocean ridge. Map prepared using GeoMapApp (http://www.geomapapp.org/).

ary (Anderson, 2000; Foulger, 2002, 2005; Anderson and Natland, 2014; Anderson and King, 2014). Moreover, there is no consensus about how to define a plume, or if they originate from deep or shallow depths in the mantle (Koppers, 2011).

Alternative shallow plate mechanism to explain seamount chains and volcanic ridges include tensional cracking (Winterer and Sandwell, 1987; Sandwell et al., 1995; Natland and Winterer, 2005), and thermal contraction of the oceanic lithosphere (Sandwell and Fialko, 2004). In the case of the Walvis Ridge, plate reorganization might have triggered periodic stress release along shear/wrench/extensional deformation zones that might have penetrated short distances into the plate from the active mid-ocean ridge (Fairhead and Wilson, 2005; Fairhead et al., 2013).

As age and geochemical information increases for hotspot tracks in the southern South Atlantic, it is becoming increasingly clear that the neither plate cracking nor plumes can explain uniquely the scattered hotspot trails on the 2000 km-wide southeast Atlantic bathymetric swell (O'Connor et al., 2012). This has led to an alternative working hypothesis that hotspot trails in the South Atlantic are the result of interplay between mantle plumes and shallow plate tectonic processes (O'Connor et al., 2012).

The involvement of a deep mantle source(s) is implied by the distribution of new and existing $^{40}Ar/^{39}Ar$ sample ages, which is compatible with the synchronous formation of parallel age-progressive (northeast-trending) hotspot trails across the southeast Atlantic hotspot swell (O'Connor et al., 2012). A stable (or constantly moving) deep mantle source(s) seems to be the only way to explain how parallel age-progressive hotspot trails formed across the posited hotspot swell. Moreover, the present locations of SE Atlantic hotspots linked to these hotspot tracks seem to line up broadly with the projected leading edge of a thermo-chemical pile (LLSVP) at the core–mantle boundary, which is posited to be the generation zone for mantle plumes (Burke et al., 2008; Torsvik et al., 2010; Steinberger and Torsvik, 2012; O'Connor et al., 2012).

A shallow plate mechanism is implied by evidence that hotspot material flowed for long distances under the lithosphere and used weaknesses in the plate, or spreading boundaries, to reach the plate surface (Kessling, 2008; Adam et al., 2010; McNutt et al., 1997; O'Connor et al., 2012). In the South Atlantic, hotspot trails seem to have been confined initially to spreading boundaries at the outer edges of the southeast Atlantic hotspot swell, until increasing proximity of the South Atlantic spreading ridge to the hotspots (O'Connor and Duncan, 1990; O'Connor and le Roex, 1992; O'Connor et al., 2012; Pérez-Diaz and Eagles, 2014) resulted in younger (weaker) lithosphere migrating over the swell hotspots, which might have facilitating the onset of more widespread hotspot volcanism across the swell (O'Connor et al., 2012).

A considerable body of work (both modeling and geochemical) suggests that when a hotspot (plume orifice) is sufficiently near to a mid-ocean ridge, buoyant hotspot/plume material flows along the base of the lithosphere to the spreading ridge to form a hotspot track (Sleep, 2002, 2008; Mittelstaedt et al., 2008, 2011). Interaction between the mid-ocean ridge and the Tristan melting anomaly might have involved, therefore, the flow of hotspot/plume material along the base of the lithosphere to the mid-ocean ridge leading, to the formation of symmetric V-shaped hotspot tracks on both the African and South American plates (Sleep, 2002). As discussed by Sleep (2002, 2006), the architecture of the base of the lithosphere acts as an upside-down drainage pattern for hotspot flow toward the spreading ridge, possibly in channels convectively eroded into the base to the lithosphere.

On a broader scale, the flow of hotspot material to the mid-ocean causes asymmetric crustal accretion in the South Atlantic (Müller et al., 1998, 2008; Sleep, 2002). Faster crustal accretion between the mid-ocean ridge and hotspots results in jumps or propagations toward the hotspots (plume orifices) on the African plate, leading to a crustal deficit on the African side of the mid-ocean ridge (Müller et al., 1998, 2008; Sleep, 2002, Mittelstaedt et al., 2008, 2011). The mechanism(s) causing jumps or propagation of the mid-ocean ridge is not well understood. One suggestion is that pressure-release melting of hotspot material flowing towards the mid-ocean ridge, where it is hotter and weaker, causes excess dyke intrusion on the ridge flank close to the hotspot (Sleep, 1975, 2002; Fujita and Sleep, 1978; Müller et al., 1998, 2008). Other mechanisms include shear on the base of the plate due to expanding plume material, as well as reheating of lithosphere as magma passes through it to feed off-axis volcanism (Mittelstaedt et al., 2008, 2011).

The DSDP Leg 74 sites across the narrow, central part of the Walvis Ridge (Fig. 1) represent a unique drill site transect across a primary hotspot track. Moreover, the Leg 74 sites are located