Geodynamics of the Amirante Ridge and Trench Complex, Western Indian Ocean

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Abstract

The formation and evolution of the \~600 km long, arcuate Amirante Ridge and Trench Complex (ARTC) is a significant geomorphic-structural feature in the western Indian Ocean (WIO). The WIO contains evidence of at least two major magmatic episodes followed by continental rifting within the span of a little more than 20 m yr. This involved the splitting of Madagascar from India at around 85 Ma, and then separation between India and the Seychelles at 64-63 Ma as a possible consequence of two powerful volcanic eruptions from the Marion and Reunion hotspots, respectively. Formation and evolution of the ARTC represents this tumultuous period in the Indian Ocean, between approximately 85 and 60 Ma (Late Cretaceous-Early Tertiary).

We integrated geophysical, paleomagnetic, and petrological data in order to examine three existing models that attempt to explain the formation of ARTC. In contrast, our study hints at several stages of extension and compression responsible for its formation. Our integrated data also suggest that the Carlsberg Ridge may have played a prominent role in evolution of the ARTC that seems to have formed through a ridge-jump process after the conjugate spreading centers—Mascarene and Palitana ridges formed earlier during the India-Madagascar separation—ceased spreading owing to violent eruption of the Reunion hotspot at around 65 Ma. The eruption disturbed the plumbing system of magma eruptions, resulting in cessation of spreading along the conjugate spreading centers, forcing a ridge jump.

A collage of seismic refraction and reflection, free-air gravity, magnetic anomaly data, and Ar dating of rocks indicates that as the Carlsberg Ridge swept the Seychelles toward south, and the crust between Madagascar and Seychelles was increasingly compressed, with the abandoned northern Mascarene spreading centre absorbing the maximum stress. With continued compression, the western limb of the abandoned spreading ridge was thrust below the eastern limb to a limited degree. This partial subduction agrees with the gravity and seismic results. Our new study also accounts for the anomalous presence of 14 km thick oceanic crust beneath the ARTC and its characteristic difference in petrology with other established subduction zones in the world.

Key Words: Amirante Trench, Amirante Ridge, cessation of spreading, partial subduction, India-Madagascar-Seychelles split, western Indian Ocean.
Introduction

Volcanism is suggested as one of the causes for dismemberment of continents. In fact, Condie et al. (2009) suggested the existence of seven major igneous activities in earth’s evolution between 3300 and 1100 Ma. The ultimate cause of volcanism during supercontinent fragmentation is linked to the dynamic continental rifting in response to mantle re-configuration events (O’Neill et al. 2009). The earth’s surface appears responsible in regulating mantle temperature, as movements of continents influence the temperature, mantle flow and enlargement of convection wavelength (Coltice et al. 2009). Accordingly, emplacement of large volumes of basaltic magma in the form of dikes, sills, and lava flows may be considered to have caused the break-up of Pangaea.

The magmatic events represent three main episodes of continental break-up starting from 180 Ma (Storey et al. 1995; Beutul et al. 2005). In the first episode, the break-up led to the establishment of seaways between South America and Africa in the west, and Antarctica, Australia, India and New Zealand in the east. Additionally, sea floor spreading occurred in the Somali, Mozambique, and perhaps in the Weddell Sea Basins, where the oldest recognised sea-floor anomalies are of 156 Ma (~M22). The second stage occurred in the Early Cretaceous (~130 Ma) when South America separated from Africa and the Africa-India Plate separated from Antarctica. Finally, in the Late Cretaceous (90-100 Ma), the break-up of Gondwanaland was completed when Australia and New Zealand separated from Antarctica, and India-Seychelles-Madagascar (Greater India) got separated from Africa and Antarctica (McKenzie and Sclater 1971; Veevers et al. 1980; Beutul et al. 2005).

It is believed that since 90 Ma, the southern part of the Indian Ocean was beginning to form when the development of the Indian Ocean Ridge system commenced (Storey et al. 1995; Parsons and Evans 2005). At anomaly A34 time (~ 85 Ma) India-Seychelles broke away from Madagascar, carrying the Mascarene Plateau including the Saya de Malha Bank (SDMB) with it. At 64 Ma (magnetic anomaly A28), a subsequent rift stage separated India from the Seychelles Plateau and SDMB. India ultimately collided with Asia at around 51 million years ago (Mukhopadhyay 1998), initiating compression in the northernmost Western Indian Ocean (Parsons and Evans 2005).

One of the remarkable features in the WIO is the long curvilinear mountain chain, Mascarene Plateau that connects granitic-continental Seychelles in the northwest to the volcanic-oceanic Mauritius in the south with a saddle in the middle known as the SDMB. Attached to the northern end of this plateau is the Amirante Ridge and Trench Complex (ARTC), whose origin and mechanism of formation are debated. One hypothesis suggests that the ARTC could be a zone of subduction (Miles 1982; Masson 1984; Mart 1988; Damuth and Johnson 1989). There have been disagreement although on the intensity and extent of such subduction, as it is largely devoid of earthquakes and typical island-arc volcanism.
Another hypothesis suggests its formation through shock-dynamics caused by huge bolide impact (Price 2000; Chatterjee et al. 2003; Stephens et al. 2009). The impact may have occurred just north of Madagascar, leading to the formation of a giant crater. By another hypothesis (Plummer 1996), the ARTC may represent a fault, or a fracture zone or a tensional rift as a result of seafloor spreading, or wrench faulting caused due to plate rotation and reorganization.

Some recent studies offer clue to the analogues character in emplacement and spreading behaviour of the Palitana and Mascarene Ridges (Krishna et al. 2006; Collier et al. 2008; Minshull et al. 2008). Taking cue, we feel that the post-formative crustal behaviour of Laxmi Ridge (in the Arabian Basin) and Amirante Ridge (in the Mascarene Basin) are also much the same. Accordingly, it appears that evolution of ARTC cannot be effectively discussed without taking cognisance of the conjugate crust located on either side of the Carlsberg Ridge (Fig. 1). This paper re-looks at the available hypotheses, existing data, and undertakes a qualitative analysis towards constructing a model on the possible timing and mechanism of formation of the ARTC.

**Geologic Setting**

The Mascarene Plateau extending from 4° S to 18° S, is stretched over 1500 km in length and covers more than 115,000 km². The origin of this part-continental and part-volcanic plateau is quite absorbing. The Seychelles lie at the northern end of the Mascarene Plateau which separates oceanic crust generated by the Central Indian Ridge (post-Eocene) and Carlsberg Ridge (post-Cretaceous) in the east, from oceanic crust of Late Jurassic or Early Cretaceous age in the south Somali Basin and of Late Cretaceous age in the Mascarene Basin (Miles 1982; Masson 1984).

Located just south of Seychelles, the ARTC is a curved bathymetric feature extending south from the western margin of the Seychelles Bank. The regional bathymetry reveals that the ARTC (with a length of only 550 km) appears to be a composite of three discrete, nearly linear, and essentially contiguous segments, having strikingly different orientations (Plummer 1996; Damuth and Johnson 1989; Fig. 1). The northern segment between 4°20’S and 6°20’S trends 030, a fairly straight central segment between 6°20’S and 8°40’S is oriented NNW (350°); and a southern segment between 8°40’S and 10°S along a NW trend of ~310°.

The ARTC, discovered during Vityaz expedition in 1959, is morphologically similar to the subduction zones in the trench-volcanic arc complexes of the western Pacific (Johnson et al. 1982). The Amirante Trench is about 5200 m deep, and 25-50 km wide (mean width 30 km). The trench is bounded on the east by the steep Amirante Ridge and to the west by
rugged basement ridges and seamounts of less relief (~1000 m). The entire ARTC covers an area of 2400 km² and volume of 95,000 km³ (Damuth and Johnson 1989).

A distinct change in magnetic character occurs along the longitude 52°30'E within the ARTC, as magnetic anomalies with large-amplitudes occur east of this longitude but on the west magnetic relief remained low. While the area with low magnetic amplitude was likely to have formed during Cretaceous magnetic quiet zone, the area east of 53°30'E, with strong anomalies and successive offset to the south, appears to have formed as a result of movement of Madagascar from India due to eruption through the Mascarene Ridge (~85 Ma; Damuth and Johnson 1989). This is supported by radiometric determination of age of tholeiitic basalts dredged from the ARTC as 82 ± 16 Ma years (Fischer et al. 1968).

The free-air gravity anomaly data (Fig. 2) compiled for the Amirante Arc, Amirante Basin and the western margin of the Seychelles Plateau (Masson 1984; Damuth and Johnson 1989) reveal that the southern Amirante Arc has a wavelength close to 75 km with average amplitude of 215 mGal. The two-dimensional seismic models encountered the Mohorovicić discontinuity here at 14 km depth beneath the arc-trough structure, which is unlikely for a normal oceanic crust (Masson 1984; Damuth and Johnson 1989). Geoid data also indicate density inhomogeneities in the lower crust and upper mantle, offering evidence for a volcanic origin for the Amirante Ridge (Miles 1982).

The trench at the ARTC is generally 25-50 km wide and contain about more than 1 km of acoustically semi-transparent to reflective, tectonically undisturbed, ponded flat-lying turbidites and mass-transport deposits that have been periodically modified by northward flowing Deep Western Boundary Current (DWBC; Johnson and Damuth, 1979). Interestingly, the 3.5 kHz echograms, piston core, and bottom photographs confirm the presence of turbidites. Gloria side-scan sonar images of the Amirante Trench between 7°S and 9°40’S reveal that strong reflective northern sediments are separated from weakly reflective southern sediments by a seamount near 8°40’S, which marks the boundary between the middle and the southern trench segments (Bernard and Munschy 2000).

**Existing Hypotheses**

Despite morphological similarities, the Seychelles Bank, the Mascarene Plateau and the ARTC show significant differences in their formational history. The Seychelles Bank is a Precambrian continental fragment, the Mascarene Plateau is a basaltic accumulation, while the origin of ARTC still remains unclear. Different hypotheses are put forward to explain the formation of the ARTC. We briefly review these hypotheses and discuss the constraints to accept such hypotheses.
(a) **Plate Reorganisation**: This links the formation of ARTC to an anti-clockwise rotation combined with sinistral strike-slip motion in the Mascarene Basin around a pivotal point in the north (near Seychelles micro-continent). The N-MORB basalt found at the Amirante Ridge dates about 82 Ma, and was derived from volcanic activity induced by the intraplate wrenching, while the Amirante Trough represents down-warping following compression induced by rotation. This dispensation may further suggest that a regime of compression characterised the northern ARTC with obduction of Baluchistan and Oman ophiolites, while extensional regime dominated the southern ARTC (Plummer 1996). Accordingly, the three distinct linear segments of ARTC may represent, from north to south, a Late Cretaceous transform fault, an Early Cretaceous lineament, and an Early Tertiary tensional rift (Damuth and Johnson 1989).

(b) **Subduction**: The second hypothesis argues in favour of ARTC representing a subduction zone. Some of the arguments are based on: (a) ARTC’s arcuate, concave morphology typically resembling subduction system (Norton and Sclater 1979), (b) its 75 km long wavelength of free-air gravity anomaly that may suggest some degree of subduction (Miles 1982; Masson 1984), (c) some amount of extension in the southern part of ARTC (Late Cretaceous-Early Tertiary), while northern portion is a part of transform fault (Masson 1984; Damuth and Johnson 1989), (d) the occurrence of a calc-alkaline suite of Eocene syenite covering some of the Seychelles Islands may suggest that the region was affected by the early stages of subduction (Mart 1988), and (e) the absence of post-Middle Eocene igneous rocks in the Seychelles-Amirante region may be due to an abrupt termination of the subduction.

(c) **Extra-terrestrial Impact**: The third hypothesis suggests that the Amirante Ridge and Trench structure may have resulted from bolide impact during Cretaceous-Tertiary boundary time (K/T boundary, 65 Ma, Hartnady 1986) or during India-Eurasia collision (51 Ma, Mukhopadhyay 1998; Stephens et al. 2009). In fact, immediately south of the Seychelles Bank, the Late Cretaceous Amirante Basin takes a circular shape of about 300 km diameter. Extensive chaotic slump structures on the East African continental margin indicate proximity to mega-earthquake and/or giant tsunamis probably triggered by the bolide impact (Alvarez et al. 1980; Chatterjee et al. 2003). Again, looking from the perspective of “shock dynamics”, Fleischer (2006) found that the long central portion of the trough directly faces the centre of the crater (Aldabra Islands). It sits on the front edge of the crater where the Australian Bight was carved out by the impact of explosion before the large scale break up of Gondwanaland commenced.

**The Constraints**: A critical assessment of the above hypotheses reveals that none of them fully clarifies the evolution of ARTC, in terms of various stages of tectonic development. The absence of identifiable magnetic anomalies in the south-eastern Somali
Basin and in the northern Mascarene Basin (Scrutton et al. 1981), and also the absence of detailed petrogenetic and radiometric age data have made the plate reorganization hypothesis unconvincing for the formation of ARTC.

The hypothesis supporting subduction as possible mechanism of origin for ARTC suffers from the fact that the ARTC- (a) is presently aseismic (Barazangi and Dorman 1969) (b) lacks an accretion sedimentary prism (Johnson and Damuth 1979), and (c) subduction-atypical rocks of andesitic composition are absent. In fact, rocks dredged from the western flank of ARTC and Seychelles are theoleiitic in composition (characteristic rocks of spreading ridge, Fisher et al. 1968), and those from the southern portion of ARTC are intrusive dolerites, olivine gabbros, and serpentinites (an ultramafic association; Auzende et al. 1994). Also the region has been free of significant volcanic activity since the early Tertiary (Fisher et al. 1968), and there is a clear absence of 250-300 km free-air gravity wavelength anomalies over the ARTC, which normally characterizes a full-grown mature subduction zones (Plummer 1996).

Further, a review of another set of geological data and observations from the region does not even support an extra-terrestrial catastrophic origin for ARTC (Johnson et al. 1982; Fleischer 2006). For instance, the bolide impact was expected to create high and intense temperature condition. The resultant high heat energy would have created reservoirs of melt and splashing would require fall of another heavy body in the melt pond. If one tries to translate it in numbers it would turn out to be unrealistic (Fleischer 2006). Moreover, no signature of pre- and syn-impact disturbance on the Late Cretaceous–Early Tertiary flat-lying sediment of undisturbed pelagic nannofossil ooze (A. mayaroensis zone; Johnson et al. 1982) is found. It appears difficult to explain how a lithosphere-shattering catastrophic impact, which claimed to have changed African plate motion and lithospheric stress patterns could leave these previously deposited pelagic sediments and several nannofossils undisturbed. Hence, above constraints appear to deny a satisfactory explanation by any one of the hypotheses to the evolution of the ARTC.

**Discussion**

From the above assessment, it appears that none of the existing hypotheses- plate reorganisation, subduction or extra-terrestrial impact- can independently account for the formation and evolution of ARTC. Again, these hypotheses theories have failed to take a holistic view of the entire spectrum of the then prevailing tectonic environment, particularly in terms of the conjugate crust located west of the Indian continental landmass. We reassessed these hypotheses together with new data and information acquired in recent years (Beutul et al. 2005; Parsons and Evans 2005; Krishna et al. 2006; Gaina et al. 2007;
Collier *et al.* 2008, Minshull *et al.* 2008; Mukhopadhyay *et al.* 2008; Melluso *et al.* 2009; Stephen *et al.* 2009; Mukhopadhyay *et al.* 2010). It seems possible to suggest that the formation and evolution of the ARTC spans over a period of little more than 20 million years, and results from a combination of several processes accomplished probably in three phases.

**Phase I: India-Madagascar split (90-85 Ma)**

It is now known that at the beginning of the Cretaceous (M11 = 130 Ma), the Gondwanaland began to break into four continental blocks, South America, Africa–Arabia, India–Madagascar, and Australia–Antarctica (Veevers *et al.* 1980). A reconstruction of paleoposition of landmasses in the western Indian Ocean and the prevailing tectonics suggests that India–Madagascar continued to move south from Africa until around M0 (=119 Ma), when the seafloor spreading between Africa and Madagascar stopped. The ocean between India and Australia–Antarctica was about 800 km wide at this time, as was the South Atlantic Ocean (Lawver *et al.* 1992). Seafloor spreading at relatively slow rates continued in the South Atlantic and Indian Oceans during the Early Cretaceous.

A major change in the pattern and rate of seafloor spreading in the Indian Ocean occurred at around 95 Ma, during the long Cretaceous normal polarity magnetic quiet zone. It is now accepted that Madagascar was separated from India during 89-85 Ma (Agarwal *et al.* 1992; Storey *et al.* 1995) probably triggered by the volcanic eruption through Marion hotspot. The concept that super-plumes (super-upwelling) break apart the continental assemblies was also put forward by some workers (Murphy *et al.* 2009; Santosh *et al.* 2009). A degree of transcurrent motion between India and Madagascar along their linear margins might have helped the separation. We suspect that the magma then emanated along a series of crustal slices oriented largely parallel to the contact of Madagascar and India (Fig. 3a). Rising and emplacement of magma along the gaps between such continental slices probably formed the spectacular Prathap Ridge and Mid-Slope Basement Ridge (Naini and Talwani 1983; Mukhopadhyay *et al.* 2008; 2010).

The magma surfaced through the intervening gaps of two such slices remained prominent (see Fig. 3a) – one each close to the east of Madagascar and the other to the west of the Indian coast. The western slice, close to Madagascar, was rechristened as Mascarene Ridge that remained active and continued spewing lavas probably during the whole of Campanian (84-74 Ma; Minshull *et al.* 2008). The spreading of Mascarene Ridge generated Gop Basin to the northeast and Mascarene Basin to the southwest (Collier *et al.* 2008). Meanwhile, the other crustal slice close to India, loaded with magma from Madagascar-India separation event, was simultaneously reactivated as Palitana spreading centre (Biswas 1988; Todal and Eldholm 1998; Krishna *et al.* 2006). The earliest seafloor magnetic
anomaly on either side of the Palitana Ridge is differently dated as 34n (84-82 Ma, Subrahmanya 2001) and C33n (79Ma, Bhattacharya et al. 1994). Based on recently acquired seismic and gravity data (Collier et al. 2008; Minshull et al. 2008), it may be suggested that both the Mascarene Ridge, and the Palitana Ridge were formed through intrusion of mixed material (continental + basalt melt) in the intervening space located between the two continental slices (Fig. 3a). It is also possible that some N-MORB type lavas erupted to form oceanic crust around, with atypical seafloor type magnetic anomalies.

In fact, the recently acquired wide-angle seismic reflection data (Collier et al. 2008) confirms that the Palitana Ridge represents a rift or fissure on the flank of the Indian continental mass that later transformed to a limited spreading centre. Its narrow width (only 120 km wide) prevented the identification of magnetic reversal sequence. The Palitana Ridge appears to be conjugate to the fading phase of the northern Mascarene Ridge, and spreading across this ridge appeared to cause splitting India from the Laxmi Ridge and Seychelles (Fig.3b, Collier et al. 2008). As mentioned earlier, some of the rocks collected from the Amirante region holds an age of 82-83 Ma and are N-MORB basaltic in nature (Fisher et al. 1968). This indicates that ARTC (better exemplified by 200 km long northern portion) was once a part of the spreading ridge that created Mascarene Basin between Madagascar and India (Damuth and Johnson 1989).

**Phase II: India-Seychelles Split (66-62 Ma)**

This period seems to have contributed substantially in configuring the western continental margin of India. As the Mascarene Basin continued to expand throughout the Late Cretaceous (80 to 65 Ma), India persistently moved away from Madagascar. Collier et al. (2008) studied detailed geochemistry, did Argon dating ($^{40}\text{Ar} / ^{39}\text{Ar}$) of rocks from the north of Seychelles, and acquired wide angle seismic refraction and seismic reflection data from Seychelles, Laxmi Ridge and Palitana Ridge. Their study indicates emplacement of Deccan Trap at 65.5Ma ± 1Ma (i.e., around 29r). The slow spreading across the Palitana Ridge started during 80 Ma and was creating Gop Basin to the northeast and Laxmi Basin in the southwest (i.e., eastern Arabian Basin and western Arabian Basin of Chaubey et al. 1993).

Consequent to the eruption from Reunion hotspot along the western margin of India during 65-66 Ma (coupled with or without any bolide impact), the regional tectonics underwent considerable change. The presence of shocked quartz below the lowest lava flow could imply that Deccan volcanism may have been triggered by bolide impact (Price 2000; Shiva (?) of Chatterjee et al. 2003). Such eruption from Reunion hotspot triggered by extraterrestrial impact was likely to have disturbed the plumbing system of magma ascension along the northern part of the Mascarene Ridge and along the Palitana Ridges. This could probably make the crust west of India vulnerable and fragile.
The scenario with Mascarene Ridge, a conjugate twin of Palitana Ridge, was equally significant. In fact, during Early Palaeocene, spreading across the northern stretch of the Mascarene Ridge nearly ceased, in contrast to the anti-clockwise fanning of its southern stretch. The fanning of the spreading between India and Madagascar in the south in an anti-clockwise direction occurred about a pivotal rotation pole located near 10°N, 35°E (Bernard and Munschy 2000). The rotational compression in the north and rotational extension in the south along this ridge created an anomalous stress regime. It points to the fact that the southern part of Mascarene Ridge may have remained unaffected by the Reunion hotspot eruption and continued to be active, while eruption did affect its northern stretch.

Following the discontinuous availability of magma owing to disruption in plumbing system caused by Reunion eruption at 65.5 Ma, the spreading across the northern Mascarene and Palitana Ridges slowed down substantially. With time these two conjugate ridges ceased to spread and consequently became abandoned spreading centres (ASC). However, the pressure of accumulated magma beneath these two abandoned spreading ridges continued to grow. This increasing pressure of magma underneath later prompted a ridge jump to a common suitably vulnerable place between Seychelles and Laxmi Ridge and resumed spreading. Although mantle melting in mid-ocean ridge settings is essentially a passive process and it seems unlikely that melt could build enough pressure, the thermal weakening of the crust associated with the Reunion hotspot (Collier et al. 2008; Bernard and Munschy 2000) has been responsible for the accumulation of optimum stress required for ridge jump.

This new eruption-cum-spreading centre thus formed around 64-63 Ma through the ridge-jump process was christened as Carlsberg Ridge that increasingly swept Seychelles away from India (Fig. 3c). The findings of Plummer (1996) that the coupling of rotation with strike-slip displacement in the northern Mascarene Basin essentially ceased when the Carlsberg Ridge developed to the northeast of Seychelles supports this line of thinking. Such a situation might have also caused sudden acceleration of India’s northward journey in excess of 150 mm/yr (Mukhopadhyay 1998; Chatterjee et al. 2003). Other workers also suggested development of the Carlsberg Ridge through ridge jump process off northern Mascarene and Palitana Ridges (Todal and Eldholm 1998; Bernard and Munschy 2000).

It seems therefore possible that the first effective spreading of the Carlsberg Ridge initiated at 63.5Ma (=28n), and separation of Seychelles occurred by the start of ~62 Ma (A27n). It is suggested that separation of Seychelles from the Laxmi Ridge as a consequence of spreading at the newly-formed Carlsberg Ridge on a thin stretched lithosphere continued owing to the combined action of plate boundary forces and mantle plume activity. In fact, the Carlsberg Ridge is still seismically active, with a major earthquake
recorded as late as on 15 July 2003 (M_w= 7.6) and the latest one occurring on 9 January 2009 (courtesy- US Geological Survey 2009).

**Phase III: Partial Subduction**

As Seychelles continued to move south owing to spreading of the Carlsberg Ridge, the crust between Madagascar and Seychelles experienced compression. And if one agrees to the paleomagnetic interpretation that both the Mascarene and Carlsberg Ridges were active simultaneously on the southwest and northeast of Seychelles respectively even for a shorter period (Minshull *et al.* 2008), the amount of compression the Seychelles micro-continent and its oceanic neighbourhood were subjected to must have been enormous. The Seychelles’s transportation to the south halted when it collided with the north-eastern edge of the Mascarene Basin.

This increased stress was needed to be compensated. The most suitable area to absorb such compressive stress was possibly the just abandoned Mascarene spreading centre located between Madagascar and Seychelles. To neutralise the increasing stress, it was plausible for the western limb (shoulder) of the then abandoned spreading ridge to subduct below the eastern limb, to ultimately form Amirante Trough. This Early Tertiary subduction uplifted the eastern limb, but did not probably continue for long due to reduction in compression between Seychelles and Mascarene Basin during the Late Eocene with the formation of the Central Indian spreading Ridge (Mart 1988), and lowering of spreading rate along the Carlsberg Ridge consequent to India-Eurasia collision occurring approximately around 51 Ma (Mukhopadhyay 1998). Hence, the short and limited subduction of one limb beneath the other accounts for anomalous presence of 14 km thick oceanic crust at ARTC, determined from the gravity and seismic studies. No wonder, the characteristics of such a short-tenured anomalous subduction in ARTC differs from other known subduction zones (Fig. 4).

**The Long Lost Twins**

The studies, particularly with regard to the timing of Deccan Trap eruption, rifting between India and Seychelles, and formation of the Carlsberg Ridge (Minshull *et al.* 2008; Collier *et al.* 2008; Melluso *et al.* 2009) when integrated with older revelations (Dyment 1993, and references therein) indicate that Amirante Ridge-Trench Complex (ARTC) in the Mascarene Basin and Palitana-Laxmi Ridge Complex (PLRC) in the Arabian Basin are conjugate (*in fact, twins*) in their origin and development. Analogues to the Mascarene Ridge that separated Madagascar from India, the Palitana Ridge, also underwent ultra-slow and limited spreading in the Gop Basin between 79 and 66 Ma to split Laxmi Ridge (plus Seychelles) landmass from India (Bhattacharya *et al.* 1994; extinct axis of Talwani and Reif 1998; Krishna *et al.* 2006). The Laxmi Basin appears to be a stretched continental crust.
formed as Madagascar and India separated during 89-85 Ma. The magnetic anomalies encountered in the Laxmi Basin may have been contributed largely by the continental slices and the intrusive mixture of hotspot melt and country rocks (Fig. 3a, b; also see Krishna et al. 2006).

Consequently, the crustal structure beneath the ARTC and PLRC show unique similarity in thickness and character. For example, the seismic cross section across ARTC, from west to east (Plummer 1996), encounters extremely flat trough/ trench full of sediment, with sharp rise of the eastern wall to encounter the Amirante Ridge. The ridge is followed further eastwards by the Amirante Basin (Fig. 5a). No wonder, the bolide impact theory emboldened considering the striking difference in depth between the trough and the basin. The crust below the ARTC is found to be about 14 km thick compared to crust of 6 to 7 km thickness in the neighbourhood (Damuth and Johnson 1989; Miles 1982). As indicated, a doubling of the crust is likely to have occurred below the ARTC as due to increased compression the western limb of the Mascarene Ridge partially subducted below the eastern limb.

In a similar manner, the conjugate part of Amirantes in the Arabian Sea, the Palitana and Laxmi Ridge show comparable morphotectonics. The Laxmi Basin and Laxmi Ridge also show unusually thick crust (12-16 km) compared to the neighbourhood. Minshull et al. (2008) reported thin (5-6 km) oceanic crust seaward of Laxmi Ridge compared to 14 km thick crust below the Laxmi Ridge. A 9-km thick high velocity layer (7.6 km/sec) is found below this ridge, which is probably due to underplating by foreign intrusive material, including fractionated magnesium-rich rocks (Fig. 5c, Minshull et al. 2008). Hence, while the Laxmi Ridge in the PLRC may have experienced magma intrusion at its base to effectively increase its crustal thickness to 12-14 km, a partial subduction of the western limb below the eastern limb along the abandoned northern Mascarene Ridge, comparably increased the crustal thickness beneath the ARTC to 14 km.

Conclusions

On studying the tectonic emplacement and evolution of the Amirante Ridge and Trench Complex in the western Indian Ocean, we conclude that:

(a) None of the existing hypotheses – plate reorganization, subduction, extraterrestrial impact – are independently tenable to explain the tectonic framework of the region with special reference to the development of neighbouring ocean basins.

(b) An evaluation of all data suggests development of the ARTC and the western Indian Ocean in three phases as follows.
(i) Madagascar separated from India between 89-85 Ma following eruption of the Marion plume along several coast-parallel continental slices. Brief conjugate spreading along two such slices occurred along the northern Mascarene Ridge (close to the Madagascar coast) and the Palitana Ridge (close to the Indian coast). The spreading along the Palitana Ridge split the Laxmi Ridge and Seychelles from India.

(ii) Ultra-slow and limited spreading along northern Mascarene Ridge and Palitana Ridge probably continued until eruption of the Reunion plume melt at 66-65 Ma. Reunion activity affected the plumbing system beneath these two ridges, resulting in temporary cessation of spreading and later abandonment of spreading along these two centres. The increased pressure from the accumulated magma beneath the abandoned Mascarene and Palitana ridges prompted a ridge jump to eventually form the Carlsberg (spreading) Ridge at a suitably vulnerable place between the Seychelles and Laxmi Ridge.

(iii) As spreading continued across the Carlsberg Ridge, India was forced rapidly northward, while the Seychelles was displaced southward. It is possible that increasing compression of the crust between the Seychelles and Madagascar was compensated at the abandoned northern portion of the Mascarene Ridge, with its western limb thrust below the eastern limb. The subduction/overriding was a temporary measure and was aborted within a short period as compression was possibly released by the opening of Central Indian Ridge and lowering of spreading rate along the Carlsberg Ridge (consequent to the India-Eurasia collision at around 51 Ma).

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**Caption to the Figures**

**Figure 1.** The figure shows the western Indian Ocean with two conjugate areas of study in the box – (a) Laxmi-Palitana Ridges (PLRC) in the northeast and (b) Seychelles-Amirante region (ARTC) in the southwest (after Todal and Eldholm 1998). Solid dots are DSDP/ODP sites, while SM-1 and NB-1 are hydrocarbon drill sites. Solid north-south line is the trace of movement of the Reunion hotspot. The eruption was initiated on the Indian plate near Mumbai, and the hotspot is now lying on the African Plate beneath the Reunion Island. Detailed satellite ETOPO bathymetry of the ARTC (left) and that of Laxmi + Palitana (right) conjugate study blocks shows NW-SE trending Laxmi Ridge. PLR= Palitana Ridge, GPB= Gop Basin.
Figure 2. Satellite gravity maps of the two conjugate blocks (PLRC and ARTC, after Sandwell and Smith 1997). Note the prominent western and eastern limbs of the Amirante Ridge, with trench in between. Although lower in values than other conventional subduction zones, the free-air gravity anomaly in ARTC (~160 km wavelength and >120 mGal amplitude, Miles 1982) suggests a phenomenon characteristic of limited subduction. Similarly, the anomalous free air gravity anomaly over the Laxmi Basin and Laxmi Ridge suggests unusually thick crust compared to the neighbourhood.

Figure 3. Dismemberment of the Gondwanaland during Late Cretaceous.

(a) As Madagascar splits from India Under the influence of massive volcanic eruption from Marion hotspot, the tearing force produced several slices of continental crust (solid dark). A mixture of acidic continental and basic oceanic melt surfaced (stippled) along the intervening stretched areas between two slices.

(b) The separation between Madagascar and India started with slow and limited spreading about twin conjugate ridges- MCR (Mascarene Ridge) and PLR (Palitana Ridge). Pratap Ridge (PTR) and Mid-Slope Basement Ridge (MSBR) may be the sliced continental fragment, mixed with intruded melt. The dashed line is approximately the shelf of India.

(c) Volcanic eruption from Reunion plume at about 65 Ma disturbed the melt plumbing system beneath PLR and MCR, and was responsible for spreading cessation. However, the subsurface accumulated magma forced a ridge jump to form the Carlsberg Ridge between Seychelles and Laxmi Ridge.

Figure 4. Schematic representation of possible tectonic scenario during Paleocene-Eocene time:

(a) Development of Amirante Basin, as spreading across the Mascarene Ridge fanned out in the south in contrast to the northern section of the ridge, which remained narrow. ARB=Amirante Basin, MCB=Mascarene Basin, MCR=Mascarene Ridge (after Bernard and Munschy 2000).

(b) The spreading along the Carlsberg Ridge since 64 Ma helped the successful breakup of Seychelles from India. The anomalous stress regime due to rotational compression in the north and rotational extension in the south along the Mascarene Ridge was further aggravated due to enormous crustal compression created by south-bound Seychelles. We sketch an approximate situation (not to scale) of the resulted limited subduction phenomenon along the extinct Mascarene Ridge through Paleocene
(top) and Eocene (bottom) periods. SEY= Seychelles, CR= Carlsberg Ridge, LXR= Laxmi Ridge, PLR= Palitana Ridge, SDMB= Saya de Malha Bank, MCR= Mascarene Ridge.

Figure 5. Seismic cross-section of the crusts across ARTC and PLRC

a) A seismic cross section across ARTC, from west to east (after Plummer 1996). Note extremely flat trough/trench full of sediment, with sharp rise of the eastern wall to encounter Amirante Ridge followed outward by the Amirante Basin. No wonder, the bolide impact theory emboldened considering the striking difference in depth between the trough and the basin.

(b) Seismic section across the Laxmi Ridge (after Krishna et al. 2006). Seaward dipping reflectors towards west indicate oceanic crust, confirming that it is a part of the continental crust and represents the crustal slice formed during the tearing apart of Madagascar from India.

(c) P-wave seismic velocity model (after Minshull et al. 2008). Contour interval 0.5km/sec below 6 km/sec and 0.2 km/sec above 6 km/sec. Receivers are shown as inverted triangle. Note underplating by foreign young igneous material at the base of the Laxmi Ridge and the continent.

References


Fig. 2
Fig. 3
Fig. 4