Unzipping the Patagonian Andes—Long-lived influence of rifting history on foreland basin evolution

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ABSTRACT

The Andean Cordillera is widely considered to be one of the type examples of a convergent margin setting. In the southernmost Andes, however, rifting and volcanism predated mid-Cretaceous breakup of Gondwana and formation of the South Atlantic Ocean by up to 40 m.y. and culminated in the opening of the Rocas Verdes backarc basin east of the Mesozoic Patagonian Batholith. We present new U-Pb geochronology from the Austral sector (49°S–50°S) that indicates rift volcanism occurred between 154 and 147 Ma near the northern terminus of the basin. Available data and observations from the southern Rocas Verdes Basin indicate larger-magnitude and longer-duration extension compared to the northern basin region. The Rocas Verdes Basin underwent progressive northward propagation and opening and was later backfilled concomitantly with the opening of the southern Atlantic Ocean by north-to-south deposition within a retroarc foreland setting. The influence of the inherited tectonic fabric of the Rocas Verdes backarc basin on the subsequent foreland basin explains many unique characteristics of the Patagonian Andes, such as a protracted deep basin that formed atop the previously rifted and weakened crust. Moreover, the early rift history helps account for intraplate deformation of southernmost South America during the opening of the South Atlantic Ocean.

INTRODUCTION

The southernmost Andes preserve a nearly complete stratigraphic record of a tectonic transition from a backarc rift basin (Rocas Verdes Basin) to a foreland basin (Magallanes–Austral Basin; Dalziel et al., 1974; Wilson, 1991; Fildani and Hessler, 2005). In southern Patagonia, the Jurassic–earliest Cretaceous backarc extension was sufficient to form a fully developed ocean basin >100 km wide (Stern and de Wit, 2003). The ensuing transition from rifted ocean basin to a contractual foreland fold-and-thrust belt has been well documented in the Ultima Esperanza sector of the basin (Fig. 1; e.g., Wilson, 1991; Fildani and Hessler, 2005). However, along-strike variations in the relative timing of these tectonic phases remain poorly constrained and a subject of debate. Previous workers have suggested a northward diachronous opening of the Rocas Verdes Basin on the basis of variations in the geochemistry and geochronology of obducted ophiolite complexes (Stern et al., 1992; Mukasa and Dalziel, 1996; Stern and de Wit, 2003). In contrast, some workers have interpreted studies of rift volcanism south of ~51°S to indicate that the basin opened simultaneously along its length (e.g., Klepeis et al., 2010). Resolving this discrepancy is important for understanding how spatial variations in tectonic evolution relate to sedimentary basin evolution, including sediment dispersal, depositional facies, and sediment accommodation (e.g., Romans et al., 2010; Fosdick et al., 2014; Malkowski et al., 2015). On a plate scale, constraining the tectonic evolution of the Rocas Verdes Basin prior to opening of the South Atlantic Ocean may help account for kinematic gaps and/or overlaps between southernmost South America and Africa in recent attempts to reconstruct the paleogeography of Gondwana (e.g., Torsvik et al., 2009; Moulin et al., 2010).

We present new field observations and geochronologic data that document the onset of rift volcanism in a segment of the Rocas Verdes Basin that was previously unstudied for this purpose. Our results are most consistent with a northward-propagating onset of rift volcanism for the entire basin. This trend was reversed during subsequent basin inversion and formation of the successor foreland basin. In this model, the southern end of the Rocas Verdes Basin was characterized by a deeper basin flooded by oceanic crust. The Rocas Verdes Basin narrowed northward and was more transitional in oceanic character. The northern basin filled progressively from north to south as defined by the onset of coarse clastic deposition associated with the successor foreland basin phase. Overall, this work highlights the long-lived spatial and temporal influence that features inherited from past tectonic episodes can have on successive phases of tectonic and basin evolution.

JURASSIC–EARLY CRETACEOUS RIFTING

Regional crustal extension initiated as large volumes of plume-related silicic magmatism referred to as the Chon Aike silicic large igneous province (e.g., Pankhurst et al., 1998, 2000). This widespread event is recorded by metaluminous assemblages of felsic volcanic and volcanioclastic rocks, which are present throughout the Patagonia region and along the Antarctic Peninsula (Fig. 1; Pankhurst et al., 1998). In southern Patagonia, these rocks are referred to as the El Quemado complex and Tobífera Formation (Fig. 2). Ages of volcanic rocks associated with the Chon Aike large igneous province range from ca. 190 to 150 Ma (Pankhurst et al., 2000). South of 50°S, crustal extension continued at least until 139 Ma (Stern et al., 1992), possibly as late as 118 Ma (Calderón et al., 2013), and resulted in generation of oceanic crust and the Rocas Verdes marginal basin (Dalziel et al., 1974).

Obducted Jurassic ophiolitic complexes are exposed south of 51°S and include the Sarmiento, Capitán Aracena, Carlos III, and Tortuga ophiolites (Fig. 1). Geochemical and compositional differences between these complexes suggest that there was a greater degree of crustal extension in the southern end of the basin (de Wit and Stern, 1981; Calderón et al., 2013). The Sarmiento ophiolite is exposed at 51°S–52°S and consists of gabbro, sheeted dikes, and lava with lesser trondhjemite and plagiogranite. About 300 km to the south (~55°S), the Tortuga ophiolite largely consists of gabbro, sheeted basaltic dikes, and lavas, but it exhibits a more continuous transition to diabase (de Wit and Stern, 1981). Geochemical results indicate that...
The transition from the Rocas Verdes back-arc basin to foreland fold-and-thrust belt deformation is indicated by marine deepening triggered by foreland flexure in the compressive regime. Foreland basin initiation is marked by the deposition of coarse clastic detritus associated with the Punta Barrosa Formation and equivalent units (Wilson, 1991; Fildani and Hessler, 2005; Malkowski et al., 2015). In the Ultima Esperanza District of Chile, paleobathymetric indicators suggest a marine deepening from 300 m water depth during Albian–Cenomanian time to up to 2000 m in Cenomanian–Coniacian time (Natland et al., 1974; Biddle et al., 1986). Sustained delivery of arc-derived coarse-clastic sediment was established by ca. 92 Ma in this basin sector (Fildani et al., 2003). While equivalent paleobathymetric data are not available from other basin sectors, there is a clear diachronous north-south trend in the initiation of coarse clastic deposition within the entire basin (Malkowski et al., 2015). Deposition of coarse-grained submarine fan systems began as early as latest Aptian time (ca. 115–112 Ma) in the Austral Basin sector (~49°S; Malkowski et al., 2015). Conversely, in the Fuegian sector (~54°S), deep-water deposition of coarse clastics initiated much later (89–85 Ma; Fig. 2; McAtamney et al., 2011; Malkowski et al., 2015). Deposition of the Yahgan Formation (~55°S; Barbeau et al., 2009a). The north-south diachronous nature of basin filling continued at least through the remainder of Cretaceous time with the deposition of the Cerro Toro, Tres Pasos/Alta Vista, and Dorotea Formations (e.g., Romans et al., 2010; Bernhardt et al., 2012).

**U-Pb Zircon Geochronology**

We report new field observations and zircon U-Pb ages from volcanic and volcanioclastic units of the El Quemado complex and detrital zircon data from the east Andean metamorphic complex and the lower Rio Mayer Formation (Fig. 2). Specific sample locations, analytical results, and methods are available in the GSA.
Data Repository.1 U-Pb zircon analyses were conducted by laser ablation–inductively coupled plasma–mass spectrometry at the University of Arizona LaserChron Center. All ages and uncertainties reported in the text are weighted means of overlapping single-grain dates and 2σ standard errors, respectively.

New data come from key sample locations, including the unconformable contact between the Jurassic El Quemado volcanics and the Paleozoic East Andean metamorphic complex exposed along Cerro Polo in the Parque Nacional Los Glaciares near El Chaltén (~49°S). The upper gradational contact between the El Quemado volcanics and the overlying Rio Mayer Formation was sampled north of Lago Argentino, adjacent to the Upsala Glacier (~50°S; Fig. 1). Data from these locations bracket the timing of rift-related felsic volcanism in the study area (Fig. 2). Sample CS47A, from just beneath the unconformity, yields detrital zircon age spectra that are consistent with derivation from the East Andean metamorphic complex, with age maxima at ca. 540 and 1050 Ma (Fig. 3; Hervé et al., 2003). Sample CS47C, from a rhyolite unit deposited upon the east Andean metamorphic complex, yields an eruptive age of 152.0 ± 2.0 Ma (Fig. 3). We interpret this age as the onset of rift volcanism in this region. Samples LT35, EQC08b, and EQC73 were also collected near El Chaltén and yield model ages of 150.4 ± 2.2 Ma, 149.7 ± 1.3 Ma, and 149.1 ± 1.5 Ma, respectively (Fig. 3).

Samples EC130, EC136, and EC140 were collected from good exposures of the transition between the El Quemado volcanics to the Rio Mayer Formation (Fig. 3B). These data from these locations bracket the timing of rift-related felsic volcanism in the study area (Fig. 2).

Figure 3. U-Pb zircon geochronology results. (A) Histograms and age probability plots of detrital zircon ages from the East Andean metamorphic complex (EAMC), a rhyolitic volcanic unit of the El Quemado complex deposited upon the unconformity with the East Andean metamorphic complex, and the lower Rio Mayer Formation. (B) Results and interpreted ages of igneous zircon samples from felsic volcanics of the El Quemado complex. MSWD—mean square of weighted deviates.

1GSA Data Repository Item 2015337, DR1: Table of U-Pb sample locations; DR2: Description of analytical methods in U-Pb zircon geochronology; DR3: Table of analytical results and isotope ratios; DR4: Imagery examples of zircon cathodoluminescence and analytical spot locations, is available at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org, Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.
MAYER FORMATION at the northwest end of Lago Argentino (~50°S). Samples EC130 and EC136, from submarine volcanic deposits, yield model ages of 148.4 ± 1.4 Ma and 148.5 ± 1.5 Ma, respectively (Fig. 3). Sample EC136, the stratigraphically youngest identifiable volcanic unit, represents the upper bound of rift volcanism. Nearly 80% of the detrital zircon ages from the lower Rio Mayer Formation sample EC140 are between 152 and 146 Ma (Fig. 3). This suggests that El Quemado volcanics were the primary source of detritus for EC140. In summary, these new U-Pb geochronology results indicate that rift volcanism was active from ca. 154 to 147 Ma (accounting for 2σ uncertainties) in the Austral sector of the basin.

DISCUSSION

Opening of the Rocas Verdes Basin may represent an early attempt to break apart Gondwana as a temporary “proto-Atlantic Ocean.” The driving mechanism of this process—whether it was driven principally by mantle plume processes (e.g., Storey et al., 2001, and references therein), or it was related to backarc extension behind the same subduction margin responsible for the Patagonian Batholith—remains a contentious topic (Stern and de Wit, 2003). In the Fuegian and Ultima Esperanza sectors of southern Patagonia, the Rocas Verdes Basin is characterized by bimodal volcanism. This includes felsic volcanic units of the Tobífera Formation and mostly mafic rocks associated with the ophiolite complexes. Geochemical and compositional variations between ophiolitic complexes indicate that crustal extension was greater for the Tortuga ophiolite than the more northerly Sarmiento ophiolite (de Wit and Stern, 1981). The absence of ophiolite within the Austral sector indicates that extension was insufficient to generate oceanic crust at this latitude. At least by Late Jurassic time, a backarc setting for the Rocas Verdes Basin is supported by coeval arc magmatism and early emplacement of the southern Patagonia Batholith both before and after mafic magmatism of the ophiolite complexes (Hervé et al., 2007).

The south-to-north decrease in the magnitude of rifting is also associated with a south-to-north decrease in the timing of initial rifting. The upper and lower contacts of the El Quemado volcanics are well exposed between latitudes 49°S and 50°S, near the inferred northern terminus of the Rocas Verdes Basin. Our U-Pb ages from volcanic deposits indicate that rift volcanism initiated at 152.0 ± 2.0 Ma at this latitude. The oldest ages obtained from the equivalent Tobífera Formation in the Ultima Esperanza and Fuegian sectors are ca. 172 Ma and 178 Ma, respectively (Fig. 4; Pankhurst et al., 2000). Thus, available geochronology data among all three basin sectors support a northward-progressing initiation (ca. 178–152 Ma) of rift volcanism from ~55°S to ~49°S (Fig. 4). The duration of rift volcanism also decreases northward, with ages in the Ultima Esperanza and Fuegian sectors spanning at least 30 m.y., and volcanism in the Austral sector only lasting ~7 m.y.

The exact timing and mechanism for the cessation of rifting in the Rocas Verdes Basin remain unclear. The southern Atlantic Ocean may have begun to form as early as 132 Ma or earlier (Rabinowitz and LaBrecque, 1979; Nürnberg and Müller, 1991). A northward-propagation model has been proposed for the opening of the southern Atlantic Ocean. The initial phase in this model begins along the southern tip of South America between 150 and 130 Ma (Nürnberg and Müller, 1991). Although precise age resolution is lacking, this timing corresponds closely with late-stage rifting and the formation of oceanic crust beneath the Rocas Verdes Basin between 150 and 139 Ma (Stern et al., 1992; Mukasa and Dalziel, 1996). Thus, if seafloor spreading initiated by ca. 150 Ma and was continuous until ca. 132 Ma, even very slow spreading rates (e.g., 1 cm/yr) could have resulted in an ocean basin that was nearly 200 km wide.

Cretaceous closure of the Rocas Verdes Basin required significant internal shortening in southern Patagonia and ultimately resulted in obduction of the ophiolitic complexes. Kinematic thrust belt reconstructions show a consistent north to south increase in shortening, including minimum estimates that range from >100 km (Klepeis et al., 2010) to 300–600 km (Kraemer, 2003) at the southern end of the fold-thrust belt (Betka et al., 2015). Both the initial rifting and subsequent closure of the basin were of sufficient magnitude that they need to be accounted for in kinematic models for the opening of the southern Atlantic Ocean. In particular, accounting for this intraplate deformation may...
help to ameliorate highly overlapping plate re-constructions for southernmost South America and Africa (e.g., Torsvik et al., 2009).

The postrift phase of the Rocas Verdes Basin is recorded primarily by the widespread deposition of the fine-grained Rio Mayor Formation (Zapata Formation equivalent; Fig. 2). The thickness of this unit varies from 200 to 500 m in the northern sector to greater than 1000 m in the southern basin (Biddle et al., 1986; this study). The 30–50 m.y. period of fine-grained Rio Mayor Formation deposition was followed by the reappearance of coarse clastic sedimentation related to the successor foreland basin (Malkowski et al., 2015). Consistent coarse-clastic deposition began first in the north by 112 Ma (Malkowski et al., 2015), but did not appear in the Fuegian sector of the basin until 89–85 Ma (McAtamney et al., 2011) or possibly at late as 81–73 Ma (Fig. 4; Barbeau et al., 2009a). This may indicate that the initiation and development of the foreland basin system evolved diachronously in a way that mirrored the precursor basin history (Fig. 4). Regional basin-filling patterns show that progressive southward infilling of the successor basin continued through the remainder of the Cretaceous (Romans et al., 2010; Bernhardt et al., 2012).

We favor a model of diachronous rift tectonism for the Rocas Verdes Basin that preceded (but may have overlapped and been related to) opening of the South Atlantic Ocean. Northward propagation of the Rocas Verdes Basin occurred during Middle to Late Jurassic time and generated an ocean basin that widened and deepened southward. The Rocas Verdes ocean basin likely opened by backarc spreading in a setting similar to the modern Sea of Japan (Dalziel et al., 1974). Cretaceous convergence closed this basin and resulted in obduction of ophiolites before 80 Ma (Calderón et al., 2013). Lithospheric shortening during this convergence resulted in a fold-and-thrust belt and flexural loading of a successor basin underlain by oceanic and attenuated continental crust of the Rocas Verdes Basin. This weakened crust enhanced the effects of flexural loading to permit anomalously thick deep-water foreland basin stratigraphy (Fosdick et al., 2014) and may have facilitated increased thrust belt-related shortening from north to south (e.g., Betka et al., 2015).

**SUMMARY**

A north-south gradient in the timing and extent of rift volcanism is associated with the opening of the Rocas Verdes Basin. New zircon U-Pb geochronology data from key exposures show that rift volcanism occurred between 154 and 147 Ma in the Austral Basin sector. Combined with previously published ages, our results suggest diachronous initiation of rifting that propagated northward through time and culminated in an ocean basin that widened southward. These along-strike variations in the geometry and palaeogeography of the Rocas Verdes Basin should be accounted for in plate models associated with the opening of the southern Atlantic Ocean. Diachronous opening also characterized the southernmost Atlantic Ocean, beginning in Early Cretaceous time. Cretaceous shortening ultimately closed the Rocas Verdes Basin and established a successor foreland basin in its place. Many characteristics of the foreland basin, including north to south variations in crustal shortening, the timing of coarse sediment dispersal, and the distribution of depositional facies, are in large part due to the earlier rifting history.

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