Plate Tectonic History of the Indian Ocean

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Abstract:- The fragmentation history of East-Gondwana is divided in five periods, each period being preceded by mid-oceanic ridge closings and jumps. These plate movements were controlled by three branches of convection currents (CC): the western, the central and the eastern ones. Period 1 began with the rise of compressional constraints in the Neo-Tethys region caused by the anticlockwise rotation of East-Antarctica/Australia as the interaction effect with the newly formed off-South African E-W CC at M10. This led to the northward detachment of continental fragments from Northwest Australia and northeast India, the creation of an oceanic basin north of India and the spreading cessation of the Somali Basin at M0. Period 2 was marked by southward ridge jumps from the Somali Basin and the north of India. The influence of the E-W CC ended after the Lower Aptian fan-like rifting between India and Sri Lanka. From then on, plate movements occurred in N-S direction and the rotation of East-Antarctica/Australia got reversed. This period ended with the fan-like spreading of the Western Enderby Basin, during which the two arms of the central CC reunited and East-Antarctica/Australia was "trapped" within the South Pole Region and rotated anticlockwise. During Period 3, simultaneous ridge jumps in Middle Cenomanian conducted to the fan-like eastward opening of the Eastern Enderby Basin, whereas rifting activities occurred between Madagascar and India and between East-Antarctica and Australia. In Lower Campanian, the oceanic opening between East-Antarctica and Australia provoked the dispersal of the Eastern Enderby CC allowing the creation of new oceanic basins from C33 to C31 and a backward ridge propagation at C32. Starting from C31, the northwestward propagating CC underwent sidelong collisions with the Great Mascarene Basin before setting between the Seychelles and India where they merged with the "jumped" Mascarene CC at C29. After the collision of India against Eurasia in Middle Eocene (C21), Period 4 was marked by the creation of SEIR, the connection of CIR with SEIR and the separation of SWIR from CIR. Northward ridge jumps from SWIR at C5 generated the East-African Rift system. A pre-breakup rifting phase started since the Pleistocene in N-S direction.

Keywords:- *East-Gondwana; Plate Tectonics; Up-Welling Mantle Convection Currents; Mid-Oceanic Ridges; Oceanic Opening.*

I. INTRODUCTION

The aim of this study is to establish a precise and a continuous approach of the geodynamic processes that constructed the Indian Ocean. The split history of East-Gondwana spanned in age from the Early Cretaceous to the present and involved several detached continental fragments such as East-Antarctica, Australia, India, Madagascar and the Seychelles. As crustal extension preceded the breakup of continents, new land masses formed between them. It happened that they undergone a second phase of extension and then got isolated between oceanic crusts and formed deep undersea plateaus and rises considered as base-flattened and thinned landmasses. This implicates a lot of pieces in the puzzle. The latter may expand, compress, rotate and change form and direction through geologic times with new components added into it such as fracture zones, hotspots, volcanic seamounts, thrust zones etc. The extinction relayed by "jump" of mid-oceanic ridges are common phenomena. The causes are numerous and can be plate collision, drifting plate rotation or the side interaction between adjacent convection currents of different direction. This paper is based upon the consideration that only one wave of N-S convection currents existed to have formed the Indian Ocean. This complex exercise necessitates the need of a great number of data such as the outcrop geology, published papers, sea level contour maps, Google seafloor satellite pictures, paleomagnetic data of expanded oceanic crusts, earthquake records, etc. It is good to be aware that the position of Madagascar with respect to Africa underwent unsolved changes caused by compression during the creation of the Mascarene Basin and the Central Indian Ridge. The delineation of continent/ocean boundaries becomes uncertain when rift-related fragments are in concern such as undersea plateaus and rises. Also, global mapping imperfections cannot be overcome especially when divergent continents are far distant from one to another. The use of a computer with appropriate software would permit precisely positioning continents on the spherical globe surface rather than on a plan as applied in the illustrations. The present paper described of the main geodynamic events in stressing on the cause-to-effect relationship, a continuous chronology and relative plate kinematics. In the Figures shown in this paper, Africa is considered fixed with respect to detached fragments.

II. FRAGMENTATION OF EAST-GONDWANA

Five periods of plate reorganization respectively dated in the Hauterivian, the Early Aptian, the Middle Cenomanian, the Middle Eocene and the Middle Miocene, characterized the fragmentation history of East-Gondwana, two of them being preceded by the anticlockwise rotation of drifting continental block and the others by plate collision against Eurasia.

A. Period 1 (Figures M1 to M3).

East-Gondwana (EG) started to drift to the south away from West-Gondwana (WG) in the Early Oxfordian at ~156 Ma. These plate movements were controlled by three branches of N-S upwelling mantle convection currents (UMCC). The western and central branches split Gondwana in two parts, whereas the eastern one generated the Neo-Tethys Ocean. The Davie FZ acted as a major transform fault that separated the Mozambique Basin (MB) in the west and the Somali Basin (SB) in the east.

The drift trajectory of EG began to bend to the south-southeast after covering 930 km distance away from East-Africa. This is the effect of the interaction of E-W convection currents that just started an oceanic opening in the west of the Mozambique Basin associated with the plate separation of Africa from South America. The opening of the South Atlantic Ocean began from the south with the creation of two ridge axis separated by the Agulhas-Falkland transform fault, the southern ridge being located off-South Africa. This event is dated in the Hauterivian at M10 (Royer, 1990). Different authors date it at 130 Ma (Rabinowitz et al., 1983, Coffin & Rabinowitz, 1987, Lawver et al., 1990) or at 131.9 Ma (Marks & Tikku, 2001). In this paper, the date of 133.5 Ma is retained as interpreted from the global eustatic curves (Haq et al., 1987).The pre-breakup rifting phase is dated in the Lower Hauterivian at 135.5 Ma. The South African E-W convection currents deflected the course of EG to about 12° south-southeast. This resulted to the anticlockwise rotation of EG giving rise to compressional constraints in the northern Neo-Tethys oceanic regions. Madagascar underwent about 16° anticlockwise rotation. The Neo-Tethys ridges got closed progressively from east to west, "jumped" to the south afterwards. The associated rifting event was marked by regional erosional unconformities dated in the Lower Hauterivian according to the outcrop geology in Madagascar (Bésairie, 1972) (Figure 1). The appearance of marine carbonates in the Upper Hauterivian (Figure 2) indicates a post-breakup deposition. The ridge jumps and the oceanic openings were fragmented and repetitive (Powell et al., 1988). Ridge segments were responsible of the northward detachment of several continental fragments away from northwestern Australia and northeastern India. The opening began lately at M4 in Western Australia and at M3 in the north of Naturaliste Plateau (Royer, 1990).

An oceanic opening is assumed to have taken place between northern India and Iran during a limited time period prior to M0. The timing of this plate tectonic event is a matter of guess. Nevertheless, the plate separation probably started at M2 just after the detachment of Tibet away from India/Western Australia and ceased at M0 simultaneously with the Somali Basin. This suggests the existence of an oceanic crust of about 250 km extent between India and Iran. SB ceased to spread in the Early Cretaceous at 115 Ma (Segoufin & Patriat, 1980) or at 120.4 Ma (Marks & Tikku, 2001). The average drifting full rate of EG was 58 mm/yr in considering the date of SB drifting cessation at 122.0 Ma (interpreted from Haq et al., 1987) in the Lower Aptian.

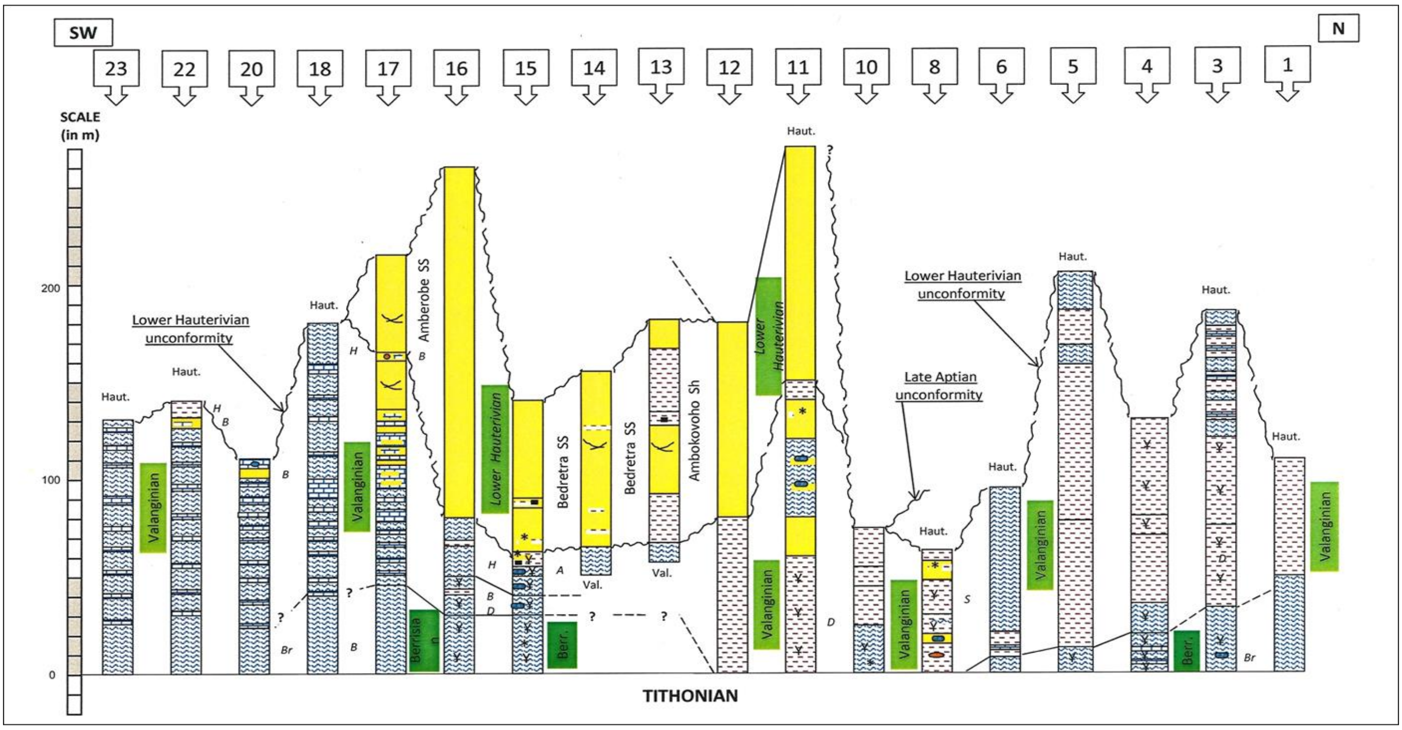

Fig 1 Correlation of the Berriasian Up to the Lower Hauterivian Outcrop Sediments in the Majunga Basin, Northwest Madagascar (Location of the Cross-Sections in Figure 1a and legend in Figure 1b).

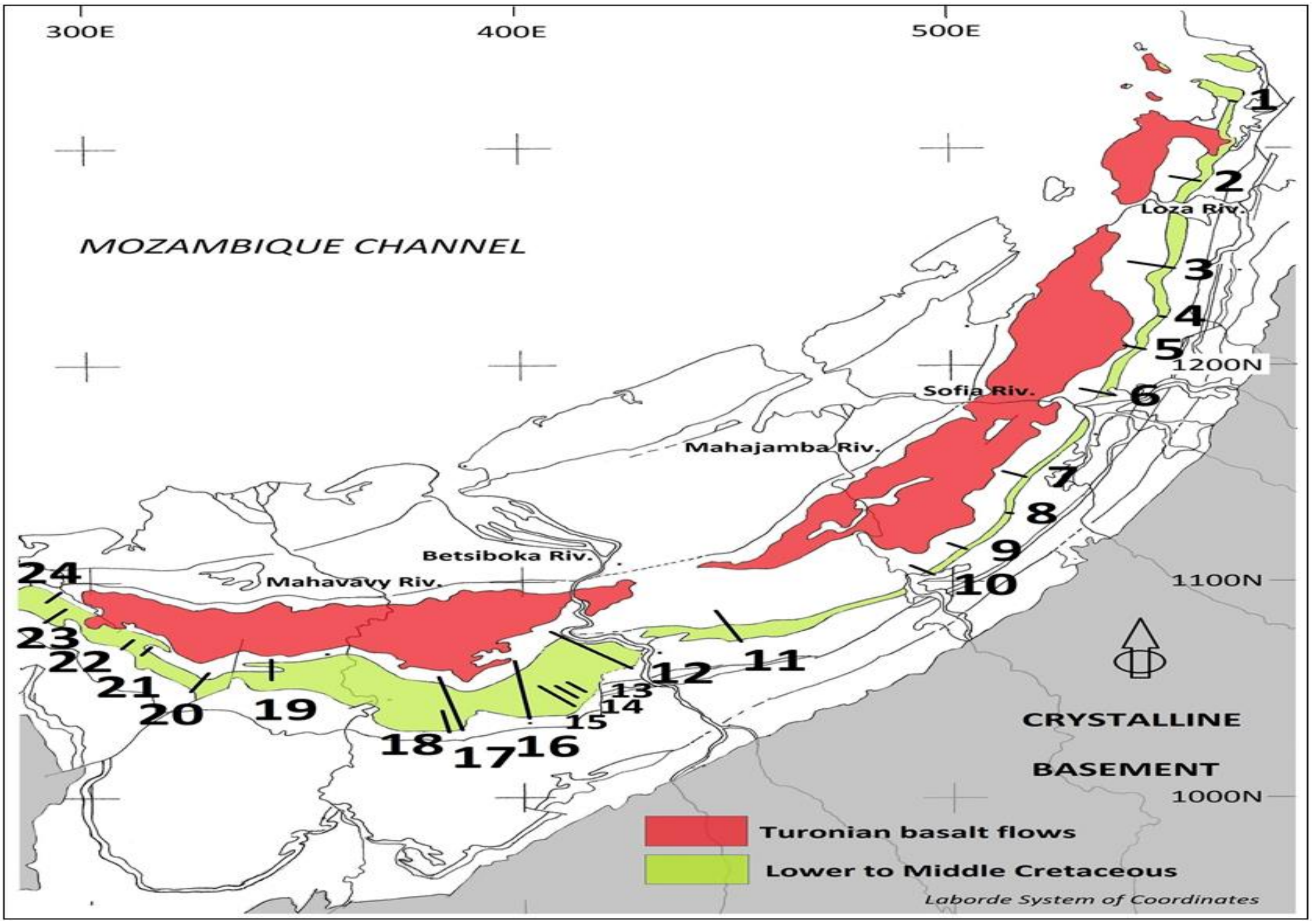

Fig 1a Location of the Geologic Cross-Sections in the Majunga Basin (According to Bésairie, 1972).

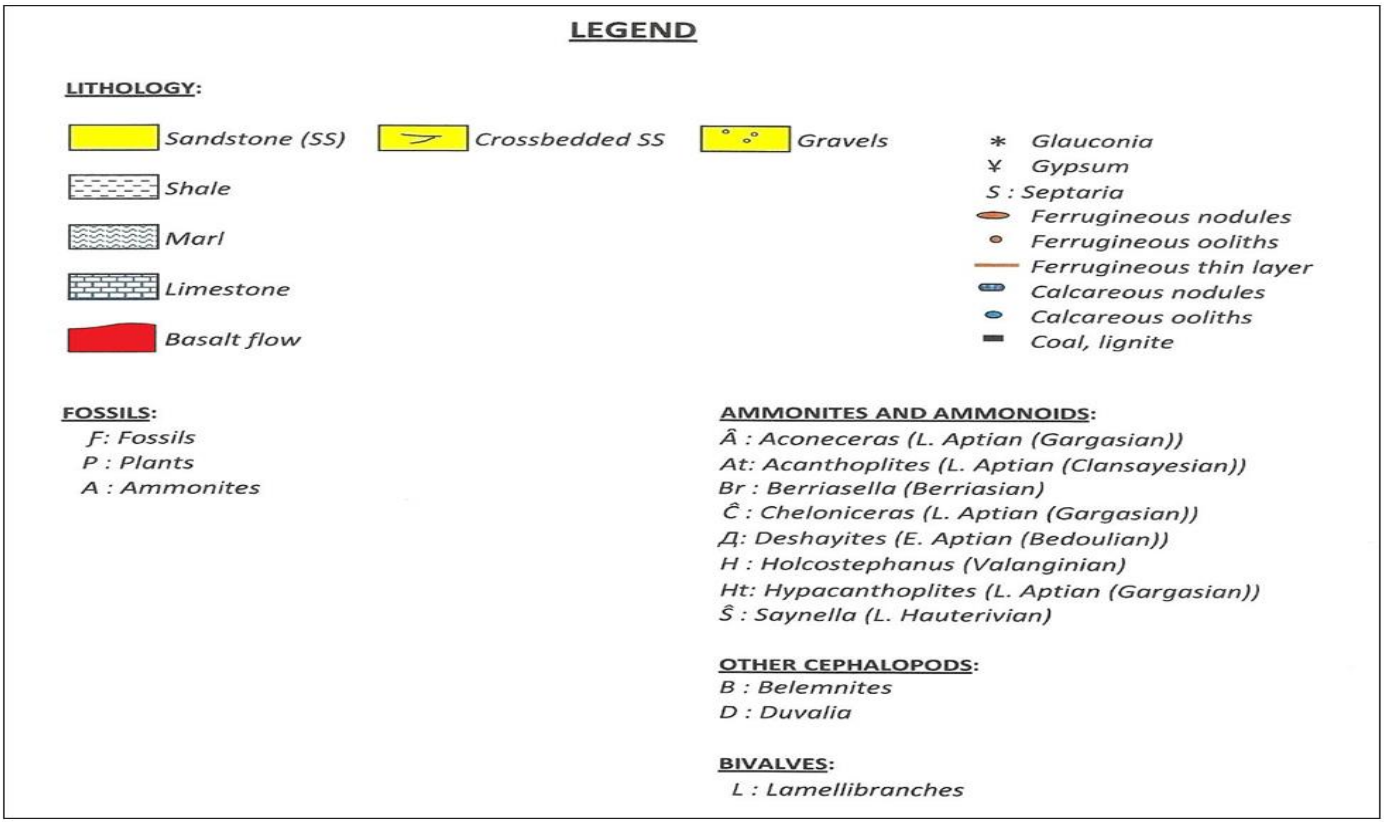

Fig 1b Legend for the Figure 1.

B. Period 2 (Figures M4 to M9).

➢ *Aptian Rifting Events.*

The central UMCC were split into two arms that separately developed tectonic activities in two distinct regions. The first arm jumped from the Somali Basin in Region 1 located between India and Sri Lanka/East-Antarctica and set up fan-like rifting activities during the Lower Aptian, Sri Lanka being attached to East-Antarctica. As a result, the anticlockwise rotation of the Sri Lanka/East-Antarctica/Australia block accentuated, giving rise to northward ridge jumps in the Tethys region (Figures M4 and M5). The second arm moved from the north of India to Region 2 located between India and East-Antarctica. The rifting activities in this region did not fully develop since the rotation-induced compression still prevailed. The South-African UMCC started to reduce interacting with EG at the end of this first rifting phase. The decrease of the conflicting relationship between the central and the Tethys regions strengthened the southward pushing effect of the eastern UMCC leading to the rotation reversal of the East-Antarctica/Australia block. The second rifting phase was accompanied by 7° clockwise rotation of the latter. A major fracture zone (FZ) separated Region 1 and Region 2.

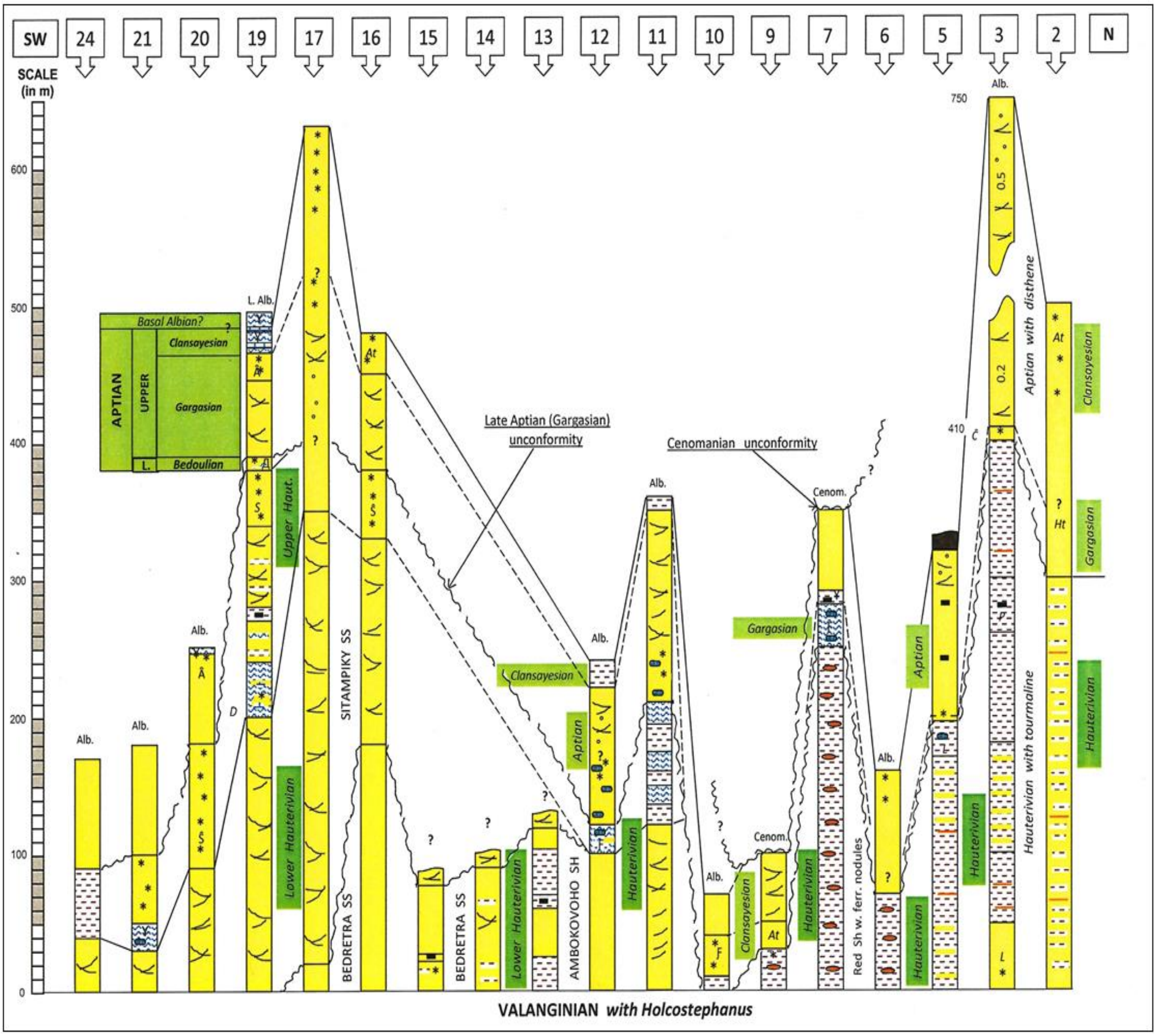

Fig 2 Correlation of the Hauterivian Up to the Aptian Outcrop Sediments in the Majunga Basin (Location of the Cross-Sections in the Figure 1a and Legend in Figure 1b).

The surface geology in Madagascar shows an erosional unconformity event dated in the Gargasian (Upper Aptian) presumably related to the pre-breakup rifting phase (Figure 2) in the central regions.

These Aptian activities initiated the setting of the long lasting positive anomaly superchron C34 characterized by the absence of the Earth magnetism inversions. This remained unchanged till the regional oceanic spreading started to reverse in Period 3.

➢ *Plate Tectonic Activities in Region 1.*

The plate tectonic movements in Region 1 were first marked by the fan-like rifting between India and Sri Lanka/East-Antarctica (first rifting period). It was the combination of 174 km translation and 26 degrees anticlockwise rotation centered at a point located near the city of Pondicherry. This translation lets suggest the existence of a low-rate extensional tectonism between India and East-Antarctica in spite of the prevalence of the rotation-inducted compression. The translation movement of Sri Lanka away from India took a 24°SE direction in using the present day map of India/Sri Lanka. It corresponds to ~20° SW direction at that Aptian times provided that the N-S orientation of Africa didn't change much since then. The rifting activities resumed afterwards between India/Sri Lanka and East-Antarctica (second rifting period). The plate movements were characterized by a series of southward ridge jumps, starting with the continental extension between Sri Lanka/South Madagascar Plateau (SMP) and the block Croset Plateau/Del Cano Rise/East-Antarctica (third rifting period). Afterwards, the rift center resumed between Croset Plateau/Del Cano Rise and East-Antarctica (forth rifting period). The next ridge jump occurred between Croset Plateau/Del Cano Rise and East-Antarctica resulting in the formation of the rift-related Conrad Rise and then after the creation of about 300 km wide oceanic crust. Once again, the ridge jumped further south between the Conrad Rise and East-Antarctica creating a fan-like oceanic opening that formed the early Western Enderby Basin (WEB). These repetitive ridge closings and jumps were the result of the conflicting situation between Regions 1 and 2 induced by the clockwise rotation of East-Antarctica/Australia.

➢ *Plate Tectonic Activities in Region 2.*

The continental extension in Region 2 led to the creation of base-flattened continental landmasses between India and East-Antarctica that comprised the Kerguelen-Heard Plateau (KHP) and the Broken Ridge Plateau (BRP). The subsequent oceanic opening occurred from the east in north-south direction (creation of the Bay of Bengal) accompanied by the clockwise rotation of the East-Antarctica/Australia block. This event is presumably dated in the Clansayesian (Upper Aptian) corresponding to the apparition of marine deposition in the Majunga Basin (Figure 2).

➢ *Entrapment of East-Antarctica within the South Polar Region:*

As the fan-like opening of early WEB developed, the East-Antarctica/Australia block rotated anticlockwise forcing the mid-oceanic ridges in Bay of Bengal to close. These ridges jumped to the south afterwards and joined those in the WEB. The convection currents in Regions 1 and 2 connected for the first time. The eastward expansion of WEB accelerated, and so was the anticlockwise rotation of East-Antarctica/Australia. As a result, the mid-oceanic ridges in the Tethys Ocean also got extinct. This ridge closing definitely marked the end of the southward drift of East-Antarctica/Australia.

III. DISCUSSIONS

The block East-Antarctica/Australia is believed to have virtually stopped drifting southward after entering the South Polar Region. The existence of concentric centrifugal forces in the upper mantle below the South Polar Zone may explain the "entrapment" of East-Antarctica/Australia. The intensity of these forces is proportional to the Earth's rotation speed. This natural phenomenon presumably had favored the setting of downwelling mantle convection currents below the South Pole that might have forced the convection currents in the WEB to move back like a Ping-Pong ball.

C. Period 3 (Figures M10 to M13).

A general plate tectonic reorganization took place in the Middle Cenomanian leading to the detachment of continental fragments towards the north and the northeast. The three branches of UMCC arose in different distant regions with no apparent link between them:

- The plate movements in MB resumed between Madagascar and India/Sri Lanka in an unusual WNW-ESE rifting direction.
- At about the same time, northward ridge jump from the WEB initiated the oceanic opening in the Eastern Enderby Basin (EEB) in a fan-like form. This opening propagated towards the southeast.
- Rifting activities centered along the Polar Circle started between East-Antarctica and southern Australia.

➢ *Rise of Convection Currents (CC) between East-Antarctica and Australia.*

The rifting between East-Antarctica and southern Australia started during the superchron C34 positive anomaly at ~95 Ma, (Royer, 1990). According to the eustatic change curves (Haq et al., 1987), its initiation and end are respectively dated at 94 Ma and at ~78.5 Ma (Early Campanian, C33), whereas the associated pre-breakup rifting phase is fixed at ~79.5 Ma. This yields ~27 mm/yr extension full rate. The earliest period of oceanic opening was confined between the Wilkes Land in East-Antarctica and South Australia with relatively low rates ranging from 5.9 to 16.6 mm/yr increasing inwards.

➢ *Rise of CC between Madagascar and India.*

The continental extension between Madagascar and India began in the Middle Cenomanian in 7° WNW-ESE direction. The related extensional faults observed at the surface generally run parallel to the east coast line with about 20° NNE-SSW orientation. The rift central axis bumped against a FZ in the south of Madagascar/Sri Lanka. At the end of the rifting activities in the Early Campanian, Seychelles/India was displaced to about 420 km with respect to Madagascar allowing an extensional full rate of ~25 mm/yr. The present day continent/ocean boundary (COB) is located at 150 km average distance from the east coast of Madagascar. It is not a straight line as previously adopted, but has a sawtooth shape (Figure 3).

The oceanic spreading occurred in two phases. The first phase started just after the last rift-related volcanic activities in Madagascar dated in the Early Campanian on the basis of paleontological analysis of outcrop rock samples (Bésairie, 1972). It took a 29 degrees NE-SW direction and ended in the Late Maastrichtian at C31 (~70.4 Ma). The spreading axis was bounded to the south by the Mascarene FZ located between the SMP and the Closet Plateau. This FZ was a right lateral lithospheric fracture separating a moving plate on its northern side to a static one on the southern side. It marked the southern boundary of the Great Mascarene Basin (GMEB). The second spreading phase began while the Croset Basin (CB) started to form at C31 in taking a 55° NNE-SSW direction. Compressional constraints prevailed in GMEB as the latter underwent a sidelong collision with the powerfully expanding CB.

➢ *Ridge Dispersal in EEB. Formation of the Elan and the Wharton Basins.*

The plate movements in EEB showed a complex ridge dispersal likely contemporaneous with the breakup between East-Antarctica and Australia dated at C33. The interaction between the two spreading basins, which show 42 degrees difference of ridge orientation, caused the cessation of the southeastward progression of EEB relayed by a series of northward jumps and a backward ridge propagation to the northwest (Figure M12) as detailed below:

- The first northward ridge jump was originated from the Princess Elizabeth Trough and formed the Eastern Wharton Basin (EWB) at C33 in the north of the southern KHP/BRP.
- The right lateral Elan FZ divided KHP/BRP into two parts during the creation of the Elan Basin at C32 as the result of northward ridge jumps to the northern boundary of EEB. The plate movements resumed then after at the northern KHP/BRP's COB at C31 and formed the Western Wharton Basin (WWB). The rift-related Kerguelen hotspot probably arose at C32 before changing place to COB and generated the Ninetyeast Ridge during the oceanic expansion. The Elan FZ separates EWB from WWB.
- A ridge propagation towards the northwest appeared at C32 from the western part of EEB. This ridge propagation reversal is unique in the plate tectonic history of the Indian Ocean.

The WB got curved to the east during its northward expansion because of the interaction with the northeastward expanding GMEB from C33 to C29.

➢ *Northwestward Propagation of the Enderby Convection Currents (ECC).*

The northwestward progression of ECC manifested in the following order (Royer, 1989):

- Acceleration of oceanic spreading in the east of the Conrad Rise at C32.
- Initiation of oceanic spreading in the north of the Croset Plateau at C31.
- Opening of the Madagascar Basin (MRB) at C30.
- Merge with the "jumped" Mascarene convection currents at C29.
- Rifting between the Seychelles/MP and India from C29 to C28.
- Oceanic spreading between the Seychelles/MP and India and opening of the Arabian Sea from C27 to C18/19. The ridge propagation further to the northwest has formed the Gulf of Oman and the Persian Gulf before the C18/C19 ridge closure.

The ridge propagation speed is approximately estimated at 290 mm/yr between west EEB and MRB.

The northeastward expansion of GMEB was under way while ECC hit the Mascarene FZ. Their 26°difference of spreading directions generated northward compressional constraints in GMEB leading to the closing of its mid-oceanic ridges probably at C31 (~70 Ma) in its southernmost region and at C29 (~65.6 Ma) in the Mascarene Basin (MEB). The Croset FZ, which bounded CB to the west, hit GMEB from the south and cut the Mascarene FZ in two segments. It relayed the Mascarene FZ from controlling the northward drift of India. The southern GMEB CC and ECC "fused" at C30 (first step of merge). The "sum" of these CC ensured the expansion of MRB bounded to the south by the Mascarene FZ and to the north by the Mauritius FZ. The spreading direction is considered to be the resultant of the CB and the GMEB ones. During the creation of MRB, the southernmost oceanic crust of GMEB (formed between C33 and C31) was pushed to the northeast, got compressed towards the Croset FZ and belonged from then on to the Seychelles/Indian block. Despite the strong difference of path angle between the Mauritius and the Croset fractures, they never crossed each other and gave to the MRB a curved funnel-like shape as it expanded towards the northeast. During the opening of MRB, MEB got its turn compressed and fractured as shown in the Figure 3. This is the second phase of compression in the GMEB. F1a and F1b trended towards the north and cut across the mid-oceanic ridges. Another fracture F1c opened the COB off-southern India and created the Mauritius hotspot. About 30 km of left lateral displacement is recorded along F1a, whereas it is estimated 25 km along F1b. These fault-controlled motions compressed the MEB mid-oceanic ridges leading to their extinction at C29, date after which the plate tectonic activities resumed between the Seychelles and India. The MRB ridges, which inherited the northwestward propagation process, joined the 'jumped' MEB ones and merged with the later (second step of merge).

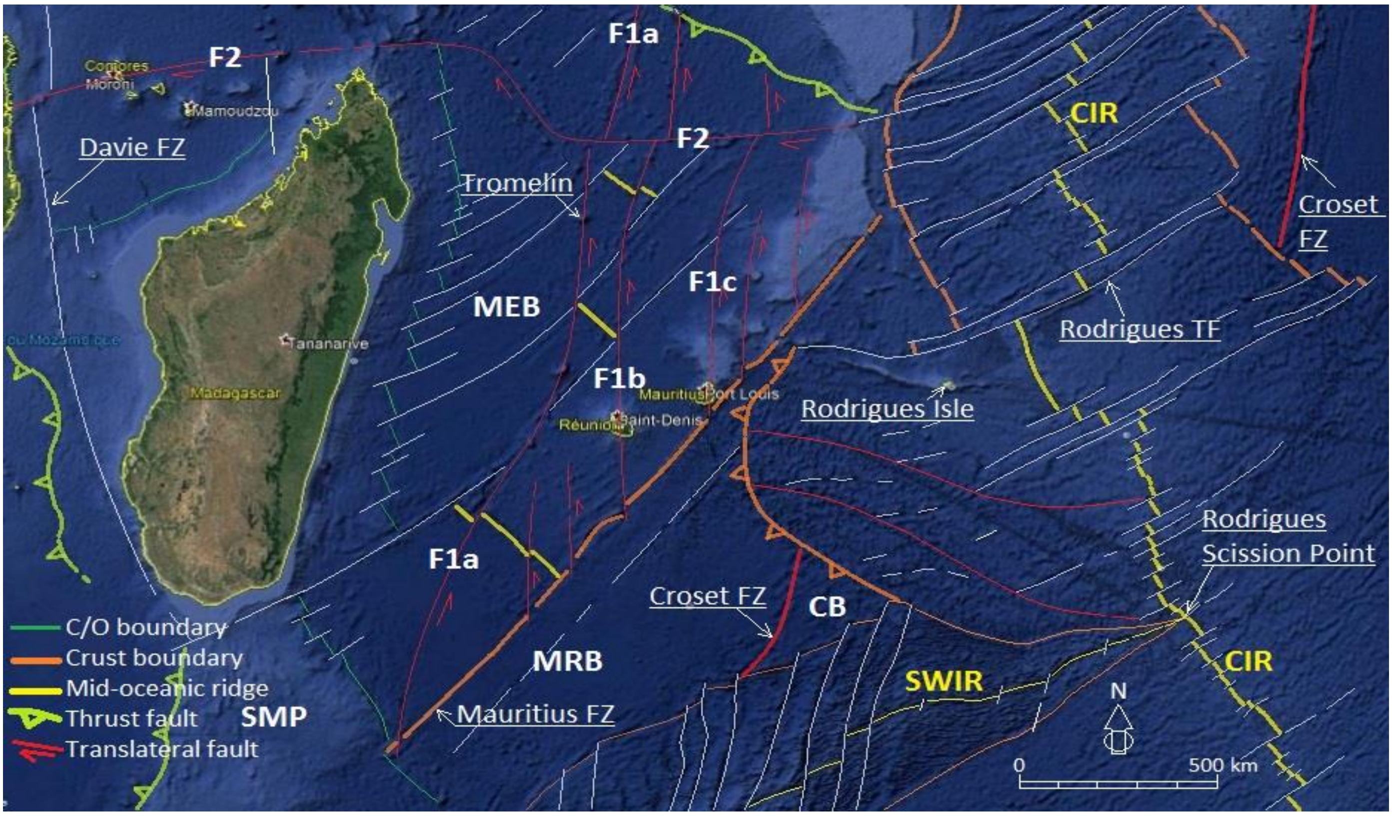

Fig 3 Setting-Up by Sidelong Compression of North-South Trending Fractures (F1a, F1b, F1c, etc.) in the Mascarene Basin (MEB) from C30 to C29. MRB Madagascar Basin, CIR Central Indian Ridge, SWIR Southwest Indian Ridge, SMP Southern Madagascar Plateau, CB Croset Basin.

- *Volcanic Activities and Hotspots.*

The Mauritius hotspot and its related trail of undersea volcanic mounts (Nazareth Bank and the Chagos Archipelado) appeared during the period of the MEB expansion from C30 to C29. The plate movements resumed afterwards between the Seychelles/MP and India in developing a crustal extension controlled by the “fusion” of the jumped CC from MEB and the northwestward propagating MRB ones. A mega-hotspot arose in central western India generating tremendous volcanic outpourings (Deccan Traps). Volcanism occurred in the MEB as well with the birth of the Reunion hotspot and seamounts (Tromelin Isle) through reopened fractures. The Reunion hotspot didn’t generate traces of seamounts since it was formed in an oceanic crust that was in a static position. The Deccan hotspot got extinct just after the oceanic opening between the Seychelles and India. It changed place to the southwest of India, merged with the newly formed ridge and became the Saya de Malha hotspot that generated the Saya de Malha Bank (SMB). As India rapidly drifted northward away from the Seychelles/MP, the hotspot gushed out the seafloor the Laccadive Ridge, a long chain of volcanic islands and seamounts that comprise the Laccadive Islands and the Maldives.

- *Setting of the Deccan Traps. Relationship with the Croset FZ and the Laccadive Ridge.*

The Deccan volcanic activities occurred during the continental extension between the Seychelles/MP and India at the end of the Cretaceous period (KTB). This rifting is unique in the plate tectonic history of the Indian Ocean since it was associated with the fusion of two waves of UMCC: the western CC and the western arm of the central ones. The reopening of basin faults crossed by the Croset FZ generated the Deccan “super volcano”. The mouth of the latter is well observed on the Bouguer Gravity Anomaly map of India (Tiwari et al., 2014). The Deccan region hosted the centers of the most powerful shield volcanoes of all Cretaceous times. They can be gathered within a circular area of about 730 km diameter centered at the point (75°E, 19°N) located on the track of the Croset FZ (Figure M12). Further to the north on the same trend, important volcanic manifestations are reported in the Vinghya region in association with extensional faults (Biswas & Thomas, 1990). Outside the circle, similar features are scattered all over the west of India (the Kutch and the Kathiawar regions extending south to the continental shelf off Mumbai), the Satpura and the Godavari basins in the east.

The Laccadive Ridge started to form at 14°00’N latitude at a distance more than 700 km south-southwest from the center of the Deccan volcano complex. The newly formed mid-oceanic ridge between the Seychelles/MP and India generated compressional constraints within the Indian continental crust that resulted to the closing of the hotspot. Afterwards, the later jumped to the south-southwest, merged with the mid-oceanic ridge and created SMB. During the northward drift of India, the Croset FZ and the SMB hotspot volcanic trail kept trending parallel one to another and never intersected each other.

➢ *Paleoposition of India and Related Tectonic Features.*

The Croset FZ was the key feature of the drift pathway of India. From C31 to C29, the latter underwent about 15 degrees anticlockwise rotation. Acting as an active crust boundary between CB and MRB, this fracture runs across the Laccadive Sea along the 75°38'E longitude, hits India at the city of Kollam, ~11°27' latitude, 30 km north of Calicut and trends north across western India in passing by Shimoga in Western Ghats. Not defined on the surface geology map of India, it is however well observed along the axis formed by the cities of Jammu and Srinagar crossing the Vale of Kashmir in northern India. The 75°E FZ, as also it can be called, sources a number of lakes and rivers in the Western Ghats and the northern India.

The rifting between India and the Seychelles trended in the same direction than the Croset FZ. India was displaced to ~266 km north-northeast during the time period spanning from C29 (~66.3 Ma) to C28 (~63 Ma) (Shellnutt et al., 2017) with 80.6 mm/yr extensional full rate. The paleoposition of India with respect to the Seychelles/MP during the breakup put SMB at (71°52'E, 14°00'N) which coincides to the departing point of the Laccadive Ridge. The southern Laxmi Ridge lined up adjacent to the Seychelles Plateau. The Mauritius hotspot's oldest position (Chagos Archipelago) was situated at ~430 km to the south-southwest of SMB. The Laccadive Ridge trended originally parallel to the Croset FZ, but got compressed towards the latter during the Late Tertiary CIR opening.

D. Period Four (Figure M14).

➢ *Late Tertiary Plate Reorganization.*

After the collision of India/Iran against Eurasia in the Middle Eocene at ~45 Ma, C21 (Royer, 1990), the mid-oceanic ridges in the Indian Ocean got closed. Then after, a new plate tectonic reorganization set up progressively from the east to the west starting at C18 (~42 Ma) in the Middle Eocene and ending in the Middle Miocene at C5 (~11 Ma or 10.6 Ma from Haq et al., 1987):

- In the eastern region, the northward-expanding ocean between the Antarctica and Australia accelerated and formed the Southeast Indian Ridge (SEIR).
- In the central region, the two Wharton Basins ceased to spread at C18/19. Their ridges jumped afterwards respectively between the South Kerguelen Plateau and the Naturaliste Plateau and between the North Kerguelen Plateau and Brocken Ridge in the Late Eocene at C15 (~38 Ma) (Royer, 1990), as shown in the Figure M14. So was created the eastern arm of CIR. The eastern (SEIR) and the central UMCC (CIR) were connected for the first time since the breakup of Gondwana and are separated by a transform fault cutting the ridge at 106°E longitude. The central UMCC progressed towards the northwest with the creation of the western portion of CIR characterized by the Rodrigues Scission Zone, the split-up of the Chagos Archipelago from the northern part of the Mauritius volcanic trail at about C13 (~35 Ma), the creation of the Carlsberg Ridge at C10? (~29 Ma) (Acharyya, 2000) and finally the oceanic spreading in the Gulf of Aden from C5 to end Tertiary.
- The western UMCC got separated from the central ones after 24 Ma of merge history in forming the Southwest Indian Ridge (SWIR) along the track of western portion of the Mascarene FZ between SMP and the Croset Plateau. Still, their respective mid-oceanic ridges remain connected at the Rodrigues Scission Point (20°30′S, 70°00′E). The creation of the SWIR began simultaneously with CIR in the Late Eocene at C15.

➢ *Effects of Compression Issued from the CIR and the Carlsberg Ridge.*

From the Late Eocene to the Oligocene, the Somali Basin, Madagascar, the Mascarene Basin and the Mascarene Plateau were under compressional constraints originated from the CIR and the Carlsberg Ridge as illustrated in Figure 4. Several dextral fractures were generated and named from the oldest to the youngest as F2 to F5. The following features can be depicted:

- The block composed by MEB and Madagascar laterally slid westward alongside F2 fracture, which tied in the east with a major CIR's TF. F2 cut the WSB from east to west. Its right lateral displacement across the Davie Ridge is estimated ~45 km (Figure 5).
- The landmass formed by the Seychelles Plateau (SP) and the Mascarene Plateau (MP) underwent ~23°anticlockwise rotation centered at the intersection with a CIR's TF (Figure 4). The rotation was controlled by F3 running on the northern side of SP. The rotation process was combined with about 190 km right lateral displacement allowing the setting-up of thrust zones (Amirante Trench) in the western regions.
- The compressional constraints originated from the CIR might have provoked the extinction of the Reunion hotspot.
- Two other fractures, F4 and F5, cross the WSB from the north to the southwest. The fracture F4, named Chain Ridge as it crosses the WSB, represents the southward continuation of the Owen TF that separates the Carlsberg Ridge (Indian plate) and the Gulf of Aden (Arabian plate). F5 was formed during the rifting in the Gulf of Aden that started at ~29 Ma in the Oligocene.
- The Chagos Archipelago was related to the Mauritius hotpot, but became aligned with the Laccadive Ridge in the south of SMB during the opening of CIR. The new ridge passed in the east of the SMB hotspot and cut in two parts the Chagos Archipelado at the 61°E longitude.
- Compressed, the SMB hotspot jumped to the south at the western tip (60°E, 19°S) of the Rodrigues TF. It became the Rodrigues hotspot and developed an undersea volcanic trail in the south of the Rodrigues TF during the CIR expansion. The merged mid-oceanic ridge and hotspot became simultaneously extinct in the Middle Miocene at C5. The Deccan, the SMB and the Rodrigues hotspots were generated by the same mantle plume. The Deccan hotspot was of continental origin, whereas the SMB hotspot arose at the India's COB and the Rodrigues hotspot in a spreading oceanic crust.

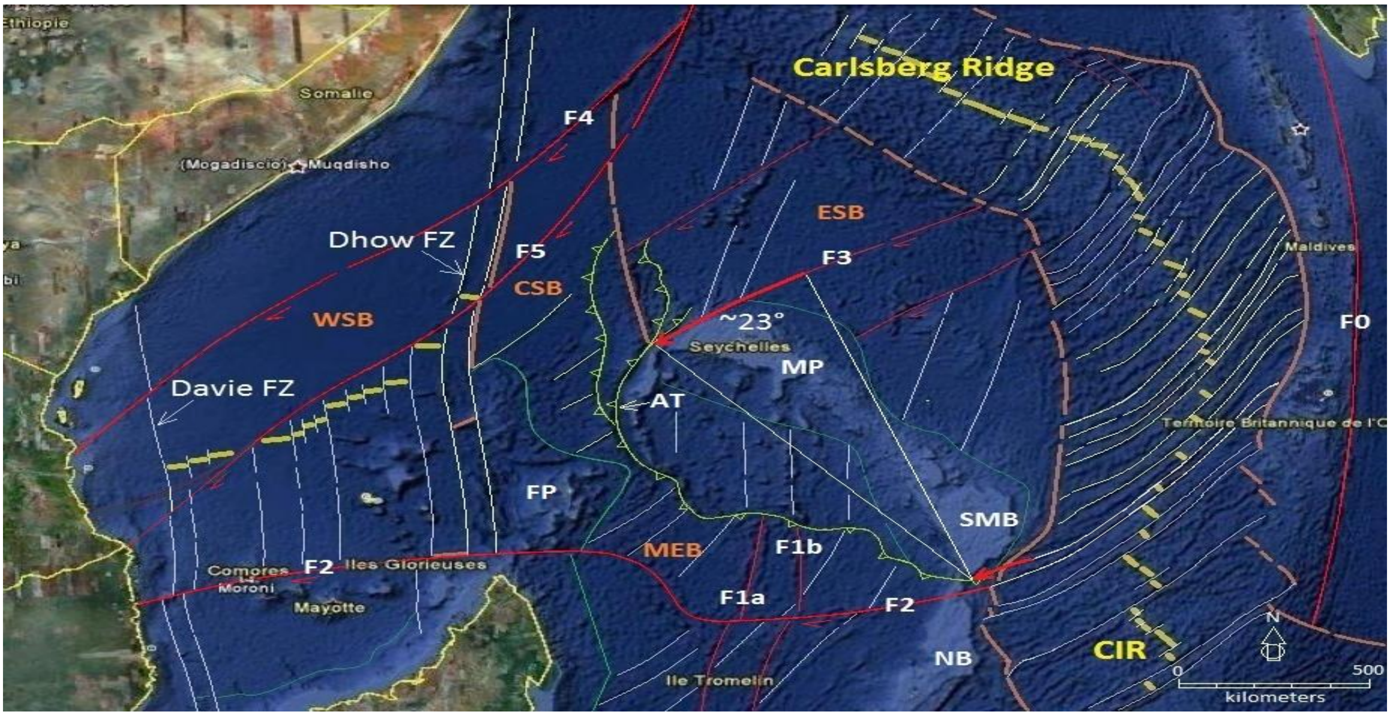

Fig 4 Tectonic Features Caused by the Compressional Constraints Originated from the CIR in the East and the Carlsberg Ridge in the North-East. Abbreviations used: AT Amirante Trench, MEB Mascarene Basin, FP Farquhar Plateau, MP Mascarene Plateau, SMB Saya de Malha Bank, NB Nazareth Bank, ESB Eastern Somali Basin, CSB Central Somali Basin, WSB Western Somali Basin. F0 Croset FZ.

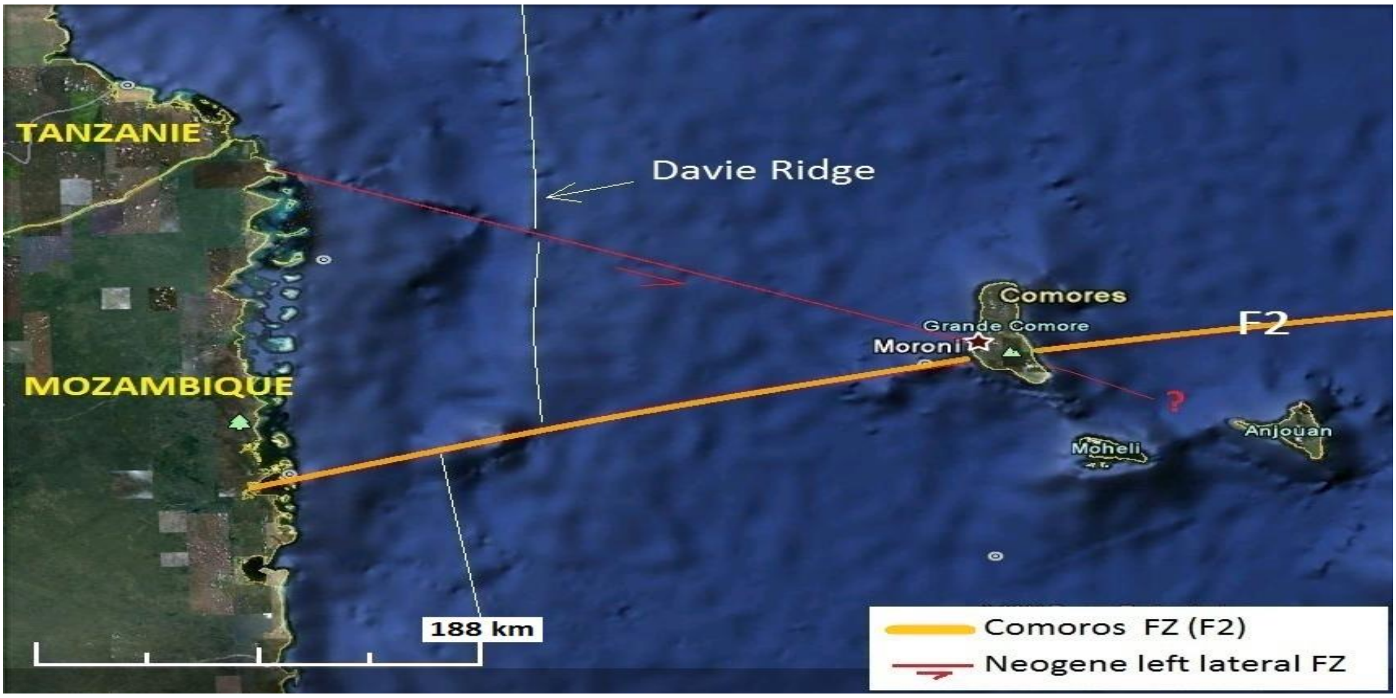

Fig 5 The Comoros FZ (F2) at its Intersection with the Davie Ridge.

E. Period Five (Figure M15).

➢ *Plate Tectonic Activities in the Gulf of Aden, Red Sea and East-Africa.*

Starting in the Oligocene (~29 Ma) at C10 (Royer, 1990), a new plate tectonic development involved the African and the Arabian plates leading to the rift settings in the Gulf of Aden in the northeast-southwest direction. The oceanic spreading began in the Middle Miocene at C5. The East-African rift system was set up in the Middle Miocene in northwest-southeast direction as the result of northward ridge jump from the SWIR. The newly set UMCC in East Africa joined those in the Gulf of Aden at the Afar Triple Junction with the following divergent plates in concern: the African (Nubian), the Somalian (Horn of Africa) and the Arabian plates. The different branches of the East-African Rift system from the Afar Region in the north to Mozambique in the south are separated by a northwest-southeast trending left lateral FZ shown as orange lines in the Figure 6 (Mougenot et al., 1986). The Somalian plate in fact comprises a much greater block including the regions in the east of the Rift Valleys, the Somali Basin, Madagascar and the Indian Ocean. In Madagascar, these tectonic activities generated several facing-west extensional faults especially in western and northwestern sedimentary basins, in the central (Antsirabe) and the eastern regions (creation of the Alaotra Lake and the Bay of Antongil, split of the Sainte Marie Isle from the main land). Important volcanic eruptions (Barren Isles in western off-Madagascar, Nosy Be isle and Ambre Mountain in the north, Ankaratra Mountain in the center, etc.) took place. Extensive iron-rich hydrothermal outpourings occurred as well. In the Indian Ocean, the Reunion hotspot may have been reactivated after 30 Ma lasting extinction.

The East-African and Arabian plate tectonic activities already resumed to new places and set off a second rifting phase in north-south direction since the Pleistocene (Figure 6). It is considered to be the precursor that will conduct to an imminent crustal final breakup. The surface geology in Madagascar (Bésairie, 1972) shows two areas where Quaternary tectonic activities can be observed: (1) in the Tuléar region, southwestern Madagascar and (2) in the Diego Basin, northern Madagascar.

The geologic map of the southwestern region of Madagascar shows north-south trending fractures crossing the coastal areas in 15° NNW-SSE direction (Figure 7). Marine reflection seismic data confirm their presence in the east of the Davie Ridge in parallel direction to the later. They evoke the existence of a southward moving plate in the west of Madagascar (Mozambique plate). A major left lateral fracture running alongside the Davie Ridge controls these movements, the Davie volcanic mounts being included inside the Mozambique plate. It bends to the south-southwest in the south of the point (25°S latitude, 44°E longitude), cuts across the Davie FZ and joins the SWIR's Prince Edward and Marion fracture zones at the 36°E longitude (Figure 8). This area records powerful earthquakes with magnitudes that may reach 7.0 on the Richter scale (Wikipedia).

The origin of Quaternary plate movements in East-Africa is defined in Tanzania between the 8°S and 9°S latitudes. A marked crevasse off-Tanzania at 8°50'00''S latitude between the 41°00'00''E and 41°30'00''E longitudes is assumed to indicate the location of the rift center (Figure 9). It is the largest of a series of crevasses separated by transform faults. They are formed in the sedimentary section overlying the continental crust which undergoes heating, uplift and stretching on both sides. These convection currents are the result of ridge jump from their previous emplacement in the East-African Rift Valley system. They are considered to belong to the **western branch** of UMCC. The western boundary of the Mozambique plate is suggested to trend alongside the East-African grabens running roughly along the 35°E longitude south of the 9°S latitude towards the southern Mozambique offshore zone.

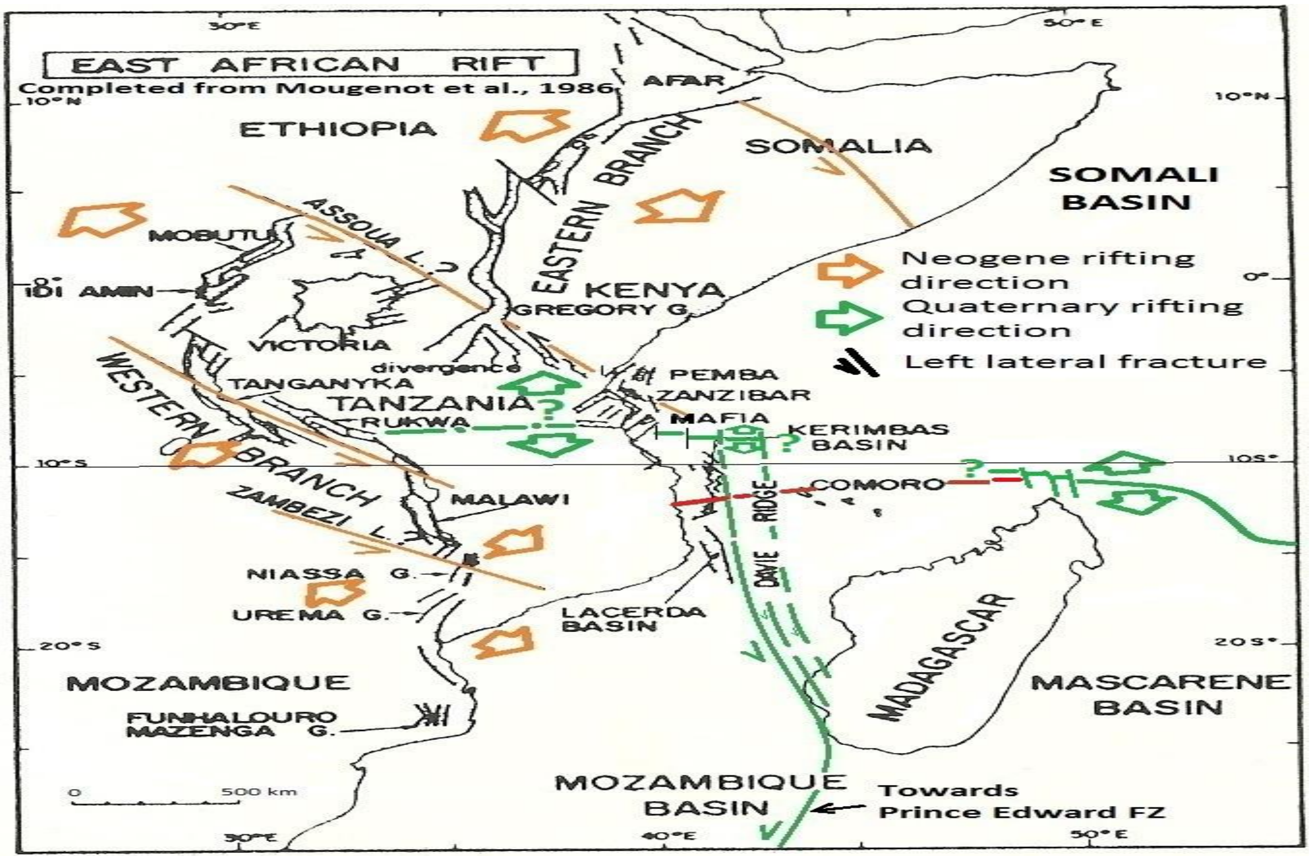

Fig 6 Neogene Rifting Phase (in Orange) Leading to the Creation of the East-African Rift System. The Quaternary Pre-Breakup Rifting Features are Shown in Green Color.

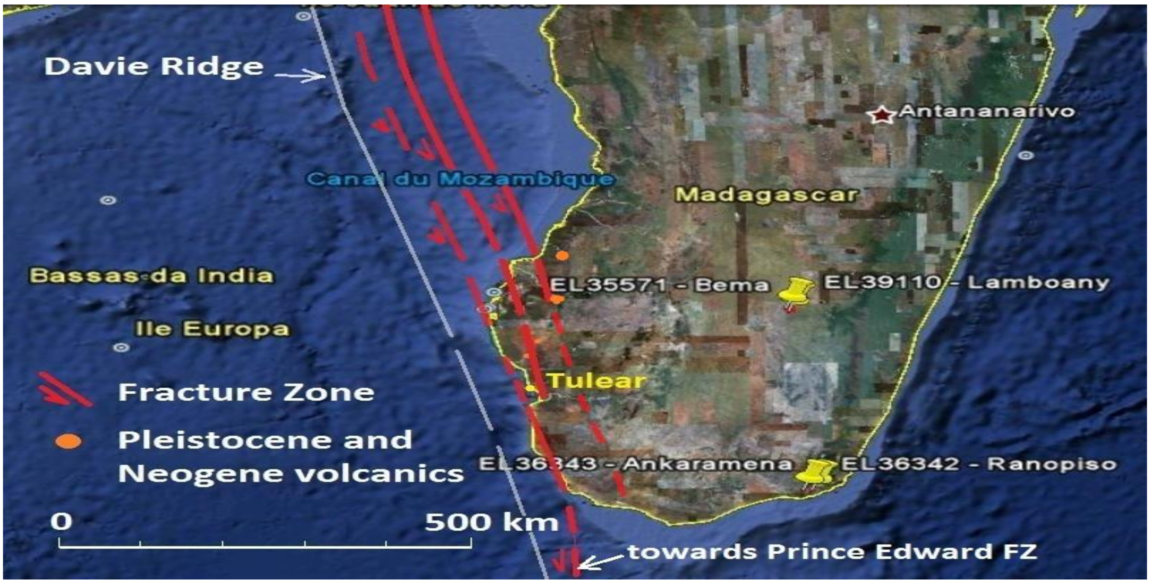

Fig 7 NNW-SSE-Trending Left Lateral Fracture Zones of Pleistocene Age Hitting the Southwestern Coastal Areas of Madagascar and Associated Volcanic Outpourings.

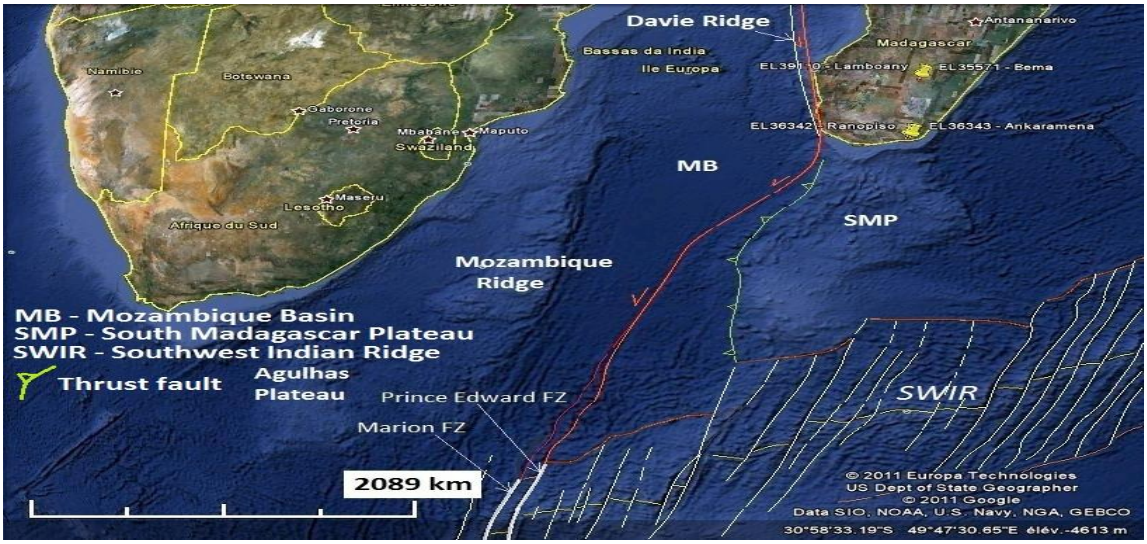

Fig 8 Connection of the Major Left Lateral Fracture in the Eastern Boudary of the Mozambique Plate with the SWIR's Prince Edward Transform Fault.

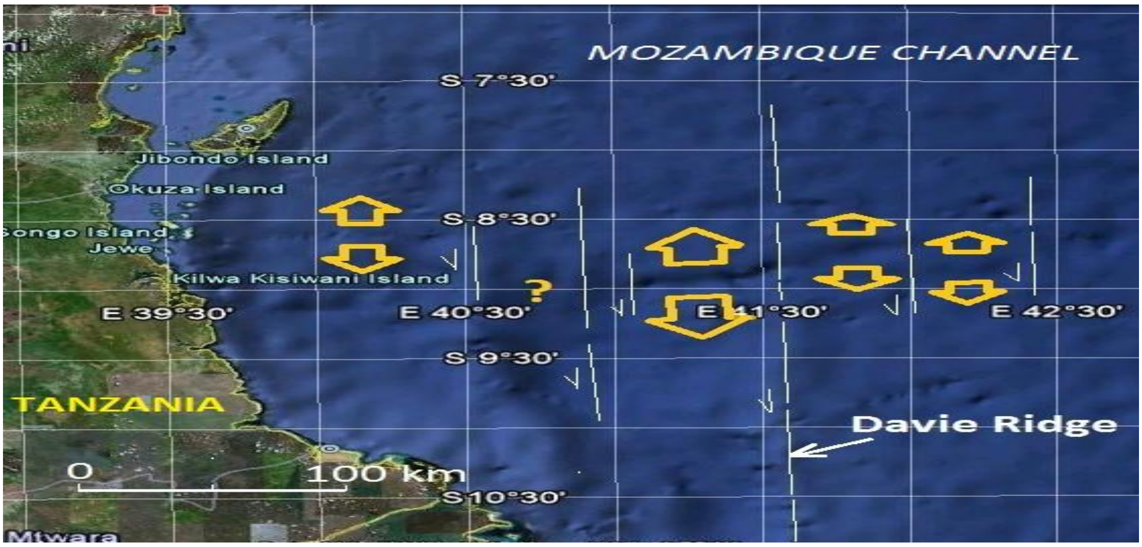

Fig 9 Position of the Quaternary Rift Center Off-Tanzania as Segmented Crevasses Separated by Left Lateral Transform Faults.

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A dense grid of dextral fractures associated with the Quaternary extensional tectonic activities is observed on outcrop geology in the Diego Basin, northern Madagascar (Figure 10). On land, fractures originated from the rift center cut across the Ankara limestone platform with 10°SSE orientation and generated right lateral displacements that may reach 5 km. Eruptive volcanic and hydrothermal activities are wide spread (Montagne d'Ambre, Nosy Be isle, etc.). The rift central axis is visibly defined as an elongated crevasse at 11°20'S latitude, 110 km northeast of the Diego city harbor. It partly runs along the F2 fault that separates Madagascar and the Farquhar Plateau between the 50°E and 50°45'E longitudes. It is attributed to the **central branch** of convection currents that likely left the Gulf of Aden at the end of the Tertiary.

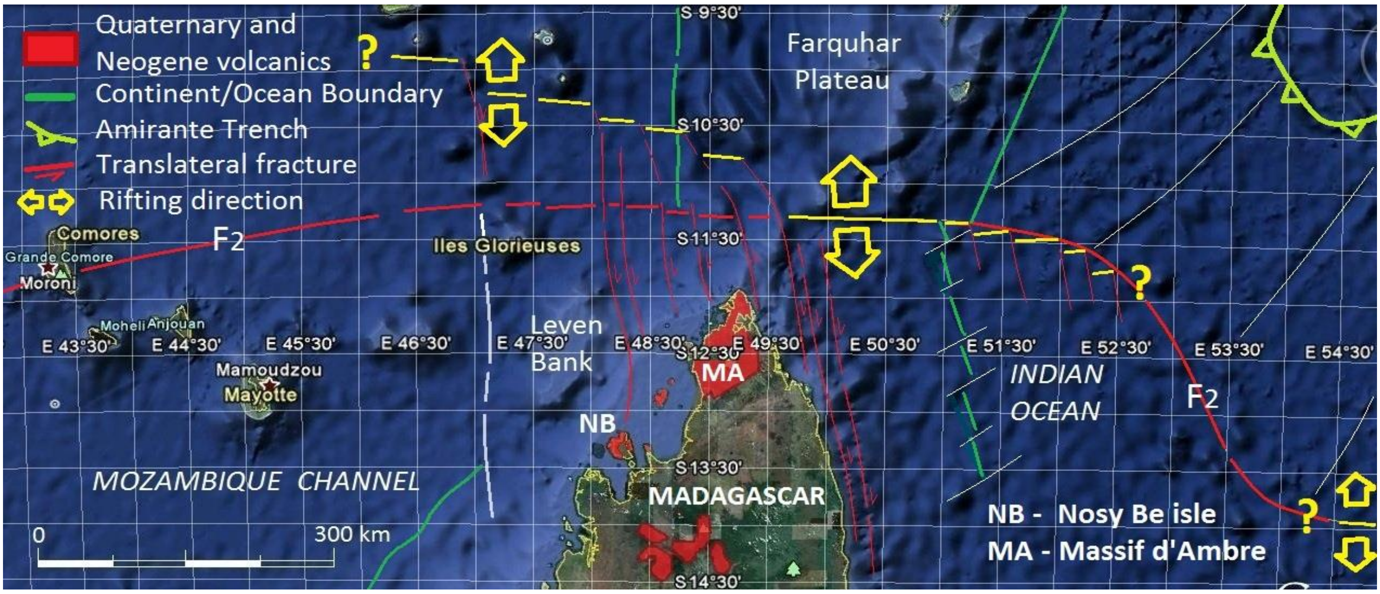

Fig 10 Present Day Position of the Rift Center Axis in the North of Madagascar.

The **eastern branch** of UMCC that left the SEIR in the Miocene probably moved to southern latitudes near the Antarctica Polar Circle at a presumed location in the east of 94°E longitude alongside the Antarctica's continental slope, which appears to be a zone of weakness for the next crustal breakup.

The Quaternary pre-breakup rifting phase occurred after Late Tertiary rifting period of about 9.36 Ma duration. It is inferred that its duration should not exceed 2.0 Ma.

➢ *At a Glance, Paths of the Three Branches of the Indian Ocean CC:*

In the beginning of the Period 1, three branches of N-S convection currents initiated the southward drift of EG, the western, the central and the eastern branches that respectively created the MB, the SB and the New Tethys Ocean. From then on, they evolved as follows:

- The **eastern branch** continuously generated the Tethys Ocean during the Periods 1 and 2, moved between East-Antarctica and Australia in Period 3 and created the SEIR in Period 4. Nowadays, they are assumed to set up a pre-breakup rifting phase along the South Polar Circle since the end Tertiary (Period 5).
- The **central branch** is divided in two arms that separately controlled the tectonic activities in two distinct regions: in Region 1 (western), fan-like rifting between India and Sri Lanka, formation of continental plateaus (SMP, Croset/Del Cano and Conrad Rise) separated by oceanic crusts, and creation of the Bay of Bengal in Region 2 (eastern). The fan-like spreading of WEB was made by the merge of the two arms. In Period 3, it formed EEB. A ridge dispersal split it into three arms. Two of them formed the WB, whereas the third arm propagated towards the northwest in creating CB/CIB and MRB before merging with the western branch between the Seychelles and India. In Period 4, it created the CIR, the Carlsberg Ridge and the oceanic basin in the Gulf of Aden. A rift center is observed at the present day between Madagascar and the Farquhar Plateau (Period 5).
- In Period 3, the **western branch** left MB and jumped between Madagascar and India to form GMEB. In Period 4, it got separated from CIR and created SWIR. It generated the East-African Rift Valley in Period 5. It changed place in Tanzania in setting up a pre-breakup rifting phase.

The side interactions with the central branch are the principal causes of continent fragmentations that conducted to the formation of the Indian Ocean. The most spectacular of them took place in the Early Campanian between the eastern and the central branches when oceanic opening started between East-Antarctica and Australia. The central CC in the Eastern Enderby Basin acted as a firing blocked-gun barrel that blows up in the shooter's face. In addition to northward ridge jumps, a backward ridge propagation also occurred and lasted a long time period from C32 to C19.

➢ *Discussions: Impacts on the Present Day Global Climate Changes.*

The convection currents within the Earth mantle affect the planet in two different manners:

- They generate heat, multiple fractures and faults within the lithospheric crust and volcanic activities, especially during the periods of extension before the crust breaks up along mid-oceanic ridges. The present paper reveals that N-S convections currents reappeared in the Indian Ocean since the Pleistocene. The associated rift center axis cuts across the Indian Ocean from Tanzania in the northwest to the eastern Antarctica in the southeast in passing by the north of Madagascar. These rifting activities are the precursor of imminent crustal breakup in N-S direction. Since then, they kept the Southern Hemisphere warmer than the other half during the Quaternary Glaciation that ended while the Holocene Glacial Retreat started about 11700 years ago (Wikipedia). The presence of upwelling CC below the eastern South Polar Zone is the main cause of ice melting in the Antarctica resulting to worldwide sea level rise.
- Nowadays the magnetic poles are moving towards the equator with increasing speed. It is possible that this will lead to the reversal of the Earth's magnetic field polarity. Does this phenomenon have relationship with the ongoing plate tectonic activities in the Indian Ocean? Since the intensity of the magnetic field decreases from the poles to the equator, the drift of the poles towards the equator will put the polar and the temperate regions in high risk of solar radiation exposure generating high temperatures ever recorded at the surface and brutal changes of climate.

IV. CONCLUSION

The opening of the South Atlantic Ocean launched by causal relationship the geodynamic processes that constructed the Indian Ocean. Three branches of convection currents (CC) spread out the puzzle pieces in synchronized manner during five periods of plate reorganization, each period being preceded by compression-induced mid-oceanic ridge closings relayed by ridge jumps. Period 1 was marked by the northward detachment of continental fragments in the Tethys region, the creation of an oceanic crust between northern India and Iran and the spreading cessation of the Somali Basin at M0. During Period 2, the central branch of CC split up East-Gondwana into two parts, but the conflicting relationship between the western and the Tethys regions still remained until the end of the fan-like rifting between Sri Lanka and India in Lower Aptian. It ensued the rotation reversal of East-Antarctica/Australia and the change of direction of plate movements to N-S. The oceanic opening (Bay of Bengal) started in late Upper Aptian and developed from the east, whereas a series of ridge jumps prevailed in the western adjacent region in forming rift-related landmasses separated by oceanic crusts. The formation of the fan-like Western Enderby Basin marked the "entrapment" of East-Antarctica into the South Pole Region and provoked a series of events that led to general ridge closings. From Middle Cenomanian (Period 3), simultaneous northward ridge jumps generated plate movements between Madagascar and India/Seychelles and between East-Antarctica and Australia. Meanwhile, an eastward fan-like opening formed the Eastern Enderby Basin. From C33 to C31, a ridge dispersal in this basin conducted to a series of jumps that formed the Elan Basin and the Wharton Basins. A backward ridge propagation created the Croset Basin at C31 and hit the Great Mascarene Basin giving rise to complex sidelong collision processes and ridge closings at C31 and C29. The plate movements resumed between the Seychelles and India and, from then on, were controlled by the fusion of the western and the central CC. The rift-related Deccan mega hotspot arose at C28 and moved place to the India's COB at ~C27. After the collision of India against Eurasia at C21, Period 4 was characterized by the connection of SEIR with eastern CIR and the separation of SWIR from northern CIR. At C5, ridge jump from SWIR set up the East-African Rift system (Period 5). A pre-breakup rifting phase in N-S direction is under way since the Pleistocene.

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ABBREVIATIONS USED

BRP	Broken Ridge Plateau
CB	Croset Basin
CC	Convection currents
CIR	Central Indian Ridge
COB	Continent/Ocean Boundary
CSB	Central Somali Basin
ECC	Enderby Convection Currents
EEB	Eastern Enderby Basin
ESB	Eastern Somali Basin
FZ	Fracture Zone
GMEB	Great Mascarene Basin
KHP	Kerguelen-Heard Plateau
KTB	Cretaceous Tertiary Boundary
MEB	Mascarene Basin
MP	Mascarene Plateau
MRB	Madagascar Basin
SB	Somali Basin
SEIR	Southeast Indian Ridge
SIFZ	South India Fracture Zone
SMB	Saya de Malha Bank
SMP	South Madagascar Plateau
SWIR	Southwest Indian Ridge
TF	Transform Fault
UMCC	Upwelling mantle convection currents
WEB	Western Enderby Basin
WSB	Western Somali Basin

GRAPHICAL MONTAGE

- *Period 1: Drift Deflection.*

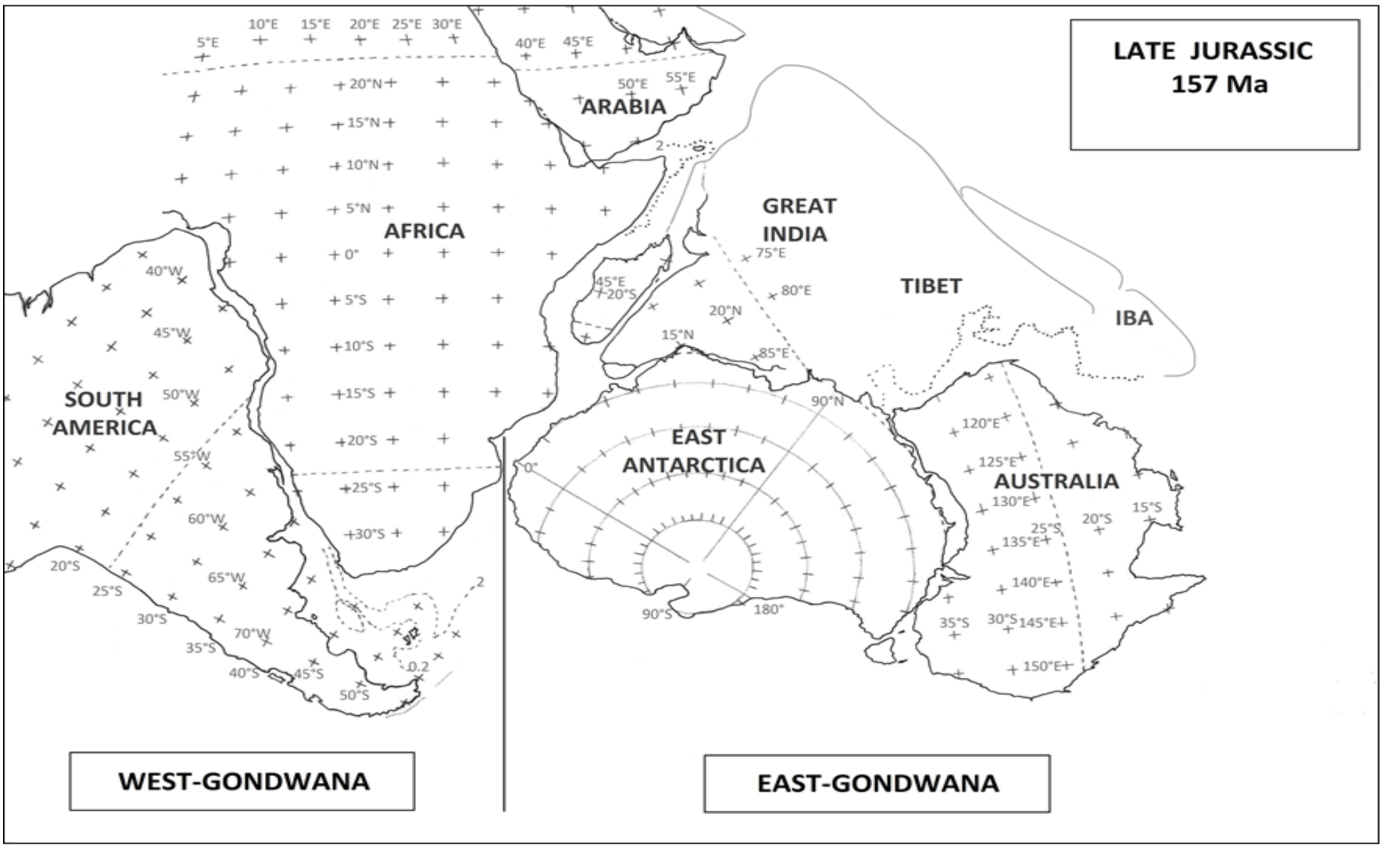

Fig M1 Paleoposition of Madagascar in Gondwana.

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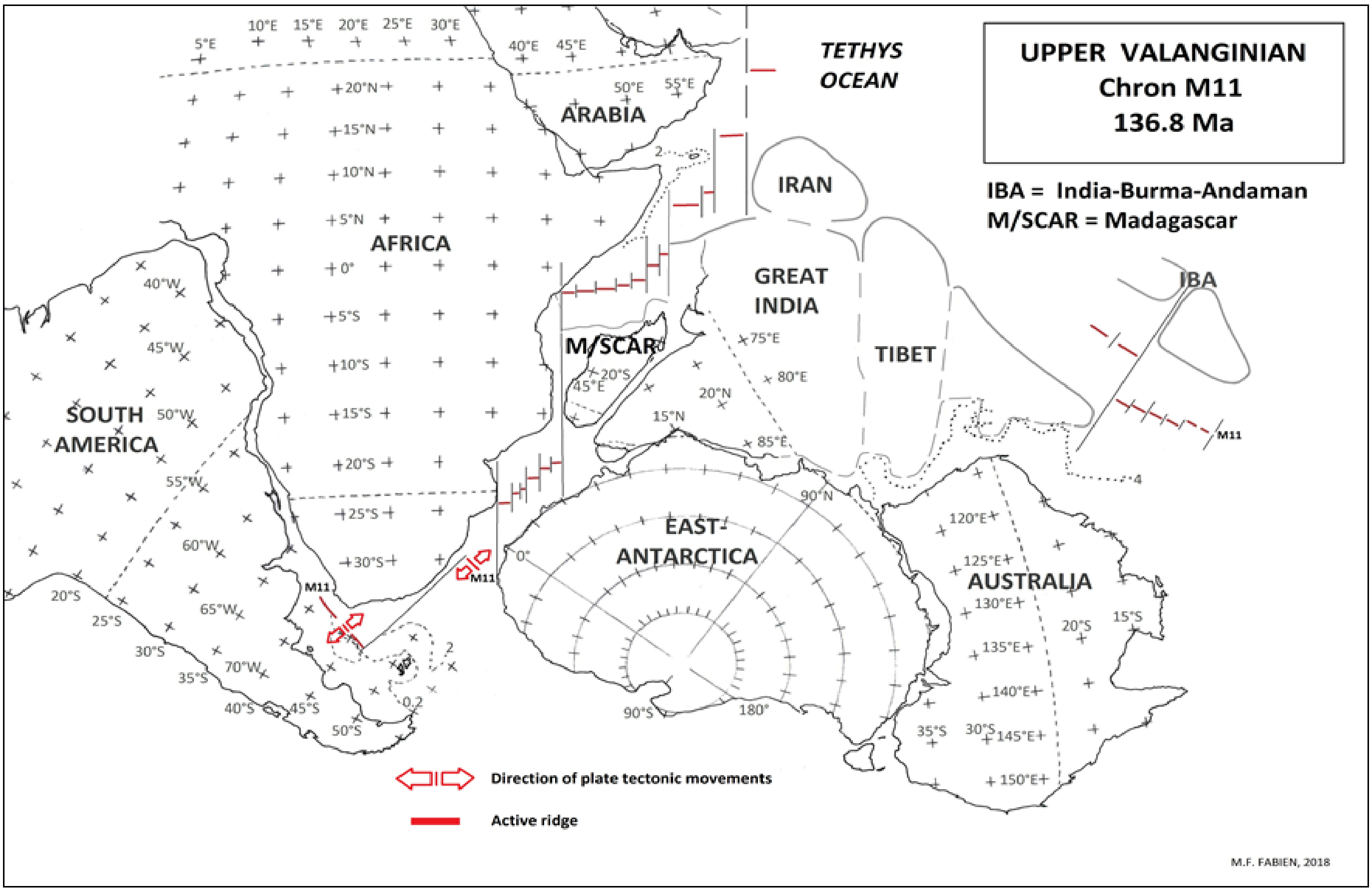

Fig M2 Southward Drift of EG.

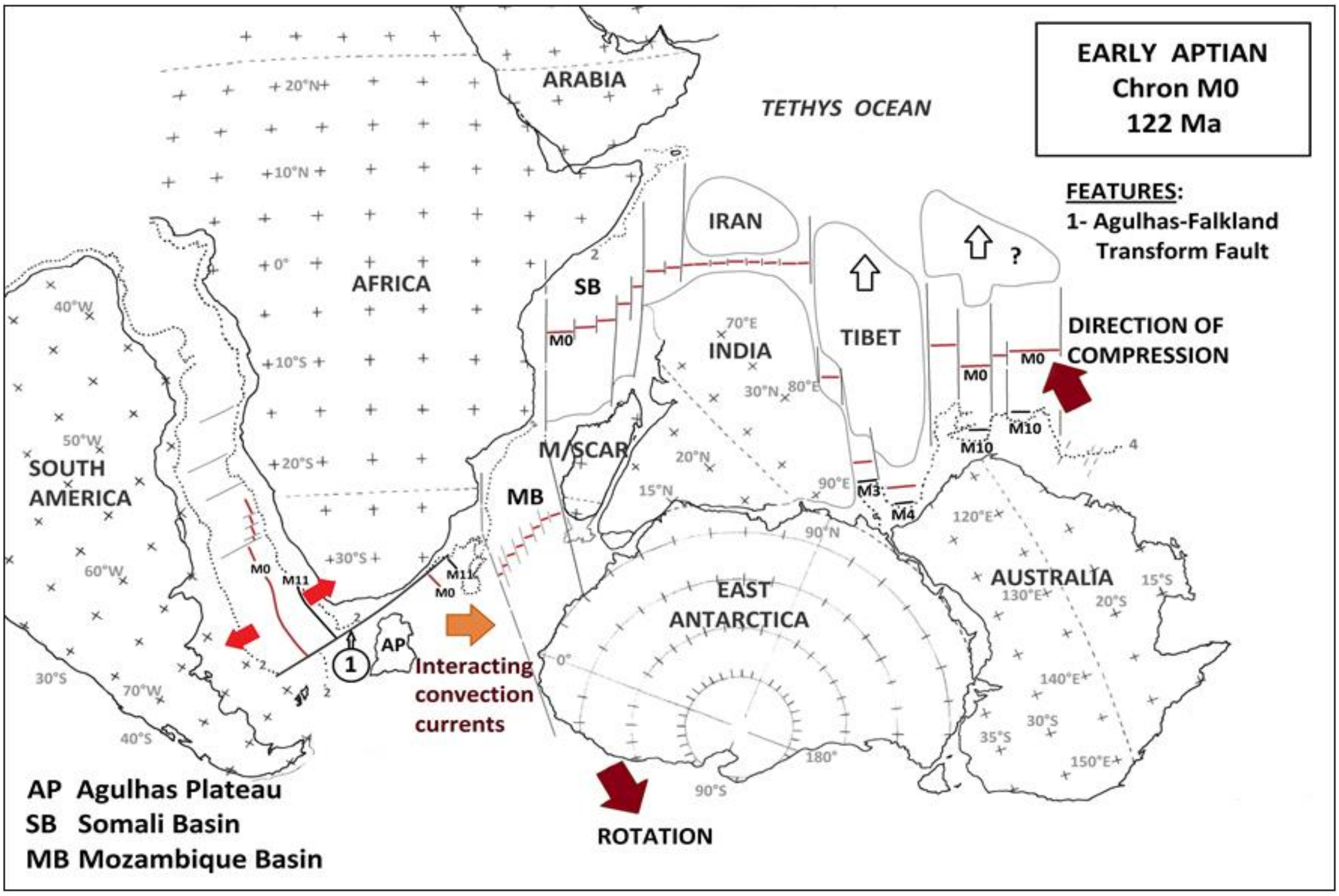

Fig M3 Anticlockwise Rotation of EG Leading to a Series of Ridge Closings and Southward Jumps in the Tethys Ocean.

➢ *Period 2:*

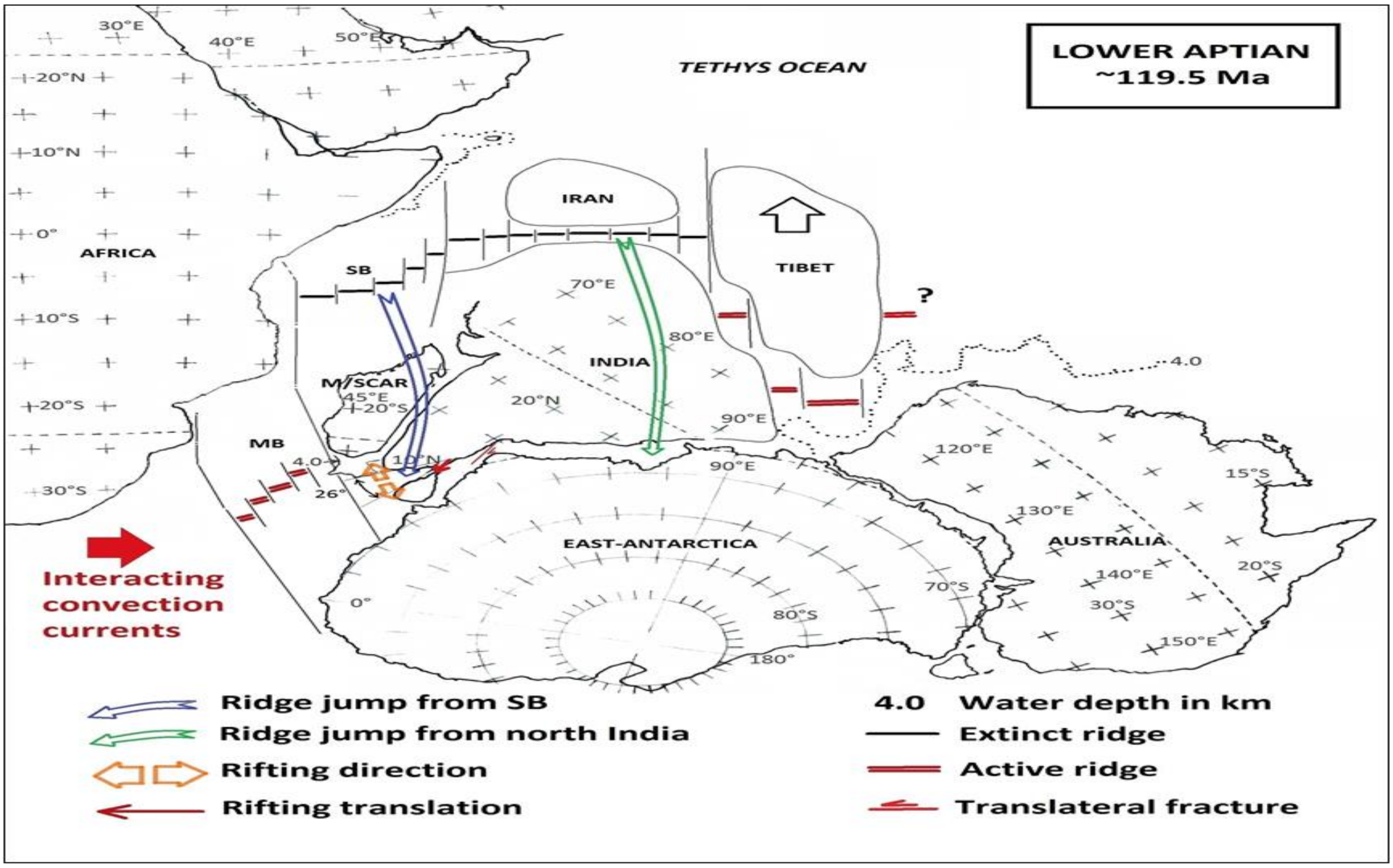

Fig M4 Lower Aptian Rifting Activities Caused by Two Separate Ridge Jumps.

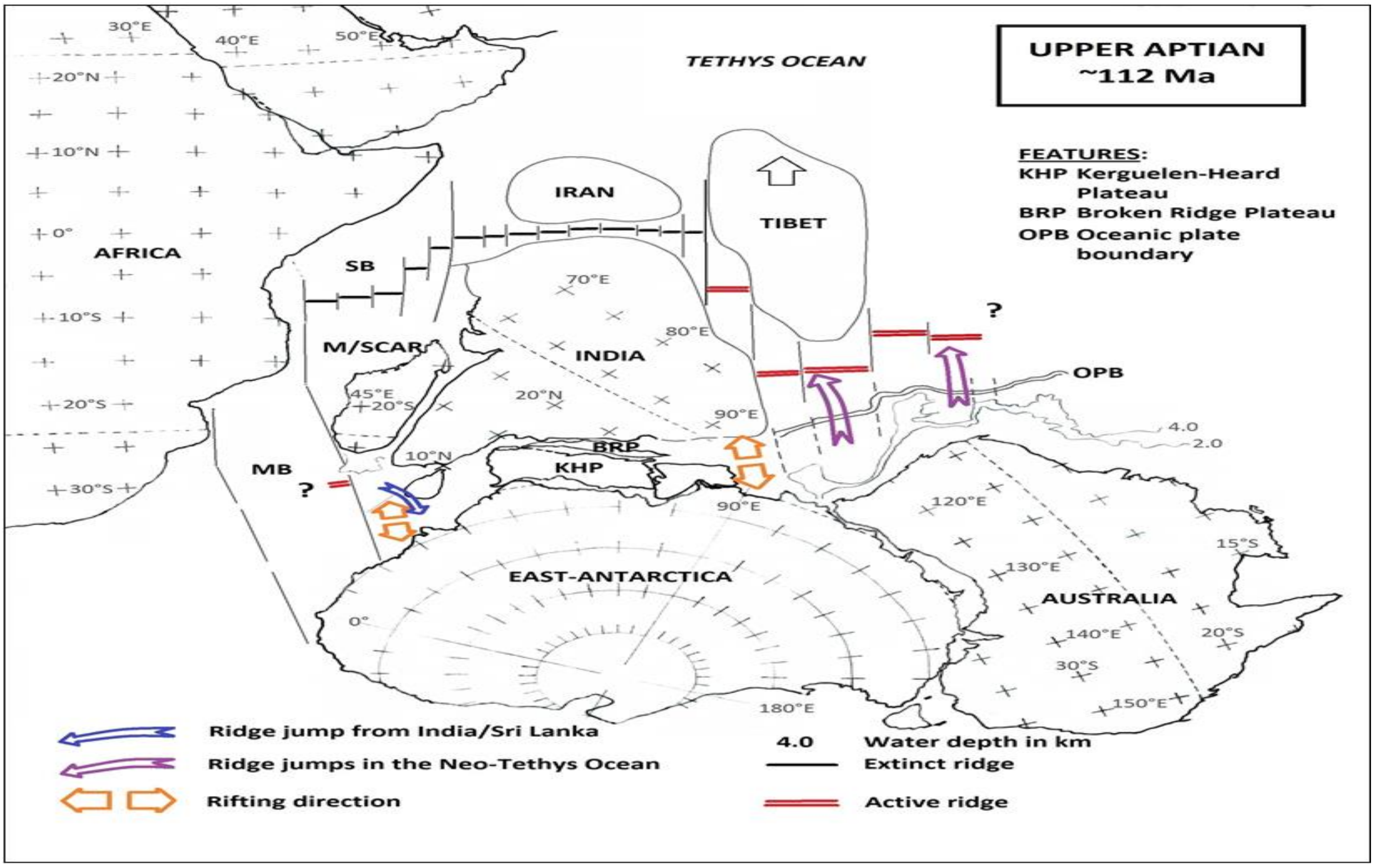

Fig M5 End of Rifting between Madagascar/Sri Lanka/India and East-Antarctica/Australia.

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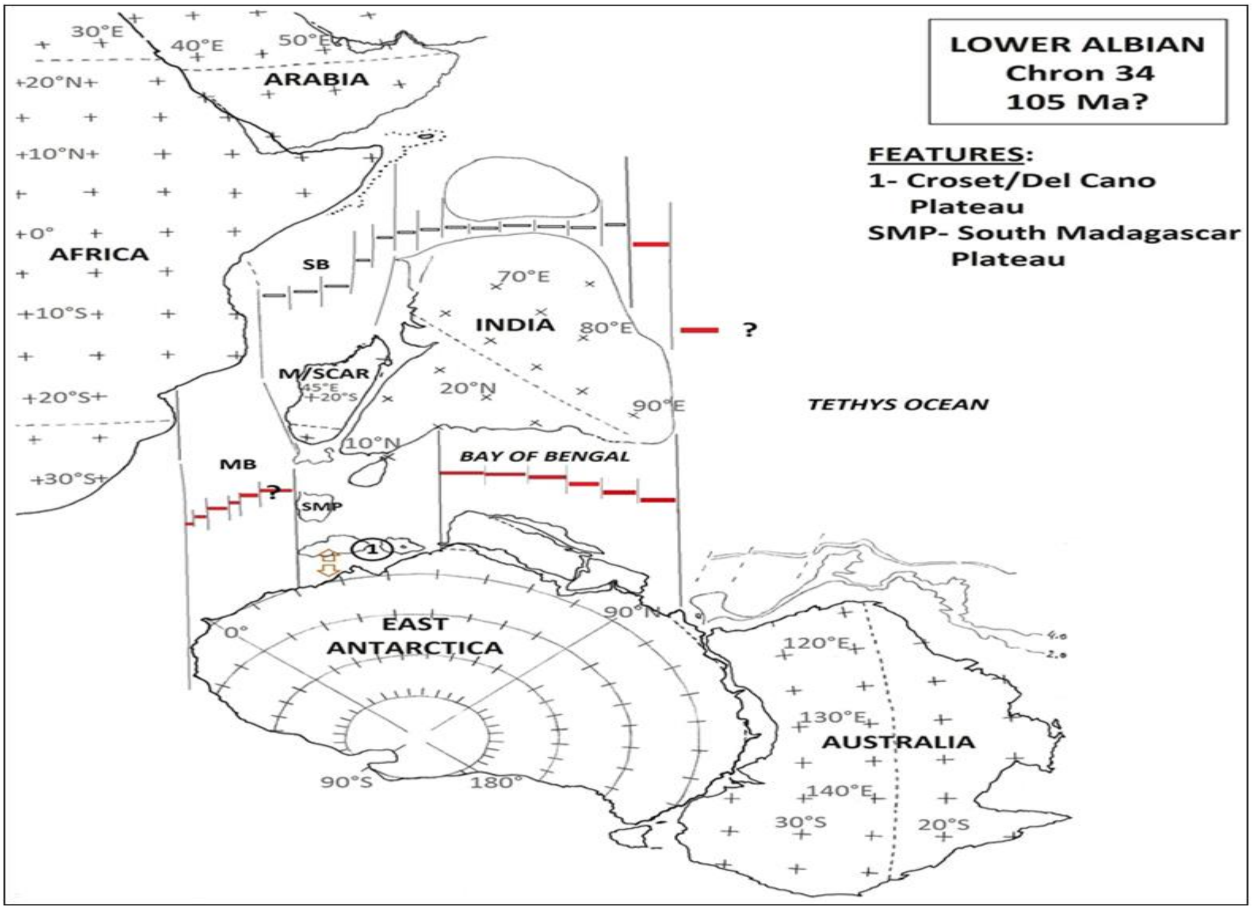

Fig M6 Rifting between SMP and CDCP.

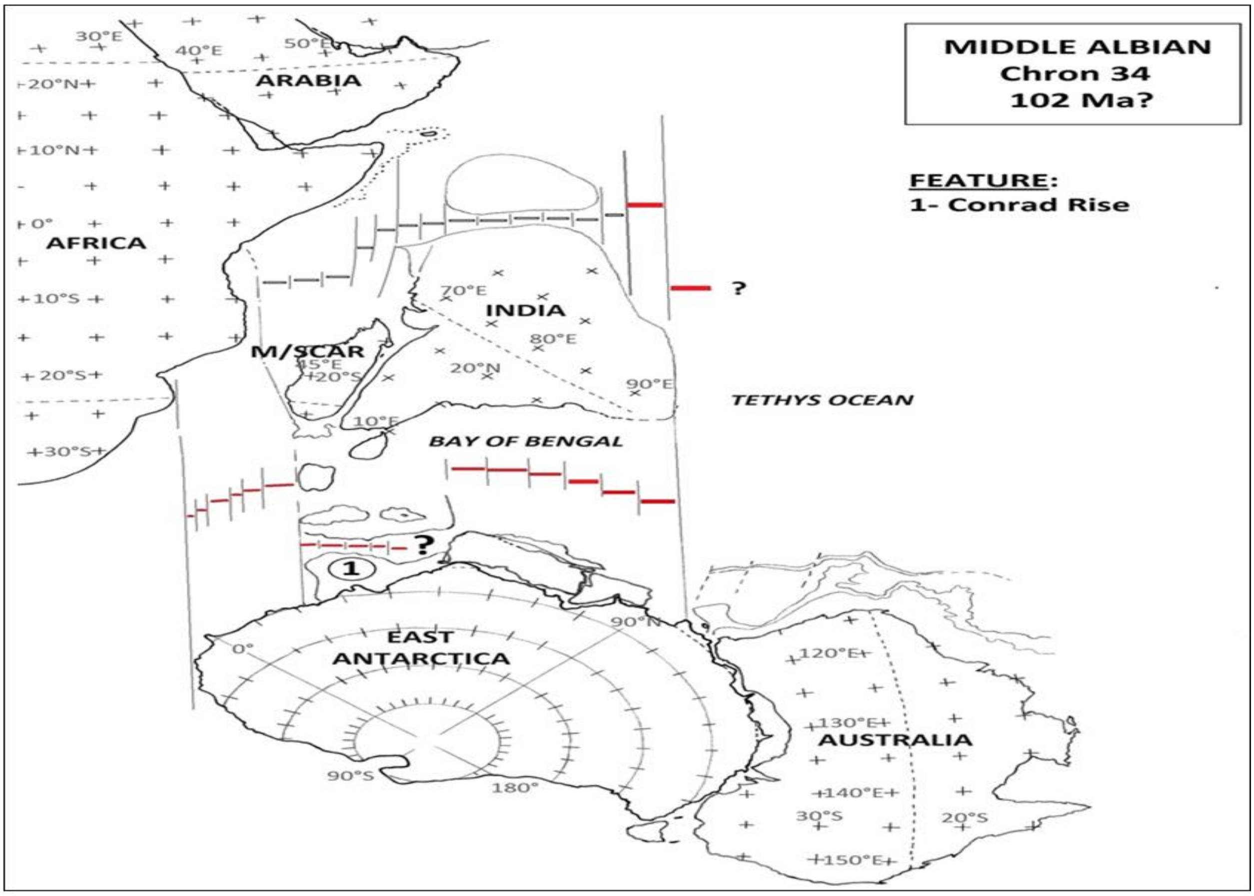

Fig M7 Rifting and Oceanic Opening between CDCP and East-Antarctica.

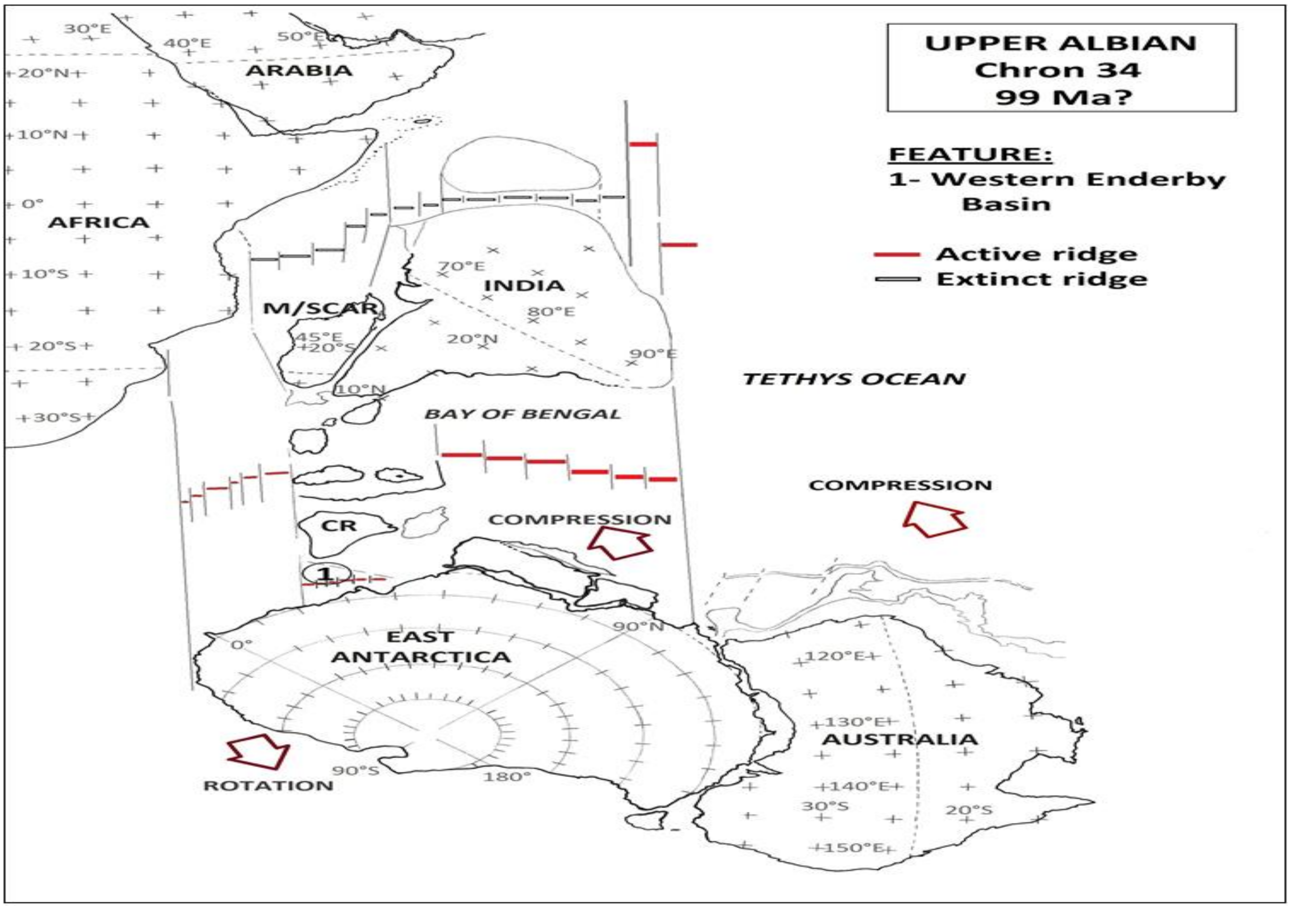

Fig M8 Fan-Like Opening in the Central Region between CR and East-Antarctica.

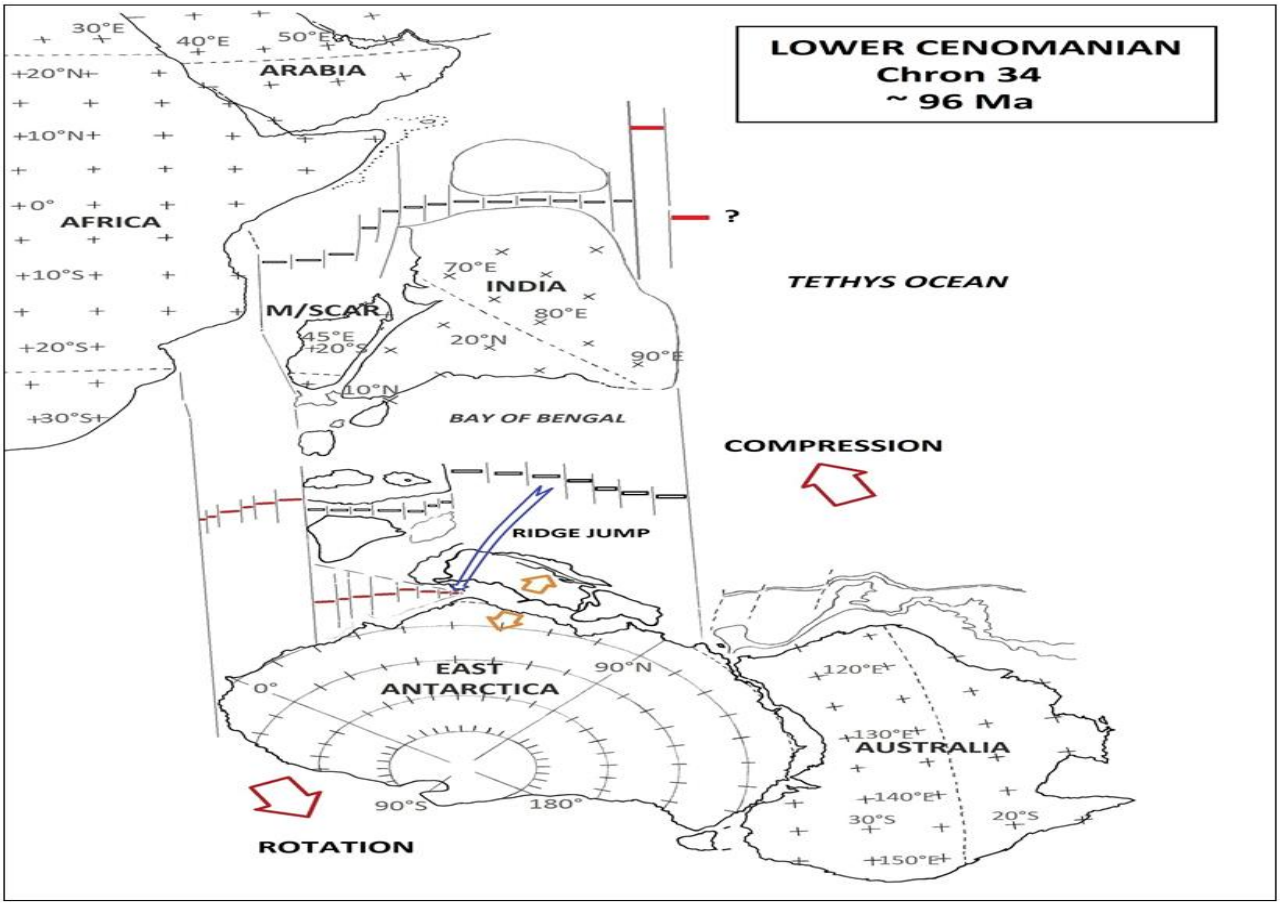

Fig M9 Merge of the N-S Convection Currents from the Central and the Eastern Regions. Eastward Expansion of WEB.

➢ *Period 3:*

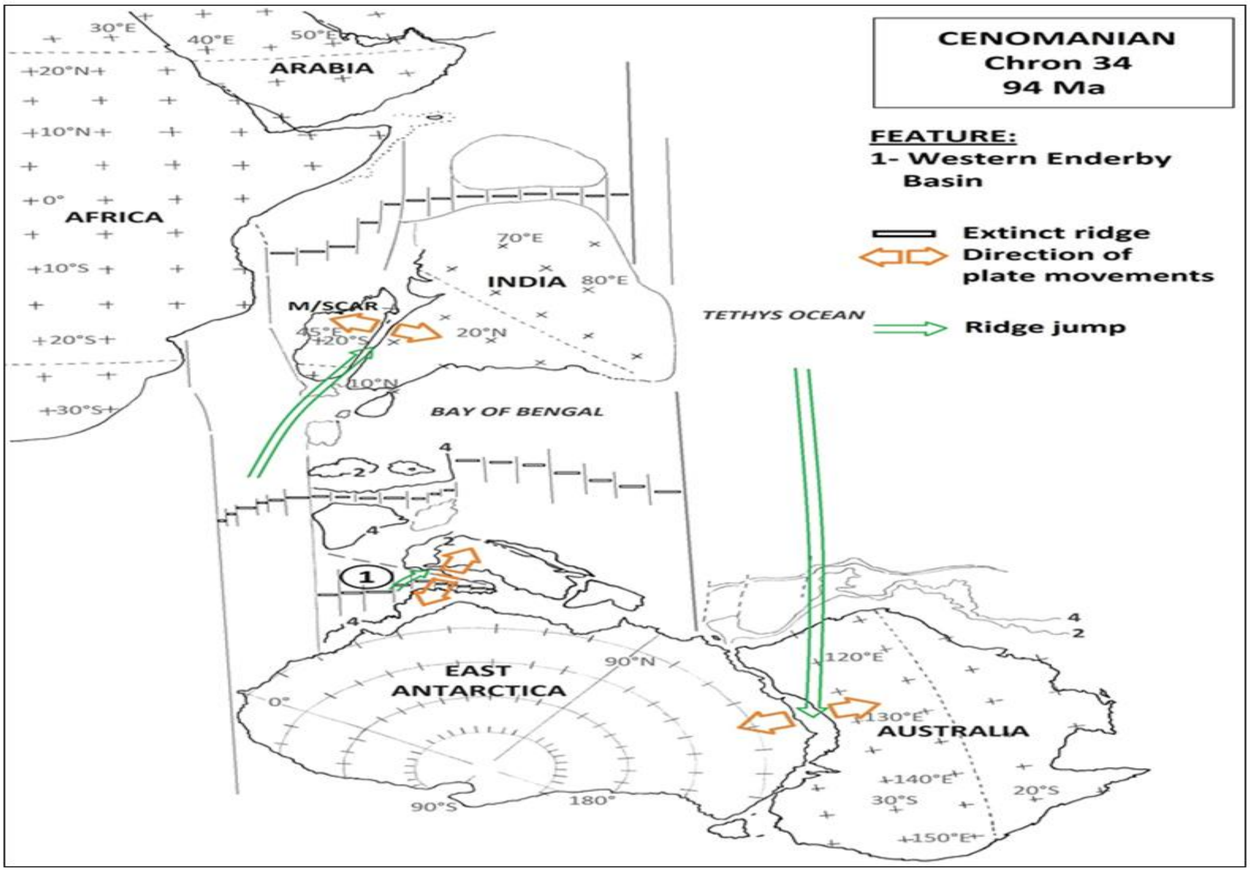

Fig M10 "Ridge Jump" Process after Compression-Induced Ridge Closings.

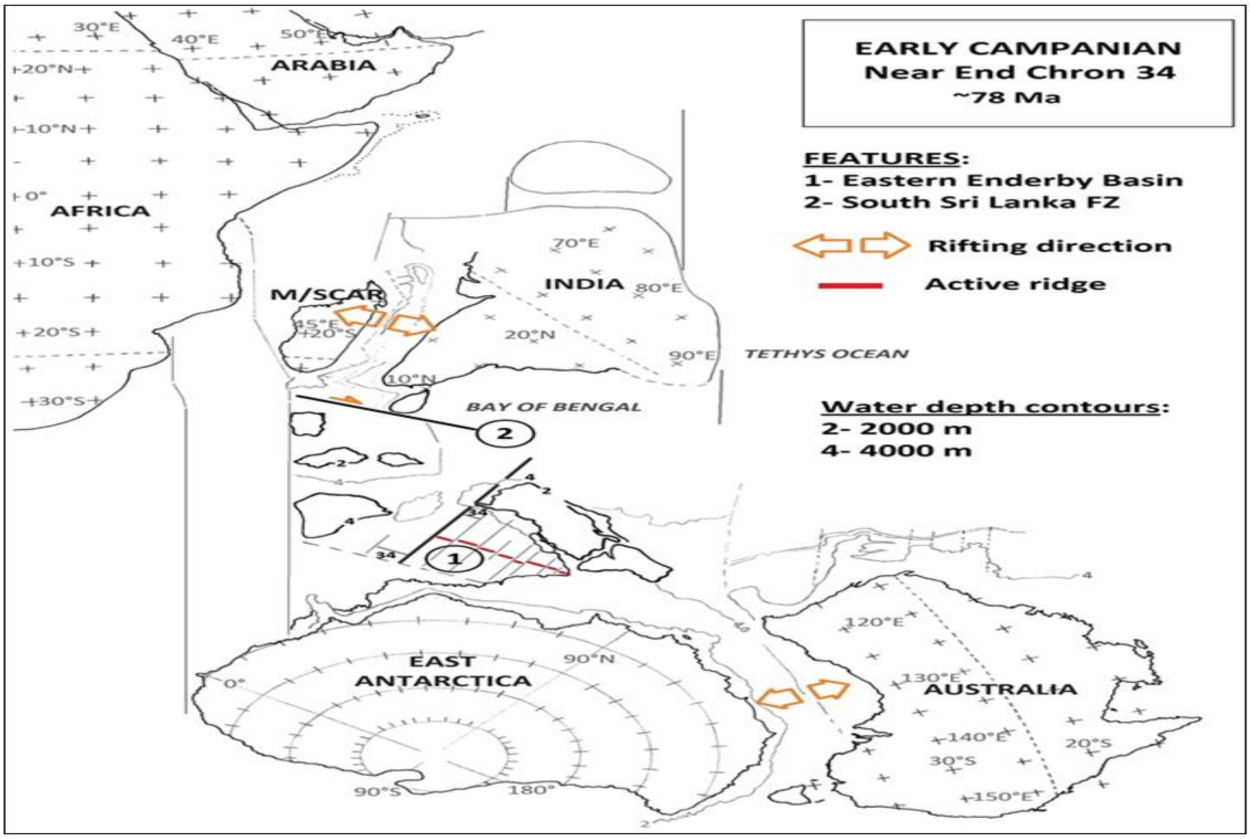

Fig M11 General Reorganization of Plate Movements with Uncommon Directions. Northeastward Oceanic Spreading between East-Antarctica and the Kerguelen Plateau.

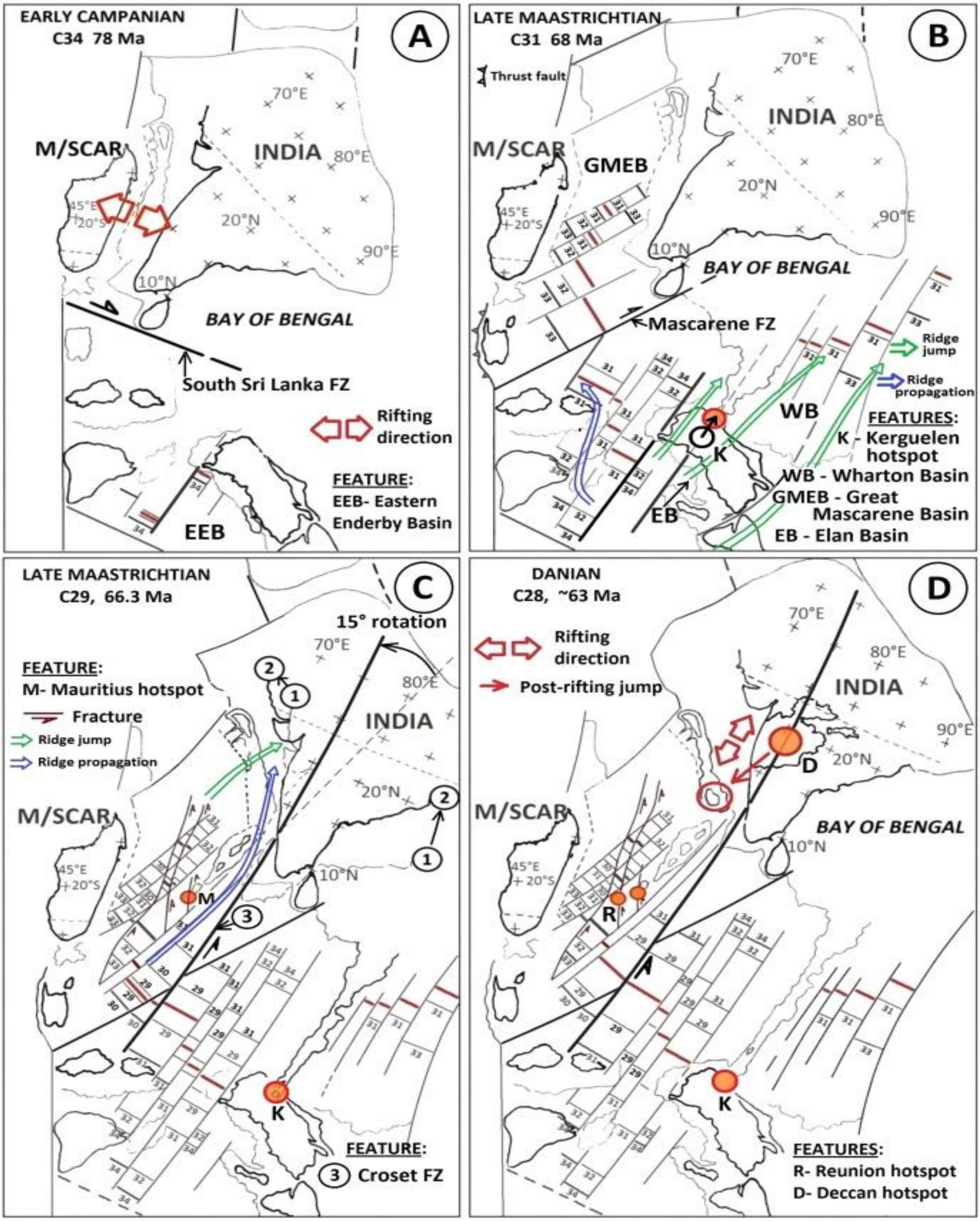

Fig M12 Complex Development of the Northeastward Oceanic Openings Characterized by Ridge Jumps and Interactions between Convection Currents. The Rifting between the Seychelles and India was Marked by the Merge of the Central and the Western Convection Currents.

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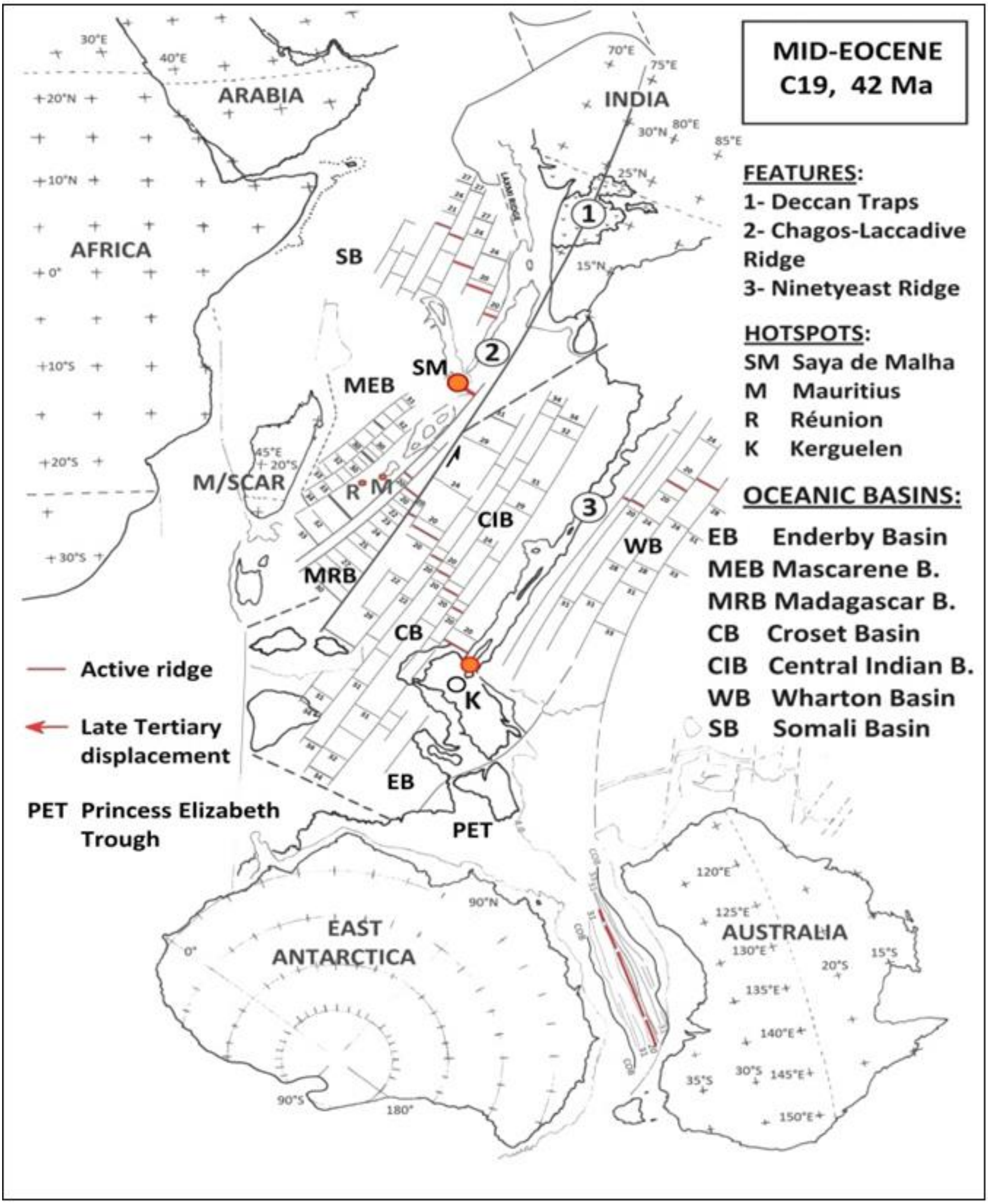

Fig M13 Northward Drift of India Controlled by the Croset (75°E) Fracture Zone. Fusion of the Saya de Malha Hotspot with the Mid-Oceanic Ridge. Collision of India Against Eurasia.

➢ *Period 4:*

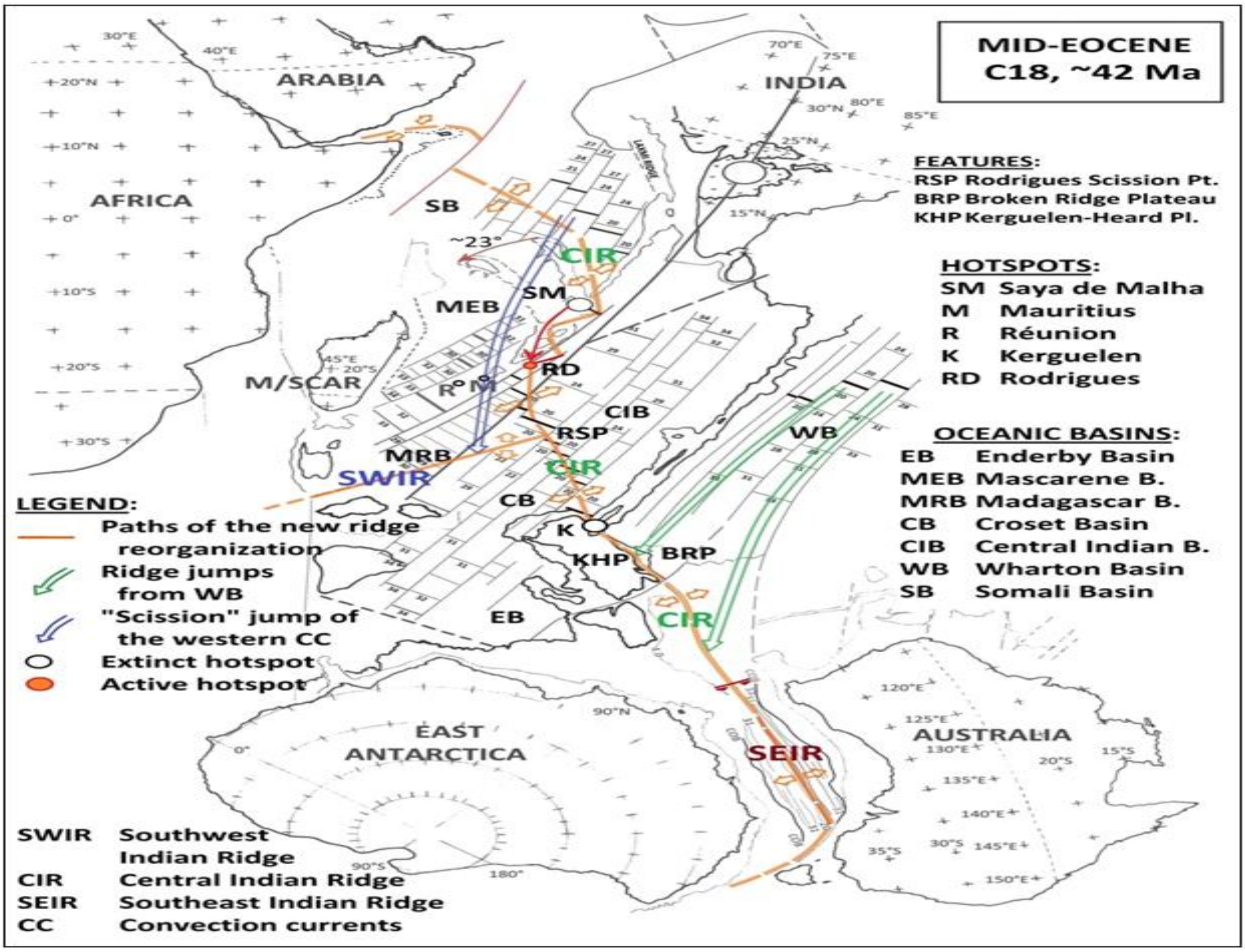

Fig M14 Mid-Eocene Plate Reorganization Characterized by (1) the Connection of the Eastern (SEIR) and the Central (CIR) Convection Currents and (2) the Split of the Western Ones to Form the SWIR. Southward Jump of the Saya de Malha Hotspot Generated the Rodrigues Hotspot. Separation of the Chagos Archipelago from the Mauritius Volcanic Trail.

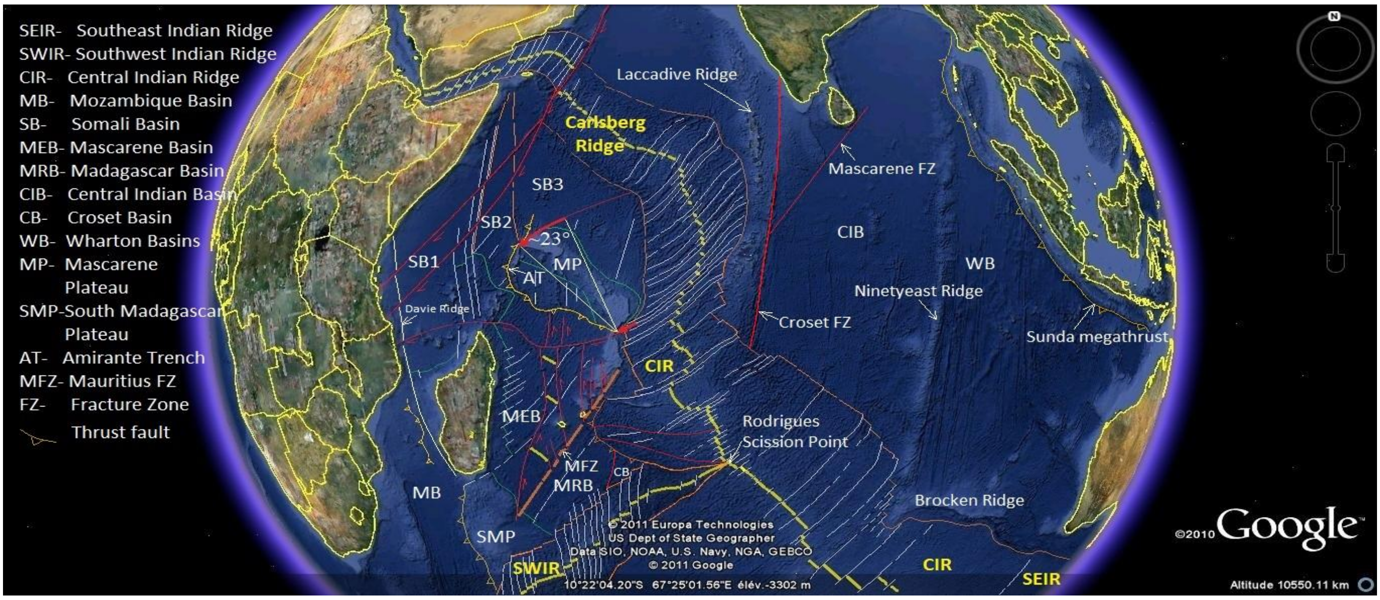

Fig M15 End Tertiary Up to the Present day Configuration of the Indian Ocean Showing the Relics of the Recent and Ancient Plate Tectonic Movements.