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New constraints on the age and style of continental breakup in the South Atlantic from magnetic anomaly data

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A B S T R A C T

We present new constraints on the opening of the South Atlantic Ocean from a joint interpretation of marine magnetic anomaly grids and forward modelling of conjugate profiles. We use 45,000 km of recently collected commercial ship track data combined with 561,000 km of publically available data. The new data cover the critical ocean–continental transition zones and allow us to identify and downgrade some poorly navigated older ship tracks relied upon in earlier compilations. Within the final grids the mean cross-over error is 14 nT computed from 8,227 ship track intersections. The forward modelling used uniformly magnetised bodies whose shapes were constrained from coincident deep-seismic reflection data. We find the oldest magnetic anomalies to date from M10r (134.2 Ma, late Valanginian) north of the Falkland-Agulhas Fracture Zone and M3 (129.3 Ma, Barremian) south of the Rio Grande Fracture Zone. Hence, assuming the GPTS used is correct, continental breakup was contemporaneous with the Parana and Etendeka continental flood basalts. Many of the landward linear anomalies overlap seismically mapped Seaward Dipping Reflectors (SDRs). We interpret this to mean that a significant portion of the SDRs overlay crust formed by subaerial seafloor spreading. Here crustal accretion is envisaged to be similar to that at mid-ocean ridges, but sheet lava flows (that later form the SDRs) rather than pillow basalts form the extrusive component. Segmentation of the linear anomalies generated implies that this stage of continental breakup is organised and parallels the seafloor spreading centre that follows. Our results call into question the common assumption that at volcanic continental margins the first linear magnetic anomalies represent the start of conventional (submarine) oceanic crustal generation.

1. Introduction

The South Atlantic has a long history of plate reconstruction, having been one of the subjects of the first computerised fit of the continents by Bullard in 1965. The region is often taken as a textbook example of plate tectonics, with orthogonal plate separation that was free of tectonic complexities seen at many other locations. In recent years, as oil and gas exploration has moved into deeper water, attention has been focused on describing the late stages of continental separation. This has resulted in numerous competing plate reconstruction models being published (Konig and Jokat, 2006; Eagles, 2007; Torsvik et al., 2009; Moulin et al., 2010; Heine et al., 2013; Pérez-Díaz and Eagles, 2014). The difference between these models can be attributed to three main areas of uncertainty: the location of intracontinental deformation; the location of the continent–ocean transition zone (and how to correct for its tectonic extension and/or magmatic addition during rifting) and the recognition of the earliest seafloor spreading anomalies.

The uncertainty over the location of the continent–ocean transition zone and magnetic anomaly identification stems from two causes: the remoteness of the area and hence incomplete data coverage; and the fact that continental breakup was achieved either shortly before or during the long normal-polarity chron C34 or Cretaceous Magnetic Quiet Zone, (CMQZ). This produced only a short M-series of anomalies south of the Rio Grande Fracture Zone which can be difficult to sequence. A further problem with previous magnetic anomaly studies has been the presence of syn-rift volcanics on the continental margins. These provide sources of magnetism unrelated to oceanic crust and so complicate conventional interpretations of seafloor spreading anomalies (Hinz et al., 1999; Blaich et al., 2009; Moulin et al., 2010; Koopmann et al., 2014). For plate reconstruction of the early stages of breakup

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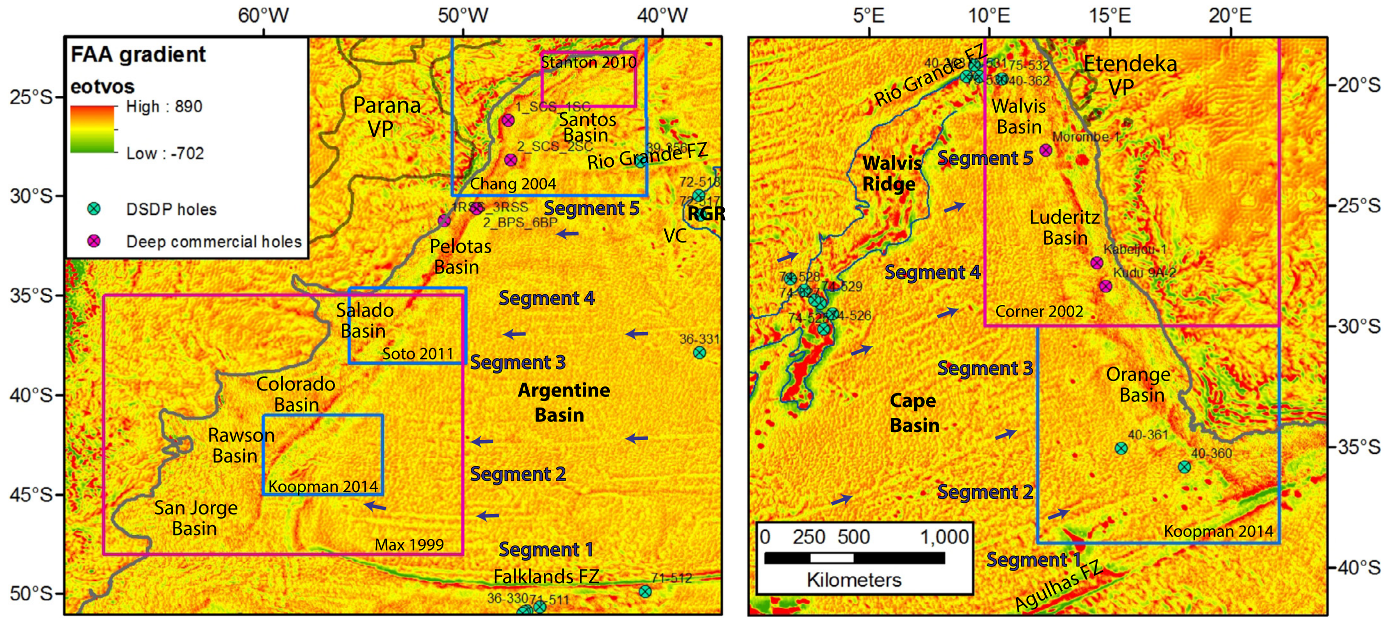

Fig. 1. Map of the study area showing the vertical gradient of the free-air anomaly (FAA) from Sandwell et al. (2014). The fracture zones that mark the northern and southern extents of the study area are labelled. Note that the Rio Grande FZ is sometimes referred to as the Florianopolis FZ in the literature. Dark blue arrows mark other prominent fracture zones which are used to subdivide the study area into five segments. The locations of previous magnetic anomaly studies are marked with boxes, with those in pink showing aeromagnetic studies (Max et al., 1999; Corner et al., 2002; Stanton et al., 2010) and blue marine studies (Chang, 2004; Soto et al., 2011; Koopmann et al., 2014). The dark blue lines mark the 4000 m bathymetric contour of the Rio Grande Rise (RGR) and Walvis Ridge. VC marks the Vema Channel which is a fossil ridge. Onshore, the black lines mark the outlines of the Paraná and Etendeka Volcanic Provinces (VP). (For interpretation of the colours in this figure, the reader is referred to the web version of this article.)

these problems are compounded by the inability to identify fracture zones in the oldest oceanic lithosphere from satellite data due to sediment accumulation close to the continents (Fig. 1).

In addition to providing a temporal framework for plate reconstructions, correctly identifying magnetic anomalies allows us to investigate the relationship between continental breakup and continental flood basalt eruption. Within our study area continental breakup is linked with the emplacement of the Paraná–Etendeka flood basalts in the Early Cretaceous (White and McKenzie, 1989). Many dating studies have shown these provinces erupted between ca. 140 Ma to ca. 129 Ma, with a peak in activity 134 to 132 Ma (e.g. Renne et al., 1992; Turner et al., 1994; Milner et al., 1995; Stewart et al., 1996; Thiede and Vasconcelos, 2010). However, whilst the age of the onshore volcanism is well established, the age of breakup is not. Only a handful of drill holes on the continental shelves have sampled basalts and of these only those in Brazilian waters have been dated and published (Fig. 1). In the Santos Basin ages range between 124 and 112 Ma (Fodor et al., 1983) and in the Pelotas Basin 124 and 113 Ma (Lobo, 2007; Gordon and Mohriak, 2015). Unfortunately, all these holes are close to the coastline and only sample the topmost sequences (Fig. 1). Dating of syn-rift/early post rift sediments is also generally lacking in the region. From three holes on the African side ages of Early Aptian, Early Barremian and Early Aptian (approximately 130–120 Ma) have been obtained from microfossils (DSDP 361, Kudu 9A-2 and DSDP 363 respectively, McMillan, 2003). Establishing the relative age of the continental flood basalts and the volcanic margins (which together form the Large Igneous Province or LIP) has important consequences for assessing any causal relationships between them. Analysing the magnetic anomalies across the margins therefore offer an alternate route for providing age constraints.

The motivation for this study comes from access to a new set of commercial ship-board magnetic profiles offshore southern Brazil, Uruguay, Argentina and Namibia. When combined with academic data available from other sources, it allows us to make magnetic anomaly grids for the margins of the South Atlantic south of the Rio Grande Fracture Zone. Our grids cover larger areas than those of Max et al. (1999), Corner et al. (2002) and Koopmann et al. (2014) (Fig. 1) and improves resolution compared to the global grids of Maus et al. (2009) and Lesur et al. (2016). Importantly, the commercial surveys also provide coincident, deep-imaging seismic reflection profiles from which to determine the origin of the observed magnetism. We select representative conjugate profiles and conduct forward modelling with magnetic body geometries constrained by migrated images. This analysis allows us to present a new interpretation of the M-series anomalies in the South Atlantic and hence gain new insights into the style and timing of the initial opening.

2. Study area

Our study area lies between the Falkland-Agulhas and Rio Grande fracture zones. The first comprehensive interpretation of the offshore magnetic anomalies in this area was done by Rabinowitz and LaBrecque (1979). These authors identified seafloor spreading anomalies back to M11 off Cape Town, but only back to M4 off the conjugate part of Argentina. The seafloor spreading anomalies were shown to young northwards, with the opening north of the Rio Grande Rise/Walvis Ridge complexes being entirely within the CMQZ. As part of their study, Rabinowitz and Labrecque identified a magnetic anomaly (which they named Anomaly G) near the shelf edge along most parts of the margins. Due to its unusually high amplitude and width, this feature was not considered a seafloor spreading anomaly but rather an edge anomaly at the boundary between oceanic and continental crust. However, later seismic reflection profiling along both sides of the ocean showed this anomaly to coincide with thick wedges of seaward-dipping reflectors (SDRs) interpreted as massive basaltic lava flows extruded during the latest stages of rifting (Hinz, 1981; Austin and Uchupi, 1982; Gladczenko et al., 1997; Bray et al., 1998). Subsequently, by forward modelling of magnetic