**The opening of the South Atlantic**

In Early Cretaceous times, West Gondwana broke up to form South America and Africa and in between seafloor spreading resulted in the continuous expansion of the South Atlantic Ocean. The contemporaneous Paraná–Etendeka continental flood-basalt provinces in Brazil and Namibia, respectively, are frequently referred to the influence of the Tristan da Cunha hot-spot with the Walvis Ridge and Rio Grande Rise as the expression of the plume tail (e.g. Morgan, 1981).

## Rifting and magmatism

Regardless of the remarkable geometrical fit between the rifted continental margins of South America and Africa, first recognized by Wegener (1915), the rift phase and breakup were rather complex. Continental extension may have begun in isolated centers in South America during the Late Triassic (at about 210 Ma) when almost all of south and west Gondwana was affected by magmatism resulting in a very high heat flow (Macdonald et al., 2003). In addition to this Late Triassic to Early Jurassic rifting phase, there was a Middle Jurassic extensional phase and it took almost 40 Ma, from Valanginian to late Albian time, for Africa and South America to separate completely (Keeley and Light, 1993; Szatmari, 2000). The line of continental separation and the position of the principal failed rifts were controlled by both, the position of boundaries between different ages of basement and the structural grain of the basement (Macdonald et al., 2003). Tough breakup is reasonably well understood, the location and magnitude of continental intraplate deformation during rifting, particularly affecting South America is an open question and widely discussed (see e.g. Eagles, 2007; Heine et al., 2013; Moulin et al., 2009; Torsvik et al., 2009).

Continental breakup and initial seafloor spreading in the South Atlantic were accompanied by extensive transient magmatism as inferred from sill intrusions, flood basalt sequences, and voluminous volcanic wedges and high-velocity lower crust at the present continental margins. Voluminous volcanism affected both Mesozoic intracratonic basins onshore (Paraná-Etendeka flood-basalt province; (Peate, 1997; Renne et al., 1992; Trumbull et al., 2007)) and the rifted crust offshore (Bauer et al., 2000; Franke et al., 2007; Gladczenko et al., 1997; Gladczenko et al., 1998; Hinz et al., 1999; Koopmann et al., 2014a; Mohriak et al., 2008; Paton et al., 2016; Stica et al., 2014). Menzies et al (2002) and Moulin et al. (2009) compiled published geochemical data and radiometric dates for the dikes and the lava flows in the Paraná–Etendeka flood-basalt provinces. According to these compilations volcanic activity peaked in the late Hauterivian–early Barremian (133-129 Ma and 134–130 Ma, respectively). Apart from the age of the basalts, there is much controversy about the source of magmas in the Paraná–Etendeka province and it’s origin (see e.g. Comin-Chiaramonti et al., 2011; Foulger, 2017; Hawkesworth et al., 1999; Peate, 1997; Renne et al., 1992; Rocha-Júnior et al., 2013; Trumbull et al., 2007; Will et al., 2016).

The Early Cretaceous opening of the southern South Atlantic took place between 137 to 126 Ma (Heine et al., 2013; Macdonald et al., 2003; Moulin et al., 2009; Rabinowitz and Labrecque, 1979). From multichannel seismic and potential field data, Koopmann et al. (2016), confirming Moulin et al. (2009), conclude that the oldest magnetic chron in the southern South Atlantic, related to oceanic spreading is M9 (c. 135 Ma). Older anomalies, previously identified as M11 (c. 137 Ma) are found within the SDRs (Corner et al., 2002; Koopmann et al., 2016). There is still some uncertainty about the age of the first oceanic crust in the proximity of the Falkland Plateau, where strike-slip deformation in the proximity to the Falklands-Agulhas fracture zone hampers the identification of the earliest spreading anomalies. In a recent study, Collier et al. (2017) identified M10r (134.2 Ma, late Valanginian) as the oldest recognisable chron at the southern tip of the South Atlantic. However, Becker et al. (2012) suggested that the breakup unconformity, identified in rift basins at the northern edge of the Falkland plateau, is a time-equivalent to the well dated rift-to-sag unconformity in the North Falkland Basin, indicating a Valanginian (~137 Ma) age for the first oceanic crust in the southern South Atlantic.

Most of the southern South Atlantic continental margins are of the volcanic type (Gladczenko et al., 1997), however, the southernmost, about 400 km long portion lacks SDRs (Becker et al., 2012; Franke et al., 2010; Koopmann et al., 2014b). Thus, from the magnetic anomalies interpreted seaward of the SDRs there was an abrupt onset of volcanic rifting at shortly before 137 Ma (Koopmann et al., 2016). From this point on towards the north the progressive continental breakup was accompanied by large-scale transient magmatism with the formation of voluminous SDR wedges, accompanied by high-velocity lower crustal bodies over the ~1.800 km to the Florianopolis/Rio Grande fracture zones offshore Namibia/Brazil (Becker et al., 2014). The SDRs were emplaced consecutively northward, as indicated by the progressively termination of the pre-M4 magnetic seafloor spreading anomalies within the volcanic wedges. Only from magnetic chron M4 (c. 130 Ma) onward oceanic crust was formed in the entire southern South Atlantic (Koopmann et al., 2016).

At the latitude of the Paraná–Etendeka flood-basalt provinces, the rift was stuck. At this position, one of the fundamental structures in the South Atlantic development (Moulin et al., 2012), the Florianópolis (or Rio Grande) fracture zone is found. This fracture zone had an remarkable offset during breakup (150 km; (Elliott et al., 2009) and delayed breakup by 10- 20 My. Immediately to the north, the central South Atlantic is characterized by the presence of an approximately 1–2 kilometre-thick Aptian salt layer (Mohriak et al., 2008). Minor SDRs reveal an age, very close to the salt deposits. A number of aborted rifts developed (Campos, Santos, Esperito Santos Basin) along the Brazil margin and the crust was extremely stretched and thinned before the two spreading axis in the central and southern South Atlantic connected (Evain et al., 2015; Mohriak et al., 2002).

Sporadic but widespread magmatic activity continued well after breakup (80 Ma and younger) in southern Africa and Brazil (Comin-Chiaramonti et al., 2011) The most common expression of this are alkaline intrusions, which are locally numerous (e.g., kimberlite fields) but involve smaller volumes compared with the Early Cretaceous activity.

## Timing of rifting and magmatism

A key question is the relative timing of extension and the emplacement of the large-volume magmatic flows, both onshore (Paraná–Etendeka flood-basalts) and offshore (SDRs). From plate tectonic reconstructions and based on dating of the continent–ocean transition it is believed that rifting adjacent to the Walvis Ridge/Rio Grande Rise initiated at about 134 Ma (Moulin et al., 2009) or 135 Ma (Bradley, 2008). Thus, as pointed out by Foulger (2017), extension occurred where the Paraná and Etendeka basalts were emplaced. This is well in line with the magma flow directions of both, the basaltic rocks from the Etendeka igneous province of Namibia and from the Paraná province in Brazil. In both provinces, the basalts were deposited in north-south–trending rift basins, revealing that rifting even preceded flood volcanism, at least in the portion of the magmatic province within 100 km of the nascent spreading ridge (Clemson et al., 1997; Glen et al., 1997).

The peak magmatism (~132 Ma) predated the seafloor-spreading stage at the latitude of Paraná–Etendeka flood-basalt by about 20 million years. Final breakup in the central South Atlantic occurred at the Aptian–Albian boundary (112-113 Ma; (Heine et al., 2013; Moulin et al., 2009; Torsvik et al., 2009)), when seafloor spreading commenced north of the Walvis Ridge–Rio Grande Rise. According to the Global Time Scale 2012 (Gradstein et al., 2012), the emplacement of SDRs occurred prior to the peak activity of the Paraná–Etendeka flood-basalts. This is certainly the most widespread used time-scale, however, when considering the M-sequence geomagnetic polarity time (Malinverno et al., 2012) the SDRs would have been emplaced simultaneously (Koopmann et al., 2016). As the SDRs mark the final stage of the continental rifting phase it is evident that the complete extensional phase and likely also earliest seafloor spreading in the southern South Atlantic predate the emplacement of the Paraná and Etendeka basalts (Franke, 2013).

## Kinematics of the South Atlantic rift

A South to North propagating opening of the southern South Atlantic is commonly accepted (Austin and Uchupi, 1982; Gaina et al., 2013; Heine et al., 2013; Jokat et al., 2003; Macdonald et al., 2003; Moulin et al., 2009; Rabinowitz and Labrecque, 1979; Seton et al., 2012). As pointed out by Franke (2013), this opening direction contradicts the hypothesis that rifting migrated away from the Paraná–Etendeka flood-basalt provinces. In the contrary, rifting migrated towards it, which is at odds with a continental breakup being triggered by the Tristan da Cunha hotspot. What else then could have resulted in continental separation?

When reconstructing the South Atlantic the Cape fold belt in South Africa aligns nicely with the Ventana (or Sierras Australes) Hills in Argentina. By identifying the South African Cape fold belt offshore South Africa, Paton et al. (2016) propose that initial rifting along western Gondwana was a consequence of the extensional reactivation of the western Gondwanan Fold Belt. As these rift basins are thought to have formed through a gravitational collapse of the fold belts, the rift basin geometry was controlled by the underlying fold belt geometry, resulting in a broadly SW-orientated (with respect to Africa) extension in the area of Argentina/South Africa. According to Paton et al. (2016), during the mid-Cretaceous, the rift configuration changed significantly and extension now was merely following a north–south trend, i.e. perpendicular to the fold-belt. This geometry fits well with the earlier proposed clockwise rotation of the extensional deformation throughout the Early Cretaceous (Franke, 2013), based of structural data from the continental margins.

The structure and shape of the continental margins show considerable deviations from symmetric structures as would expected by active rifting, triggered by a source centred below the rift. With respect to extruding lava volumes, high-velocity lower crust, dyke orientations, and fault patterns, the complementary southern South Atlantic passive margins experienced a distinct asymmetric evolution during breakup (Becker et al., 2014; Becker et al., 2016; Koopmann et al., 2016; Salomon et al., 2017). The asymmetry in offshore magmatism with considerably more SDRs and volume of high-velocity lower crust on the African margin is surprising, given the opposite asymmetry in the onshore Paraná–Etendeka flood-basalt provinces. The possible explanation of a greater extent of postrift uplift and erosion on the African margin has been ruled out by Becker et al. (2014), because fission-track and denudation studies on both margins do not support this. In their view, South America offered more favourable structures for magma ascent and extrusion than South Africa. All this providing evidence for mainly passive rifting, as earlier proposed by Maslanyj et al. (1992).

The highly asymmetric subequatorial margins of Brazil and West Africa almost certainly did not rift apart in a pure-shear fashion, and an evolution model assuming simple-shear–type rifting mechanisms is suggested (Mohriak et al., 2008).

A seismic refraction study at the easternmost Walvis Ridge, including the junction with the Namibian coast found a small intruded area around the Walvis Ridge (Fromm et al., 2015). Also onshore, in the landfall area of the Walvis Ridge at the Namibian coast a narrow region (<100 km) of high-seismic-velocity anomalies in the middle and lower crust, interpreted as a massive mafic intrusion has been identified by seismic reflection and refraction data (Ryberg et al., 2015). From these data, it appears likely that at least no broad plume head existed during opening of the South Atlantic.

To the north of Walvis Ridge, a sudden absence of SDRs (Elliott et al., 2009) comes along with a dramatic decrease in crustal thickness from 35-km-thick crust below Walvis ridge to 5–6-km-thick oceanic crust in the central South Atlantic (Fromm et al., 2015). A similar sudden absence of SDRs occurs south of a major transfer zone in the southern South Atlantic (Becker et al., 2012; Koopmann et al., 2014a). These abrupt changes in emplaced magmatic volume question the hypothesis of a major influence thermal variations in the sublithospheric mantle as origin for the magmatism. Gradual variations of mantel properties and dynamics are expected to generate smooth transitions over at least a hundred or a few hundreds of kilometers rather than sharp transitions.

The architecture of the SDRs, in addition implies an episodic emplacement with multiple magmatic phases alternating with magma-starved phases (Franke et al., 2010). The South Atlantic unzipped in jumps from south to north and the SDRs were emplaced consecutively along the successive northward propagating rift zones (Clemson et al., 1997; Franke et al., 2007; Koopmann et al., 2014a; Stica et al., 2014). Between the Falkland-Agulhas fracture zone and the Walvis Ridge/Rio Grande Rise, this process lasted for approximately 10 Ma, as derived from the earliest magnetic chrons adjacent to the SDRs (Koopmann et al., 2016).

Austin, J.A. and Uchupi, E., 1982. Continental-Oceanic crustal transition of southwest Africa. AAPG Bulletin, 66 (9): 1328-1347.

Bauer, K. et al., 2000. Deep structure of the Namibia continental margin as derived from integrated geophysical studies. Journal of Geophysical Research, 105(B11): 25829-25853.

Becker, K. et al., 2012. The crustal structure of the southern Argentine margin. Geophysical Journal International, 189(3): 1483-1504.

Becker, K. et al., 2014. Asymmetry of high-velocity lower crust on the South Atlantic rifted margins and implications for the interplay of magmatism and tectonics in continental breakup. Solid Earth, 5(2): 1011-1026.

Becker, K., Tanner, D.C., Franke, D. and Krawczyk, C.M., 2016. Fault-controlled lithospheric detachment of the volcanic southern South Atlantic rift. Geochemistry, Geophysics, Geosystems: n/a-n/a.

Bradley, D.C., 2008. Passive margins through earth history. Earth-Science Reviews, 91(1): 1-26.

Clemson, J., Cartwright, J. and Booth, J., 1997. Structural segmentation and the influence of basement structure on the Namibian passive margin. Journal of the Geological Society, 154(3): 477-482.

Collier, J.S. et al., 2017. New constraints on the age and style of continental breakup in the South Atlantic from magnetic anomaly data. Earth and Planetary Science Letters, 477(Supplement C): 27-40.

Comin-Chiaramonti, P., De Min, A., Girardi, V.A.V. and Ruberti, E., 2011. Post-Paleozoic magmatism in Angola and Namibia: a review. In: L. Beccaluva, G. Bianchini and M. Wilson (Editors), Geol. Soc. Am. Spec. Papers 478, pp. 223-247.

Corner, B., Cartwright, J. and Swart, R., 2002. Volcanic passive margin of Namibia: A potential fields perspective. In: M.A. Menzies, S.L. Klemperer, C.J. Ebinger and J. Baker (Editors), Volcanic Rifted Margins. Geological Society of America, Boulder, Colorado, pp. 203-220.

Eagles, G., 2007. New angles on South Atlantic opening. Geophysical Journal International, 168(1): 353-361.

Elliott, G., Berndt, C. and Parson, L., 2009. The SW African volcanic rifted margin and the initiation of the Walvis Ridge, South Atlantic. Marine Geophysical Researches, 30: 207-214.

Evain, M. et al., 2015. Deep structure of the Santos Basin-São Paulo Plateau System, SE Brazil. Journal of Geophysical Research: Solid Earth, 120(8): 5401-5431.

Foulger, G.R., 2017. Origin of the South Atlantic igneous province. Journal of Volcanology and Geothermal Research.

Franke, D., 2013. Rifting, lithosphere breakup and volcanism: Comparison of magma-poor and volcanic rifted margins. Marine and Petroleum Geology, 43: 63–87.

Franke, D. et al., 2010. Birth of a volcanic margin off Argentina, South Atlantic. Geochem. Geophys. Geosyst., 11(2): Q0AB04.

Franke, D., Neben, S., Ladage, S., Schreckenberger, B. and Hinz, K., 2007. Margin segmentation and volcano-tectonic architecture along the volcanic margin off Argentina/Uruguay, South Atlantic. Marine Geology, 244(1-4): 46-67.

Fromm, T. et al., 2015. South Atlantic opening: A plume-induced breakup? Geology.

Gaina, C. et al., 2013. The African Plate: A history of oceanic crust accretion and subduction since the Jurassic. Tectonophysics, 604(0): 4-25.

Gladczenko, T.P. et al., 1997. South Atlantic volcanic margins. Journal of the Geological Society, 154(3): 465-470.

Gladczenko, T.P., Skogseid, J. and Eldhom, O., 1998. Namibia volcanic margin. Marine Geophysical Researches, 20(4): 313-341.

Glen, J.M.G., Renne, P.R., Milner, S.C. and Coe, R.S., 1997. Magma flow inferred from anisotropy of magnetic susceptibility in the coastal Paraná-Etendeka igneous province: Evidence for rifting before flood volcanism. Geology, 25(12): 1131-1134.

Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G.M., et al., 2012. The Geologic Time Scale 2012 1st Edition. Elsevier, Boston, USA. , 1176 pp.

Hawkesworth, C., Kelley, S., Turner, S., Le Roex, A. and Storey, B., 1999. Mantle processes during Gondwana break-up and dispersal. Journal of African Earth Sciences, 28(1): 239-261.

Heine, C., Zoethout, J. and Müller, R.D., 2013. Kinematics of the South Atlantic rift. Solid Earth Discuss., 5(1): 41-116.

Hinz, K. et al., 1999. The Argentine continental margin north of 48°S: sedimentary successions, volcanic activity during breakup. Marine and Petroleum Geology, 16(1): 1-25.

Jokat, W., Boebel, T., König, M. and Meyer, U., 2003. Timing and geometry of early Gondwana breakup. Journal of Geophysical Research, 108(B9).

Keeley, M.L. and Light, M.P.R., 1993. Basin evolution and prospectivity of the Argentine continental margin. Journal of Petroleum Geology, 16(4): 451-464.

Koopmann, H. et al., 2014a. Segmentation and volcano-tectonic characteristics along the SW African continental margin, South Atlantic, as derived from multichannel seismic and potential field data. Marine and Petroleum Geology, 50(0): 22-39.

Koopmann, H. et al., 2014b. Segmentation and volcano-tectonic characteristics along the SW African continental margin, South Atlantic, as derived from multichannel seismic and potential field data. Marine and Petroleum Geology, 50: 22-39.

Koopmann, H., Schreckenberger, B., Franke, D., Becker, K. and Schnabel, M., 2016. The late rifting phase and continental break-up of the southern South Atlantic: the mode and timing of volcanic rifting and formation of earliest oceanic crust. In: T.J. Wright, A. Ayele, D.J. Ferguson, T. Kidane and C. Vye-Brown (Editors), Magmatic Rifting and Active Volcanism, Geol. Soc. London Spec. Pub. Geol. Soc. London, London pp. 315-340.

Macdonald, D. et al., 2003. Mesozoic break-up of SW Gondwana: implications for regional hydrocarbon potential of the southern South Atlantic. Marine and Petroleum Geology, 20(3-4): 287-308.

Malinverno, A., Hildebrandt, J., Tominaga, M. and Channell, J., 2012. M-sequence geomagnetic polarity time scale (MHTC12) that steadies global spreading rates and incorporates astrochronology constraints. Journal of Geophysical Research.

Maslanyj, M.P., Light, M.P.R., Greenwood, R.J. and Banks, N.L., 1992. Extension tectonics offshore Namibia and evidence for passive rifting in the South Atlantic. Marine and Petroleum Geology, 9(6): 590-601.

Menzies, M.A., Klemperer, S.L., Ebinger, C.J. and Baker, J., 2002. Characteristics of volcanic rifted margins. In: M.A. Menzies, S.L. Klemperer, C.J. Ebinger and J. Baker (Editors), Volcanic Rifted Margins. Geological Society of America Special Paper Boulder, Colorado, pp. 1-14.

Mohriak, W., Nemčok, M. and Enciso, G., 2008. South Atlantic divergent margin evolution: rift-border uplift and salt tectonics in the basins of SE Brazil. Geological Society, London, Special Publications, 294(1): 365-398.

Mohriak, W.U., Rosendahl, B.R., Turner, J.P. and Valente, S., 2002. Crustal architecture of South Atlantic volcanic margins. In: M.A. Menzies, S.L. Klemperer, C.J. Ebinger and J. Baker (Editors), Volcanic Rifted Margins Geological Society of America Special Paper Boulder, Colorado, pp. 159-202.

Morgan, W.J., 1981. Hotspot tracks and the opening of the Atlantic and Indian Oceans. In: C. Emiliani (Editor), The Sea (vol. 7). Wiley-Interscience, New York pp. 443-487.

Moulin, M., Aslanian, D., Rabineau, M., Patriat, M. and Matias, L., 2012. Kinematic keys of the Santos–Namibe basins. Geological Society, London, Special Publications, 369.

Moulin, M., Aslanian, D. and Unternehr, P., 2009. A new starting point for the South and Equatorial Atlantic Ocean. Earth-Science Reviews, 97(1-4): 59-95.

Paton, D.A., Mortimer, E.J., Hodgson, N. and van der Spuy, D., 2016. The missing piece of the South Atlantic jigsaw: when continental break-up ignores crustal heterogeneity. Geological Society, London, Special Publications, 438.

Peate, D.W., 1997. The Paraná-Etendeka Province. In: J.J. Mahoney and M.F. Coffin (Editors), Large Igneous Provinces: Continental, Oceanic, and Planetary Flood Volcanism. American Geophysical Union, pp. 217-245.

Rabinowitz, P.D. and Labrecque, J.L., 1979. The Mesozoic South Atlantic Ocean and evolution of its continental margins. Journal of Geophysical Research, 84(B11): 5973-6002.

Renne, P.R. et al., 1992. The Age of Paraná Flood Volcanism, Rifting of Gondwanaland, and the Jurassic-Cretaceous Boundary. Science, 258(5084): 975-979.

Rocha-Júnior, E.R.V. et al., 2013. Sr-Nd-Pb isotopic constraints on the nature of the mantle sources involved in the genesis of the high-Ti tholeiites from Northern Paraná Continental Flood Basalts (Brazil). Journal of South American Earth Sciences, 46: 9-25.

Ryberg, T. et al., 2015. Crustal structure of northwest Namibia: Evidence for plume-rift-continent interaction. Geology.

Salomon, E., Passchier, C. and Koehn, D., 2017. Asymmetric continental deformation during South Atlantic rifting along southern Brazil and Namibia. Gondwana Research, 51(Supplement C): 170-176.

Seton, M. et al., 2012. Global continental and ocean basin reconstructions since 200 Ma. Earth-Science Reviews, 113(3–4): 212-270.

Stica, J.M., Zalán, P.V. and Ferrari, A.L., 2014. The evolution of rifting on the volcanic margin of the Pelotas Basin and the contextualization of the Paraná–Etendeka LIP in the separation of Gondwana in the South Atlantic. Marine and Petroleum Geology, 50(0): 1-21.

Szatmari, P., 2000. Habitat of petroleum along the South Atlantic margins. In: M.R. Mello and B.J. Katz (Editors), Petroleum systems of South Atlantic margins. AAPG Memoir pp. 69-75.

Torsvik, T.H., Rousse, S., Labails, C. and Smethurst, M.A., 2009. A new scheme for the opening of the South Atlantic Ocean and the dissection of an Aptian salt basin. Geophysical Journal International, 177(3): 1315-1333.

Trumbull, R.B., Reid, D.L., de Beer, C., van Acken, D. and Romer, R.L., 2007. Magmatism and continental breakup at the west margin of southern Africa: A geochemical comparison of dolerite dikes from northwestern Namibia and the Western Cape. South African Journal of Geology, 110(2-3): 477-502.

Wegener, A., 1915. Die Entstehung der Kontinente und Ozeane. Sammlung Vieweg, Heft 23. Friedr. Vieweg & Sohn, Braunschweig 94 pp.

Will, T.M., Frimmel, H.E. and Pfänder, J.A., 2016. Möwe Bay Dykes, Northwestern Namibia: Geochemical and geochronological evidence for different mantle source regions during the Cretaceous opening of the South Atlantic. Chemical Geology, 444: 141-157.