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East Africa: From Anza to Madagascar: A Relic and Active 4000-km Intraplate Strike-Slip Corridor*

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Abstract

Evidence of an intraplate strike slip structural system has been discovered by correlative potential fields interpretation of the East African Transform Margin. Seismic and well records have been integrated in this study that support the presence of a 4,000km strike slip fault system. The interpretation reveals typical examples of strike slip tectonics, such as transpression, transtension, duplexing, and syn-/antithetic faults. The interpretation provides a rigorous, regionally consistent framework to assess this transform margin. In consequence, this has significant and positive implications on deep-water, distal petroleum exploration in the Somali Basin.

The continental margin of East Africa is the result of several superimposed structural events, commencing episodic extensional (Karoo) rifting during the Permo-Triassic, followed by rifting and separation of eastern Gondwana in the early Jurassic. As East Gondwana drifted south in the later Jurassic and early Cretaceous, a transform margin propagated bound by the Davie Walu fault system with oblique rifting and oceanic spreading to the west of Davie Walu and further south. Spreading in the deep-water Somalia Basin stopped in the Aptian and the transform margin subsided during the later Cretaceous and early Cenozoic to be buried by thick deltaic to deep marine clastics, interrupted by periods of regional uplift and tilting bound by strike slip structures. Through the Tertiary, underlying Jurassic and Permo-Triassic faults of the old transform margin were reactivated to form a wider zone of secondary phase transpressional to transtensional and duplex deformation west of the bounding transform fault. The western margin is expressed as a 4,000km long dextral strike slip fault.

The latest satellite products of Sandwell’s Free Air Gravity (Sandwell et al., 2014) and the Enhanced Magnetic Model (Chulliat et al., 2015) are selected in this work. A re-assessment of earlier views is enabled utilizing (1) decompensative residual gravity and (2) reduced to pole, IGRF and amplitude gain corrected residual magnetics. No discrete modelling has been used in the interpretation, other than assuming Airy isostasy and therefore the qualitative interpretation provides an elegant solution to mapping geological structures and correlating with other scientific observations. It is concluded the margin represents a broad transform zone bound to the east by a dextral strike slip fault delimiting the Somali Basin spreading centre.

Summary

New evidence of a cohesive intraplate strike slip structural system has been discovered by correlative potential fields interpretation of the East African Transform Margin. Numerous seismic and well records have been integrated in this study that support the presence of a 4,000km strike slip fault system. The interpretation reveals typical examples of strike slip deformation, such as transpression, transtension, duplexing, and synthetic/ antithetic faults. Systematically processed derivatives of the latest satellite products of Sandwell's Free Air Gravity (Sandwell et al., 2014) and the Enhanced Magnetic Model (Chulliat et al., 2015), supported by published geological terrane studies, seismic profiles, well data, cores and seismicity provide a rigorous, regionally consistent framework to assess this transform margin, that has been reactivated through several distinct deformation phases. It is concluded the entire margin represents a broad transform zone bound to the east by a dextral strike slip fault delimiting the Somali Basin spreading centre and oceanic crustal domain. In consequence, this has significant and positive implications on deep-water, distal petroleum exploration in the Somali Basin and further south towards the Comores.

Introduction to Tectono-Stratigraphic Evolution of the East African Transform Margin

The continental margin of East Africa is the result of several superimposed structural events that culminated in the development of the transform margin. These events include:

- Late Precambrian (Neoproterozoic) suturing (Fritz et al., 2013) forming the crustal consolidation of the Gondwana supercontinent, that influenced later rifting and the separation of East and West Gondwana along the transform margin.
- Permo-Triassic episodic extensional ('Karroo') rifting, utilizing some of the sutures of Neoproterozoic crust that formed an intracontinental rift system extending north to Tethys. Its sedimentary fill records two brief marine transgressions flooding far to the south in late Permian and early Triassic reflecting periods of significant crustal extension between East and West Gondwana (Boote et al., 2017)
- Early Jurassic extensive plateau volcanism (Bouvet "Plume") in southern Africa records the onset of breakup of Gondwana (Reeves et al., 2016). As East Gondwana drifted south, a transform margin propagated southward along the axis of the Davie Transform Margin bounding extensional oblique rifting between northern Madagascar and Somalia in the east, and compressional segmentation to the west of the present-day Davie Walu axis.

Following significant oblique rifting between the Madagascan Majunga and the offshore Kenyan Lamu, oceanic spreading commenced in the Somali Basin.

A further phase of extension in the very early Cretaceous was responsible for a new transcontinental rift system stretching across Central Africa from the Benue Trough to Anza Graben and Lamu Basin of Kenya where it now merges with the Davie Walu Ridge at the northern end of the Davie Transform, refer to Giraud and Maurin, 1992 for example.

Spreading in the deep-water Somalia Basin stopped in the Aptian, accompanied by the end of East Gondwana's southerly drift. The transform margin became dormant at this time.

The Seychelles and Indian subcontinent broke away from Madagascar during the late Cretaceous with extensive Turonian volcanism (Bardintzeff et al., 2010) associated with the Marion 'plume'. The southern part of the reactivated transform margin, defined by the Davie Ridge, west of present day Madagascar, underwent uplift and compression at this time.

From then on until the early Cenozoic, the transform margin subsided with increased deposition rate and accompanied by deltaic to deep marine clastic influx, interrupted later by Tertiary regional uplift and tilting bound by strike slip structures.

During the Neogene and into the Plio-Pleistocene, the transform margin was reactivated to form a wider zone of secondary phase transpressional to transtensional and duplex deformation west of the bounding transform fault. The transform margin is still active offshore southern Madagascar. The Neogene onset of the East African Rift System was locked by the transform margin's strike slip margins.

The present-day western margin is expressed as a 4,000km long dextral strike slip fault, closing in the north by rotation on the eastern margin of Anza, and in the south closure by active strike slip offshore southern Madagascar.

Methodology

Complete processed derivatives of the latest satellite products of Sandwell's Free Air Gravity (Sandwell et al., 2014) and the Enhanced Magnetic Model (Chulliat et al., 2015) released in 2015 are utilized in this work. These raw data products were processed to yield (1) decompensative residual gravity (Cordell et al., 1991) and (2) reduced to pole, IGRF and amplitude gain corrected residual magnetics.

No discrete modelling has been used in the interpretation, other than assuming Airy isostasy and therefore the qualitative interpretation provides an elegant solution to mapping geological structures and correlating with other scientific observations. The data sets were selected based on their complementary utility, since the residual gravity enables interpretation of shallow crustal structure, whereas the lower resolution magnetic record links deeper crustal, magnetized structural controls on the shallow propagation and growth of faulted structures in the overburden. Assessment of these products with published seismic in literature provide clear correlations of the defined fault structures (Long, 2017).

Structural Architecture of the Davie Transform Margin

In the following sections, commencing from the north of the Davie Transform Margin, reference is made to the structures depicted in Figure 1, decompensative gravity, and Figure 2, the residual magnetics. The deeper lower crustal structure mapped from the longer wavelength magnetic anomalies generally correlate with shallower offsets seen in the shorter wavelength residual gravity anomalies and indicate the same sense of slip movement. The three main faults in the Davie Transform Margin, namely the eastern and western bounding faults, and the central strike slip fault show consistent dextral slip offsets that have deformed separately the western onshore and eastern offshore corridors of the Davie Transform Margin. However, the anomalies differ where the lower crust has been deformed by ductile shear, versus shallow brittle response. This is clearly evident in the central part of the Davie Transform Margin, where the en echelon magnetic basement underlies the Southern Kerimbas Graben, and further north in the en echelon sequence, the early failed rifting (aulacogen) partially overrides the outer magnetic high.

Anza Graben and Onshore Lamu

In the north we identify Neogene inversion in the Anza Graben as the reactivation of the transform fault that ends in active strike slip south of Madagascar. The strike slip corridor extends over 700km in width westwards to the western arm of the East African Rift System (E.A.R.S.), with distinct deformation provinces developed within the transform zone. The Anza Basin, believed to be an early Cretaceous rift basin, lies over the Neoproterozoic Barsaloi suture zone (Fritz et al., 2013). Morley et al., 1999, remarked that the Cretaceous fill visible on seismic is so thick it is impossible to see older pre-Cretaceous structures. It is well known relic faults and sutures remain lines of weakness through geological time. There are direct correlations between the sutured margin of cratonic West Gondwana and younger Neoproterozoic terranes on the East African margin that are highly correlative to the potential fields interpretation of shallow density contrasts, and deeper magnetization contrasts. It is generally believed that paleomagnetic reconstructions of Madagascar onshore the East African margin are too tight given well control on facies transitions of pre-Gondwana breakup, see Boote et al., 2017. The interpretation of Precambrian cratonic terrane onshore Madagascar, with the interpreted suture of Azania in Kenya suggests the propagation of the transform margin occurred earlier, at a time when the regional tectonic stress field transferred from north eastern trending ‘Karroo’ extensional rifting, to orthogonal intraplate strike slip faulting trending south east initially, onshore Kenya. The onshore Lamu Basin defined by early Permo-Triassic ‘Karroo’ rifting shows evidence of later Jurassic transform margin propagation in offsets in residual gravity anomalies demonstrating dextral strike slip transform movement.

Axis of Davie Walu Ridge and Pemba, Zanzibar, Mafia Islands, Offshore Lamu

The onshore dextral sense of movement is consistent with an offshore Jurassic extensional pull apart basin south southeast of the southern vergence of the Davie Walu Ridge. Offshore seismic indicates the Davie Walu Ridge formed by post rift compression, as part of a later Davie Transform reactivation. East of Davie Walu Ridge, crustal extension of the offshore Lamu Basin is evident as a transition to an obliquely rifted, passive margin to the east of the bounding transform fault that correlates to a broad residual gravity and magnetic low. The southern limit to the passive margin is directly correlated between the shallow residual gravity low and deeper magnetic low that defines the continental-oceanic boundary, outboard and to the east of the main transform fault. The oldest magnetic chron picks lie to the south of this rifted passive margin, and east of the transform margin. Using Davis et al., 2016 Chron dates, indicates Jurassic extensional rifting culminated in Somali oceanic spreading in the Kimmeridgian, and that the conjugate Majunga Basin offshore northern Madagascar may also have significant Jurassic rifted basin width, extending in excess 250km north, towards the Comores.

South of Anza, a transpressional horsetail splay of synthetic faults is present nearshore Kenya and Tanzania, bound by the Davie Walu Ridge in the east, and to the west by a significant strike slip fault initially trending at 135 degrees that bends 100km north of the Rovuma Delta and then strikes south following the coastline and defining the western margin of the present day offshore transform corridor to southern Madagascar. Pemba, Zanzibar, and Mafia Islands are all components to the transpressional zone. Regional seismic confirms the interpretation of the reactivated restraining bend of the strike slip fault system, since the post-rift sequence is clearly highly faulted inboard of the bend, Figure 3, versus outboard of the strike slip fault, the equivalent post-rift seismic sequence is unfaulted and appears to onlap the Davie Walu structure. Initially the western margin of the Davie Transform would have been under compression creating antithetic fold systems sub parallel to the older Karroo rift trends. These synthetic folds would have developed at an obtuse angle to the axis of the Davie Walu Ridge, which separated eastern extensional oblique rifting, offshore Lamu, from western compressional folding. Later it is possible the reactivation of the Transform margin in response to onshore Tertiary rifting created the second order synthetic fault system characterizing the transpressional fault splay. These structures are depicted in Figure 3.

Offshore Tanzania

Transpression is replaced eastwards across the Davie Walu on trend southern axis by extensional deformation evidenced by a pull-apart basin and further south a failed triple 'R' aulacogen, expressed as a triple residual gravity low with trough axes striking WNW, SSW, and ENE. The aulacogen coincidently lies on trend with well documented M0 chron picks derived from existing shiptrack data in the western Indian Ocean. It is clear the transform margin acted as a transfer zone that segmented the influence of oceanic spreading to the west of the bounding transform margin, resulting in the failed triple rift junction. Storti et al., 2003 discusses the implications of strike slip tectonism on later geological processes, and these observations are consistent with their study. Further south, a transition into duplex structures is seen. Underpinning the duplex structure, an en echelon configuration of right stepping magnetized deep basement blocks is supportive of the development of duplexes, as described by Woodcock and Fischer, 1986. This en echelon configuration provides the key link between well documented northern transpressional structures, and southern transtension in the definition of the transform margin, from offshore Lamu in the north, to the southern offshore of Madagascar. A published ION line in McDonough et al., 2012, extending from just south of Tsongo Island, out to the M0 chron picks for the Somali spreading centre, indicates that Jurassic rifted continental margin extends out in excess 300km from the Tanzanian coast, and 80km beyond the subcrop of the Davie Ridge antiformal structure.

Offshore Northern Mozambique

The 200km wide corridor of duplex fold structures underpinned by en echelon basement horsts, limited to the east by the transform margin, and a restraining strike slip bend to the west transfers to a narrow transtensional zone, reactivated in the Tertiary, comprising the Kerimbas and Lacerda graben systems. The initiation of the transtension likely occurred at the time of the propagation of the Transform Margin, sometime between Late Jurassic and the Aptian cessation of Transform Margin propagation. The influence of the divergent transform margin on the distribution of recent seismicity (Mulibo and Nyblade, 2016), is clearly expressed by the transition of shallow, synthetic Riedel faults to linear graben formation further south. These structures were mapped by Mougenot et al., 1986, and correlative to the transition from duplexing to transtension along the transform margin, in that the Tertiary fault system was locked by the first order control of the strike slip tectonism, and therefore the en echelon fault pattern is controlled by the pre-existing fault structures. This transition occurs west of the St. Lazarre seamount and is visible on seismic (Franke et al., 2015). The influence of the East African rift faulting dissipates to the south, north of the Sakalaves seamount.

Davie Ridge and the Morondava Basin

The transtensional zone is transferred into another transpressional leg that is defined by a restraining bend west of Madagascar and defines the fold axial plane of the Davie Ridge. The seismic and prominent residual gravity high signature confirm the Davie fold hinge plunges north along its axis and terminates at the junction of the duplex system, east of the Angoche Basin. The Angoche Basin is defined by an antithetic fault zone that appears to have propagated prior to the opening of the Lacerda graben system. Sea bed cores lithofacies along the Davie Ridge, noted by Bassias and Bertagne, 2015 indicate a northward origin, supportive of the dextral sense of fault movement along the margin.

The Morondava Basin terminates at the eastern edge of the Davie Transform Margin, which also defines the eastern boundary of the deformed Davie Ridge fold system that was initiated possibly as early as the Lower Cretaceous, or prior to final Aptian dextral slip movement on the eastern margin of the Davie Transform.

Western Transform Margin and Central, Southern Mozambique

The sigmoidal closure of the western margin of the strike slip deformation zone traces the margins of the relict Precambrian cratons of Tanzania, and Bangweulu (Zimbabwe), utilizing juvenile Neoproterozoic sutures formed during Gondwana congealment. The bounding fault locks western East African rifting to the west, defined by the eastern shore of Lake Malawi, and strikes south along the western margin of the Northern Mozambiquan Neoproterozoic terrane. It appears to terminate at the foot of the Lower Zambezi, or at least separates the offshore Zambezi Delta Basin in the east, from the near coast parallel trace of the East African Rift System in the west, comprising the Urema and Chissenga rift basins. This implies the pre-breakup fit of Antarctica did not once overlap the present-day Southern Mozambique Basin.

Cap St Marie and Southern Madagascar

The transform margin turns east into a present-day active strike slip fault offshore southern Madagascar, and at this stage it is believed the influence of the Marion Plume generation diverted the fault propagation due east around Late Cretaceous times. Reeves et al., 2016 dates the Marion plume onset from 88Ma, in Coniacian times, but onshore Madagascar, volcanism has been dated at 93Ma, Turonian (Bardintzeff et al., 2010), which is consistent with the approximate age of the diversion of the transform, and the break-up of India from Madagascar. The influence of the Marion Plume can be traced by a residual gravity low anomaly, south of Madagascar, and the closure of the Western Davie Transform, by active strike slip.

Conclusions

We conclude the Davie Transform margin has evolved from a Jurassic extensional dextral strike slip fault system into a regional sigmoidal complex system defined by many common structures associated with strike slip tectonics, spanning over 4,000km arcuate length. The margin propagated from as far northwest as Anza, which is believed to overlie the original Neoproterozoic suture between West Gondwana cratonic centre and Azania, East Gondwana. The final breakup of Eastern Gondwana in the Late Jurassic was constrained by lines of pre-existing crustal weakness to form a north-south dextral slip transform boundary between West Gondwana (East Africa) and East Gondwana (Madagascar and Antarctica western margins), subsequently reactivated several times through the Cretaceous and Tertiary. Generally, the first order transform margin structures young south along the length of the present-day strike slip zone. The bathymetric expression of the Davie Ridge represents the Tertiary uplift and offshore reactivation of the Transform Margin, which is bound to the west by older transtensional structure of the transform margin. The Davie Fold itself likely formed at least as early as Cretaceous. Offshore regional seismicity events directly correlate with movement along faults within the still active transform margin.

This study confirms the utility of correctly processed and derived potential fields data in direct correlation to geological structure without the need to introduce complicated modelling and estimations of physical rock properties. The interpretation provides an elegant, robust, regionally consistent framework to examine and assess this reactivated transform margin. Further discoveries of significant correlations between real geological structure and geophysical anomalies will lead to better understanding of regional tectonic frameworks with reference to structural deformation. In consequence, this will provide significant controls on regional hydrocarbon provinces, and more locally basin reconstructions and modelling.

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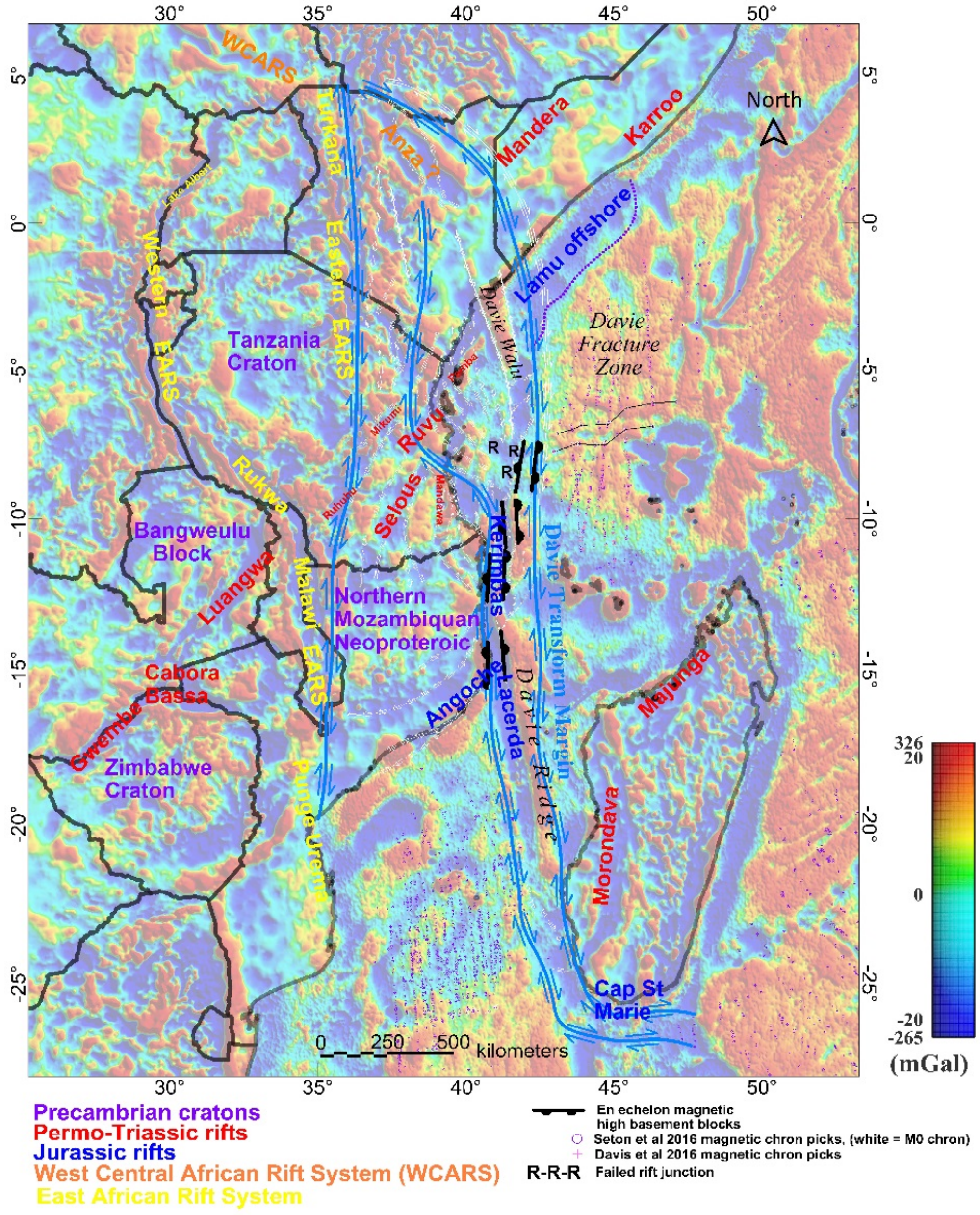

Figure 1. Decompensative gravity residual map annotated with dominant rift trends, coloured by age, cratons, and the structure of the Davie Transform Margin (light blue).

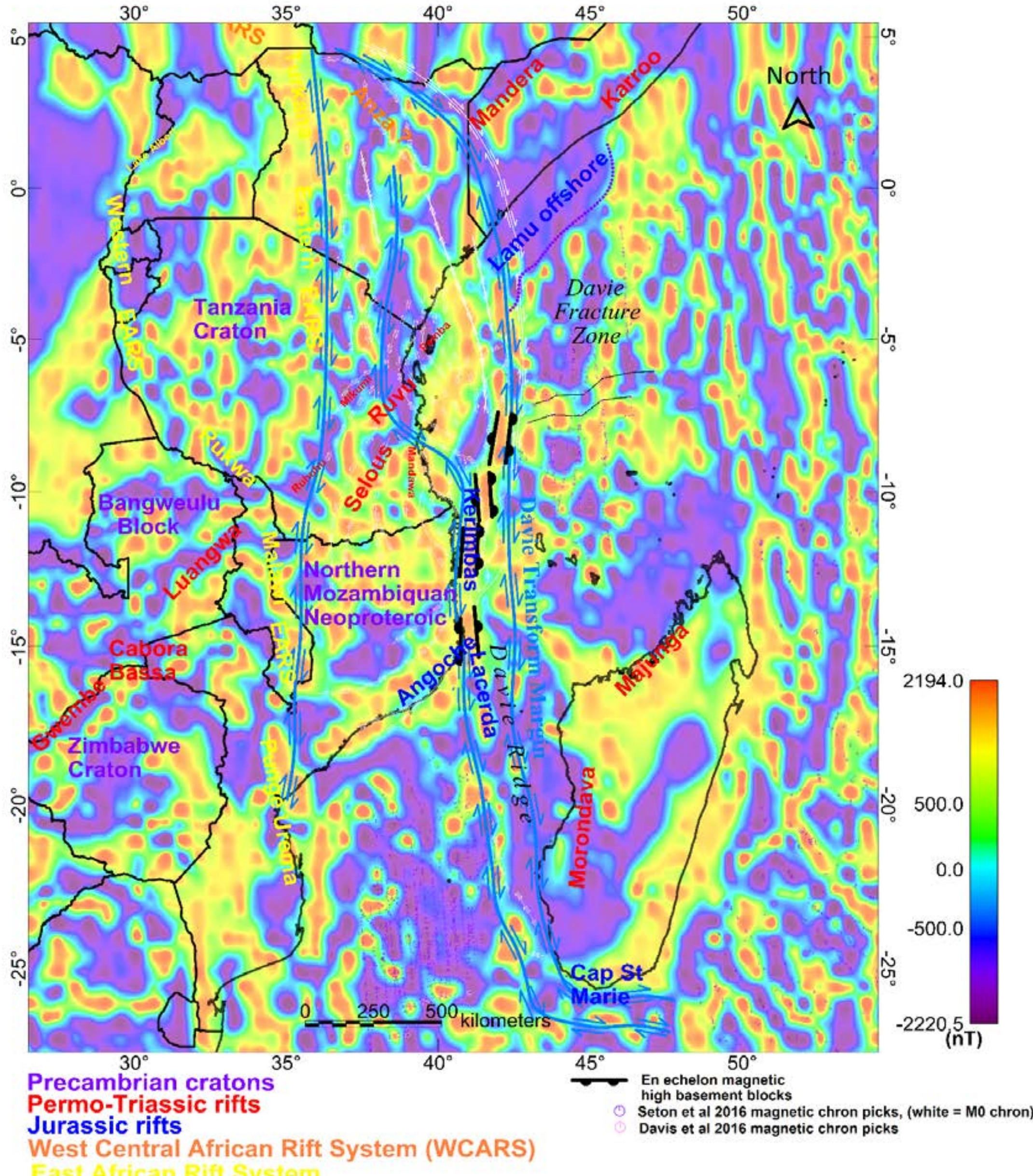

Figure 2. Residual magnetics, reduced to pole map annotated with dominant rift trends, coloured by age, cratons, and the structure of the Davie Transform Margin (light blue).

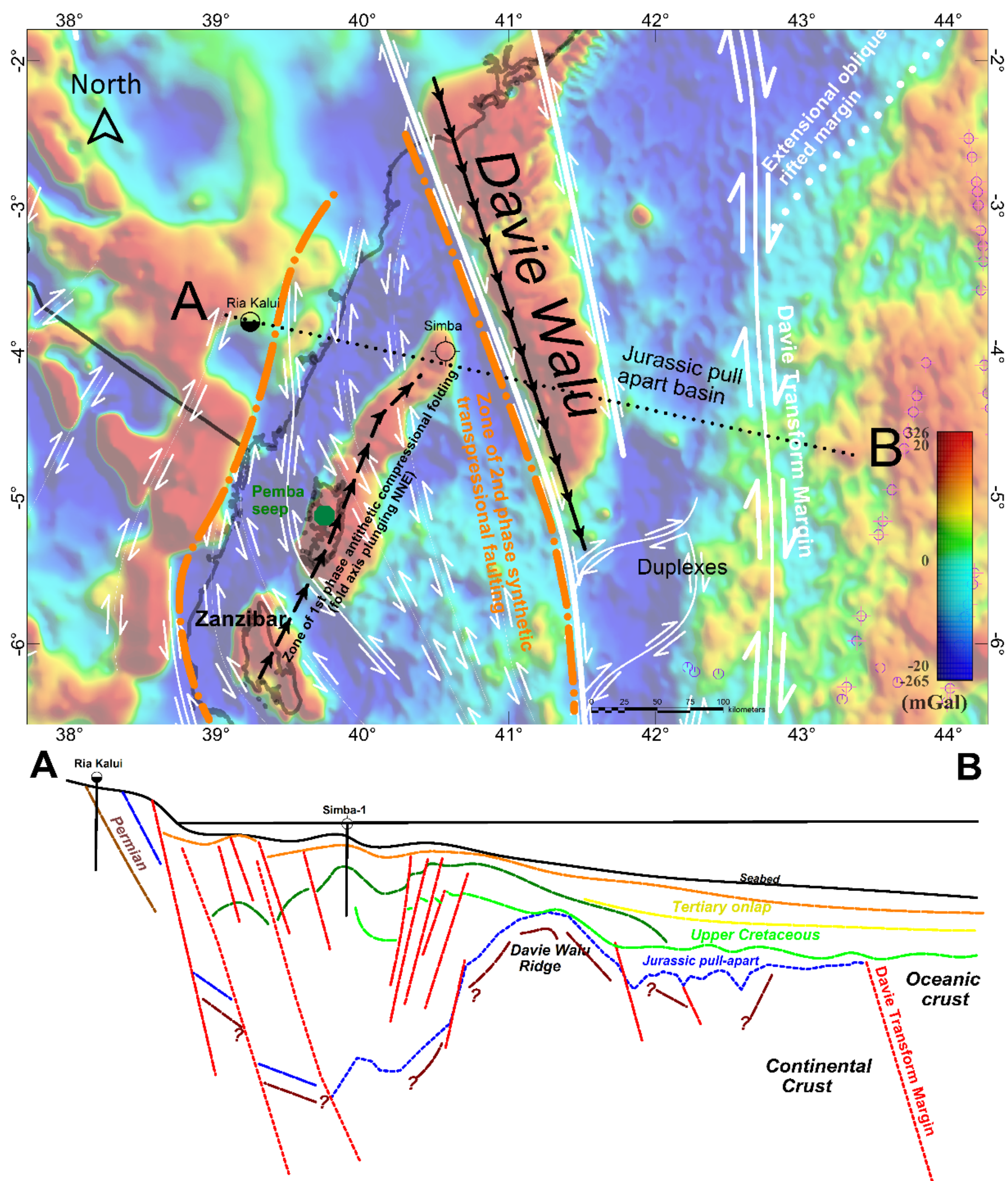

Figure 3. Decompensative residual gravity, with 1st and 2nd phase deformation structures annotated in the transpressional zone offshore Tanzania and Kenya, with typical cross section annotated and shown below.