# Evolution of seaward-dipping reflectors at the onset of oceanic crust formation at volcanic passive margins: Insights from the South Atlantic

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**ABSTRACT**

Seaward-dipping reflectors (SDRs) have long been recognized as a ubiquitous feature of volcanic passive margins, yet their evolution is much debated, and even the subject of the nature of the underlying crust is contentious. This uncertainty significantly restricts our understanding of continental breakup and ocean basin–forming processes. Using high-fidelity reflection data from offshore Argentina, we observe that the crust containing the SDRs has similarities to oceanic crust, albeit with a larger proportion of extrusive volcanics, variably interbedded with sediments. Densities derived from gravity modeling are compatible with the presence of magmatic crust beneath the outer SDRs. When these SDR packages are restored to synemplacement geometry we observe that they thicken into the basin axis with a nonfaulted, diffuse termination, which we associate with dikes intruding into initially horizontal volcanics. Our model for SDR

formation invokes progressive rotation of these horizontal volcanics by subsidence driven by isostasy in the center of the evolving SDR depocenter as continental lithosphere is replaced by more dense oceanic lithosphere. The entire system records the migration of >10-km-thick new magmatic crust away from a rapidly subsiding but subaerial incipient spreading center at rates typical of slow oceanic spreading processes. Our model for new magmatic crust can explain SDR formation on magma-rich margins globally, but the estimated crustal thickness requires elevated mantle temperatures for their formation.

## INTRODUCTION

Volcanic passive margins are a globally significant end member in the process of continental breakup and are characterized by seaward-dipping reflectors (SDRs), which are thick wedges of mainly volcanic material that thicken oceanward within the continent-ocean transition (Mutter et al., 1982; Planke et al., 2000; Menzies et al., 2002; Geoffroy, 2005; Franke, 2013; Pindell et al., 2014). To understand the processes involved in volcanic margin evolution, several studies in the Afar Depression (East Africa) have investigated the interaction of crustal stretching, mechanical rifting, and magma-related diking from rift onset to the initiation of seafloor spreading (Bastow and Keir, 2011; Keir et al., 2011; Wright et al., 2012; Corti et al., 2015). These studies are complemented by insights into fully mature SDR systems utilizing seismic reflection data (Franke, 2013; Pindell et al., 2014; Quirk et al., 2014) and provide insights on longer time scales and incorporate SDR formation from subaerially deposited volcanic rocks to subsequently rotated and buried packages (White et al., 1987; Menzies et al., 2002; Franke, 2013; Pindell et al., 2014; Quirk et al., 2014). Despite these studies, the evolution and the nature of the underlying crust of SDRs are debated. In this study we propose that SDRs are akin to the uppermost part of oceanic crust and they form as part of newly created oceanic crust. We then consider the implications on asthenospheric temperature and paleogeography of evolving volcanic margins.

**MARGIN GEOMETRY**

A controlled source seismic reflection profile from the Argentinian margin provides a unique image of the continent-ocean transition (COT), illustrating the thinning of 25-km-thick continental crust to 7-km-thick oceanic crust (Figs. 1A–1D). The high-fidelity depth imaging of the profile allows us to consider the magmatic processes during Late Jurassic–Early Cretaceous (Macdonald et al., 2003) lithospheric separation within the context of a fully evolved rifted margin.

The eastern end of the profile has definitive oceanic crust (Figs. 1A, 1C) with a reflection character above the Moho that conforms to a layered oceanic structure (Penrose field conference on ophiolites [Geotimes, v. 17 , p. 24–25]. with broadly concordant reflections (layers 1 and 2a; sediments and extrusive lavas), seismically transparent packages (layers 2b and 2c; massive basalts and sheeted dikes), and high-amplitude discordant reflections (layer 3; gabbro- and/or melt-depleted magma chambers). In contrast, the continental crust comprises continuous reflectivity constrained by faults in the shallow section (synrift basin fill), bimodal character of either chaotic reflectivity or high-amplitude discordant reflections (acoustic basement and mid-crustal structural heterogeneity), and high-amplitude anastomosing reflectivity within the lower crust (Clerc et al., 2015). The COT is between demonstrable oceanic and continental crusts, and in our data is characterized by a series of wedge-shaped high-amplitude reflections typical of SDRs (Figs. 1B, 1D), a seismically transparent package, and high-amplitude reflections above a well-defined Moho reflection. The landward SDRs are underlain by synrift seismic packages and reflectivity consistent with continental crust, while the oceanward SDRs are on crust corresponding to the tripartite oceanic crustal structure (Figs. 1C, 1D), albeit with the layer 2a equivalent forming a greater proportion of crust and likely comprising interbedded basalts and terrestrial sediments (Wickens and Mclachlan, 1990; Planke et al., 2000).

Gravity modeling of crustal-scale profiles cannot provide a unique solution of crustal densities; however, as seabed, top and base SDR interfaces, and Moho are well constrained we provide a suite of scenarios that considers sub-SDR densities (Fig. 2), from which we infer crustal type. Thermal corrections are not accounted for because they will be relatively small given the age of the margin (Cowie et al., 2015) and will affect both the oceanic and COT portions of our profile similarly.

We present two baseline cases that model a unified crustal density of 2.8 g/cm$^3$ (scenario 1), and a differentiated upper and lower continental crust (scenario 2) defined by crustal reflectivity (Fig. 1A); neither scenario provides a strong match between predicted and observed signatures (Fig. 1B). Our reflection profile suggests a more complex COT crustal architecture, which is accounted for in scenarios 3–6 (Figs. 1C–1F). Scenario 3 uses a basalt density for the entire SDR package and an upper continental crust density for the sub-SDR crust (Fig. 2C) and provides a strong correlation between predicted and observed gravity signatures (Fig. 2D). There is a poor match when the continental layer is replaced with a density equivalent to oceanic mid-crust (scenario 5; Figs. 2E, 2F). However, a more realistic density for the bulk SDR package is 2.75 g/cm$^3$, due to the inclusion of interstratified sediment (Wickens and Mclachlan, 1990; Planke et al., 2000). When this density is used (scenario 4; Fig. 2C), the result produces a poor match between modeled and observed signatures in the case of continental sub-SDR crust (Fig. 2D). In contrast, a magmatic sub-SDR density provides a strong match (scenario 6; Figs. 2E, 2F).

While we recognize that our gravity modeling is a nonunique solution, the results demonstrate that our geological interpretation of a magmatic crust for the COT is most consistent with the observed gravity signature (scenario 6; Fig. 2E) and with the seismic character. We propose that while the inner SDRs are emplaced onto attenuated continental crust, the outer SDRs are contained within magmatic crust equivalent to oceanic crust (Fig. 3).

## EVOLUTION OF OUTER SDRS

Our proposed interpretation of a volcanic margin, in particular the classification of outer SDRs being contained within a magmatic crust, is consistent with both the SDR interpretation in the reflection data and the temporal evolution of the system. From the identification of discrete stratal reflections we define nine individual SDR packages (Figs. 1A, 1D). Synrift volcanic packages show localized thickening into fault-controlled accommodation space, whereas the earliest SDR packages overlie these synrift intervals and are not obviously fault controlled. Each package diverges oceanward, and although the reflection that defines the base of each package is well constrained, their oceanward termination is commonly diffuse and poorly defined, suggesting that individual packages are not truncated by significant and coherent fault planes, as previous models invoked (Menzies et al., 2002; Franke, 2013). To understand the sequential development of each package (Mutter et al., 1982), we take the three packages that are best imaged and restore them sequentially (time steps t1–t3; see the GSA Data Repository[1]). We consider an end-member case in which magma supply is via asthenospheric upwelling below a symmetrical incipient spreading center such that each time step reveals the syndepositional and/or emplacement geometry across the conjugate margin (Fig. 4).

At t1, restoration of the oldest volcanic package reveals a lenticular cross-sectional geometry that confines the SDR flows (Corti et al., 2015) (Fig. 4A; Fig. DR3 in the Data Repository). Single flow lengths emerging from the fissure eruptions and point sources associated with the incipient spreading center exceed 40 km because of their subaerial nature. Crustal extension in magmatic systems (Keir et al., 2011; Wright et al., 2012) is accommodated through dike emplacement rather than mechanical faulting; therefore, at this early stage of SDR formation, which is equivalent to inner SDRs (e.g., Franke, 2013), the system comprises flat-lying extrusive volcanic flows being fed from sheeted dikes at mid-crustal levels (Desissa et al., 2013). Associated magmas are likely to have crustal contamination as they have passed through attenuated continental crust (Roberts et al., 1984; Rooney et al., 2012).

In contrast to numerous existing studies (e.g., Planke et al., 2000; Franke, 2013; Quirk et al., 2014) we define our static frame of reference as the incipient spreading axis such that at t2 the magmatic system of t1 moves away from the axis by the product of the half-spreading rate and duration of t1. This extension is accommodated by sheeted dikes that feed the overlying extrusives of t2. Critically, the t1 flat-lying extrusives closest to the axis are intruded by sheeted dikes of t2, resulting in the diffuse reflection termination. Although we observe faults in our data that are substantiated from analogous field

[1]GSA Data Repository item 2017xxx, Figures DR1–DR4 (supplementary information to support the analysis presented), is available online at http://www.geosociety.org/datarepository/2017/ or on request from editing@geosociety.org.

observations (Meshi et al., 2010), these do not have sufficient throw to explain the observed rotation. Subsidence in the center of the SDR system coupled with loading by subsequent magma emplacement drives the rotation of the initially flat-lying SDRs toward the basin center (Fig. DR3d). By this stage the crust is composed of entirely new magmatic crust that does not require a residual axial horst block of previous models (e.g., Quirk et al., 2014) (Fig. 4B), and explains the mid-oceanic ridge basalt geochemical signature in analogous areas of the North Atlantic (Roberts et al., 1984).

With continued lithospheric divergence during t3, the lenticular basin geometry is maintained and comprises extrusive material fed by sheeted dikes and depleted gabbros that intrude the t2 sequence (Fig. 4C). Continued subsidence in the center of the basin in conjunction with magmatic loading and associated flexure (Corti et al., 2015) results in the progressive rotation of both t1 and t2 volcanics. During this phase we observe a reduction in SDR length (Fig. 4C; Fig. DR3d) and speculate that this is a consequence of the narrowing of the SDR depocenter as subsidence focuses on the incipient spreading center.

In contrast to most previous studies, because our model invokes generation of new magmatic crust, the Moho reflection can be considered as a passive marker in the restoration. Our restoration suggests that the crust formed during this time step can be excessively thick (>10 km; Fig. DR3), while having a gross architecture similar to that of typical oceanic crust, but with interbedded sediments in the layer 2a equivalent.

## IMPLICATIONS AND CONCLUSIONS

We suggest that the similarity between SDR and oceanic crust extends to oceanic crustal processes. In our model (Fig. 4) we consider the development of three SDR packages, although we identify a total of nine distinct packages along the profile (Fig. 1A). This suggests an episodic supply of magma with shifts in magmatic focus and/or periodicity in supply volume. We propose that this is evidence of variable magma supply along the incipient spreading center, which is also observed on active mid-ocean ridges (Carbotte et al., 2015). Furthermore, the 9 SDR packages in our profile represent a total width of 80 km and, although we cannot quantify the duration of the individual volcanic events, biostratigraphic constraints from equivalent SDRs on the Namibian margin constrain the age of the entire SDR system to be between the latest Valanginian–Hauterivian (ca. 133 Ma) and magnetic chron M4 (126 Ma; Wickens and Mclachlan, 1990; Cohen et al., 2014; Mohammed et al., 2016). This gives an oceanic half-spreading rate of 11 mm/yr, which conforms to predicted rates of early South Atlantic opening (Heine and Brune, 2014).

Isostatically balanced normal thickness oceanic crust should form at a water depth of ~2.6 km (White et al., 1987). The inference that the SDRs are interbedded with fluvial sediments (and likewise eolian sediments in the equivalent Namibian SDRs; Wickens and Mclachlan, 1990) leads to the fundamental question of how oceanic crust forms in a subaerial setting. White et al. (1987) concluded from observations in northwestern Europe that overthickened oceanic crust, which is a function of melt generation derived from higher potential asthenospheric temperatures, can form in isostatic balance at or above sea level; by analogy with Iceland (Darbyshire et al., 2000), ~20-km-thick magmatic crust can form at sea level. Our geometric restorations, which incorporate the Moho reflection, reveal that SDR-bearing crust can form at slow spreading rates but is consistently at least 10 km thick, much thicker than the typical 7 km oceanic crust in the east of the profile. Therefore, in our model SDRs form the uppermost layer of excessively thick oceanic crust, are formed as a consequence of an anomalously high asthenospheric temperature (>1333 °C) at the incipient spreading center, and are subaerially deposited. However, it is intriguing that our restorations imply that despite the anomalous crustal thickness, the crust is less than the ~20 km required by isostasy to be at sea level, although the SDRs were emplaced in a subaerial setting. This may be a consequence of the interplay of isostatically driven subsidence and local sea level observed on other margins (e.g., Karner and Gambôa, 2007) (Fig. 4). Although our model of magmatic origin of SDR crust raises questions with respect to paleogeography and subsidence, it provides an explanation of SDR formation that can applied to magma-rich margins globally.

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**FIGURE CAPTIONS**

Figure 1. Profile across the Argentinian passive margin. A: Pre-stack depth-migrated seismic reflection profile with seaward-dipping reflectors (SDRs) and Moho interpreted. Inset is a free-air gravity anomaly map (Sandwell et al., 2014). B: Profile in A restored to a horizontal datum representing the margin geometry at the final SDR package. C: Tripartite seismic reflection character of the oceanic crust. D: Tripartite seismic reflection character of the SDR packages.

Figure 2. Gravity modeling of the profile across the Argentinian passive margin. Six crustal scenarios are presented with corresponding calculated and observed gravity signatures. Parameters for each crustal block are summarized in the table at the bottom of

the figure. A, B: Scenarios 1 and 2 correspond to the baseline cases. C, D: Scenarios 3 (basalt) and 4 (basalt incorporating sediments) with continental crust beneath the seaward-dipping reflector (SDR) package. E, F: Scenarios 5 (basalt) and 6 (basalt incorporating sediments) with magmatic crust beneath SDRs. Densities listed below the table were held constant for all scenarios.

Figure 3. Summary interpretation of a volcanic passive margin. SDR—seaward-dipping reflector.

Figure 4. Model of the evolution of seaward-dipping reflector (SDR) packages. A: Time step t1—mechanical processes dominate crustal stretching with lithospheric thinning resulting in magma generation in the center of the rift system. B: Step t2—strain is accommodated through diking; therefore, new magmatic crust is generated at the incipient spreading center. Shallow-level igneous material is fed by sheeted dikes that intrude through the crust generated during t1. C: Step t3—plate separation occurs and oceanic crust processes dominate the system, albeit with overthickened oceanic crust.