ANNÉE 2017





THÈSE / UNIVERSITÉ DE RENNES 1

sous le sceau de l'Université Bretagne Loire

pour le grade de

DOCTEUR DE L'UNIVERSITÉ DE RENNES 1 Mention : Sciences de la Terre

Ecole doctorale EGAAL

JOSEPH OFFEI THOMPSON

Préparée à l'unité de recherche UMR 6118 CNRS Géosciences Rennes UFR Sciences et Propriété de la Matière

Thèse soutenue à Brest le 21 Novembre 2017

devant le jury composé de :

The opening of the Indian Ocean: what is the impact on the East African, Madagascar and Antarctic margins, and what are the origins of the aseismic ridges?

Professor Mohamed SAHABI Professor Faculté des sciences d'El Jadida, Moroc/examinateur

Dr Stefane MAHAJANE Geoscientist National Petroleum Institute Maputo/examinateur

Professor Maarten de WIT Professor, Nelson Mandela University/ rapporteur

Dr Wilfred JOKAT Researcher, Alfred Wegener Institute/ rapporteur

Dr Charlotte NIELSON (Geological Engineer Total) – examinateur

Professor François GUILLOCHEAU Professor Department of Geoscience, Université de Rennes 1 / directeur de thèse

Dr Maryline MOULIN (Researcher Ifremer) / co directeur de thèse

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Figure 1: Sandwell et al., (2014) free-air satellite-derived gravity anomalous tectonic features on the seafloor of the Indian Ocean. The magnetic anomaly plots were derived from The Global Seafloor Fabric and Magnetic Lineation Data Base Project (GSFML). The ocean is the third largest of the world's oceans, covering approximately 20% of the earth surface with an average depth of 3.741m and a maximum depth of 7.906m. AP: Agulhas Plateau; AR: Astrid Ridge; BH: Beira High; CKP = Central Kerguelen Plateau; ESB: Eastern Somali Basin; EB: Elan Bank; LP: Laccadive Plateau; MadR: Madagascar Ridge; MP: Maud Rise; MOZB: Mozambique Basin; MadR: Madagascar Ridge; NP: Mascarene Plateau; NNV: Northern Natal Valley, NKP = N Kerguelen Plateau; SB: Saya de Malha Bank; SL is Sri Lanka and SKP = South Kerguelen Plateau; SNV: South Natal Valley; WSB: Western Somali Basin. Red lines: fracture zones. The North Mozambique Basin of MOZ3-5 to consist mainly of sediments muscle on a thinned continental crust (Lepretre et al., 2017; Moulin et al., submitted). The Southern Mozambique Ridge maybe composed of volcanics (Gohl et al., 2011) probably emplaced at a triple junction. (Mercator projection)



Figure 2: Gravity and bathymetry map of Mozambique Channel, showing the complexity and segmentation of the East African margin. The top and middle arrows corresponds to the movement of the Madagascar and Antarctica tectonic plates respectively, and the lower arrow corresponds to a later event involving the drifting of the Falkland and Patagonian plates. NNV= North Natal Valley; NMR= North Mozambique Ridge; SMR= South Mozambique Ridge; NMadR= North Madagascar Ridge; SMadR= South Madagascar Ridge. Notice the positions of DSDP 245, 246, 247, 248, 249. In red= Volcanism. (Mercator projection)



Figure 3: Gondwana reconstructions models by (Smith and Hallem, 1970; Norton and Sclater, 1979; Sahabi, 1993; Reeves and de Wit, 2000; Marks and Tikku, 2001; Konig and Jokat, 2006; Eagles and Konig, 2008; Leinweber et al., 2012; Gaina et al., 2013). The models present different positions for the plates, and result in overlaps, gaps, latitudinal, and angular differences. (Mercator projection).

Evolution of Plate tectonic studies in the Indian Ocean: Hypothesis, general concepts, technology and data



Figure 4: Evolution of plate tectonics studies in the Indian Ocean, from 1500s to present day. The land bridge theory and the compression theory were poposed in the1500s and 1800s, respectively. Wegener (1924) proposed the continental drift hypothesis, in which he stated that all the continents were once compressed together into a single super-continent which he called Pangaea. His ideals were not accepted until Holmes (1944), Harry Hess (1962) and Deitz (1961) elaborated on one of his idea, and showed that the mantle undergoes thermal convection. The initial reconstruction of the Indian Ocean was based on the shape of the continents (Wegener 1929 and duToit, 1937). Notices the rapid increase in data for the reconstruction from the 1970's to present age

Satellite altimetry Basement geology Hotspot track Gravity data Bathemetry Seismic reflection Seismic refraction Volcanism Paleomagnetism Pre-post Karoo sediment Physigraphical data Sedimentological data Magnetic anomaly Continent morphology

India Ocean

1.Fracture zones not clearly visible close to continental margins

Sandwell et Smith, (1992) Smith & Sandwell (1997) Sahabi, (1993)





Ideas relevant to older Wilson cycles (Wilson, 1966)

Modeling Seismic refraction (Ocean Bottom Seismometers, Ocean Bottom Cable, Onshore Seismoters, Wave Field Seperation, ESP) Seismic reflection (Passive Seismic Tomography) Satellite magnetic Satellite altimetry Hotspot track Basement geology Gravity data Bathemetry Seismic reflection Volcanism Paleomagnetism Physigraphical data Pre-post Karoo sediment Magnetic anomaly Continent morphology

India Ocean

1.Problem of consencus on the interpretation of the first true magnetic anomaly in the Indian Ocean

Reeves, (2014) Gaina et al., (2013) Torsvik et al., (2012) Leinweber and Jokat, (2012) Konig and Jokat, (2006) Marks and Tikku, (2001) Jokat et al., (2003)



Figure 5: Three possible initial fit positions proposed for Madagascar. (i) Green: a position adjacent to East Africa (Kenya and Tanzania), originally proposed by du Toit (1937) and later favored by Smith and Hallam (1970). (ii) Yellow: a position adjacent to Mozambique proposed originally by Wegener (1929) and supported by Flores (1970, 1972). (iii) Black; Madagascar staying at its present position since the Paleozoic (Francis et al., 1966). In blue: Beira High. Arrows: Madagascar's drift path to present position. (Mercator projection).



Figure 6: Reconstruction model of Smith and Hallem (1970). Their model presented a good fit of Gondwana, except in Zambezi Basin, where Antarctica overlaps the Beira High. Their model also leads to ~400km between Madagascar and India. Poles for South American plate provided by author. The PanAfrican orogeny in figures 6-23 are represented by author.BH: Beira High, LP: Limpopo Basin, NNV: North Natal Basin. (Mercator projection).



Figure 7: Reconstruction model of Norton and Sclater (1979). They placed the Mozambique Ridge loosely between Africa and Antarctica, treating it as a pre-drift structure. The Gondwana sequence in India and Antarctica are misaligned. The model also results in ~260km of gap between Madagascar and India. Poles for the South American plate provided by Norton and Sclater (1979). BH: Beira High, LP: Limpopo Basin, NNV: North Natal Basin, ZB: Zambezi Basin. (Mercator projection).



Figure 8: Reconstruction model of Powells et al. (1980). Based on their observation of the pattern of seafloor spreading between Madagascar and India, that India-Antarctica-Australia originally farther south than previously proposed by Smith and Hallem. (1970). Their model results in very large gaps in the initial fit of Gondwana; a 500km gap between India and Madagascar, and 800km gap between Antartica and Africa. (Mercator projection).



Figure 9: Reconstruction model of Martin and Hartnady (1986). They proposed the Limpopo Basin to be underlained by oceanic crust or very highly extended continental crust, and existence of extinct spreading center northern Natal Valley. (Mercator projection).



Figure 10: Reconstruction model of Sahabi, (1993). He predicted continental origin for the Limpopo Basin, Natal Valley, and the South Mozambique Ridge, avoiding overlap by Antarctica. However, his model leads to an overlap of Antarctica with the Beira High. The model aligns the Batsimisaraka Shear Zone, to the Moyar Cauvery Shear Zone. BSZ: Batsimisaraka Shear Zone. BH: Beira High, LP: Limpopo Basin, NNV: North Natal Basin, ZB: Zambezi Basin. (Mercator projection).



Figure 11: Reconstruction model of Kovacs et al. (2001). They presented a compilation of magnetic data in the Weddell Sea, in agreement with Livermore and Hunter (1996) and Marks and Tikku (2002). Their model results in an overlap of Antarctica on NNV and the Mozambique Ridge. Poles for South American plate provided by author. (Mercator projection).



Figure 12: Reconstruction model of Marks and Tikku (2002). They proposed the Mozambique Ridge behaved like a microplate with its own independent motion between anomaly M11 and M2. Their model result overlap of Antarctica across the Mozambique ridge. (Mercator projection).



Figure 13: Reconstruction model of Tikku et al. (2002). They suggested a continental origin for the Mozambique Ridge, considering the ridge as a microplate. They suggested the existence of an active spreading center in the North Natal Valley. Their model leads to a gap of ~800km between Antarctica and Mozambique. LP: Limpopo Basin, NNV: North Natal Basin. (Mercator projection).



Figure 14: Reconstruction model of Jokat et al. (2003). They argue that the Karoo and Dronning Maud Land magmatism occurred well before any new ocean floor was created in the Indian Ocean, and therefore the oldest oceanic in the ocean cannot be related directly to any plume event. The model results in 150km overlap Antarctica across Africa. ((Mercator projection).



Figure 15: Reconstruction model of Konig and Jokat (2006). They proposed extinct spreading center in the NNV and discussed the existence of an independent Mozambique ridge microplate prior to 120 Ma. Their model results in large overlap of the Mozambique Ridge in the Limpopo Basin in the initial fit of Gondwana. (Mercator projection).



Figure 16: Reconstruction of model of Eagles and Konig (2008). They assumed oceanic origin for the Mozambique ridge and the Southern Mozambique plains. The model results in ~700km overlap between India and Antarctica, and a 300km overlap of the Antarctic plate across Africa. (Mercator projection).



Figure 17: (a) Reconstruction model of Konig and Jokat (2010). They considered oceanic origin for the Mozambique Ridge, with an emplacement between 140-120Ma. The model result in ~90km of overlap between Antarctica and Africa. Mercator projection.

Figure 17 (b) Flowlines for Antarctica proposed in Konig and Jokat (2010). The flowlines crosses the magnetic spreading anomalies in the South Natal Valley (SNV). Implying the SNV was generated between Antarctica and Africa



Figure 18: Reconstruction model of Seton et al. (2012). They adopted a model for Gondwana whereby pre-breakup margin extension was initiated at 180 Ma as a response to thermal weakening by the eruption of the Karoo flood basalts, and initiated seafloor spreading at 160Ma along the entire East Africa margin after the cessation of rifting in the Karoo Rift, about 5 million years before the last confidently dated magnetic anomaly (M25). Following Torsvik et al. (2012), they reconstructed Antarctica with an overlap on the Beira High, NNV, N Mozambique Ridge, and Limpopo basin Poles for South American plate provided by Seton et al. (2012). (Mercator projection).



Figure 19: Reconstruction model of Torsvik et al. (2012). Their model assumes oceanic origin for the Limpopo Basin, Natal North Valley, and the Mozambique Ridge. Allowing Antarctica to overlap these structures, and results in ~300km of overlap between Antarctica and Africa. Poles for South American plate provided by Torsvik et al. (2012). (Mercator projection).



Figure 20: Initial fit of Leinweber and Jokat, (2012). The model is based on interpretation of magnetic anomaly M41 in the Zambezi Basin, and assumption of an Early Jurassic Gondwana breakup, close time wise to the Karoo magmatic activity (179-182Ma). Their initial fit of Antarctica with respect to Africa leads to a tight fit, with a resulting ~300km overlap of Antarctica on Africa inMozambique. They assumed oceanic origin for the Beira High, Limpopo Basin, the North Natal Valley, and the Mozambique ridge, permitting overlap by Antarctica. Poles for South American plate provided by Leinweber and Jokat, (2012. (Mercator projection).



Figure 21: Reconstruction model of Gaina et al. (2013). Following Leinweber and Jokat, (2012), Gaina et al. (2013) assumed magnetic anomaly M41 (167.5 Ma Gradstein et al., 2012) as the oldest Jurassic anomaly in the Mozambique Channel, and additionally proposed anomaly M41 in the Somali to achieve a cohesive initial East-West Gondwana drift from Africa. Their model results in overlap of Antarctica over the Beira High, the Limpopo Basin, the North Mozambique Ridge, and the North Natal Valley. The model further results in ~200km overlap between India and Antarctic, and ~140km gap between India and Madagascar. Poles for South American plate provided by Gaina et al. (2013). (Mercator projection).



Figure 22: Reconstruction of Reeves et al. (2015). Their original model incorporated reconstruction of distinct rotation poles for several Precambrian cratons and continental fragments. Their fit for India-Madagascar-Sri Lanka-Antarctica was model after Ghosh et al., (2004). They suggested significant extension of the continental crust about 200Km. To examine their model on the same scale as the others, the coastline of the plates was used. The model results in ~300km of overlap of Antarctica on the African plate (in the Limpopo Basin). Notice Antarctica completely overlaps the Beira High, the North Mozambique Ridge and the North Natal Valley. PSZ: PanAfrican Shear Zone after de Wit et al. (2001). (Mercator projection).



Figure 23: Nguyen et al. (2016) adopted the pole of Gaina et al. (2013) for the initial fit of Madagascar relative to Africa, and Seton et al. (2012) for the rest of the East Gondwana plates. The model results in ~300km overlap of Antarctica over Africa, and ~140km gap between India and Madagascar. PSZ: PanAfrican Shear Zone. (Mercator projection).



Figure 24: Reconstruction of Madagascar relative to Africa by Phethean et al., (2016). They proposed new spreading lineaments in the Somali Basin, based on directional derivatives of free-air gravity anomalies in support of a tight fit of Madagascar to Africa, with significant crustal extension between the two plates. Their initial fit of Madagascar in their model is after Revees et al. (2015). The model has consequences on the position of Antarctica and the rest of the East Gondwana (India, Sri Lanka, Australia) relative to Africa as it may result in overlap of Antarctica over Africa in Mozambique (see Revees et al. (2015). PSZ: PanAfrican Shear Zone after de Wit et al. (2001). (Mercator projection).



Figure 25: Map showing comparing the reconstruction models of Sahabi, (1993), Leinweber and Jokat, (2012), Gaina et al., (2013), Reeves et al., (2015) at the same scales. Notice the large differences in the placement of the plates in terms of latitude and angle. With regard to the fit between Africa and Antarctica, notice the overlap of Antarctica on the Limpopo basin in (Reeves et al., 2015; Gaina et al., 2013 and Leinweber and Jokat, 2012). The North Mozambique Ridge (In yellow) was found during recent expedition in the Mozambique Basin of MOZ3-5 to consist mainly of sediments on a thinned continental crust (Lepretre et al., 2017; Moulin et al., submitted). The Southern Mozambique Ridge (In black) maybe composed of volcanics (Gohl et al., 2011) possibly emplaced at a triple junction. (Mercator projection).



Figure 26: Comparing the evolution partings of Madagascar in (Reeves et al., 2015; Gain et al., 2013; Leinweber and Jokat, 2012; and Sahabi, 1993). The models of Reeves et al., (2015) and Leinweber and Jokat, (2012) starts with an initial overlap of Madagascar on the African plate before a southward drift to the present position. Notice Leinweber and Jokat, (2012) start with an initial phase of compression. (Mercator projection).



Figure 27: Evolution of Antarctica with respect to Africa in (Reeves et al., 2015; Gain et al., 2013; Leinweber and Jokat, 2012; and Sahabi, 1993). Notice the initial relatively zig zag motion in Gaina et al, (2013), and the overlap of the Antarctic plate and Africa plate in Reeves et al. (2015) Gain et al., (2013), Leinweber and Jokat (2012) calling into question the nature of the crust underlying this area. (Mercator projection).



Figure 28: Reconstruction of Thompson et al. (submitted), showing the main distribution of pre-drift Karoo sediments and volcanics in Africa, Madagascar, and Antarctica. The Southern Africa continent is characterized by vast network of sills and dykes (182-183Ma) which are pre-syn-post Karoo magmatism (179-182Ma). This magmatic event was also witnessed in the Dronning Maud Land of Antarctica (Elliot and Fleming 2000), and the Ferrar Province (Antarctica, Elliot and Fleming 2000). World Geodectic System 1984. Blue circle shows the possible location of the tripple junction considered for the plume hypothesis.



Figure 29: (a) Schematic diagram by Bristow (1980), illustrating the geochemical and isotopic relationships of how the Lebombo volcanics may have been sourced, and how low-MgO volcanics may have developed. (b) A schematic diagram by Bristow (1980), showing how early formed picritic magmas would equilibrate with mantle phases at higher pressures than those magmas formed later in the volcanic event.

| Sample | Material | Total Fusion Age, Ma | Plateau Age Ma | ³⁹ Ar of Total % | Isochron Age, Ma | N | 40Ar/ 36 Ar Intercept ± 1 σ | J |
|----------------------------|-------------|-------------------------|--|--------------------------------|---------------------|--------|---|-----------|
| | | | Sa | wth Africa: Lesotho | | | | |
| OXB-01 | basalt | 187.5 | 1865+19 | 81 | 1896+32 | 5 | 235.1 +21.6 | 0.001686 |
| ML P-172 | basalt | 180 3 | 1795+21 | 79 | 1817+22 | 3 | 2809+96 | 0.001680 |
| BUS-18 | basalt | 184.8 | 1824 ± 17 | 94 | 1864+26 | 5 | 283 5 +28 3 | 0.001690 |
| POMOI | basalt | 190.4 | 180.0 + 2.1 | 99 | 1806 + 4.2 | 3 | 253.5 ±20.5 | 0.001605 |
| KOM-01 | Uasait | 100.4 | 180.0 ± 2.1 | 60 | 1810+23 | 2 | 200 2 + 5 6 | 0.001503 |
| PMC 04 | handt | 100.0 | 104.4 ± 1.0 | 09 | 101.9 ± 2.3 | 2 | 298.2 ± 5.0 | 0.001595 |
| DMC-04 | Dasan | 164.5 | 164.5 ± 1.7 | 95 | 185.5 ± 1.9 | 2 | 292.2 ± 0.4 | 0.001688 |
| NN-01 | Dasan | 190.4 | 182.9 ± 2.1 | 60 | 184.1 ± 2.5 | 3 | 287.2 ±10.9 | 0.001688 |
| ON-014 | basalt | 100.7 | the state of the state of the state of the state | | 1 | | | 0.001095 |
| KF-10 Omeg ^a | basalt | 173.7 | 183.9 ± 1.0 | 77 | 183.5±1.7 | 5 | 302.7 ± 9.1 | 0.001653 |
| | plagioclase | 187.9 | 183.9 ± 0.7 | 93 | 183.8 ± 2.4 | 6 | 294.7 ± 2.7 | 0.001496 |
| MF-09 Moshesh ^b | basalt | 185.9 | | | | | | 0.001358 |
| KRB-7 Moshesh | andesite | 183.2 | 181.0±1.7 | 82 | 182.0 ± 3.2 | 4 | 295.8 ±27.9 | 0.001628 |
| KR-29 Moshesh | basalt | 190.5 | 186.5 ± 1.1 | 72 | 184.5 ± 3.2 | 3 | 308.9 ±70.6 | 0.001324 |
| | | | Sar | uth Africa: Lehamba | | | | |
| KVII-5 Iozini | rhyolite | 190.3 | 1797+07 | 02 | 180.0 + 1.9 | | 315 3 401 7 | 0.001460 |
| KYO-5 Jozini | myome | 180.5 | 179.7 ± 0.7 | 20 | 100.0 ± 1.8 | 2 | 313.3 191.7 | 0.001409 |
| DCC 92 Cable | hoselt | 170.0 | 178.1 ± 0.0 | 91 | 177.0 ± 1.9 | | 206.0 ±12.0 | 0.001430 |
| KOL 2 Sable | basan | 1/9.0 | 181.2 ± 1.0 | 19 | 182.0 ± 2.1 | * | 290.0 ±13.9 | 0.001398 |
| KOL-2 Sable | Dasalt | 180.2 | 183.2 ± 1.3 | 83 | 181.4 ± 3.7 | 4 | 306.0 ± 9.5 | 0.001680 |
| RSV-4 Sabiec | basalt | 180.8 | | | | 1 12 | | 0.001503 |
| RSV-35 Sabie | basalt | 188.4 | 184.2 ± 1.0 | 81 | 182.8 ± 4.9 | 3 | 305.6±51.7 | 0.001525 |
| | plagioclase | 190.4 | 184.2 ± 0.6 | 76 | 182.9 ± 2.5 | 6 | 295.1 ± 3.4 | 0.001574 |
| RSS-8 Sabie ^b | basalt | 186.7 | | | | | | 0.001621 |
| KP-121 Letaba | picrite | 184.5 | 182.7 ± 0.8 | 90 | 182.2±2.5 | 4 | 356.6 ±31.6 | 0.001675 |
| KP-111 Letaba | picrite | 129.5 | 141.9 ± 1.5 | 62 | 139.8 ± 2.5 | 3 | 267.0±14.1 | 0.001385 |
| KP-83 Mashikirid | pephelinite | 219.4 | | | | | | 0.001382 |
| KP-92 Mashikiri | nephelinite | 194.2 | 1821+16 | 54 | 1817+39 | 2 | 313 1 +29 0 | 0.001436 |
| KOL 17 Machikicib | nephelinite | 206.2 | 102.1 1 1.0 | 54 | 101.7 1 3.9 | - | 515.1 225.0 | 0.001500 |
| KOL-17 Mashikii1- | nepileinnte | 200.3 | | | | | | 0.001399 |
| TPA-71C | plagioclase | 177.2 | South Afric | a: Transvaal Dikes ar | nd Sills | | | 0.001378 |
| TRA-76 | plagioclase | 180.6 | 181.4±1.1 | 95 | 183.5 ± 1.6 | 7 | 257.2 ±35.5 | 0.001391 |
| TRA-84 | plagioclase | 189.4 | 1828+16 | 68 | 1824+28 | 4 | 309 0 +25 0 | 0.001470 |
| TRA-95 | plagioclase | 207.6 | 180.3 ± 1.8 | 65 | 184.1 ± 2.2 | 4 | 294.8 ±16.0 | 0.001353 |
| | | | | Namibia: Hardan | | | | |
| HAR-02b | hasalt | 188.4 | | | | | | 0.001265 |
| | nlagioclase | 183.4 | 1830+06 | 100 | 1844+18 | 6 | 2946+26 | 0.001448 |
| HAP 07b | basalt | 193.4 | 105.0 ± 0.0 | 100 | 104.4 1 1.0 | • | 274.0 2 2.0 | 0.001746 |
| HAR-07 | basah | 102.7 | 1842+10 | 50 | 105 4 + 10 | | 200 2 + 2 7 | 0.001/40 |
| HAR-00 | basalt | 195 4 | 184.2 ± 1.0 | 50 | 185.4 ± 1.9 | 4 | 290.2 ± 3.7 | 0.001275 |
| HAK-15 | Dasait | 185.4 | 180.0 ± 0.8 | 92 | 187.4 ± 2.0 | 2 | 291.0 ± 2.1 | 0.001005 |
| | | | Nami | bia: Keetmanshoon | | | | |
| KEE-020 | hacalt | 170 8 | | one neemanoop | | 0.001 | 0.0 | |
| KEE-03 | plagioclase | 183.4 | 847+05 | 05 | 192 9 + 1 7 | 0.001. | 505 | 0.001.010 |
| KEE-05 | plagioclase | 176.0 | 1815+08 | 50 | 103.0 ± 1.7 | 8 | 268.1 ±37.6 | 0.001548 |
| KEE orb | plagioclase | 170.0 | 101.5 ± 0.8 | 50 | 182.9 ± 2.8 | 3 | 295.2 ± 8.5 | 0.001641 |
| KEE-0/* | basan | 185.0 | 1047+07 | 100 | 1050100 | | | 0.001774 |
| KEE-10 | Dasait | 184.1 | 184.7±0.7 | 100 | 185.8 ± 2.0 | 6 | 292.5 ± 3.8 | 0.001710 |
| KEE-11a | basalt | 189.0 | 180.5 ± 0.7 | 90 | 181.8 ± 2.3 | 4 | 294.7 ± 4.1 | 0.001591 |
| | | | Antarcti | ca: Kirwan Mountaine | | | | 0.001255 |
| | | | aniarca | ca. Kirwan mountains | | | | |
| LAD-7 | plagioclase | 183.9 | 180.6 ± 0.6 | 89 | 182.0 ± 3.2 | 5 | 291.9 ± 3.1 | 0.001650 |
| LAG-22 | plagioclase | 182.1 | 182.7 ± 0.6 | 97 | 180.9±2.0 | 6 | 294.9 ± 0.9 | 0.001630 |
| 1277120202 | The Second | | 1000000-000000 | | | - | | 0.001000 |
| LAG-31 | plagioclase | 183.4 | 182.8 ± 0.6 | 98 | 181.5±1.5 | 7 | 293.2 ± 4.3 | 0.001640 |
| | | | | | | | | |
| | | | | | | | | |

| Table 1. The 40Ar-39Ar Radiometric Ages for the Karoo Igneo | ous Province in South Africa and Namibia and Correlative Rocks in East Antarctica |
|---|---|
|---|---|

Figure 30: Radiometric ages of Karoo volcanism presented Duccan et al. (1997) in Africa compared to Antarctica. The ages suggest contemporanous emplacement.



Figure 31: Geological map of the Lebombo Monocline by Klausen (2009). Distribution of Karoo sediments (Late Carboniferous to Middle Jurassic) and overlying volcanic rocks in Klausen (2009), showing the distribution of earliest nephelinite, overlain by picritic Letaba River basalt formation, and lateral high- to low-(Ti, Zr) transition in Sabie River basalt Formation. Note northward disappearance of younger lava formations beneath unconformable cover of Cretaceous–Tertiary sediments. The insert describes the distribution of dykes on the Lebombo. The N–S and NW–SE trending dykes are Jurassic dykes. The predominant SW–NE dykes are cut by the N–S and NW–SE; therefore older than the Karoo Supergroup.



Figure 32: (a) Lithotectonic model by Geiger e al. (2004). In their model, Gondwana breakup was preceded by several Karoo rifting events, but only the Early Jurassic (Toarcian) Andafia rift finally resulted in crustal separation. (b) Generalized stratigraphic scheme by Hankel (1994) for pre-drift sediments of East Africa and Madagascar showing major subdivisions and events. Notice the age difference predicted for the start of drifting in the two schemes Toarcian in Geiger and Bajocian in Hankel (1994).


Figure 33: Lihotectonic chart of Karoo Basins in Africa. The yellow circle correspond to breakup contemporanous with the Karoo magmatic event. The blue circle age of magnetic anomaly M41, and the red circle corresponds to the confidently dated magnetic anomaly in the Somali Basin. Legend same as figure 34.

| ATERNARY | - |
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| | DEEEDENCES |
| | Flores, 1984 Robbert Rutten Foster, 1975 |
| | Robbert Rutten Flores, 1973 |
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| | Catuneanu, (2004) |
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| i Beds | Nicolas et al., 2006 www.tpdc-tz.com 20/04/2015 www.mbendi.com 03/05/2015 |
| | Foster, 1975 Robbert Rutten |

| | STO | RMBERG GF | ROUP | | KAROO MAG | MATISM | | POST KAROO | | | | | | | | | |
|-----------------|--------------------------------------|--|---|--------------------------|--|--------------------------------------|-----------------------------|-----------------------|-----------------------------|------------------------|----------------------|---------|--------------|---------------------------------|----------------------------------|------------------------------|-------------------|
| BASIN | LATE TRIASSIC | EARLY | JURASSIC | Μ | IIDDLE JURASS | SIC | | U | UPPER JURASSIC LOWER CRETAG | | | ACEOUS | UPPE | ER CRE | FACEOUS | | |
| | CARNIAN NORIAN | HETTANGIAN | TOARCIAN | N AALENIAN | BAJOCIAN | BATHONIAN | CALLOVIAN | OXFODIAN | KIMMERIDGIAN | TITHONIAN | HAUTERVIAN | APTIAN | ALBIAN | CENOMENIAN | TURONIAN | MAASTRICHTI | AI PA |
| MORONDAVA | lsalo Fm (Sandsotne) | ? | And (Sandst | dafia Fm tone, Shale) | Bemaraha Fi (Carbonate platfo | Sakanavaka Pm (Sandstone) prm) | Duvalia (Mudstor | Aarl nes) | Argiles and N | Narls | Ma | irls | | Sand | Basalts | Continer Layer | ntal |
| MAJUNGA | * | ? | Beronono (Marl, Sha | Fm le, Sandstone) | Lir | nestones and N | larls | Argi | iles and Marls | i | Marls | and Lic | gnite | Sand | Basalts | Continent Layer | al |
| MANDAWA | Mbuo Fm (Sandstone, claystone) | Pindiro S Nondwa (Evaporites, shales) | Mihambia Fi (Clastic sedimen limestone, shale | m, | Mtumbei Series Kidugallo Limes (Limestones and ? | and tones d Marl) | hale | Mitole Fm | n Lower Tendagura Series | Kipatim | | | | Lov Nangurul | ver Kilw kuru Fn | ra Group n Kivir | ıje l |
| TANGA | Matolani | Ng (1 | erengere Beds Nondwa) | | | Amboni Kidulgallo Mtumbei | Tilting | Bagamoy | vo Fm | Kipatimu | beds Regression | | Sa | akura Fm | F | {uareke F (Claysones) | m I |
| SELOUS | Mkuju-Luhumb | ero | Ngerengere Beds (Madaba Fm) | | Mamdanga Fm | 7 | | | | | | | | | | | |
| RUFIJI | Tanga | a l | Ngerengere Beds | | Makarewale (Shale) | Fm Kidul | oni gallo Tilting | Bagamo (Argillaced | oyo Fm eous sediments) | Kipatimu | u beds Regression | | | Kingongo Marl Kihuluhulu Mar | s ^{rls} Nan <u>c</u> | Jurukuru | Kiv |
| RUVU | Tanga | | Ngerengere Beds | | Makarewale | Ambo Fm Kidul ? | oni gallo | Bagamo | oyo Fm | Kipatimı Г | u beds | | | | Ruare (Clays | ke Fm ones) | |
| NORTH RUVUMA | • | Pindi | ro Series | 5 | Mtumbei | M: | andawa Serie Salt diapir | 5 9 | Lower Tei Series | ndagur _{Kipa} | timu Beds | | Mako Beds | King onde Kong (Mar | JO 1) Nanguru | wer Kilwa Kiv ıkuru Fm | Gro rinje I |
| | ŧ | Rifting | ŧ | Rift reactivation | Subsidence | e 📥 Uplift | | Lavas and | basalts | | Hiatus or Unconf | formity | | | | | |

Figure 34: Litotectonic chart of Karoo basins in East Africa and Madagascar Basin. Notice the different ages predicted for the start of drift in Gondwana; the yellow and blue circles correspond to the predictions of Geiger et al. (2004) and Hankel, (1994), respectively. The red circle correspond to the age of the first oceanic crust in Somali Basin. Legend same as figure 33.

| | TERTIARY RIFTING AND VOLCANISM | | | | | | | | | |
|---|--------------------------------|-----------------------------|----------------|------------|------|-------|--------------|---------------------|------------|----|
| | QUATERNARY | | E Q | DGENE | NEC | | ENE | LEOGE | Ρ | |
| REFERENCES | HOLOCENE | STOCENE | NE PLEIS | PLIOCEN | CENE | | OLIGOCEN | OCENE | OCENE | EC |
| Hankel, 1994 Catuneanu, (2004) Pique et al. (1998) | | Limestone, and Sandstone | | | | | | | | |
| Catuneanu, (2004) Hankel, 1994 Rafindrazaka, 1999 | | | arls | and Ma | ne a | dstor | te, Sano | olomi | | |
| Hankel, 1994 Catuneanu, (2004) Nicolas et al, 2006 www.mbend.com/8/5/2015 Hudson and Nicholas, 2014 | - | | ds | kuledi Bed | | | Group nde | oer Kilwa oFm Pa | U n Mas | 'n |
| Guillocheau and Liget, (2009) Nicolas et al., 2006 www.nbendicom 18305/2015 Kejato, 2003 | | | u | Pugu Fm | | | | ed | Unnar | |
| Nicolas et al., 2006 Hankel, 1994 | | | | | | | | | | |
| Kejato, 2003 Nicolas et al, 2006 www.mbendi.com 03/05/2015 | | ura | Ras B clays | | | | Pande | Isoko | ije I | nj |
| Nicolas et al., 2006 www.mbendi.com 03;05/2015 | | | fia | Maf | | | e Beds | eogen ? | Pa | |
| Nicolas et al., 2006 www.mbendi.com 03/05/2015 Hankel, 1994 | indani | Miki | | | | e | Pande | oer Kilw soko | p U M | 2 |



Figure 35: Structural map of the Limpopo basin after Salman 1985. The nature of the crust underlying the Limpopo basin remains unknown. Cox (1992) proposed the basin's development to be related to a plume event that resulted in suppressed breakup, extensive volcanism, and subaerial spreading. Salman and Abdulla (1995) and Flores (1975), however, interpreted the basin to be characterized by the existence of a series of parallel, trending fractures issuing ever younger magma from west to east. The regional low and high are derived from gravity.. Map drawn after Salman, (1985).

| No. | Name | Elevation (sea level) | Thicknes (m) | ss Radiometric age, MM yrs. | Rock type |
|-----|---------------|--------------------------|-----------------|--|------------------------|
| 1 | 2 | 3 | 4 | 5 | 6 |
| 1 | Balano 1 | -2,861.1 | 256.1 | / - \ | Basalt |
| 2 | Domo 1 | -2,980.9 | 57.0 | K/Ar - 137.0 | Olivine, basalt |
| 3 | Zandamela 1 | -1,770.2 | 926.0 | - \ | Basalt, rhyolites |
| 4 | S.Massinga 1 | -4,169.0 | 27.4 | - | Basalt |
| 5 | Mambone 1 | -3,247.9 | 353.6 | - | Basalt, alkali basalt |
| 6 | Nhamura 1 | -5,140.1 | 301.2 | (Karroo?) | Dolerite |
| | | -5,441.3 | 27.4 | (PreCambrian) | Dolerite |
| 7 | Nhachangue 1 | -4,479.6 | 46.9 | | Olivine basalt |
| 8 | NE Palmeira 1 | -4,441.2 | 13.7 | K/Ar - 285.6 <u>+</u> 14.3 | Basalt |
| 9 | NW Macia 1 | -2,122.0 | 152.2 | | Basalt |
| 10 | Funhalouro 1 | -4,054.1 | 49.7 | - | Weathered basalt,tuffs |
| 11 | Nemo 1x | -3,709.4 | 396.3 | | Tuffs,alkali basalt |
| 12 | Sunray I IA | -3,507.0 | 38.4 | K/Ar - 129.6 <u>+</u> 4.0 | Basalt |
| 13 | Sunray 2 IA | -1,105.2 | 118.8 | K/Ar - a)116.8 ⁺ 1.8 b)8.47 ⁺ 1.0(1 | Weathered basalt ?) |
| 14 | Sunray 3 | -3,552.7 | 28.0 | \ - / | Weathered basalt |
| 15 | Sunray 4 IB | -1,325.9 | 19.5 | MAr - 74.2+3.0 | Basalt |
| 16 | Sunray 7 | -2,595.7 | 463.3 | \ - / | Basalt |
| 17 | Sunray 12 I | -2,159.8 | 282.8 | K/Ar - 18.120.3 | Tuffs, basalt |
| | | | | | |

Table 1. Mozambican wells that encountered volcanics*

Figure 36: Chart of Mozambique well that encountered volcanics by Flores (1984), showing the episodic event of the Karoo volcanism.



Figure 37: Magnetic anomaly identification in the Riiser-Larsen Sea and Mozambique Basin. (A) Magnetic anomaly identification in the Riiser-Larsen Sea by Leinweber and Jokat (2012). The lower right inlet shows the tracks of their lines. The yellow elipse marks anomaly M25 (157Ma), the oldest magnetic anomaly identified in the Riiser Larson Sea. (B) Magnetic anomaly in the Mozambique Basin. The small inset map in the left bottom shows their lines used. The yellow and red circle marks magnetic anomaly M25 and M41 (166Ma) respectively, identified by Leinweber and Jokat (2012), who identified anomaly M41 as the oldest magnetic anomaly in the Riiser Larson Sea. Dash lines indicate the Continent Ocean Transition Boundary (COTB) by Raillard (1990).



Figure 38: (a) Free-air satellite-derived gravity anomaly of the Mozambique Channel by Sandwell et al., (2014). The black line across the Beira High shows the location of the seismic refraction profile 2014001014 of Muller et al. (2016). The north Mozambique Ridge (in red) discovered in recent expedition in the Mozambique Basin of MOZ3-5 to be compose mainly of sediment on a thinned continental crust (Lepretre et al., 2017; Moulin et al., submitted). The southern Mozambique Ridge (in black) maybe composed of volcanics (Gohl et al., 2011) possibly emplaced at a triple junction. (b) The free-air gravity anomaly along the profile (c) Magnetic anomaly along the profile. The magnetic anomalies were from Leinweber and Jokat (2012). (d) Wide-angle seismic profile 2014001014 seismic across the Beira High and the Zambezi depression by Muller et al., (2016). They interpreted the Beira High to be of continental origin, and that the Zambezi depression consists of stretched continental crust. (Mercator projection figure 11-23).



Figure 39: Free-air satellite-derived gravity anomaly (Sandwell et al. 2014) of Mozambique and Madagascar. The Mozambique ridge is formed of several bathymetric plateaus rising up to 3500m from the ocean floor. It has broad, elevated topography especially on its southern half, falling away steeply into the Mozambique basin to its east (Gohl et al., 2011). The Madagascar Ridge extends a distance of 1300km from the southern tip of Madagascar, and ~400 km across. The ridge protrudes at water depth between 2 and 3 km across most of the plateau. (Mercator projection).



Figure 40: Geology of North Mozambique by Bingen et al. (2009), showing Mozambique Belt, a complex rift-orogenic belt. At least three orogenic episodes are recognized along the belt.



Figure 41: Synthetic chart of the passive margin of southern Africa: magmatism, oceanic accretions, regional scale deformations and stratigraphic record by Baby (2017).



Figure 42: Map of seafloor fabric and magnetic anomalies data used in the study in the Somali Basin and East Indian Ocean. The magnetic anomaly plots were derived from EMAG3 and Williams et al. (2013). ZP: Zenith Plateau, NP: Naturaliste Plateau, WZFZ: Wallaby Zenith Fracture Zone. BK: Batavia Knoll, GDK: Gulden Draak Knol,; DHR: Dirck Hartog Ridge, BR: Broken Ridge, FZB: Fracture Zone Bends. (Mercator projection).



Figure 43: Map of seafloor fabric and magnetic anomalies data used along the study in the Africa-Antarctic corridor and the Australia-Antartic Basin. (Mercator projection).



Figure 44:) Free-air satellite-derived gravity anomalies of the Somali Basin by Sandwell et al. (2014. Magnetic anomalies are from Dais et al. (2016) in Somali Basin, and Leinweber and Jokat et al., 2012 for the Zambezi basin. Gravity grid legend is same for figures 46-49.. (Mercator projection).



Figure 45: Map of satellite-derived free-air gravity data of the Antarctica Africa corridro by Sandwell et al. (2014); MozR: Mozambique Ridge; SMR: Madagascar Ridge, NMR: North Mozambique Ridge,; NNV: Northern Natal Valley, SWIR: Southwest Indian Ocean. (Mercator projection).



Figure 46: Map of Sandwell et al. (2014) satellite-derived free-air gravity data of the Central Indian Ocean Ages of magnetic anomalies are same for figure 45-49. LR: La Réunio, M: Mauritius, MP: Mascarene Plateau, N: Nazareth Plateau, SM: Saya de Malha Bank, SP: Seychelles Plateau; SEIR: Southeast Indian Ocean; SWIR: Southwest Indian Ocean. (Mercator projection).



Figure 47: Free-air satellite-derived gravity anomalies of Eastern Indian Ocean by Sandwell et al. (2014). EP: Exmouth, Plateau. ZP: Zenith Plateau, WP: Wallaby Plateau, NP: Naturaliste Plateau, WZFZ: Wallaby-Zenith Fracture Zone. BK: Batavia Knoll; GDK: Gulden Draak Knoll; DHR: Dirck Hartog Ridge; BR: Broken Ridge: FZB, Fracture Zone Bends : NP: Naturaliste Plateau: ZP: Zenith Plateau, WP; Wallaby Plateau. (Mercator projection).



Figure 48: Free-air satellite-derived gravity anomalies by Sandwell et al. (2014) (a) Antarctic-Australia Basin (b) Enderby and surrounding basins. Ages of magnetic anomalies are same as in figure 45 BK: Batavia Knoll; CKP: Central Kerguelen Plateau; DHR: Dirck Hartog Ridge; GDK: Gulden Draak Knol, NKP: North Kerguelen Plateau, WP: Wallaby Plateau, NP: Naturaliste Plateau, SKP: South Kerguelen Plateu, NP: Naturaliste Plateau, ZP: Zenith Platea. (Mercator projection).

OCEAN EVOLUTION

PLATE-PLATE BREAKUP AGE



DRIFT: oceanic a Break-up unconfor RIFT: tilted blocks AFRICA VOLCANISM

| Gaina et al., (2013) König and Jokat, (2010) Leinweber and Jokat, (2011, 2012), Goslin et al., (1981) Schlich et al., (1974) Royer and Coffin, (1992) Jokat et al., (2010) | Sandra E. Robles-Cruz, (2012) Skinner et al., (2004) Watkeys, (1998) Kreuser, (1995) Virloqeux, (1984) Hesselbo et al. (2000). Duncan et al., (1997) | Caimcross, (2001) Daly et al., (1989) Bordy, et al., (2005) Wanke., (2000) Veevers, (1994) (Delvaux, 1990) Rogers., (2004) | Guillocheau and Liget, (2009) McClintock et al., (2008) Watkeys, (2002) Jourdan et al., (2005.) Riley et al., (2004) Reeves, (1978) | Raillard, (1990) Cox, (1992) White, (1997) Jourdan et al., (2007) Le Gall et al., (2005) http://news.xinhuanet.com/english/business/2013-10/17/c_132804993.htm |
|--|--|--|--|---|
| ic accretion IIIIIIIIII DYKES AND SILLS nformity IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII | MAIN MAGMATIC SYSTEMS RAPPS) basalts, ites) DLCANISM ALKALINE MAGMATIC ROCKS | Major Minor UNCONFORMITIES EUSTATIC MAXIMUM FLOODING SURFACES NO DEPOSITION KARROO SUPERGROUP | Ntabankosi Rhyolites Uplift Chilwa Province | Convergence Continental Ridge Oceanic ridges |

Ferrar Province Dronning Maudlands Enderby Basin

Mıddle Miocene Ellendale and volcanism in Western Victoria Hard collision Indian-Asia Burdigalian Early Lutetian Early Ypresian urduwadi and Koyna ri Campanian Rifting initiating Indian Madagascar seperation Jurassic -Late Cretaceous E. Cenomanian Volcanism associated with Indian-Australian plate seperatio in Argo, Perth, Cuvier Gascogne and Wharton basins Dronning Maud dykes Explora wec **HIIII** Oceanisation ' Mahanadi Rift Valley Pranhita-Godavari Rift Valley Jurassic Antartatic-Tasman _ambert Rift Valley Robert Rift Valle thermo-tectonic event Timber Greek Kimberlite Jutulrora dyke swarm Abercorn trough, Esk Ba

Watkeys, (1998) Gaina et al., (2013 Jeffrey et al., (1980) (Raillard, (1990) König and Jokat, (2010) Elliot and Flemming, 2000) Wellman and McDougall (1974) Sutherland, (1978) Martin and Hartnady, (1986), Leinweber and Jokat, (2012) Burke and Dewey (1973) Mike de Wit, 2010 Goslin et al., (1981) Eagles and Konig (2008) König and Jokat (2010) Schlich et al., (1974) Gaina et al., (2013) enton etal., (2012) König and Jokat, (2010) Leinweber and Jokat, (2011, 2012) Goslin et al., (1981) Schlich et al., (1974)

Figure 50: Map Karoo sediments and igneous rockss distribution in Gondwana. World Geodectic System 1984.

KAROO BASINS AFRICA CLIMATE

| | Climate Facies | Cold semi-arid Glocio-lacustrine | Temperate Warm humid Hot arid semi-arid Warm humid Lacustrine Swarmps, meaders Lacustrine Lacustrine Lacustrine | humid Basins Warm semi-arid Warm Hot semi humid Semi-ari strine Playas braid-rivers Fluviatile Fluvio-deltaic | id Semi-arid to arid Arid Non- marine, fluvio environment Non-marine | Arid Fluviatile environment | | |
|---|--|---|--|--|---|---|--|---|
| | · | Africa at the couthnole Glacial naleoclimate | Deglaciation transition to lacustrine environment. Africa moving gradually from the south pole into a warm environment. The Groun did not extend | | | | East African rift and volcanism | |
| | | extended to north Africa and Yemen | ECCA GROUP | Arid coninental paleoclimate, with the development of acolian, fluvial, lustrine envi wyka Africa moving farther way from the south pole | STROMBERG GROUP KAROO VOLCANISM | Gondwana breakup Alkaline volcanism, rifting and sub- | idence accompanied by Milocus marine regression transgession | |
| | BASINS | Carboniferous | Basins Early Permian | Basins Late Permain Triassic | Basins Late Trassic Early Jurassic Middle Jurassic | Upper Jurassic Lower Cretaceous Upper Cretaceous | Paleogene Neogene Quaternary | |
| Flexural tectonism in relation to process | esFOLDBELT | Mississipian Pennsyvanian | Asselian Sakinarian Artinskian Kungurian Ufit Foldbelt | imian/ zanian Vodu Cuylania Wukipuja Charphingia India Olerkian Entry Anisian Late Anisian L Foldbelt | adinian Carrian Norian Hettangian Toarcian Aalenian Callovian Oxfori | m Kimmeridgian Tsthonian Hauterivian Aptian Albian Cenomenian Turonin Massirethian | Palacene Eocene Oligocene Miocene Pfiocene Pfeistocene Holocene | Basin References |
| of subduction, accretion and mountain building along the Panthalassan (palaeo-Pacific) margin of Gondwana. Initiation of the Cape Orogeny. | Cape foldbelt | ? Dwyka | Cape Foldbelt Kommunication Kommunic | nape & Cape foldern Balfour formation ? Katheng formation Burger dorp formation | Iphifik flexual bulging Moleno formation Elliot formation Drakensberg ? Ethrore foreland System Elliot formation Elliot formation Elliot formation Elliot formation | Alkaline Volcanism ? Alkaline Volcanism | .2 Ca Ca Bri | Catuneanu, (2004) Catuneanu et al., (2002) ristow and Saggerson, (1983) |
| Foreland system in the evolution | SYSTEM MAIN KAROO SOUTH AFRICA (southwest) | | SYSTEM Main Karoo (southwest) Prince Albert Whitehill (mdsc) Skoorsteenberg Kookfontein (mds) & V (mds) & Collingham (utr. [sst; mds), mds) [ierberg (mds)] (sst) | Naterbrid Main Karoo Tapinocephalus Pristengulus Dicynodon Lystrosauns Procolophon Cynoguthus Cynoguthus (sst, mds, sit) | Man Karoo Basin Drakensberg Drakensberg | | Co En Cr | Cole, (1992) Eriksson, (1985) Catuneanu, (2004) |
| of the main Karoo Basin, flexural tectonics supplemented by dynamic subsidence. | (south) | Dwyka | (south) Prince Albert Wisterkill Langeburg (st. &Collingham Masset) Fort Brown, Waterford | I (mds; sst Cynografins Cynografin | Moto function Ellist formation Curres function | rist plase of Alkalme Volcanism Second phase of Alkalme Volcanism ? | ີ ດີນນີ້ [] [] [] [] [] [] [] | fuillocheau and Liget, (2009) furner, (1999) ankard et al., (1982) |
| creating additional accommodation | (southeast) (north and northeast) | | (southeast) Prince Albert Whitehil Kipon (sst) Fort Brown & W Collingham northeast) Pietermaritzburg (mds; sit) Vryheid (mds; sit; sst; cgl; c) Vc Sh | Vaterford Olksrust hale Ecca Gp Beaufort Gp | | | Vis Bris Wi | Visser and Loock, (1987) ristow and Saggerson, (1983) Vickens, (1992) |
| | EASTERN RFT BA Lebombo Springbok Flats | INS Dwyka | Lebombo Pietermantzburg Vryheid Volkar Springbok Hammanskraal (sst: mds: c) Flats Geochemistric | strategy and strat | Eastern Rift basir Molteno Fm ELLIOT Fm Clarens (45m) Lembombo (>10 km) Springbak Flats Codrington Member (10m) Upper Irrigasie (80m) Clarens (80M) Letaba floodbasalts | Rivabines Bumbeni Maputo Fm Domo Singuedzi U | Janetze Elefantes Jofane Ca Bc | Catuneanu, (2004) Bordv and Catuneanu, (2002) |
| Back-arc basin? | Ellisras | Dwyka | (mds) | Ellisras Groot Fm ? | Elisras Greenwich (30m) Lisbon (100m) Lebata fiodbasalts | Alkaline Volcanism Alkaline Volcanism | rau Cat Gui Gui | aure et al., (1996) atuneanu, (2004) uillocheau and Liget, (2009) ilev etal., (2004) |
| | 1 smprse | Dwyka | Tshipise Madzaringwe (sst; c) Mikambeni (si ? | it: sst:c) Mikambeni Fm FRIP Fm | Tshipise Klopperfontein (20m) Bosbokpoort and red rocks Clarens (150m) | | Gu Gu | uillocheau and Liget, (2009) atuneanu, (2004) |
| | SWAZILANI | | SWAZILAND Pietermaritzburg Vryheid V | /olkarust | | Thrustuing and rifting | | uncan., (1997) |
| | BU I SWANA Kalahari: | Malongong | g BOTSWANA | BOTSWANA Tlabala/Kwetla/Kule formations e Fm Otshe Fm Kule Fm | | | | reen et al., (1980) |
| | (southwest) (southeast) (central) | Dukwi | (southwest) Kobe (mds) Otshe (sstp: sst; mdsc (southeast) Makoro (mds) Kamotaka (sstp Morupule (central) Bori (mds) Kamenen (sst) Borise (sst) | Morupule Fm Serowe Fm morupule fm serowe fm for the formed seroed ser | Kalahari-SW Lowermost Upper Nkalalou 2 Dondong Dondong (60m) 0 0 Kalahari central Lowermost Upper Ntance 0kavango Kalahari central Lowermost Upper Ntance 0kavango | ? | Contraction Contra | nnun, (1964) atuneanu, (2004) uillocheau and Liget, (2009) man, et al., (1997) |
| | (east) (northeast) | | (centr) Bort (mor) Providing (cost) Derivatives (cost) Bort Miconame (cost) Miconame (cost) (mosc; sstp) (mortheast) Tswane (mds) Mea Arkose (sstp) Tlapana (m | nds) Tale Fm Makawena | Mosolotane Wosotsane COUTLY (<10m) | | | |
| | <u>(northwest)</u> Tuli | ? Dwvka | Image: northwest) Tale (mds: mdsp) Marakwena Tuli Motdiahogolo (mds) Seswe (mds; sst: c) | (sstp) Seswe Fm (mds; sst) | Tuli Middle Unit (70m) Upper Unit (200-280m) Clarens (140m) Lebata and Echaram Limpopo | | | ordy and Catuneanu., (2001) juillocheau and Liget, (2009) |
| | $ \vdash $ | V | | | June 1997 Swarm | Thrustuingend rifting | ╡┼┼┼┼┤ ╞ | |
| | NAMIBIA | | NAMIBIA Karasburg Prince Albert Whitehili (m Aussenkjer (sst; mds | 3) | ? Okavango Dyke swarm | | Guitering Carbonitit | iuillocheau and Liget, (2009) immler et al., (2008). Catuneanu, (2004) |
| | Aranos Waterberg | Gibeon Mb ? Tevrede formaton | Aranos Prince Albert ss: mds. c) Waterberg Tevrede (cg mds; c) | Waterberg | Waterberberg Lowermost Upper Etjo 7 (<10m) | | | uillocheau and Liget, (2009) Catuneanu, (2004) |
| Extensional tectonism in relation to | Ovambo Huab | Dwyka | Ovambo Prince Albert (sst; sit, a Huab (ethrandeBerg (sst; mds; mds;; c) Forzabic (sst; cit; mds; (b) | Gaiss Fm | Hunb Twyfelfontein | | | olzförster et al., 1999 |
| spreading processes along the Tethyan margin of Gondwana. | ZIMBABWE | Dwyka | ZIMBABWE | | Tuli Middle Unit Upper Unit Clarens Limpopo | | Gu | /anke et al., (2000) uillocheau and Liget, (2009) uillocheau and Liget, (2009) |
| with the northern part of the Falkland-East African-Tethys | Tuli (Save) Save | 2 wyka ? Dwyka | I uli (Save) (unnamed) Fultons Dnith Muds sandstone) Save Lower Mkashwe Songwe Grits Mailongwe Shale Save Lower Mkashwe Songwe Grits (c) and Mkwasine Mailongwe Grits | e Mudstner (c) | (70m) (200-280m) (140m) Lebata dyke swarm Unner Bond Sandota Mkunrwe Acolian Sandstone (130m) Karoo Volcanism | Belo Maputo Domo Gru | dja (heingona Inharrime Emanel Jofane Gu | Catuneanu, (2004) arber, (1985) fuillocheau and Liget, (2009) Cotuneanu, (2004) |
| shear system and the rift structure between Africa/Arabia and Madagascar/India. | Mid-Zambe | Dwyka | Mid-Zambez Sandstone Mid-Zambez Mid-Zambez Mid-Zambez Mid-Zambez Mid-Zambez Mid-Zambez Mid-Zambez Mid-Zambez Mid-Zambez Mid-Zambez | Admabias ZIMMARWE Admabias Zimmeri Admabias Mudumabias Mudumabias Mudumabias Mudumabias Mudumabias Mudumabias Mudstone Escarpement Grit Fm red mary Fn | rkose Fm Mid Zambezi Escarpment Grit Red Marley Upper Scythian Anisian Comparison (100m) Batoka 2 | 2 2 2 | Dest Gu | esterlen and Lepper, 2005. uillocheau and Liget, (2009) |
| | MOZAMBIOUE I ete Mozambique basin | ▲ ? ▼ | VIOZAMBIQUE Tere Productive Ses(ps): mdsc; c) Main | nocempto Lugno series ? | 2 Rifting initiating oceanisation ? ? Wozmbujue | 27 Lupata formation | Gu Guida termationChering | iuillocheau and Liget, (2009) Catuneanu, (2004) |
| | MALAWI Southern Basin (SumbChiromo | | MALAWI Southern Basins (SumbChiromo) Un | inamed e Malawi Cineta Bels | 7 | Chilum Drawing | Alkaline igneous Volcanism Jør | atuneanu, 2004 purdan., et al., 2005. |
| | Northern Basins (Ngana) Northern Basins (Livingstonia) | ? | Northern Basins No (Ngana) Basadgi stratigraphy) Lower Coal (sst; mds: c) Upper Shale Se Northern Basin No (Livingstrain) kerstigraphy) Basal cgl Unnamed sst and c Unn | named ss mds | 2 | ? | 7 | uncan et al., 1997. |
| | ZAMBIA Mana Pools | | ZAMBIA Mana Pools Siankandobo sst & Maai Gwembe Coal (sst: md | ? .uangwa Valley S: C1 | Zambia Escarpment rit Upper Angwa Red sandstone | 2 | | Satureanu (2004) |
| | (Gwembe) | ? | (Gwembe) | | (1700-2500m) (930m-5500) (300m) Seythian-Norian Camin-Norian ? | ? Alkaline Volcanism | | ourdan,, (2007) |
| | (Luano) Luangwa | Luwumbu Fm | Luangwa Luwumbu Coal Formation (c) mds; sst; Lowu (sst | er Madu sst; mds) Madumabisa Fm Exapact (ài fn Ntawere Fm Red Mi | rl Fm ? Upper Red Grit Fm ? Dykes Karoo Lava | 2 | Bai John John John John John John John John | anks et al., (1995) blns., (1986) uillocheau and Liget, (2009) |
| | Barotse (centra Zambia) SAG BASINS | Kado Fm | Sarotse (central Kado Sandstone (sst) Luampaoar (sst: mds; Lowe | Variegated mudstone F Michili Fm Kahare Fm SAG BASIN | The Sag Basin | 2 2 | | Catuneanu., 2004 |
| | ANGOLA | Lutoe Gp | ANGOLA Lutoe Gp Lower Cassanje Middle Upper Cassanje (Upp (sst; mds) Cassanje (sst)mds) Cass | per ssanje ANGOLA Upper Upper Cassanje Upper Cassanje Upper Cassanje Upper Cassanje | ? Cafefe Ignimbrites ? Not dated | Akaline volcanism ? | Gui C: | duillocheau and Liget, (2009) Catuneanu, (2004) |
| The origin of the Karoo sag basins may be related to the release of | TANZANIA | | TANZANIA | | Tanga Kilulu | | Alkaline Ce | Iankel, (1993) Catuneanu, (2004) |
| heat following the formation of the Karoo rift basins of eastern | Ruhuhu | Idusi Fm | Ruhuhu Idusi Fm Mchuchuma (sst; mds; c) Mbuyura (ss mds) | ¹ (ssl; me kuhuhu Basin Songea Grou Songea Grou | | | | reuser et al., (1990) Kreuser, (1994) |
| Africa, or thrusting and contraction are related to the collision along | Metangula (Mhukuru) | ? | Metangula Mchuchuma (s Mbuyura (s Mhukuru: (Mhukuru) e) mds) | | | | | atuneanu, O., 2004 emiers et al., (1989) Catuneanu, 2004 |
| the Panthalassa margin. | D.R. CONGO | Conglomerates | congo Coal Measures. Lukuga Formation mst.&sst. Unn | named ss Lukuga Gp Haute Lueki Gp | Haute Lucki Gp | | Bo | Bose, (1971) |
| | KENYA Duruma | ▲ ? | KENYA Duruma Lower Tam gits (og); sta | pp. ssl) Uppe | | | Rec Cat | eeves et al. (1986) atuneanu, (2004) uillocheau and Liget, (2009) |
| | RIFT BASINS MADAGASCAR | | MADAGASCAR | RIFT BASIN MADAGASCAF Sakamena F | IXITE DAS IDS MADAGASCAR Isalo II ? ? | Within plate volcanism ? | US Ankaratra Ankiloaka Ambre Moutains and Volcanism NosyBe Island Vilcanism B2 | atuneanu, 2004 Iankel, O., 1993 Bardintzeff et al, (2009) |
| | Majunga | . ? | Majunga | Najunga | Majunga ? | ? | ? Gui | uillocheau and Liget, (2009) mith, (2000) |
| | Morondawa Mandawa | Glacial beds | Morondawa Black shale Coal beds Lower red beds Marine limestone Lower | r bakamena Amerika and a sakamena 2 Middle Sakamena Lower | salo Morondawa ower Isalo Andafi Fm Salt or Shale Bemarahar Duvalia Marl Ngerenger Beek Ngerenger Beek Salt or Shale 2 Diapir Salt or Shale 2 Diapir Pir | ndiro Shales ? Kipatimu Fm Ruareke Fm | Paleogene Mafia | Vright and Askin, (1987) Guillocheau and Liget, (2009) Catuneanu, O., 2004 |
| | Diego | | Diego | Diego ? | Second phase of fitting responsible or breakup and oceanization in the Sornali basin ? | | Sr Hi | mith, R.M.H., 2000. Iankel, O., 1993 |
| | Rukum-Malawi (TRM) GABON | Idusi Fm ? Nkom Fm | (TRM) Idusi Fm Mchuchuma Fm GABON Agoula Fm | (TRM) ? GABON Agoula Fm Agoula Fm Agoula Fm | (TRM) GABON | | 2 2 2 2 2 2 2 C 2 Gt | uillocheau and Liget, (2009) Catuneanu, O., 2004 Guillocheau and Liget, (2009) |
| | Cassanje | conglomerates ? | Cassanje Sands and conglomerate SOMALIA | Cassanje Cassanje Group | Cassanje Cafefe Ignimbrites | Cretaceous alkaline volanism | | Catuneanu, O., 2004 uillocheau and Liget, (2009) Iirsch, (1987) |
| | SUMALIA | | | | Second phase of rifting responsible for ? breakup and oceanization in the Somali basin ? | ? | | (reuser (1994) |
| | SOMALIA Mandera-Lugh TANZANIA | 2 | Mandera-Lugh TANZANIA | 7 TANZANIA Hatambal | ahoro ? | | Krv | Jonfnor or J V (1001) |
| | SOMALIA Mandera-Lugh TANZANIA Selous Tanga | ? Dwyka | Mandera-Lugh TANZANIA Scious Tanga Mbuyura (sst; mds) Tanga beds | TANZANIA ? Sclous Hatambulo Tanga Kilulu | Integer TANZANIA Selous Mkuju & Luwegu Ngerengere beds ? Tanga Second phase of rifting responsible for ? | ? | | Vopfner and Kaaya, (1991) Catuneanu, (2004) Suillocheau and Liget, (2009) Hankel, (1993) uillocheau and Liget, (2009) |
| | SUMALIA Mandera-Lugh TANZANIA Selous Tanga Duruma ETHIOPIA | ? Dwyka ? ? ? ? Taru Fm Calub Fm | Mandera-Lugh Image: Constraint of the second seco | TANZANIA Rufui ? Sclous Rufui ? Tanga Kilulu ? ver Majiya Duruma Mariakani upper Majiya Chumvi printipola Babb En | Image TANZANIA Selous Mkuju & Luwegu Ngerengere beds ? adaehero Image Matolani Second phase of rifting responsible for ? Duruma Adigrat Fm Second phase of rifting responsible for ? Fm Image of the state ? | | | iopfiner and Kaava, (1991) :atuncanu, (2004) iuillocheau and Liget, (2009) iuillocheau and Liget, (2009) iuillocheau and Liget, (2009) iuillocheau and Liget, (2009) Vorku and Astin, (1992) |
| | NUMALIA Mandera-Lugh TANZANIA Selous Tanga Duruma ETHIOPIA Ogaden Basin Southern Uganda Vorhen Lak Victoria | ? Dwyka ? ? ? ? Taru Fm Calub Fm ? | Mandera-Lugh Image: Constraint of the sector of the sec | TANZANIA Sclous Hatambulo Rufui ? 1 I Tanga Kilulu ? 1 wer Majiya mwi Duruma Mariakani upper Majiya Chumvi ? 1 Order Basin Southera Uganda Bokh Fm Gumburo Gumburo Southera Uganda ? 1 1 | Integration TANZANIA Selous Mkuju & Luwegu Ngerengere beds ? Image: Comparison of the select of the s | Image: second | Image: Section of the sectio | iopfiner and Kaava, (1991) :attuncentu, (2004) iuillocheau and Liget, (2009) iuillocheau and Liget, (2009) iuillocheau and Liget, (2009) iuillocheau and Liget, (2009) Vorku and Astin, (1992) schlueter et al., (1993) |
| | NUMALIA Mandera-Lugh TANZANIA Selous Tanga Duruma E-THIOPIA Ogađen Basin Southern Ugandi Norden Like Victoria | ? Dwyka Dwyka ? ? Taru Fm Calub Fm ? | Mandera-Lugh Image: Constraint of the state of the st | TANZANIA Selous Hatambulo Rufui ? 1 Tanga Kilulu ? 1 ver Majva mutu Duruma Mariakani upper Majiya Chumvi . Matolani ETHHOPIA Opaden Basin Bokh Fm ? Gumburo Southera Uganda | Integer TANZANIA Selous Mkuju & Luwegu Ngerengere beds ? Image Matolanii Second phase of rifting responsible for ? Fm Ogaden Basin ? Southern Uganda Adigrat Fm ? | | Image: Second | iopfiner and Kaaya, (1991) iopfiner and Kaaya, (1991) iuillocheau and Liget, (2009) iuillocheau and Liget, (2009) iuillocheau and Liget, (2009) iuillocheau and Liget, (2009) Vorku and Astin, (1992) schlueter et al., (1993) |
| | NUMALIA Mandera-Lugh TANZANIA Selous Tanga Duruma ETHIOPIA Ogaden Basin Southern Uganda Norhera Lak Victoria | ? Dwyka ? ? ? Taru Fm ? Calub Fm ? Guillocheau and Liget, (2009) Veevers, (1994) Veevers, (1994) | Mandera-Lugh Image: Constraint of the second seco | TANZANIA Selous Hatambulo Rufui ? Tanga Kilulu ? I ver Majya Duruma Mariakani upper Majiya Chumvi Matolani miti FTHIOPLA Ocaden Basin Bokh Fm Gumburo Suthern Uganda ? I Suthern Uganda ? I | Italogs ? TANZANIA Selous Mkuju & Luwegu Ngerengere beds ? ? adambero Tanga Duruma Matolani Adigrat Fm Second phase of rifting responsible for ? ? Fm Ugaden Basin Adigrat Fm ? Southern Ugada ? ? Guillocheau and Liget, (2009) Raillard, (1990). Watkeys, (2002) Cox, (1997) | Image: Second | | iopfiner and Kaava, (1991) iopfiner and Kaava, (2004) iuillocheau and Liget, (2009) iuillocheau and Liget, (2009) iuillocheau and Liget, (2009) vorku and Astin, (1992) Schlueter et al., (1993) |
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| | NUMALIA Mandera-Lugh TANZANIA Selous Tanga Duruma ETHIOPIA Ogaden Basin Southern Uganda Vordern Lak Victoria | ? Provide a series of the se | TANZANIA Ecca Group TANZANIA Sectors Sectors Tanga Duruma ? ? Tanga Mbuyura (st; mds Tanga beds Duruma ? ? Taru Calub Fm Bokh Fm Bokh Fm Southern Uganda Image Image Image Juillocheau and Liget, (2009) Vopfner, (1999) Visser, (1987) Johnson, (2006) Visser, (1987) Caluneau and Elango, (Banks et al., (1995) Southern Uganda Image Image Image Juillocheau and Liget, (2002) Wopfner, (1999) Visser, (1987) Vevers and Cole, (1994) Salman & Abdullah, Wopfner, (2002) Watkeys and Sokoutis, (1998) Salman & Abdullah, Woolley, (1991) Batail et al., (1985) Image Image Batail et al., (1987) Image Image Image Bristow and Sageerson, (1983) Image Image Image | TANZANIA Selous Hatambulo Rufui ? ! Tanga Kilulu ? ! ! rem Mijyo Duruma Mariakani upper Majiya Chumvi Matolani FTHIOPIA Mariakani upper Majiya Chumvi Gumburo Southera Ugana ? . Southera Ugana ? . (2001) Euillocheau and Liget, (2009) Kreuser, (1995) Delvaux, (1991) Cole, (1992) Daly etal., (1980) (2010) Cole, (1992) Bokh Fm . (2010) Cole, (1992) Daly etal., (1980) . (2010) Cole, (1992) . . . (1995) Delvaux, (1991) . . . (2010) Cole, (1992) (1995) Output etal., (2004) (1995) Marine (1995) Marine (1995) Marine . . </td <td>those ? TAVZANIA Selous Mkuju & Luwegu Tanga Matolani Duruma Adigrat Fm Vigaden Bashi Adigrat Fm Southern Ugada 2 Guillocheau and Liget, (2009) Raillard, (1990). Watkeys, (2002) Jourdan et al., (200 Jourdan et al., 2005. Jourdan et al., (200, Riller et al., (1978) White, (1977) Duran et al., (1978) White, (1997) Virlogeux, (1984) Hesselbo et al. (200 Glacial Rifting Subsidence Rifting Flatue Folding</td> <td>Image: Second state of the se</td> <td></td> <td>iopfiner and Kaava, (1991) iopfiner and Kaava, (2004) iuillocheau and Liget, (2009) iuillocheau and Liget, (2009) iuillocheau and Liget, (2009) iuillocheau and Liget, (2009) Vorku and Astin, (1992) schueter et al., (1993)</td> | those ? TAVZANIA Selous Mkuju & Luwegu Tanga Matolani Duruma Adigrat Fm Vigaden Bashi Adigrat Fm Southern Ugada 2 Guillocheau and Liget, (2009) Raillard, (1990). Watkeys, (2002) Jourdan et al., (200 Jourdan et al., 2005. Jourdan et al., (200, Riller et al., (1978) White, (1977) Duran et al., (1978) White, (1997) Virlogeux, (1984) Hesselbo et al. (200 Glacial Rifting Subsidence Rifting Flatue Folding | Image: Second state of the se | | iopfiner and Kaava, (1991) iopfiner and Kaava, (2004) iuillocheau and Liget, (2009) iuillocheau and Liget, (2009) iuillocheau and Liget, (2009) iuillocheau and Liget, (2009) Vorku and Astin, (1992) schueter et al., (1993) |

Figure 51: Litho-stratigraphic and event chart of Karoo basins in Africa. The Karoo basins preserve the sedimentary record from Late Carboniferous–Early Jurassic of the Karoo Supergroup deposited into intracratonic rift basins in Gondwana, and the formation of these basins was in Quenced by the pre-existing crustal architecture of the African continent. The deposition of sediments was controlled mainly by tectonic and climatic changes.

Figure 52: Litostratigraphic chart of Karoo basins in Africa.

Figure 53: Litostratigraphic and event chart of Karoo basins in Africa.

BREAKUP

RUHUHU BASIN LUANGWA BASIN MAIN KAROO BASIN Jpper Grit Unit Clarens Fm Elliot Fm Molteno Fm Ntawere ormation Burgerdorp Frr scarpment Grit ngori ndstone Katberg Fm Upper Madumabisa Viember Balfour Fm Ruhuhu rmation Lower Madumabisa Member GOGEA G GROU Mukumba Mb Musipixi Cgl Mhukuru Fm Collingham Frr Whitehill Fm Prince Albert F J chuma Fr Luwumbu Coal Formation Waaipooort Fm dusi Formation Banks et al., (1995) Johns., (1986) Catuneanu et al. 200: Guillocheau and Liget, 2009 Hankel, 1994 Woffner, 1994 Woffner, 2002 Catuneanu et al. 200 Guillocheau and Liget, 2009

Figure 54: Lithostratigraphic and event chart in the south Tanzania Basins, the figure shows the general incoherencies in the predicted periods of oceanization and breakup in the Somali. Breakup ages start from as early as Late Triassic to Oxfordian, but oceanization is predicted to start with the Toarcian with the deposition of the Andafia beds.

ALKALINE BASALTS RHYOLITES

Figure 55: Lithostratigraphic and event chart in the Mozambique Basin, the highlights the general incoherencies in the predicted periods of oceanization and breakup in the basin. The rifting is predicted to have started in the Late Triassic and ended in the Lower Jurassic with the Karoo volcanic event, but Salazar et al. (2013) and others, argue rifting to have continued into the Late-Middle Jurassic affecting the Belo Formation

Figure 4: Magnetic anomaly interpretations in the Mozambique and Riiser Larson Sea by Leinweber and Jokat (2012)

Figure 7: Seismic analysis of Zambeze Basin by Castelino et al., (2015), showing the location of magnetic anomalies on the continental Beira High crust.

Figure 56: Summary of major lithotectonic events recorded in the Indian Ocean and the Tethys Ocean. The Tethys Ocean existed before the breakup of Gondwana, and its proximity to the Indian Ocean permitted recording of major tectono-magmatic events that affected the two ocean.

Figure 57: Summary of major events recorded Mozambique basin and the Tethys Ocean (in the ophilitic belt of Eastern Oman and Western Pakistan from figure 56. Notice the good correlation of the tectonic events with the Indian Ocean, and the absence of record of the M41 event in both the Mozambique basin and the Tethys Ocean.

Figure 58: Map showing the seismic lines used in the study in the Mozambique Channel. (offshore lines in white) (Mercator projection)

Figure 59: Seismic interpretations of lines LINE- 09 and LINE- 10 delineating different identified domains across the Limpopo basin. LINE- 09 was combined with lines B03-A B03-B, and B01-A, and LINE- 10 was similarly combined with lines B02-A and B03-B to extend our interpretations onshore and to investigate the trend of the landwarding reflectors, previously interpreted Karoo volcanics and SDR's (Cox, 1992, Klausen, 2009). The brown horizon (Pre-drift Karoo sediemnts) continues landwards into intracratonic basins from the uplifted zone where it sharply dips into the basin and into the intracratonic basins. The uplifted zone is characterized by flexural uplift of the basement leading to margin morphology change and erosion of the Maputo sediments.

Oceanic Domain

MBWG13-035

Figure 60: Interpretations on seismic lines LINE-11 and LINE-12. The green horizon lies directly above basement offshore, mostly in the transition zone. It represent the first rift infilling to flexural uplift and early drift sediments in the Limpopo basin. Notice the thickening of the progradational blue horizon (The Lower Domo Shales) seaward, and the major fault deformation within the oceanic domain. Line LINE-11 show evidence of recent volcanic activity.

Figure 61: Seismic line LINE-13 in the Limpopo basin. Notice in the wedging zone, the trend landward dipping reflectors previously interpreted as Karoo volcanics, and the more recent volcanic activity within the transitional domain; intruding the green, yellow and blue horizons.

Figure 62: Seismic lines LINE-03 and LINE-04. Notice the different volcanic episodes on seismic MBGW13-027, and the capping of the brown horizon by 'Karoo volcanics'.

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Figure 63: Event and chronostratigraphic chart of Natal and Limpopo Basins compared to major global tectonic events.

Distance (km)

Figure 64: Seismic lines LINE- 01, LINE- 02, and LINE- 05 of the Zambezi basin delineating the extent of the continental, transitional domains and oceanic domains in the basin.

Figure 65: Seismic lines LINE- 06, LINE- 07, and LINE- 08 of Zambezi basin, showing margin structuration and delimitation

Figure 66: Map of Limpopo-Natal Basin showing the structure of the margin and the delineation of the different domains (Oceanic, continental, and thinned continental crust).

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Figure 67: Basement geology of Antarctica compiled from (Rediel et al., 2013: Boger, 2011: Gosh et al., 2004: Kelly et al., 2002 – see Plate 1 supplementary material). Base on geochronological properties and similar orogenic history, the area marked Zone 1 (Blue rectangle) is related to the Kaapval craton of Southern Africa, Zone 2 (Red rectangle) is related to the Eastern Ghats craton of Eastern India, and Zone 3 (Yellow rectangle) is related to the Australian plate. The trace of the Beardmore, Mawson, Mesoproterozoic A, D, E, and the accreted pre and post Gondwana sediments in Antarctica and Australia is After Boger (2011). World Geodectic System 1984 figures 68-74.







Figure 68: (a) Geological map of Africa compiled from (Foster et al., 2015: Rekha et al., 2014: Jacobs et al., 2008: Guiraud et al., 2005: Dewaele, 2003: Daly et al., 1989. The zone 1 (blue rectangle figure 67), marks a domain of similar geochronological properties with Antarctica. (b) Zoom on figure 5a showing the domain of shared geological history with the Antarctica plate. The archean Kaapvaal Craton bear similar geochemical signatures similar to archean Grunnehogna Craton, most likely forming a single craton. The Namaqua-Natal belt formed during the Namaquan Orogeny (1.1-10Ga), and is regarded as an extension of the Mesoproterozoic Maud Belt (1.1Ga) in Antarctica.



Figure 69: Geology of India basement compiled from (Tucker et al., 2014; Rajaprian et al., 2014; Dasgupta et al., 2013; Ghosh et al., 2004; and <u>www.portal.gsi.gov.in/portal 11/07/2016</u>. The marked area zone 2 (figure 67), indicates area of similar geological similarities with Antarctica. Rocks of the Ghats share similar geochronological properties with rocks of Enderby Land in East Antarctica. The Dharwar Craton of India shares similar geochemical and geochronological properties with the archean rocks of earstern Madagascar.



Figure 70: Basement geology of the Australian modified (after Borg and DePaolo, 1991 and Boger, 2011). Zone 3 indicates area of sheared geological similarities with Antarctica. The Mawson and Beadmore cratons of Antarctica continue into the Gawler and Curnamon blocks in Antarctica respectively, bearing similar geochemical and geochronologically characteristics.



Figure 71: Geology of Madagascar compiled from (Tucker et al., 2014: Rekha et al., 2014: Rasoamalala et al., 2013; de Wit et al. 2003; Nesen et al., 198;: Courrier and Lafont, 1987; Besairie and Collignon, 1972). The Western Dharwar craton Of Madagascar shares similar geochemical and geochronological properties with the Dharwar craton in India. The Batsimisaraka shear zone in Rekha et al., 2014, is argued by Tucker et al., 2014 not to be evident.



Figure. 72: Geological map of the Falkland Plateau compiled from (Lock, 1978; Martin et al., 1981; Marshall, 1994; Curtis and Hyam, 1998). DSDP Hole 330 was bottomed in Precambrian rocks (554± 66Ma Lorenzo and Mutter, 1988) correlative with the Pan-African ~650-500Ma Cape basement of Southern Africa.



Figure 73: Basement geology map of Sri Lanka (modified after Koner et al., 2003; Bingen et al., 2009; Kelly et al., 2002; and Tucker et al., 2014– see Plate 6 supplementary material).







Figure.74 Comparing the kinematic models of Nguyen et al. (2016), Klimbe and Franke (2016), Davis et al. (2016), Reeves et al. (2015), Gaina et al. (2013), Leinweber and Jokat, (2012), Seton et al. (2012), Torsvik et al. (2012) and Sahabi (1993). The red, ash, blue, yellow and deep blue polygons represents overlap, Neoproterozoic terrain, Mesoproterozoic accreted terrain, Late Archean rocks, Paleo-Meso Archean rocks respectively.. The blue circle compares the geology of the India-Madagascar-Sri Lanka-Africa domain. Leinweber and Jokat (2012), Reeves et al. (2015), Davis et al. (2016) are model after the geochronological studies of Ghosh et al., 2004. In these models, the Agavo Ifanadiana shear zone (Madagascar) is aligned with the Moyar shear zone (West India). This results in overlap between India and Antarctica. Gaina et al. (2013) and Sahabi (1993) on the other hand, fit the Batsimisaraka shear zone to the Moyar shear zone avoiding the overlap, but inaccurately fit Mesoproterozoic rocks to Archean rocks. The models of Seton et al. (2012) and Torsvik et al. (2012) result in misalignment of Archean rocks of the Napier complex (Antarctica) and the Eastern Ghat craton (East India), and the conjugate Gondwanaian rifts basins. Sahabi (1993) and Davis et al. (2016), on the other hand presents alignment of Archean rocks of the Napier complex and the Ghat craton and a good alignment of the Gondwanian rifts basins. Klimbe and Franke (2016) prefer a more southward position of Madagascar leading to huge gap of about 1000km between Antarctic and Africa taken into consideration current information and observations we have gathered on the surrounding plates. (Mercator projection).



Figure 75: Comparism (zoom) of India and Antarctica with referencee to Africa for the models of Nguyen et al. (2016), Reeves et al. (2015), Gaina et al. (2013), Leinweber and Jokat (2012), Seton et al. (2012), and Sahabi (1993). The models of Nguyen et al. (2016), Gaina et al. (2013) and Seton et al. (2012) result in misalignment of Archean rocks of the Napier complex and the Ghat craton, and the Gondwanaian rifts basins. Reeves et al. (2015), Leinweber and Jokat (2012) and Sahabi (1990), on the other hand results in a perfect alignment of Archean rocks of the Napier complex and the Ghat craton, and Gondwana rifts basins. Notice the large overlaps in Nguyen et al. (2016), Reeves et al. (2015), Gaina et al. (2013) and Leinweber and Jokat, (2012). The pink color represent gap between the plates. (Mercator projection).



Figure 76: Comparing reconstruction of Madagascar and India with referencee to Africa in Nguyen et al. (2016), Reeves et al. (2015), Gaina et al. (2013) and Leinweber and Jokat (2012) Seton et al, (2012), and Sahabi (1993). In Reeves et al. (2015) and Leinweber and Jokat (2012), the Agavo Ifanadiana shear zone is aligned with the Moyar shear zone, resulting in Mesoproterozoic rocks of Ikalamavony in Madagascar fitted with Archean rocks Dharwar craton in India. Nguyen et al. (2016), Gaina et al, (2013) and Seton et al. (2012), on the other hand results in about ~140km gap between India and Madagasca, and fits Mesoproterozoic rocks to Archean rocks between the two plates. The pink color represent gap betweeen the plates. (Mercator projection).



Figure 77: Comparing the fits between Antarctica with respect to Africa, and the consequence on the Beira High continental crust and the Limpopo basin. The yellow line crossing the Beira High continental block shows the location of the seismic refraction profile 2014001014 of the MOCOM-Cruise (See figure 11). Notice all the models except Sahabi, (1993) overlap on the Beira high, the North Natal Valley, a part or the total Limpopo Basin and the North Mozambique ridge. The North Mozambique Ridge (NMR, in red) consist mainly of sediments muscle on a thinned continental crust (Lepretre et al., 2017; Moulin et al., submitted). The Southern Mozambique Ridge (SMR, in black) maybe composed of volcanics (Gohl et al., 2011). (Mercator projection).



Figure 78: Comparing the proposed fit for the Falkland-Patagonia in the reconstruction of Martin and Hartnady (1986) and Martin et al. 1982 (green) and the models Leinweber and Jokat (2012) and Konig and Jokat (2006) (orange) relative to African plate. Notice Leinweber and Jokat (2012) and Konig and Jokat (2006) (orange) significantly overlap the North Natal Valley, which is underlain by continental crust (Moulin et al., submitted). Red line: refraction profile M7 Pamela Moz3-5 of Lepretre et al. (2017); Blue line the limit of the South Tegula Ridge. SMR= South Mozambique Ridge. (Mercator projection).



Figure 79: Map showing our reconstruction of Antarctica with respect to Africa. Notice the Antarctica plate do not overlap the Beira High continental crust, and the extent of the Archean Kaapval and Grunneghona Craton. The two cratons bears strong geochemical signatures with each other. The reconstruction of the Falkland Plateau to Africa shows the similarities between the geology of the Pan-African basement and the rocks of the Maurice Ewing Bank. Green line: refraction profile M7 Pamela Moz3-5 of Lepretre et al. (2017); Blue line the limit of the South Tegula Ridge. (Mercator projection)



Figure 80: Map showing our reconstruction of India and Antarctica (with respect to Africa). The Archean rocks of the Napier complex in Antarctica and the Eastern Ghats craton share similarly geochemical characteristics. The Rayner Complex extends from Enderby Land (Antarctica) into the Mesoproterozoic rocks of the Eastern Ghats Granulite in India. Notice the alignment of the conjugate Carboniferous-PermoCretaceous rift basins of Godavari and Mahanadi in India, and the Lambert and Robert rift valleys in Antarctic. The ~120km overlap between India and Antarctica (red area) within Southern Bangladesh is explained by the not clearly defined limits of the India plate within the region, and the characterization of the region by Large compressional deformation. (Mercator projection)



Figure 81: Map showing our reconstruction of Australia and Antarctica (with respect to Africa). Notice the alignment of the Beardmore and Curnamona cratons, and the continuation of the Mesoproretozoic rocks (Boger, 2011) between Antarctica and Australia. (Mercator projection).



Figure 82: Map showing our reconstruction of Madagascar with respect to Africa The continuation of the Vohibory Pan-African shear zone to the Pan-African shear zone in Tanzania (de Wit et al., 2001; Reeves and de Wit., 2000), the Brava fault in Kenya to continue with the Andreaparaty shear zone in Madagascar, and the Belet Uen fault to be continues with the fault lying to the northern fringe of Madagascar. (Mercator projection).



Figure 83: Map showing our reconstruction of India and Madagascar. Note the correspondence of Eastern Dharwar craton of India and the Western Dharwar craton of Madagascar. We fit the Precambrian shear zones of Agavo Ifadiana shear zone of Madagascar to the Palghat shear zones of India. This results in alignment of Archean and Mesoproterozoic rocks in both in Madagascar and India. (Mercator projection).



Figure 84: Our proposed initial fit of Gondwana. This new model shows the full extent of the Dharwar craton traced from the India plate into Madagascar and possibly into the Bur Acaba of Africa and beyond. It permits a very good alignment of the Beardmore and Mawson cratons in Antarctica and Australia, and allows a good trace of Mesoproterozoic rocks of Antarctica and Australia to be traced into each other. It also grants a perfect alignment of Archean rocks of the Napier complex and the Ghat craton, and a good alignment of Gondwana rifts basins. LB: Elan Bank. (Mercator projection).



Figure. 85: Zoom on figure 22, showing perfect alignment of Precambrian shear zones of the Agavo Ifadiana shear zones of Madagascar, to the Palghat shear zones of India respectively. It also shows the full extent of the Pan-African orogenic event and the Karoo volcanism in Gondwana. (Mercator projection).



Figure. 86: New reconstruction model showing the main distribution of Karoo sediments and volcanics in Africa, Madagascar, and Antarctica. The Southern Africa continent is characterized by vast network of sills and dykes which are pre-syn-post Karoo volcanism.



Figure 87: Reconstruction of the Indian Ocean at anomaly during the mid-late Jurassic, East -West Gondwana separated. The break-up of Gondwana was accompanied by active seafloor spreading in the Western Somalia and Mozambique Basins with the formation of first oceanic crust at M25 (157Ma). LB: Elan Bank. (Mercator projection).



Figure: 88: Reconstruction of the Indian Ocean at anomaly at M22 (48.57Ma). (Mercator projection).



Figure 89: Reconstruction of the Indian Ocean at anomaly at M15 (135.96Ma). (Mercator projection).



Figure 90: Reconstruction of the Indian Ocean at anomaly at M10r (128.93Ma). This period saw large scale plate reorganisation in the Indian Ocean, leading to the formation of Curvier, Perth and Gascogne basins on the northwestern Australian margin (Veevers et al., 1988), and breakup of the South Atlantic Ocean the formation of the first oceanic crust in the North Natal Valley. EB: Elan Bank (Mercator projection).



Figure 91: Reconstruction of the Indian Ocean at anomaly at M5 (126.57Ma). (Mercator projection).



Figure 92: Reconstruction of the Indian Ocean at anomaly at M0r (120.6Ma). The Madagascar-Greater India-Sri Lanka block stopped its southward drift from Africa at M0. The accretion in the Curvier, Perth and Gascogne basins also stopped at M0. The South Mozambique Ridge, Maud Rise, Aquihas Plateau, and northern part of the Astrid Ridge these four ridges overlap at the Southern Mozambique Ridge at M0, which means they may hve emplaced during tht time, possibly due to anormalous volcanism. The North Kerguelen Plateau may have been initiated around this time. (Mercator projection).



Figure 93: Reconstruction of the Indian Ocean at anomaly C34 (83Ma). Breakup and first oceanic recorded between Madgascar and India, and Australia and Antarctica. Anomalous oceanic plateaus (Conrad Rise, Crozet Ridge, Del Cano Rise and the South Madagascar Ridge) became emplaced during this period. The Del Cano Rise is a companion feature of the southern Madagascar according to Goslin et al., 1981. The Middle Kerguelen Plateau and the Broken Ridge were emplaced around this time. AP: Agulhas Plateau; BR: Broken Ridge; CB: Crozet Bank; CKP: Central Kerguelen Plateau; DCR: Del Cano Rise; LR: Chagos- Laccadive; LA: La Réunion; M: Mauritius; MP: Mascarene Plateua; N: Nazareth Plateau; SB: Saya de Malha Bank; NKP: North Kerguelen Plateau; South Kerguelen Plateau; SP: Seychelles Plateau. (Mercator projection).



Figure 94: Reconstruction of the Indian Ocean at anomaly C28 (62.49Ma). The Mascarene Basin stopped its accretion at C27, and a ridge jump initiated seafloor spreading between Seychelles and India at C27. The Chagos-Laccadive (LR), the Ninetyeast Ridges, North Kerguelen Plateau may have been emplaced during this period. AP: Agulhas Plateau; BR: Broken Ridge; CB: Crozet Bank; CKP: Central Kerguelen Plateau; DCR: Del Cano Rise; LR: La Réunion; M: Mauritius; MP: Mascarene Plateua; N: Nazareth Plateau; SB: Saya de Malha Bank; NKP: North Kerguelen Plateau; South Kerguelen Plateau; SP: Seychelles Plateau. (Mercator projection).



Figure 95: Reconstruction of the Indian Ocean at anomaly C18 (39.5Ma). formation of first oceanic crust between Arabia and Africa. AP: Agulhas Plateau; BR: Broken Ridge; CB: Crozet Bank; CKP: Central Kerguelen Plateau; DCR: Del Cano Rise; LR: Chagos- Laccadive; LA: La Réunion; M: Mauritius; MP: Mascarene Plateua; N: Nazareth Plateau; SB: Saya de Malha Bank; NKP: North Kerguelen Plateau; South Kerguelen Plateau; SP: Seychelles Plateau. (Mercator projection)



Figure 96: Map showing the evolution of the Madagascar in our model from fit to present position. (Mercator projection).





Figure 97: (a) Map showing the evolution of the Antarctica in our model from fit to present position. (b) Comparism of the evolution of the Antarctica and Madagascar in our model (Mercator projection).




Figure 98: (a) Map showing the evolution of Madagascar in (Reeves et al., 2015; Gain et al., 2013; Leinweber and Jokat, 2012; and Sahabi, 1993), compared in (b) with the evolution of Madagascar in our model. The black arrows indicate the direction of movement of the plates through time. Reeves et al., 2015 closest tour model. (Mercator projection).





Figure 99: (a) Map showing the evolution of Antarctica in (Reeves et al., 2015; Gain et al., 2013; Leinweber and Jokat, 2012; and Sahabi, 1993), compared in (b) with the evolution of Antrctica in our model. The black arrows indicate the direction of movement of the plates through time in published models. Sahabi, 1993, closest to our model. (Mercator projection).



ALKALINE BASALTS

RHYOLITES

Figure 100: Reinterpretation of the lithostratigraphic and event chart in the Mozambique Basin (figure 55). We propose rifting may have continued until late-Middle Jurassic. This implies the Belo formation maybe is a synrift formation, as has previously proposed by [(Salazar et al., 2013 See figure 101)], and oceanization did not occur with the Karoo magmatic event (182-186), but was initiated around anomaly M25 in the early-Upper Jurassic (157Ma). 106



Figure 101:2D seismic reflection interpretation offshore Zambezi Basin by (Salazar et al., 2013). Notice the Karoo and the Belo Formation are interpreted as syn-rift formation. The insert above: location of the seismic lines use in their study.



Figure 102: Reinterpretation of the lithostratigraphic and event chart in the South Tanzania Basin (figure 56). The rifting may have started in Triassic and ended in the Callovian, initiating breakup and oceanization onwards.



Figure 103: Labails et al. (2010), observed in the Central Atlantic a major change in direction of plate propagation from NW-SE to WNW-ESE. Notice the huge change in direction of propagation between BSMA and anomaly M25 (b and c).



Figure 104:.(a) (c) Sandwell et al. (2014) free-air satellite-derived gravity anomaly of the Mascarene showing clear fracture zones between Madagascar and India. (b) Satellite-derived gravity anomaly of the Mascarene Basin The red lineindicate major fracture along which the India plate moved. (c) Reconstruction of Madagascar and India by Aswhal et al. (2016). They found Archaean zircons in Miocene oceanic hotspot rocks and establish ancient continental crust beneath Mauritius. They proposed the Mauritius continental plate bewteen Madagascar and India.



Figure 105:Map showing the reconstruction of India to Madagascar and the possible position of the Archaean zircons. The clear fracture zones between India and Madagascar indicates that the two plates separated from each other. Hence, the retrieve Archean rocks could well be fragments of India as it continued it drifting from Madagascar. (Mercator projection).



Table 1: Poles Antactica-Africa

| Age | Latitude | Longitude | Rotation | Source |
|-------|----------|-----------|-----------|-----------------------|
| Ano18 | 13.6 | -41.4 | 7.47 | Bernard et al. (2005) |
| Ano23 | 8.5 | -40.8 | 10.01 | Bernard et al. (2005) |
| Ano28 | 11.3 | -49.6 | 11.11 | Bernard et al. (2005) |
| Ano32 | -1.2 | -42.4 | 12.38 | Bernard et al. (2005) |
| Ano34 | -1.3 | -34.7 | 17.78 | Bernard et al. (2005) |
| M0 | 11.72991 | 154.0759 | -42.51146 | This study |
| M5n | 12.68688 | 154.0827 | -44.66053 | This study |
| M10r | 9.705075 | 152.8902 | -46.33414 | This study |
| M15n | 9.864203 | 153.7544 | -50.71872 | This study |
| M22n | 8.271569 | 152.2943 | -53.09270 | This study |
| M25n | 8.428259 | 152.0446 | -55.43329 | This study |
| Fit | 8.969426 | 151.6038 | -58.75505 | This study |

Table 2: Poles Madagascar-Africa

| Age | Latitude | Longitude | Rotation | Source | |
|-------------|----------|-----------|-----------|------------|--|
| Initial fit | 9.384853 | 117.2845 | -15.40567 | This study | |
| M25n | 5.161909 | 110.0051 | -12.69742 | This study | |
| M22n | 2.188300 | 102.7732 | -10.97189 | This study | |
| M15n | 4.675859 | 97.03268 | -8.123477 | This study | |
| M10r | 3.488152 | -98.77951 | 6.404223 | This study | |
| M5n | 8.683980 | -107.8003 | 5.789815 | This study | |

| M0r | 0.000 | 0.000 | 0.000 | |
|-----|-------|-------|-------|--|
| | | | | |

Table 3: Poles India-Africa

| Age | Latitude | Longitude | Rotation | Source |
|-------|----------|-----------|-----------|--------------------------|
| Ano5 | 22.1900 | 33.4100 | -4.7100 | Eagles and Hoang (2013). |
| Aoo18 | 16.2000 | 48.4700 | -25.2400 | Eagles and Hoang (2013). |
| Ano21 | 17.8400 | 44.4200 | -25.7700 | Eagles and Hoang (2013). |
| Ano22 | 18.1100 | 42.3000 | -27.2100 | Eagles and Hoang (2013). |
| Ano24 | 18.4800 | 37.8600 | -29.9500 | Eagles and Hoang (2013). |
| Ano25 | 18.5300 | 33.6600 | -34.4300 | Eagles and Hoang (2013). |
| Ano26 | 19.1200 | 31.6200 | -35.9000 | Eagles and Hoang (2013). |
| Ano27 | 20.1500 | 28.4900 | -38.0500 | Eagles and Hoang (2013). |
| Ano28 | 21.6700 | 25.8200 | -39.8000 | Eagles and Hoang (2013). |
| Ano31 | 22.6100 | 24.0400 | -45.1600 | Eagles and Hoang (2013). |
| Ano32 | 22.4900 | 24.2200 | -47.5200 | Eagles and Hoang (2013). |
| Ano34 | 22.4300 | 24.9600 | -53.6300 | Eagles and Hoang (2013). |
| M0r | 22.22783 | 24.40480 | -56.71661 | This study |
| M5n | 22.16459 | 29.60182 | -60.14409 | This study |
| M10r | 23.17356 | 30.41119 | -60.07137 | This study |
| M15n | 25.46677 | 32.16216 | -59.68924 | This study |
| M22n | 26.59191 | 35.30000 | -59.83694 | This study |
| M25n | 28.44201 | 36.86446 | -59.31655 | This study |
| Fit | 31.31943 | 38.96307 | -58.86290 | This study |

Table 4: Poles Australia-Africa

| Age | Latitude | Longitude | Rotation | Source |
|-------|----------|-----------|-----------|------------|
| AnoO | O.000 | O.000 | O.000 | This study |
| Ano18 | 16.30318 | 50.92139 | -22.41163 | This study |
| Ano28 | 10.92827 | 61.22190 | -26.94301 | This study |
| Ano34 | 16.90723 | 75.47579 | -27.48594 | This study |
| MO | 24.73430 | 107.5313 | -41.06655 | This study |
| M5n | 26.15952 | 109.5644 | -42.60602 | This study |
| M10r | 23.21838 | 111.0177 | -44.40272 | This study |
| M15n | 24.13406 | 115.6568 | -47.28139 | This study |
| M22n | 22.52906 | 116.5607 | -49.91948 | This study |
| M25n | 22.88478 | 118.0439 | -51.93749 | This study |
| Fit | 23.67146 | 119.8226 | -54.90728 | This study |

Table 5: Poles Sri Lanka-Africa.

| Age | Latitude | Longitude | Rotation | Source |
|------|----------|-----------|-----------|------------|
| | | | | |
| M0r | 10.11700 | 42.55943 | -81.32627 | This study |
| | | | | |
| M5n | 10.18472 | 45.66046 | -85.58115 | This study |
| M10r | 10.99839 | 46.09781 | -85.72527 | This study |
| | | | | |
| M15n | 12.82913 | 47.08052 | -85.77724 | This study |
| M22n | 2.044542 | 52.97449 | -52.31302 | This study |
| | | | | |
| M25n | 15.41446 | 49.81841 | -86.50547 | This study |
| | | | | |
| Fit | 17.65087 | 50.91434 | -86.33724 | This study |
| | | | | |

From anomaly C34 Sri Lanka together with India.

Table 6: Poles Seychelles-Africa.

| Age | Latitude | Longitude | Rotation | Source |
|------|----------|-----------|-----------|------------|
| | | | | |
| M0r | 2.905783 | -136.6054 | 45.91607 | This study |
| | | | | |
| M5n | 2.311616 | -133.3757 | 51.06846 | This study |
| | | | | |
| M10r | 1.266099 | -132.3603 | 51.14625 | This study |
| | | | | |
| M15n | 1.030455 | 49.95525 | -51.10443 | This study |
| | | | | |
| M22n | 2.044542 | 52.97449 | -52.31302 | This study |
| | | | | |
| M25n | 3.771343 | 55.01324 | -52.15144 | This study |
| | | | | |
| Fit | 6.548114 | 57.69930 | -52.07016 | This study |
| | | | | |

Seychelles move India after the separation of India and Madagascar until the final drift at anomaly C28.

Table 7: Poles Falkland-Africa

| Age | Latitude | Longitude | Rotation | Source |
|-----|----------|-----------|----------|------------|
| Fit | 46.92559 | -33.09283 | 57.66492 | This study |



APPENDIX FIGURES

Figure 1: Reconstruction model of Powells and Veevers (1987). Mercator projection.





Figure 3: Reconstruction model of Tikku and Cande (1999). Mercator projection







| | | | | Pa | lec | ogene Tir | ne So | al | е | | |
|-------------|-------|-----------------------------------|----------|-----------------------|----------------|---|-----------------------------------|-------------------|------------|--|------------------------|
| AGE (Ma) | Ep | ooch/Age (Stage) | Polarity | · | Plankt | onic Foraminifera | Larger Benthic Foraminifera | C | alcare | eous Nannofossils | Mega- Cycles R T |
| 45 - | | Lutetian | C20 | P10 | E8 | Guembelitrioides | SB713 | NP15 | CP13 | Chiasmolithus gigas Chiasmolithus gigas Nannotetrina | |
| | | 47.8 | C21 | 21 P9 E7 Turborotalia | | Turborotalia frontosa | | NP14 | CP12 | Blackites inflatus Discoaster subladgensis | Lut |
| 50 - | ocene | | C22 | P8 | a | Acarinina cuneicamerata | SBZ11 | NP13 | CP11 | (5-rayed) | Yp10 |
| | ш | Ypresian | C23 | P7 | E5 | Morozovella subbotinae aragonensis | SBZ10 | NP12 | CP10 | Tribrachintus orthostylus | |
| | | | | Рбь | E4 | Morozovella formosa | SBZ9 SBZ8 | NP11 | СР9 | Discoaster koloensis Tribrachiatus orthostytus Discoaster Tribrachiatus | |
| 55 - | | 56.0 | C24 | P6a P5 | E3 E2 E1 | Pseudohastigerina wilcoxensis Morozovella velascoensis | SBZ7 SBZ6 SBZ5 | NP10 | CP8 | diastypus rito achaids contortus Tribrachiatus bramlettei Rhomboaster spp. | |
| | | Thanetian | | | P5 c | Acarinina soldadoensis Globanomalina pseudomenardii | SBZ4 | NP9 | CP7 | Campylosphaera eodela Discoaster multiradiatus (common) Discoaster nobilis | - Th5 - |
| | | 59.2 | C2 | P4 | P4 b | | | NP8 NP7 NP6 | CP6 CP5 | Heliolithus riedelii Discoaster mohleri Heliolithus kleinpellii | |
| 60 - | ocene | Selandian | C26 | | <u>a</u> | Globanomalina pseudomenardii Parasubbotina loorina albeari varioscira | | NP5 | CP4 | Fasciculithus | Sel2/Th1 |
| - | Pale | 61.6 | | P3 | P3 a P2 | Morozovella angulata Praemunica | SBZ2 | NP4 | СРЗ | Fasciculithus 2nd radiation | Sel1 |
| | | Danian C28 P1 P1 b Subtrian | | SBZ1 | NP3 | CP2 | Chiasmolithus | | | | |
| 65 - | 0 | 66.0 | C29 | Pa | Pa Pa | Subbotina trikoculinoides Parvularugoglobi- gerina eugubina Globotrumoura | V | NP2 NP1 | CP1 | Cruciplacolithus tenuis Blantholithus sparsus; Calcisphere FLOOD Micula murus, | |
| I - | C | etaceous | | - | | Giocotruncana | | | | other Cret. nannos | |

(c)

| | | | С | retac | eous | Time | S | C | ale | | | |
|-----------------|------|---------------------|-------------------|---|--|--|--------------|------|---|------------------------------|-----------------------|------------------------|
| AGE (Ma) | Eş | ooch/Age (Stage) | Polarity Chron | Western Interior Ammonoids | Inoceramids | Planktonic foraminifera | Ca | care | eous Nannofossils | 13 (per-mil -1.4 0 1.4 | C N PDB) 28 4.2 | Mega- Cycles R T |
| 85 - | | Santonian M | | D. bassleri - C. verniformis (4 zones) Clioscaphites saxitonianus | C. bueltenensis C. condiformis Cladoceramus undulatoplicatus | Dicarinella asymetrica | UC12 UC11 | CC16 | Lucianorhabdus cayeuxil Lithastrinus AgriWi Reinhardbites | | $\left\{ \right.$ | |
| | | u | | Scaphites depressus | M. crenelatus Magadiceramus subquadratus | | | | anthophorus nanus | | | |
| | | Coniacian | | Scaphites ventricosus | Volviceramus involutus - | Dicarinella | UC10 | CC14 | | L | | |
| | | 89.8 | | Scaphites preventricosus | deformis erectus (6 zones) | concarata | | | Micula stauropora | | Į | |
| 90 - | | u | | S. manasensis Prionocyclus germari - Prion. macombi (6 zones) | Cremnoceramus waitersdorfensis - Inoceramus aff. dimidius (7 zones) | | uce | CC13 | Marthasterites furcatus Lithastrinus septenarius | | $\left\{ \right.$ | Tu4. |
| | te | Turonian M | | Prionocyclus hyatti Coll. praecox Coll. woollgari | Inoceramus howelli - Mytiloides subheropricus (4 zooss) | Marginotruncana schneegansi | UC8 | CC12 | (senso lato) ▲ Eiffe6thus eximus | | $\left\{ \right\}$ | |
| - | La | 93.9 E | C34 | M. nodosoides V. birchbyi P. flexuosum W. devonense | Mytiloides mytiloides - M. puebloensis (3 zones) | H. helvetica Whiteineda | UC7 UC8 | CC11 | Kamptherius Amagnificus Quadrum chiastia gartneri Rhagodiscus | OAE 2 (Bonarell | | |
| 95 - | | ц — м | Dead Astronomy | Nigericeras scotti - Continoceras gilberti (15 zones) | Mytiloides hattini - Inoceramus prefragilis (4 zones) Inoc. rutherfordi Inoc. srvanus | Rotalipora cushmani | UC3 | CC10 | asper L. acutus Lithraphidites acutus, Cylindra Microrhabdalus biercus decoratus | | [| |
| | | – Cenomanian | | Tethyan Ammonoids | L macconneti Boreal Ammonoids | TH. POCHEN | UC2 | | _ | | | Ce3 |
| | | E | | Mantelliceras dixoni | Mantelliceras dixoni | Thalmanninella globotruncanoides | | | Gartnerago segmentatum | | | |
| 100 — | | 100.5 | | Mantelliceras mantelli | Mantelliceras mantelli | | UC1 | CC9 | Constitution kennedyi | | | |
| | | 100.5 | | Arrhaphoceras briacensis | Arrhaphoceras briacensis | Parathal- | | 1 | - - | troffer (OAE 1d) | | AI11• |
| | | | | M. rostratum | M. rostratum | appenninica | 000/ | | Hayeste atbiensis | 1 5 | | |
| - | arty | Albian | M*-3* r set | Mortoniceras fañax | Mortoniceras fallax | Pseudo- thaimanninella ticinensis | SULT | | Eiffelithus turiseittalii | 2 |) | |
| | ũ | | | inflatum | inflatum | | 8C26 | | | | | |
| - 105 — - | | | C34n | Mortoniceras pricei | Mortoniceras pricei | Pseudo- thalmanninella subticinensis | BC25 | CC8 | | | | |

| (d) | | | | | С | retac | eous | Т | ime | S | C | ale | | | |
|-----|-------------|-----|----------------|----|----------|--|---|----------|----------------------------------|--------------|-------|--|---|-----|------------------------|
| | AGE (Ma) | Ep | (Stage) | Po | larity | Tethyan Ammonoids | Boreal Ammonoids | F | Planktonic raminifera | Ca | care | eous Nannofossils | ¹³ C (per-mil P -1.4 0 1.4 2 | DB) | Mega- Cycles R T |
| | 125 | | Aptian E | | (C34n) | Deshayesites deshayesi Des, forbesi | Deshayesites deshayesi Des. forbesi | Le | upoldina cabri | BC19 | CC7 | Rhagodiscus gallagheri | OAE 1a (Selli or | | |
| | | | 126.3 | | MOr | Des. oglanlensis | Prod. fissicostatus P. bidentatum / | | | BC18 BC17 | | Hayesites Conu- | Goguel) | | Ap3 |
| | - | | | | MI | Imerites giraudi | P. scalare Sim. stolleyi | Gk | bigerinelloides blowi | BC16 | | Flabellites oblongus | } | | |
| | - | | u Barremian | | | Gerhardtia sartousi | inexum / S. pingue Paracrioceras | | | | CC6 | | | | / |
| | | | Carroman | | | A. vandenheckii | denckmanni | ⊢ | | BC15 | | | { | | Barr5 |
| | - 130 | | - | | M3 | M. moutonianum K. compressissima Nicklesia pulchella | Par. elegans | | Hedbergella similis | BC14 | | | ł | | \rangle |
| | - | | 130.8 | | | Nicklesia nicklesi Taver. hugii | rarocinctum | \vdash | | BC13 | | oblongata | | | Barr1 |
| | - | | L | | M5 | Pseudoth. ohmi | Sim. variabilis | | | BC12 | CC5 | Rucinolithus terebro- dentarius, R. windleyae | Faraoni | | \rangle |
| | - | | Hauterivian | | M6 M7 | Balear. balearis | S marginatus | | Hedbergella sigali/ | BC11 | | Speetonia | | L | Haf |
| | | | | | M8 | Pleisio. ligatus Subsaynella sayni | Cr. gottschei M. speetonensis | | delrioensis | BC10 BC9 | | Cruciellipsis | } | ſ | 100 |
| | - | | 133.9 | | M9 | L. nodosoplicatus Crioceratites loryi | End. regale | | | BC8 BC7 | | boll Tubodiscus | 3 | | |
| | - | | 155.5 | | M10 | A. radiatus Criosarasinella | E. amblygonium | | | BC6 | u. | verenae | | | |
| | 135 _ | ły | | Ξ | M10N | furcillata | Stolcoceras tuberculatum | 4 | Globuligerina | BC5 | | Eiffeithus striatus | 1 | | |
| | - | Ear | u | | | Neocomites peregrinus | Dichotomites | | | | | | 2 | | / |
| | - | | | | M11 | Saynoceras verrucosum | Prodichotomites | E. | alpionellids | | | | "Weis- sert" | | V-2- |
| | _ | | Valanginian | = | M11A | Busnardoites | | | | BC4 | | | (| | vas |
| | - | | | | M12 | campylotoxus | Polyptychites | | | | CC3 | Eiffellithus winda | 1 | | |
| | - | | E | | M12A | Timovella | Paratollia/ Platylenticeras | E | | | | | | | |
| | _ | | 120.4 | | MIS | pertransiens | Peregrinoceras | 1 | Cabinetites | BC3 BC2 | | Calcicalathina | | | |
| | - | | 139.4 | | MIS | | Suntes | \vdash | darderi | | | | | | |
| | 140 | | | | M15 | Subthurmannia | stenomphalus | D3 | L. hungarica | BC1 | | | | | / |
| | _ | | | | - | boissieri | Surites icenii | D2 | Calpionellopsis oblonge | | | | | ľ | Be7- |
| | - | | | _ | M16 | | Hectoroceras kochi | D1 | Calpionellopsis simplex | | | | 1 | | |
| | | | Berriasian | | \vdash | Cubibumanaia | | с | Tintinnopsella carpathica | | CC2 | | | | |
| | _ | | | | M17 | occitanica | Runctonia runctoni | | (large var.) | | | | | | |
| | - | | E | | | | | | | | | | | | |
| | | | | | M18 | 1 | Subcraspedites lampluohi | B | | | | Retecapsa angustiforata | | | |
| | 145 | | 145.0 | | | Berriasella jacobi | Subcraspedites | | Calpionella alpina (inter- | - | CC1 | Nannoconus kamptneri & steinmanni | | | |
| | | | Jurassic | | M19 | | preplicomphalus | A3 | mediate var.) | NJ18 | 1 LIN | Nannoconus wintereri | | | |

| | | | | - | | _ | | | | | | | | |
|-----|-------------|-----------|-------------|-----------|----------------------------|---------------|------------------------------|--|--------------------------------------|---|--------------------------|---------------------|---|--|
| (e) | AGE (Ma) | Intenatio | er- onal | 1 | Polar | ity on | Tethyan Ammonites | Briti | sh nal | Boreal Ammonites | Bore | eal mal | Russian Platform Ammonites | Northern Siberia Ammonites |
| | | L L | Late | | M15 | | Subthurmannia boissieri | ian | Late | Surites icenii Hectoroceras kochi | nian | | | Hectoroceras kochi |
| | dundan | Berriasia | Early | | M17 | | Subthurmannia occitanica | Ryazar | Early | Runctonia runctoni | Ryazar | Early | Riasanites rjasanensis | Chetaites sibericus / Praetollia maynci |
| | | | _ | | | | | 144.1 | | Subcraspedites | 144.1 | | Volgidiscus | Chetaites chetae |
| | 145 - 14 | 145.0 | | | M18 | | Berriasella jacobi | c | | Subcraspertites | | | singularis beds | |
| | | | te | | M19 | | Durangites | tlandia | Lat | Subc. primitivus | | Late | Craspedites nodiger | Craspedites taimyrensis |
| | 3 | | ٦ | | | | Microconthocoros | Por | V | Tit, anguiformis | | | Crasp. subditus Kach. fulgens | Crasp. okensis Prae. exoticus |
| | | c | | | M20 | | microcanthum | 148.0 | Ear | Galb. kerberus Galb. okusensis Gl. glaucolithus | an | 0 | Epivirgatites nikitini Virgatites virgatus | Epi. <u>variabilis</u> Tal. excentricus |
| | 1 | nia | | | | nce | M. ponti / B. peroni | | | Progalb. albani Virgato. fittoni | 'olg | iddle | | Dorso. ilovaiskyl |
| | | Titho | > | M21 Seduc | Semiformiceras fallauxi | | ian) | Pavlovia rotunda Pavlovia pallasioldes | > | W | Dorsoplanites panderi | Pavlovia iatriensis | | |
| | 150 - | | Earl | | | 2 | Semi. semiforme | | lon | Pectinatites pectinatus | | | llowaiskya pseudoscythica | Pect. pectinatus |
| | 3 | | - | | M22 | Semi. darwini | | (Bo | Pect. hudlestoni P. wheatlevensis | | arly | llowaiskya | Sphinctoceras subcrassum | |
| | | | | | MILL | | Hubonoticeree | - | | Pect. scitulus | | ш | | |
| | = | 152.1 | | L | M22A | | hybonotum | Igiai | | Pect. elegans Aulacostephanus | 152.1 | | Ilowaiskya klimovi | magnum |
| | | - | ate | _ | M23 | | Hybonoticeras beckeri | mmerid | ate | Aulacostephanus eudoxus | _ | ate | A. autissiodorensis Aulacostephanus eudoxus | |
| | 3 | giaı | - | | M24 | | Aulaco. eudoxus | Y | - | Aulacostephanus | giar | 2 | Aulocostephanus | |
| | | erid | | | MOAA | | Crus. divisum | | | mutabilis | erid | | sosvaensis | |
| | 155 | Cimm | | | M24B | | Ataxioceras hypselocyclum | | | Rasenia cymodoce | imme | | Amoeboceras | |
| | 157.3 | x | arly | | M25 | | Sutneria platynota | | arly | | ¥ | arly | RACTAIN | |
| | | | | | M25A | | Idoceras planula | | | Pictonia baylei | | | Amoeboceras bauhini | |
| | | 157.3 | - | | M27 | 70 | Epipeltoceras | 157.3 | | | 157.3 | | | |
| | | Oxfordian | 0 | | 1128 | 26 Mod | bimammatum | dian | | Ringsteadia pseudocordata | dian | æ | Amoeboceras rosenkranzi | |
| | 1111 | | Oxford | Late | | M28 | Pre-M eep-Tow | Perisphinctes bifurcatus | Oxfor | Late | Perisphinctes | Oxfordi Late | Late | Amoeboceras regulare |
| | | | | | | 0 | | | | cautisnigrae | | | Am glosense | |

| (f) | AGE (Ma) | GE Ma) Age dng S | | Deep-Tow Marine Magnetic Anomaly Interpretations Seafloor Mid-Depth | | | | | o <mark>maly</mark> h | Magnetostratigraphy of Reference Outcrops | | | Tethyan Ammonites | Boreal Sequence Sets |
|-----|--|------------------------|-------------|---|-------------------|-------------------------|-----|-------------------|--------------------------|---|-------------------------|--|--|----------------------------|
| | | | Late | | M27 M28 | | | M27r M28 | | | It-Oxf N | | Epipelloceras bimammatum | Ox8_ |
| | 160 160 160 160 170 170 170 170 170 170 170 170 170 17 | Oxfordian | Middle | | M29 | Deep-Tow Seafloor Model | | M29 | | /// | It-Oxf R | igland-Burgundy-Swabia Oxfordian composite | Perisphincles bifurcatus | ^{0x7} |
| | | | | | M30 | | | M30 M31 | | 777 | - 0.11 | | Gregoryceras transversarium | |
| | | | | | M31 M32 | | | M32 | | | m-Oxf N m-Oxf R | | Perisphinctes plicatilis | |
| | | | | | M33 | | | M33 | | | Card-N | | Cardioceras cordatum | 0x2 |
| | | 163.5 | Early | M34 M35 M36 | M34 M35 M36 | | | M34 M35 M36 | del | | e-Oxf R Cal-Oxf N | | Quenstedloceras mariae | Ox1 |
| | | Callovian | Mid Late | | M37 | | | M37 | Mo | | It-Callov R | | Quenstedtoceras lamberti | Call5 |
| | | | | | M38 | | | M38 | d-Depth | | It-Callov N | | Pellocoeras athleta Erymnoceras coronatum Reineckeia anceps | Call4 |
| | | | Early | | | | | | Mic | | m-Callov R | | Macrocephalites gracilis | Call2 |
| | | | | | M39 | | | M39 | | | e-Callov N Bat-Cal R | | Bullatimorphites bullatus | Call1 Call9 |
| | | Bathonian | Late elpp | | | | | | | | It-Bath N | s. Spain Er | Clydoniceras discus <u>Hecticoeras retrocostatum</u> <u>Cadomites bremeri</u> <u>Morrisiceras morrisi</u> Tuttes subcontractus | Bat5 Bat4 Bat3 |
| | | | Mi | | M40 | | | M40 | | | m-Bath R | | Procerites progracilis | Bat2 |
| | | | Early | | M41 | | | M41 | | | e-Bath N | | Zigzagiceras zigzag Parkinsonia parkinsoni Garantiana garantiana | Batt |
| | | Bajocian | Late | | M42 | | | M42 | | | Baj-Bat R It-Bajo N | | | Bj5 |
| | | | rly | | M43 | | | M43 | | | m-Bajo R | | Strenoceras niortense Stephanoceras humphriesianum Sonninia propinquans | Bj3 |
| | | 170.3 Aal. | ů | | M44 (M45) | | M44 | | | It-Aal R m-Aal N | s. Switz | Witchellia laeviuscula Hyperlioceras discites Graphoceras concavum | Bj1 | |

Figure 5: (a) and (b) Gradstein et al. (2012) Paleogene Time Scale. (c) and (d) Gradstein et al. (2012) Cretaceous Time Scale. (e) and (f) Jurssic Time Scale.