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

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Dr Wilfred JOKAT Researcher, Alfred Wegener Institute/ rapporteur

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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
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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	-
	DEEEDENCES
	Flores, 1984 Robbert Rutten Foster, 1975
	Robbert Rutten Flores, 1973
	Flores, 1964 Salman and Abdulah, 1995 Catuneanu, (2004)
	Robbert Rutten Flores, 1973 Salman and Abdulah, 1995 Foster, 1975
	Catuneanu, (2004) Flores, 1964 Robbert Rutten
	Salman and Abdulah, 1995 Flores, 1984 Robbert Rutten Flores, 1973
	Catumeanu, (2004) Guillochean and Liget, (2009)
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	Cooper, 1974 Robbert Rutten Foster, 1975
	Nicolas et al., 2006 Flores, 1973 Flores, 1964
	Catuneanu, (2004) Hankel, 1993 Catuneanu, (2004)
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	Catuneanu, (2004)
	Flores, 1984 Hankel, 1993 Catuneanu, (2004)
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									
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	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)
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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.