Tectonophysics 604 (2013) 139–152

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

The deep structure of the South Atlantic Kwanza Basin — Insights from 3D structural and gravimetric modelling

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ARTICLE INFO

Article history:
Received 16 March 2012
Received in revised form 3 June 2013
Accepted 19 June 2013
Available online 28 June 2013

Keywords:
Crustal structure
Passive margins
Gravity modelling
Continental break-up

ABSTRACT

We present results from 3D gravimetric modelling of the Kwanza Basin offshore Angola accomplished to investigate the deep crustal structure beneath the basin and discuss our findings with respect to their implications for the opening of the Central South Atlantic.

The Kwanza basin is located in the southern part of the Central South Atlantic. Although the post-rift evolution of the Kwanza Basin is well studied, little is known about the basin's early history. This is mainly due to the missing knowledge of its crustal structure owing to the masking effect of an up to 4 km thick salt layer, which seismically obscures the underlying basement. To get an insight into the deeper structure of this part of the Angolan margin we combined 3D structural, isostatic and gravimetric modelling. 2D seismic reflection data was used to determine the structural setting and the configuration of the stratigraphic units in the sedimentary part of the basin, whereas its crustal structure was constrained by isostatic and gravity modelling. Our modelling results indicate that high density lower crustal bodies, similar to ones found in the Northern part of the central segment, are present in the Southern part, and thus seem to be a general feature of the crust of the Central South Atlantic. Thinning of the crust occurs gradually rather than in an abrupt manner and block faulting seems to have played a significant role during rifting as is indicated by a strongly structured upper crust. In contrast, we find little evidence for ductile thinning or exhumation of the deeper lithosphere as previously suggested for the northern segment of the central South Atlantic. In its Southern segment it appears more likely that magmatic intrusions prevented mantle exhumation by sealing crustal detachment faults and giving the margin a distinct magmatic signature.

1. Introduction

Passive continental margins and their associated sedimentary basins have been characterised by classifying margins of different styles and genesis, such as narrow and wide margins or margins of volcanic (i.e. magma-rich) or non-volcanic (i.e. magma-poor) origin. Whilst the formation of magma-rich margins is accompanied by voluminous magmatism expressed in flood basalts, Seaward Dipping Reflectors (SDRs), and hig-velocity lower crustal bodies interpreted as magmatic underplating, the evolution of magma-poor margins is assumed to be dominated by tectonic processes (e.g. Blaich et al., 2011; Reston, 2009). In these "cold" settings, slow lithospheric extension is often thought to result in faulted and extremely thinned continental crust that is underlain and bounded by serpentinised and/or exhumed continental mantle separating the stretched continental crust from crust of true oceanic affinity (e.g. Péron-Pinvidic and Manatschal, 2009; Reston, 2010).

As it lacks several characteristic volcanic features of a magma-rich margin the central segment of the South Atlantic has generally been considered as a magma-poor margin. In particular, SDRs appear to be absent, an observation that, however, could also be related to imaging problems beneath the thick salt layer forming the base of the post-breakup succession. Furthermore, published seismic sections from the Northern segment of the Angola margin (e.g. Contrucci et al., 2004; Moulin et al., 2005; Unternehr et al., 2010) show evidence that tectonically controlled crustal thinning followed by mantle exhumation is a process that readily explains the opening of the Central South Atlantic: There, the crystalline continental crust thins abruptly from >25 km to as little as 4 km over short lateral distances (~50 km), and is covered by a thick wedge of subhorizontal strata, the so called "sag basin" (e.g. Aslanian et al., 2009), interpreted as syn-rift by some authors. Despite the extreme thinning of the crust large fault blocks and other indications for brittle deformation of the crust are generally sparse. The observation of a high velocity-/high density lower crustal

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0040-1951/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.tecto.2013.06.016

body beneath the zone of abrupt thinning has in the context of a magma-poor margin been interpreted as mafic to ultramafic lower crust, high grade metamorphics, or serpentinised subcontinental mantle (Contrucci et al., 2004).

Interestingly, recently published new seismic sections and crustal models derived from potential field data (Blaich et al., 2010, 2011; Lentini et al., 2010) suggest that neither the thick sag basin nor the associated abrupt thinning of the crust are general characteristics of the entire central segment of the South Atlantic. Furthermore, volcanic deposits found in recently drilled exploration wells (Reston, 2010) point to an increase in volcanic activity during the late rifting period, which might have prevented mantle exhumation in the southern part of the Central South Atlantic and thus challenge the classification of the latter as a magma-poor margin sensu stricto.

In this study, we pick up on this new hypothesis and present the results of an integrated 3D structural, isostatic, and gravimetric modelling study in which we investigated the deep crustal configuration of the Kwanza Basin offshore southern Angola. The Kwanza Basin depicts a delicate study area to test the hypothesis of Blaich et al. (2011) due to the following facts: First, it is situated in the Southern part of the Central South Atlantic that has until now received little attention in academic research. Moreover, it lacks the thick, unfaulted sag basin characterising the North Angolan margin, and evidence for strong brittle deformation of the upper crust is profound. Finally, considerable amounts of syn-rift volcanic deposits, dykes and intrusions have been found in and around the basin pointing to significant rift-related magmatic activity at the South Angolan margin (Jackson et al., 2000; Marzoli et al., 1999). Beyond the doubt of a non-magmatic origin the fundamental differences in the configuration of the crust suggests that the mechanisms driving the evolution of the Central South Atlantic were not uniform along the entire margin segment.

Three dimensional geological models constrained by potential field data have proven to be useful tools to constrain the architecture of areas where deep seismic data is missing or of limited resolution (Maystrenko and Scheck-Wenderoth, 2009, 2013). Especially in basins containing thick sedimentary and/or evaporite layers, the detection of crustal structures such as syn-rift halfgrabens or basement highs is considerably enhanced by the analysis of potential field data. Knowledge on the distribution and configuration of crustal structures is therefore inalienable for the interpretation of the tectonic history of a continental margin.

The constructed 3D model is based on hitherto unpublished seismic data that provide new insights in the architecture of the thinned continental and transitional domain of the South Angolan margin. Beyond the benefits of a completely new model basis, the application of a 3D gravity modelling approach enabled us to consider the effects of 3D lateral density variations that could not be accounted for in previous 2D potential field studies (Blaich et al., 2011).

2. Tectonic setting and models on the opening of the Central South Atlantic

The opening of the South Atlantic in response to the separation of Gondwana occurred asynchronous both in time and in space, and thus led to the formation of four separate oceanic segments, namely an equatorial, a central, a southern, and the Falkland segments (e.g. Moulin et al., 2010; Torsvik et al., 2009). The central segment spans from the Romanche Fracture Zone (RFZ) in the North to the Florianopolis Fracture Zone (FFZ) in the South and thus includes the Gabon, Congo and Angolan margin on the West African side and the Brazilian margins on the South American side (Fig. 1; Moulin et al., 2005; Torsvik et al., 2009). Our study area, the Kwanza Basin constitutes the Southern part of the Angolan margin, whose well investigated Northern part is commonly referred to as Lower Congo Basin (e.g. Marton et al., 2000).

Rifting along the Angolan margin started in the Neocomian (~144 Ma) and culminated with the onset of seafloor spreading about 15 to 30 Ma later. Different authors propose Late Barremian (~125 Ma, i.e. Brognon and Verrier, 1966; Davison, 2007; Hudec and Jackson, 2002; Marton et al., 2000) to Late Aptian ages for the onset of sea floor spreading (~112 Ma; e.g. Karner and Driscoll, 2003; Moulin et al., 2005; Torsvik et al., 2009). From their early models on margin formation Karner and Driscoll (2003) postulated that syn-rift subsidence along the West African margin occurred in three discrete rifting events from the Berriasian to the Early Barremian (145–130 Ma). The first two rifting phases, lasting from the Berriasian to Valangian (~145–136 Ma) and from the Hauterivian to Early Barremian (~136–130 Ma), respectively, led to the formation of two hinge zones: The Eastern hinge zone demarcates the Eastern limit of extensional deformation of the first rifting phase, whereas the Atlantic hinge zone (AHZ) represents the Eastern limit of brittle deformation related to the second rifting event. The third and final rifting phase started in the Early Barremian and culminated with the final break-up of the lithosphere and onset of seafloor spreading in the Late Aptian. Contrary to the first two phases, which were accompanied by normal faulting and fault block rotation between the hinges and across the Atlantic hinge zone (Karner and Driscoll, 2003), the third rift phase was characterised by large regional subsidence across the entire margin but only little attendant brittle deformation. Seaward of the Atlantic hinge zone this regional subsidence caused the development of a broad regional depocentre, which is commonly referred to as the pre-salt sag basin or pre-salt wedge (Karner and Driscoll, 2003 and references therein).

The lack of brittle deformation structures in the crust underlying the sag basin has led to the common assumption that along the Angolan margin brittle deformation of the upper crust was limited, and that the largest amount of syn-rift lithospheric extension was accommodated by thinning of the ductile lower crust and upper mantle, which eventually became exhumed (e.g. Aslanian et al., 2009; Huismans and Beaumont, 2008; Lavier and Manatschal, 2006; Péron-Pinvidic and Manatschal, 2009). The majority of rifting models postulated for the Angolan margin thus propose a depth-dependent thinning mechanism in which the brittle upper crust remains largely intact and reacts on the deformation of the deeper lithosphere by passive vertical sagging.

3. Architecture of the Angolan margin

The architecture of the Angolan margin has mainly been described based on seismic sections from the Lower Congo basin (Contrucci et al., 2004; Moulin et al., 2005; Unternehr et al., 2010; Fig. 2). In companion papers Contrucci et al. (2004) and Moulin et al. (2005) describe the architecture of the crust and the sedimentary infill of the basin based on refraction and reflection seismic data obtained during the Za ango project. Moreover, in a recent publication Unternehr et al. (2010) present their interpretation of a previously unpublished deep seismic reflection line located to the South of the Za ango profiles (Fig. 2). These seismic sections are characterised by a barely faulted crust (~25 km thickness) in the continental domain that rapidly thins to less than 4 km over a short lateral distance of about 50 km. The crystalline crust underlying the adjacent transitional domain ranges in thickness between 4 and 6 km and is covered by an up to 6 km thick layer of subhorizontal strata, the so called sag basin. A further characteristic feature is an up to 6 km thick high density/high velocity body situated in the lower crust beneath the necking zone.

Although this configuration seems to be characteristic for the Northern part of the Angolan margin (i.e. the Lower Congo Basin) seismic sections and crustal models from the Southern Kwanza Basin exhibit significant differences (Fig. 3). The Kwanza Basin consists of two subbasins, namely the Inner and the Outer Kwanza Basins (Hudec and Jackson, 2002, 2004). The Inner Basin roughly coincides with the present-day onshore part of the Kwanza Basin, whereas the Outer Kwanza Basin comprises that part which has been offshore during the