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Is the Okavango Delta the terminus of the East African Rift System? Towards a new geodynamic model : geodetic study and geophysical review

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Abstract

The Okavango Graben (OG) has been considered as the terminus of the southwestern branch of the East African Rift System (EARS) since the 1970's based on fault morphology and early seismic and geophysical data. Thus it is assumed to be an incipient rifting zone, analogous to the early stage of mature rifts in the EARS. Recent geodetic data and geophysical studies in the area bring new insights on the local crust and lithosphere, mantle activity and fault activity. In this study, we computed the velocities for three permanent GPS stations surrounding the graben and undertook a review of the new geophysical data available for the area. The northern and southern blocks of the graben show exclusively a low strike-slip displacement rate of about 1 mm/yr, revealing the transtensional nature of this basin. The seismic record of central and southern Africa is revealed to be instrumentally biased for the events recorded before 2004 and the OG may not represent the most seismically active area in Botswana anymore. Moreover, no significant lithosphere and crustal thinning is found in the tectonic structure as well as no strong negative Bouguer anomaly and surface heat flux. Thus the OG does not match the classical model for a rifting zone. We propose a new geodynamic model for the deformation observed west of the EARS based on accommodation of far-field deformation due to the differential extension rates of the EARS and the displacement of the Kalahari craton relative to the Nubian plate.

Keywords: Intraplate tectonics, Okavango, Geodesy, East African Rift System.

Highlights :

- Time series for three GPS stations astride the Okavango graben have been processed.
- The Okavango graben showed main strike-slip displacement over the five past years.
- There is no significant evidence for rifting in the area.
- Deformation in the region can be explained by far-field deformation accommodation.

1. Introduction

The East African Rift System (EARS) is a major geodynamic feature which has been splitting the African continent since the late Eocene-Oligocene (e.g., Macgregor, 2015). It propagates from the northern Afar Depression and Main Ethiopian Rift to the southern diverging branches (Fig. 1) : the eastern branch from the Kenyan rifts to

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central Tanzania and the western branch from Lake Albert to Lake Malawi. The tectonic functioning of the termini, and thus the initiation stages for continental rifting are poorly understood. Some authors (e.g., Scholz et al., 1976; Modisi et al., 2000; Bufford et al., 2012) propose that a third branch of the EARS extends southwestwards from Lake Tanganyika, named the southwestern branch, and postulate that the most remote feature is the Okavango Graben (OG).

Located in northern Botswana, the Okavango Delta is an extensive wetland (12,000 km²) confined in the OG. Its NE-SW trending faults, which match the orientation of the Lake Kariba valley, and the localised seismic activity led many authors since the late 1960's to consider it to be the final extension of this southwestern branch of the EARS and therefore as an incipient rifting zone (Scholz et al., 1976; Modisi et al., 2000; Bufford et al., 2012). Scholz et al. (1976) first postulated this OG EARS extension hypothesis in the current terms with their seismic study in the area. Apart from fault orientation and morphology, proponents of this hypothesis use the first geophysical studies to infer that rifting is at play in the OG in a similar way to that observed in the EARS (Fairhead and Girdler, 1969; Scholz et al., 1976; Wilson and Dincer, 1976; Girdler, 1975; Ballard et al., 1987). Few geological data are available due to the extensive cover of Kalahari sands of varying thickness (Haddon, 2005) but several recent geophysical studies bring new insights on the crustal and lithospheric structure, and mantle activity of the area (e.g., Forte et al., 2010; Khoza et al., 2013; Yu et al., 2015a) that call into question the rifting hypothesis for the OG. Other deformation models have been proposed (McCarthy, 2013; Yu et al., 2015a) and are supported by new available data.

In order to interrogate this problem, it is important to define criteria for a rifting zone, and to gather geophysical and geological data and points of view. In the framework of continental break-up, a rifting zone can be defined by thinning lithosphere and crust which is revealed by shallow depth to the Moho (Sengör and Burke, 1978; Allen and Allen, 2013). The upwelling asthenosphere may be revealed by a strong negative Bouguer anomaly and an increased surface heat flow. The consequent surface deformation is characterized by significant seismic activity with predominantly extensional focal mechanism solutions and border faults which can exhibit important scarps. This morphology is mainly valid for active rifts initiated by mantle upwelling, and is rarely observed in passive rifting due to crustal stretching. Volcanic activity is also expected but may only happen at an evolved stage. Kinematically, rifting zones are defined by crustal extension, marginal uplift and inner subsidence, but may appear with strike-slip displacements in accommodation zones. The order of appearance of these displacements (horizontal before vertical or vice versa) can help to characterize the process initiating the rifting. Indeed, active rifting due to mantle upwelling will induce early uplift leading to secondary crustal extension whereas passive rifting due to crust stretching will primarily show horizontal extension followed by uplift due to the consequent mantle upwelling (Allen and Allen, 2013).

This study brings new results from a geodetical study based on 5 years of records from permanent GPS stations to monitor slow displacements on the tectonic structure. Since rifting kinematics are associated with extension, the kinematics of the area then help to discriminate the processes at play in the graben deformation. We also reexamine available geophysical data in the area in order to construct an alternative model of the OG and compare it with the EARS characteristics. We propose a new kinematic model based on far-field accommodation of the deformation

due to both EARS opening and differential movements between the Kalahari and Congo cratons impacting a wide region from Lake Upemba in the north to the central Kalahari in Botswana. We thus propose to re-open the OG EARS extension hypothesis debate.

1.1. Geological setting

1.1.1. EARS

South of the Main Ethiopian Rift, the EARS separates into two distinct branches extending from north to south through a series of rift basins (Fig. 1). The older (>25 My) eastern branch extends continuously from the Afar Depression to Kenya and central Tanzania. It is characterized by important volcanism but shallow (5-15 km), low-magnitude earthquakes. The younger (>15 My) western branch extends from Lake Albert to Lake Malawi in a discontinuous series of rift basins related by transform zones in varying orientations. It is nearly amagmatic, characterized by high-magnitude (>6.5), deep (30-40 km) earthquakes and deeper rifts, and is considered as less evolved (e.g., Chorowicz, 2005; Macgregor, 2015). Overall, the EARS has propagated southwards at the rate of between 2.5 and 5 cm/yr (Chorowicz, 2005). Extension rates in those rifts vary from 5.2 mm/yr in the northern Afar Depression to less than 1 mm/yr in the south (Saria et al., 2014).

The EARS termini, and the characteristics of its propagation in the continental crust, are poorly known. The eastern branch bifurcates and dissipates in the Tanzanian divergence, an area of numerous faults oriented from NE-SW to WNW-ESE. The western branch ends in central Mozambique. Authors agree on a southwestern extension of the western branch but several grabens seem to diverge from this branch in a NE-SW orientation, from north to south : the Upemba trough, Lake Mweru, Lake Bangweulu, Luangwa Valley and the Chicooa trough (Fig. 1). While most of these tectonic structures show no evident extension, the Luangwa Valley and Chicooa trough converge towards Lake Kariba. Some authors add the OG as the terminus of the southwestern extension branch (e.g. Scholz et al., 1976; Modisi et al., 2000; Leseane et al., 2015). As this southwestern extension branch is poorly defined, we name the region from the EARS in the east, Lake Upemba in the north and the OG in the southwest, the South-Western Extension Area (SWEA). This area exhibits a gradient in fault density from north to south (Lake Upemba to the Chicooa trough) and from east to west (OG to Chicooa trough).

Du Toit (1927) first proposed a relationship between the OG and the EARS, followed by Fairhead and Girdler (1969) who proposed an EARS extension in Botswana, but oriented N-S. Then Reeves (1972a) proposed an extension of the EARS along a NE-SW axis but in the central Kalahari, 250 km south from the OG. It seems to be finally Scholz et al. (1976) who postulated the OG EARS extension hypothesis in its current form. This hypothesis has consensually led to the name of "Okavango Rift Zone" for the area, thus implying a genetic connotation for the deformation of the area.

1.1.2. Study area

The OG is located between two cratons joined by a series of Paleo to Neoproterozoic belts (Fig. 2). Bedrock outcrops are scarce in the area as it is almost entirely covered with tens to hundreds of meters of Kalahari sands, occasionally directly overlying the Karoo basalts (Haddon, 2005). But recent geophysical studies bring new insights on the distribution and importance of the main units in the area.

To the north lies the Archean Congo craton. Its southern limit was originally thought to lie in central Angola, but has subsequently been redefined further south underneath the Damara Belt in northern Botswana (Singletary et al., 2003; Begg et al., 2009; Khoza et al., 2013). Its associated lithosphere is estimated to reach a thickness of up to 250 km. To the south lies the Kalahari craton, comprised of the Kaapvaal and Zimbabwe cratons joined by the Archean Limpopo belt. This craton may extend further north beneath the Okwa block and its associated lithosphere may reach up to 220 km (Muller et al., 2009; Miensopust et al., 2011). These cratons were finally joined together by the Neoproterozoic Pan-African Damara belt. This last orogeny led to the deformation of the Ghanzi formation sediments into the Ghanzi-Chobe fold belt. This Precambrian assemblage leads to belts of different lithospheric rheology with a central younger (thus thinner and weaker) lithosphere zone surrounded by older thus thicker and more rigid belts and cratons.

The Karoo period (~ 300 My - ~ 178 My) is characterized by intense rifting, which resulted in intensive sedimentation and concluded with expansive basalt flows (~ 180 My), in particular in central and northern Botswana, and the emplacement of the ENE-WSW Okavango Dyke Swarm dated at ~ 178 My (Le Gall et al., 2002). In northern Botswana, the Karoo deposition was controlled by NE-SW syn-sedimentary tectonic and paleotopographic structures. In the southwestern part of the OG, the remaining basalts and dolerites are clearly delimited by the Sekaka Shear Zone (SSZ) and the current Lecha, Kunyere and Thamalakane faults (cf. Fig. 3 for faults location). During the Permian, a major shear zone, the Southern Trans-Africa Shear System (STASS) is thought to have developed between the Congo and Kalahari blocks to accommodate differential displacements of plates astride the current African continent, and thus controlled sedimentary deposition (De Wit et al., 1995).

During the Cretaceous, continental break-up on both sides of the African continent (South America at ca. 129-121 My, and Madagascar between 150 and 112 My.) was responsible for transform faults, which formed a series of grabens across southern Africa (Haddon, 2005) and possibly reactivating the STASS. Karoo Supergroup rocks may have subsided into NE-SW grabens preserving them from erosion. Southeast of the OG, rifting reactivated the Passarge basin structures as far south as the Zoetfontein fault (up to 300 m downthrow). Generalized uplift affected the whole of southern Africa at that time, leading to an extensive period of erosion in the Cretaceous, locally forming red sandstone beds like those near Etosha pan (Miller et al., 2010) or in the OG (Linol, 2013).

In the OG, Kalahari sediments overlie these red beds unconformably. The erosion surface between the two periods is marked by pedogenesis and is constrained between 80 and 40 My (Linol, 2013). According to Haddon (2005), Kalahari sedimentation may have been initiated mainly by Late Cretaceous inner southern Africa downwarping, as well as relative uplift of the edges as a minor contribution. This would have led to the rivers back-tilting into the basin

and the appearance of inner basin lakes. This hypothesis is supported in the northern part of the OG by stratigraphy showing a southward tilting between the possibly Jurassic-Cretaceous red beds and the Kalahari sediments (Linol, 2013). Vertical movements within the Kalahari basin occurred throughout the Cenozoic and shaped the Kalahari basin notably, along the Kalahari-Zimbabwe axis. The continuous or episodic nature of these uplifts is still in debate.

1.1.3. The Okavango graben

The OG is a tectonic structure consisted of a series of normal to dextral strike-slip faults (Fig. 3) forming a hemi-graben with the most active faults concentrated in the southeastern part (Modisi et al., 2000; Campbell et al., 2006; Bufford et al., 2012). They are distributed along a NE-SW zone from the SSZ and the Gumare fault in the SW to the Linyanti and Chobe faults in the NE.

The OG can be divided into three domains (Gumbrecht and McCarthy, 2001) : (1) the northern block containing the Panhandle, (2) the central block which hosts the Delta and (3) the southern block where the Ghanzi ridge isolates the Makgadikgadi pans. Focal mechanisms determined by Scholz et al. (1976) showed normal mechanisms, and many studies based on borehole logs (Haddon, 2005; Linol, 2013), aeromagnetic data (Modisi, 2000; Campbell et al., 2006) and electromagnetic data (Podgorski et al., 2015) have shown downthrow on the main faults (Tsau, Lecha, Kunyere, Thamalakane) and, depending on interpretation up to 600 m of sediments in the OG inner part (Lake Ngami, Bufford et al. (2012)). A slight dextral strike-slip component is revealed by an offset in the dykes (Modisi et al., 2000; Campbell et al., 2006). Both studies revealed complex fault zones (branching and an echelon faulting) for the Kunyere and Thamalakane faults rather than single faults, which could form smaller grabens and hemi-grabens within the OG. These faults are structures inherited from the underlying Proterozoic basement, occurring along the same NE-SW orientation as the Ghanzi-Damara belt, and could have been initiated during the Pan-African orogenesis. They have possibly been reactivated several times : during the STASS accommodation, the Karoo rifting and post-Karoo faulting, and the Cenozoic uplifts. Campbell et al. (2006) proposed a secondary normal fault set, as indicated in fig. 3, highlighted by lateral offset in the dykes. According to Modisi et al. (2000), these faults could be responsible for lineaments at the surface of the Okavango Delta.

Thus, the OG lies upon a zone of lithospheric weakness relative to the adjacent thick and cold cratons, affected by ancient tectonic structures, which have been reactivated several times. Vertical and sometimes strike-slip displacements have a long and complex history and a great influence on the area.

1.2. Geophysical settings

1.2.1. Seismicity

The seismicity associated with the OG is a major argument for the rifting hypothesis. Plate boundaries and continental rifting such as the EARS are associated with regular seismicity revealing the deformation consequent to crustal extension. The knowledge of the OG seismicity mostly relies on studies carried out in the 1970's that revealed a concentration of seismic activity. Seismic data are here reexamined with regard to the more recent data available on the International Seismological Center (ISC) website.

The OG seismicity was first officially described by Gane and Oliver (1953) who recorded a series of earthquakes in 1951-1953 thanks to the four first South African seismographs. From May 1952 to May 1953, 33 events were recorded, mostly exceeding magnitude 5, with a maximum of 6.7 clustering in the Okavango Delta. Until the mid 1960's, seismicity in Africa was poorly documented, mostly based on anecdotal evidence. From 1959 to 1965, the Rhodesia Meteorological Services deployed the first network of seismographs in Zimbabwe revealing the seismic activity of the OG. The closest seismic station was at Bulawayo, Zimbabwe, 400 km away from the OG. This equipment led to the founding works of Reeves (1972a) and Scholz et al. (1976), who both identified increased earthquake activity in the OG and proposed a relation between the seismicity in Botswana and the EARS. But their data differ slightly : although the article of Scholz et al. (1976) is later, it shows fewer earthquakes in the central Kalahari than Reeves (1972a). This seems to be mostly due to the different time-spans they studied (1969-1973 and Sept.1965-Aug.1971 respectively). Consequently their conclusions differ. While Reeves (1972a) proposed the Kalahari axis, a line 250 km south of the OG, for the EARS extension and proposed no solution for the OG seismicity, Scholz et al. (1976) suggested that the OG is an extension of the EARS and do not mention the seismic activity in the central Kalahari. More recently, Haddon (2005) used the data available from the ISC from 1071 to 1996 and suggested three distinct parallel NE-SW earthquake alignments in the SWEA, with the southern one ending in the OG. Between 2005 and 2008, at least 26 seismic stations were deployed through the EARS and Southern Africa by the Africa Array (Nyblade and Dirks, 2006), leading to a very large increase in the number of recorded seismic events available from the ISC database (Fig. 4). No reexamination of the seismicity in the SWEA has been made since then.

In this study, we use the unreviewed dataset from the ISC (downloaded in February 2016), which gathers records from many different seismological networks in Africa. The deployment of seismic instrumentation in the EARS took place in four stages (Fig. 4). Prior to the mid 1950's, records are scarce and mostly based on anecdotes. Then the first network of seismometers arrived, which brought the initial insights into African seismicity. The third phase began in 1993. The increase in the number of recorded events seems to be mostly due to the addition of minor earthquakes (magnitude<3), with the number of powerful events remaining constant. The current phase with a denser network began in 2004, and led to at least double the number of recorded events for both high and low magnitudes.

These new data highlight an instrumental bias in the previous seismic studies due to the paucity of seismometers on the continent. This bias is corroborated by the historical seismicity (1952-1953 seismic series and prior) recovered from anecdotal evidence in a country mostly comprised of desert, and thus sparsely inhabited. Reeves (1972b) introduced his study with these biases. The overall larger number of seismic events with magnitude over 3 recorded since 2004 compared to the 1966-2003 period indicates that this instrumental bias had an impact not only on microseismic records. Some earthquakes greater than magnitude 3 may well have remained invisible to the previous network. Due to the scarcity of seismic stations, some earthquakes can be recorded by only one seismological network. The ISC review procedure requires each earthquake to be recorded by at least two networks. This procedure can hardly be applied in Africa, justifying our usage of the unreviewed data set, although it prevents any quantitative approach. In order to get rid of this instrumental bias, data before 2004 were excluded in this study at the scale of the central and southern Africa.

In Botswana, this instrumental bias seems to have hidden or obscured major areas of seismic activity. While the OG represented a major proportion of the seismicity in Botswana before the 2004 instrumentation, it now appears to represent a minor part of it (Fig. 5). This change is due to both a decrease in the Delta seismic activity and an increase of the records in remote parts of the country because of the improved coverage of the seismic network. Seismic data since 2004 show many more earthquakes with magnitude over 3 which suggest that some areas remained invisible to the previous network, one of which is the central Kalahari.

North and west Botswana experienced a dense series of more than 400 earthquakes from August 2013 to December 2014 with a majority of magnitudes ranging from 3 to 5.6. About half of these events were located in the central Kalahari, south of the Ghanzi ridge. This area corresponds to a ENE striking Karoo failed rift filled with Karoo sediments from Permian to Jurassic, capped by Karoo basalts (Haddon et al., 1999). No particular earthquake concentration can be determined on the Zoetfontein fault. Furthermore, the seismic province shows a NW-SE orientation superimposed on a topographic ridge. During this 2013-2014 seismic series in Botswana, only 26 events were recorded in the OG, one magnitude of 4.4 occurring in the Mababe Depression.

In figure 6, only events after 2004 were plotted. Moreover, only events with a magnitude exceeding 3 have been retained, to prevent any earthquake induced by human activity such as mining. In this data set, the SWEA is seismically less defined, as the earthquakes in the central Kalahari induce a spatial continuity between the seismicity of the SWEA and South Africa. Most of the seismic stations deployed in 2004/2005 were installed in South Africa. This heterogeneity leads to a better detection of earthquakes in southern Africa, relative to the SWEA, and thus an apparent higher seismic activity.

Within the SWEA, three striking spatial features appear. (1) Whereas former data showed three distinct potential extension branches with a NE-SW orientation through the SWEA, data from between 2004 and 2016 reveals a much more dispersed seismicity in the whole SWEA. While seismic events with magnitude over 3 are indeed more dense on the three NE-SW branches described by Haddon (2005), axes of earthquake clusters are also visible on the NW-SE orientation (from mid-Congo to northern Malawi, from eastern Angola through Zambia and Zimbabwe and from eastern Namibia through central Kalahari to northeastern South Africa). Microseismicity is present throughout the grid pattern defined by these axes. (2) The Luangwa/Kariba axis shows the longest and most continuous alignment, and extends across the entire African continent as far as the Namibian atlantic coast, in continuity with the Damara belt. (3) Some areas reveal particular seismic activity, like the Loma river in eastern Congo, the previously assumed aseismic Ghanzi Ridge and the central Kalahari.

Given that the OG has been quite well-monitored since the late 1960's, we considered all recorded events for our analysis of local seismicity (Fig. 3). Within the graben, seismic activity is concentrated on the SW faults between the Tsau and Thamalakane faults on a NW-SE axis ending at MAUA in alignment with the Panhandle. To the northeast the Mababe depression shows significant seismicity whereas the southwestern Lake Ngami seems to be relatively aseismic. No activity has been recorded on the Gumare fault, where it is clearly defined, but some appears on its presumptive extension northeast of the Delta up to the northern part of the Linyanti swamps. Most of the earthquakes

are confined to the central distal part of the Delta, close to the current outlets. The northern block of the graben is stable relative to the activity in the central block. Unlike the central block, the southern block shows greater seismic activity in its southwestern part than in its northeastern part between the Delta and the Makgadikgadi pans.

This seismologic reexamination reveals an historic instrumental bias in the seismic records in southern Africa. The seismicity of the SWEA area is more homogeneously distributed over the numerous tectonic structures than previously thought and extends to the southwestern African coast. This may reveal a wider distribution of the deformation in the SWEA. Some seismically active areas were invisible to the previous network, especially the southern Karoo failed rift, reducing the significance of the seismicity in the OG relative to the rest of Botswana. This hypothesis was very recently supported by the occurrence of one of the most powerful earthquakes in Southern Africa, south of the Makgadikgadi pans ($M > 6$, <https://earthquake.usgs.gov>). Thus the OG does not seismologically conform to the strict definition of a rifting zone. There appear to be discrepancies between the distributions of events in previous studies and those derived from the current ISC database, which call for further investigation.

1.2.2. From the crust to the mantle

Crust models for the OG area are proposed by two local studies based on seismic receiver functions (Yu et al., 2015b) and aeromagnetic and gravity data (Leseane et al., 2015). Both studies indicated a thinned crust beneath the OG relative to the adjacent crust although they suggest different magnitudes for the thinning (4 to 5 km and 10 to 12 km respectively). Within the same seismic study, the estimate of crust thickness at Maun varies from 37.5 and 38 km to 43.6 and 44.2 km (respectively for the station B06OR of the temporary SAFARI Network, Yu et al. (2015b), and the station MAUN of the temporary Congo Craton Network, Kachingwe et al. (2015)), depending on the seismic rays sampled. The wide range of values highlights the uncertainty intrinsic to the interpreted thickness, and in fact this range exceeds the proposed thinning.

Various values for the OG Moho depth are found in continental scale studies; they lie between 37 km as reported by Tugume et al. (2013) to 43 to 45 km in the Earth crustal model CRUST1.0 (Laske et al., 2013). Both studies show a crustal thinning in the OG relative to the thick adjacent Congo (45 km and 46 km respectively) and Kalahari (45 km and 48 km respectively) cratons. 38 km is a thickness commonly found in the (globally relatively thick) African crust. Such a value is found at Rundu (Kachingwe et al., 2015) and even in the Congo craton, areas in which rifting is commonly assumed to be absent. This latter study found an average crustal thickness of 39 ± 2 km for southern Africa.

In the EARS, crustal thickness varies from north to south, from 25 ± 3 km in the Afar Depression, to 30 to 35 km beneath the Kenyan rift (Dugda et al., 2005) and 35 to 40 km for the eastern branch end in Tanzania. In the western branch, the Moho is at a depth of 30-35 km (Bram and Schmeling, 1975), 38 to 42 km beneath Lake Tanganyika (Dugda et al., 2005; Kachingwe et al., 2015), but differences up to 4 km are found within the same rifts (southern Kenyan rifts for instance) showing strong lateral variability. Gummert et al. (2015) developed a high-resolution Moho topography across the Albertine rift and showed that the crustal depth varies from up to 39 km at the rift shoulders to a minimum of 22 km within the rift shoulders. The wide range of values and the associated

uncertainties for depth to Moho in southern Africa make it difficult to infer a direct relationship between rifting and crustal thinning in the OG.

The lithosphere thickness in the area was determined by local magnetotelluric studies at about 160 km for the Damara belt, 180 km for the Ghanzi-Chobe belt, at least 250 km for the Congo craton, and 220 km for the Kalahari craton (Muller et al., 2009; Begg et al., 2009; Miensoopust et al., 2011; Khoza et al., 2013). The proposed Kalahari craton lithospheric thickness is supported by kimberlite pipe studies, which show a thickness of at least 200 km south of the Makgadikgadi pans (Griffin et al., 2003). It is worthwhile to note that 160 km does not represent thin lithosphere. According to Begg et al. (2009), these lateral variations in lithosphere indicate the different tectono-thermal ages for the three different units in the area (Congo craton, Damara/Ghanzi-Chobe belt, Kalahari craton). Moreover, this relative thinning of the lithosphere falls short of values given for more evolved features in the EARS : from 50 km thick in the western branch (Lake Edward, Lake Kivu) to less than 40 km in the more evolved Kenyan rift (Simiyu and Keller, 1997).

At greater depth, Yu et al. (2015a) found no perturbations in the d410 and d660 discontinuities between the deeper Congo craton (ca. 410 km) and the shallower Kalahari craton (ca. 390 km). The Mantle Transition Zone shows no significant thinning and thus no evidence for thermal perturbation beneath the OG. These observations are corroborated by seismic tomography revealing the African plume at much greater depth (Forte et al., 2010; Steinberger et al., 2010). All these models conclude on null to positive anomalies for S-waves velocity, revealing relatively colder material, down to at least 800 km in the mantle, thus excluding any mantle influence on the OG activity.

The EARS extension hypothesis for the OG was supported by the first gravity anomaly surveys (Girdler, 1975). The currently available Bouguer anomaly data (The International Gravimetric Bureau, 2012) show a great negative Bouguer anomaly tightly correlated with the EARS (from ~ -260 to $< \sim -90$ mGal). The strongest is located on the northern part of the EARS, the Afar Depression, and corresponds to the well-established section of the EARS. This negative anomaly is due to the shallow asthenosphere beneath the rift. It extends along the eastern branch. The western branch is characterized by weaker but still significant negative anomalies. An extensive area of discontinuous moderate negative anomaly extends southwestwards from Lake Tanganyika through the southern Congo, Zambia, northwestern Botswana, Angola and as far as Namibia. The strongest anomaly is found beneath lakes Mweru and Bangweulu. Beneath the OG, the average Bouguer anomaly (-112 mGal) is not significant enough to support the hypothesis of uplifted lithosphere.

Direct measurements of heat flow in the study area are scattered and inhomogeneous. Ballard et al. (1987) found greater heat flow values for sites on the Damara belt (from 50 and 80 mW/m² towards the inner belt) than on the Kalahari craton (60 to 30 mW/m² towards the inner craton). But he explains this distribution in terms of fundamental difference in thermal structure between the craton and the belt thus revealing the difference of lithospheric history and this does not necessarily imply a rift system in the area. Recently, Davies (2013) provided a global Earth surface heat flow by combining direct measurements and geology and showed no significant heat flow beneath the OG. This conclusion is supported by the absence of significant delays in teleseismic P- and S-wave traveltime

residuals (Yu et al., 2015a), which are commonly found beneath rifting zones. This lack of pronounced heat flow further supports the absence of rifting in the area.

Thus, we can not conclude that crustal and lithospheric thinning can be attributed to recent rifting from seismic and magnetotelluric tomographies, gravity anomalies and heat flow measurements. The observed thinning in the Damara belt relative to its surrounding cratons is as likely to be inherited from long tectonic history, as to be acquired by recent continental rifting. Mantle activity cannot have caused the OG tectonic activity as it has beneath the EARS.

2. Geodetic study

In the framework of the fault morphology and normal focal mechanisms proposed by Scholz et al. (1976), the displacement field across the OG would be expected to be extensional, as proposed in the World stress map (Heidbach et al., 2010). In order to constrain the OG model better, we generated three time series of precise positioning from permanent GPS stations.

2.1. Data and methods

We used Global Navigation Satellite System (GNSS) data from three permanent stations (MAUA, MONG and RUND, Fig. 1) belonging to the Africa Array (data downloadable at <http://afref-data.org>) available on the UNAVCO website (<https://www.unavco.org/data/gps-gnss/gps-gnss.html>). They were set up in August 2010. MAUA is still active whereas MONG and RUND were interrupted in 2015 and 2014 respectively. MAUA is located on the edge of the graben southern block, southeast of the Thamalakane fault. RUND and MONG are located on the northern block, on the Cubango and upper Zambezi rivers respectively. 26 International GNSS Service (IGS) or Africa Array permanent GNSS stations completed the network.

Daily solutions for station positions in ITRF08 were computed with the GAMIT/GLOBK 10.6 processing software (Herring et al., 2015), adjusting IGS final orbits and estimating tropospheric parameters (1 tropospheric zenith delay/2 h, 2 couples of horizontal gradients/day). The VMF1 Mapping function (Boehm et al., 2006), the ocean loading model FES2004 (Lyard et al., 2006), atmospheric loading according to Tregoning and van Dam (2005), and the absolute antenna phase center variation model IGS08 were used. Velocities were computed by the Kalman filter GLOBK with the "real-sigma" strategy. The reference frame is set up by constraining 19 IGS stations to their ITRF08 velocities (Altamimi et al., 2012).

The horizontal velocities of the stations MONG and RUND were then computed relative to MAUA to generate relative velocities for both sides of the graben.

2.2. Results

Time series of daily solutions for the three stations (Fig. 7) show linear tendencies modulated by a strong annual frequency. In this study we focus on the long-term linear trends and particularly on the horizontal components

which reflect displacement within the Nubian plate. The annual signal is related to seasonally pulsed surface and groundwater levels, which reflect surface response to the periodic hydrological loading as modeled in areas subject to similar variations (Tregoning et al., 2009; Chanard et al., 2014). The vertical component is particularly impacted; the observed long-term trend is thus under influence of both tectonics and hydrology and is therefore not used in this study as it will be discussed in another article (Pastier et al., in prep).

All three stations move northeastwards but their rates differ slightly. The northern block on which RUND and MONG are located shows a very slow and steady NE to ENE displacement relative to the southern one, i.e. to MAUA (respectively 1.16 ± 0.09 mm/yr and 1.33 ± 0.1 mm/yr, Fig. 8). Within the northern block, MONG moves slightly faster and in a more northerly direction than RUND. In the vertical component, the elevations of all stations are increasing but the Okavango stations (RUND and MAUA) show a higher rate than the Zambezi station (MONG). Within the Okavango system, MAUA's rate is higher than RUND's.

The horizontal inner-plate displacements between the OG northern (RUND and MONG) and southern blocks (MAUA) show no extension perpendicular to the main trend of the graben during the past 5 years (Fig. 8), but do show a low dextral strike-slip displacement. These displacements are in the ranges of standard error of Saria et al. (2014) previous study, which used GAMIT/GLOBK with another wider network centered on the EARS. Our velocities correspond still better with the MIDAS automatic computation using GIPSY OASIS II software (Blewitt et al., 2016). These results are also consistent with the predictions of Reeves (1972b) and McCarthy (2013) for a very low deformation rate in the structure.

Movement within the northern block (between RUND and MONG) appear to be a very slow (≈ 0.4 mm/y) sinistral strike-slip displacement. This slight deformation could be accommodated on the supposed faults controlling the Panhandle, the Kwando and/or the Upper Zambezi.

The observed deformation rate is very low (1 mm/y) and restricted to a dextral strike-slip displacement in agreement with the dyke offset observed by Campbell et al. (2006). Surprisingly, no extensional component perpendicular to the OG main trend is observed. This may be a result of the relatively short period of record of the GPS time series, but the fact that it includes in its entirety one of the major seismic episodes in the area gives strength to our results. No significant displacement can be associated with the 2013-2014 high seismic activity for the MAUA GPS station located on the Thamalakane fault (supposedly one of the most active). The only earthquake inducing a very slight shift on the GPS time series happened on the 4th june, 2015, in the Mababe Depression. This low deformation rate is supported by the apparently very stable surface morphology of the Delta (McCarthy, 2013). The long-term strike-slip displacement observed on the GPS time series confirms the findings of Modisi (2000) and Campbell et al. (2006) in their tectonic model for the OG. The strike-slip dominated deformation is in contrast with the extensional EARS rifts, which exhibit higher rates of extension (from 1.2 to 2.8 mm/yr in the Western Branch).

3. Discussion

3.1. Okavango Graben structural model

This geodetic study brings new constraints on the OG showing only strike-slip displacement on the tectonic structure. This movement is supported by the dextral displacement of the Karoo dykes from 1 km on the Thamalakane fault to 5 km on the Kunyere fault (Campbell et al., 2006). The strike-slip displacement could also be accommodated by the arcuate central strike-slip fault (Fig. 3). Seismic activity in the OG shows the major deformation currently occurs mostly between the Thamalakane and the Tsau faults in the vicinity of MAUA. Amongst the three depocentres described by Kinabo et al. (2007), the Mababe Depression and the Linyanti swamps show significant seismic activity, but Lake Ngami (i. e., the southern part of the Kunyere fault) shows no earthquake activity in the ISC data set. Thus deformation is mainly accommodated in the OG northeastern part. The very steady deformation rate, even during the 2013-2014 period of high seismic activity, supports the hypothesis that water may act as a lubricant in the upper part of the faults (Bufford et al., 2012). Extension within the basin could be responsible for the NW-SE geomorphologic features described by Modisi et al. (2000).

Based on its kinematics and geometry, it is still challenging to determine which model of a strike-slip basin the OG fit best : pull-apart or transtensional basin, as allowed by the uncertainty associated with horizontal displacement rates (cf. Fig. 9). Indeed, the structural heritage is so influent that it controls the faults orientation and potential activity. The SSZ can act as a lock, which can explain the lack of seismic activity SW of the OG and constrain the geometry of the current structure. Thus no direct relationship between faults orientation and activity and the regional stress can be precisely established. Based on the basin morphology, the width of the OG (≈ 150 km), its sediment thickness (600 m at its very maximum) and the number of depocenters (3) foster the transtensional type (Wu et al., 2009). The low observed deformation rate strenghtens the assumption of low subsidence based on the morphology of the surface of the Okavango Delta (McCarthy, 2013), which also supports the transtensional basin model. This observation, as well as the NW-SE extension visible in the moment tensor of the recent M6.5 earthquake in central Kalahari, is in contradiction with the stress regime defined in the World Stress Map (Heidbach et al., 2010).

As a strike-slip initiation is not precluded in a rift system, the insights brought by this review allow us to re-open the debate on the rifting nature of the OG in the context of the criteria defining a rifting zone. The lithosphere and possibly the crust show a thinning relative to the adjacent blocks. This may be explained by the relative younger age of the Damara and Ghanzi-Chobe belts (Begg et al., 2009). Thus there is no substantive evidence to determine if this thinning was acquired recently through rifting or is inherited from the long and complex tectonic history of the area. No significant heat flow seems to rise to the surface and there is no strong Bouguer gravity anomaly to indicate an upwelling asthenosphere. Once the observational bias is removed from the record, the OG is not the most prominent centre of seismic activity in the area contrary to the earlier observation, which led to the EARS hypothesis. Further, the lack of an anomaly in seismic waves observed beneath the graben suggests no influence from the mantle on the observed deformation. This re-examination of the evidence shows that the OG does not conform to the current definition of a rift system, although the possibility that it may develop into a rift system in the future cannot be ruled out. Consequently, we propose to re-name the system the Okavango Graben instead of

the Okavango Rift Zone, to avoid any unfounded implications about genesis.

3.2. Regional contextualization

Our conclusion that the OG isn't a rifting zone and hence can't be considered as an analogue of the EARS rifts is in agreement with Khoza et al. (2013), McCarthy (2013) and Yu et al. (2015a) who questioned the dynamics of the tectonic activity. Both latter studies proposed new deformation models based on accommodation of differential far-field plates movements, consequent to the EARS dynamics according to McCarthy (2013) or to Kalahari craton displacement relatively to the central to northern Nubian plate in the case of Yu et al. (2015a). We propose to reconcile these two models to explain the strike-slip displacement in the OG and more generally the deformation observed in the whole SWEA (Fig. 10). Rather than rifting features, we suggest that the numerous horsts and grabens present in the SWEA compose an extensive area accommodating two distinct plates or blocks displacements. (1) The differential displacements between the diverging Victorian and Rovuma plates and the Nubian plate exhibit a gradient in extension rates, with higher rates at Lake Tanganyika decreasing northwards and southwards (Saria et al., 2014). The differences in seismic activity on each side of the EARS western branch show that the consequent deformation is mainly accommodated in the Nubian plate. Differential displacements leading to differential deformation could cause an extensive shear zone in the far-field. (2) The displacement between the Kalahari craton and the relatively stable central and northern Nubian plate was found to be clockwise relative to the Nubian plate and to reach 0.5 to 2 mm/y (Malservisi et al., 2013). NW-SE secondary fault sets are found in many SWEA grabens. These observations support the hypothesis for at least partial strike-slip displacements in the SWEA.

The distribution of SWEA faults appears to be strongly controlled by preexisting structures. Ancient faults are reactivated in Pan-African belts, and thus most of them exhibit the Proterozoic NE-SW strike. In the northern SWEA, faults appear not to propagate far from the EARS, which may reveal the influence of the Congo craton, the crust being too old to be broken-up. On the other hand, in the southern SWEA, Pan-African belts traverse the whole continent and offer a pathway of lithospheric weakness to accommodate far-field deformation. The distribution of faults exhibits two gradients with fault density increasing from north to south and from ESE to WNW. These gradients may reveal the differential stress distribution due to the two distinct sources of displacement. In the northern SWEA, the accommodated deformation only corresponds to the EARS differential opening rates. Southwards the influence of the Kalahari craton displacement increases to reach a maximum fault density in the Luangwa Valley and Chicoma trough. In the same way, the SWEA southwestern part is under the influence of only the Kalahari craton displacement, while the influence of the EARS opening increases northeastwards. These kinematics could then induce a transtensional stress regime in the whole SWEA. Such a distributed deformation model would also better fit the diffusion observed in the geophysical parameters (seismicity and Bouguer anomaly) than a model based on localized EARS extension branches.

4. Conclusion

The present geodetic study shows a very low strike-slip displacement on the entire OG at a rate about 1 mm/yr. This deformation, as well as the recent available geophysical data, does not support the OG EARS extension hypothesis. The processes at play regarding the activity of the OG faults are called into questions, as the tectonic structure better fits a transtensional basin model. The OG does not conform well with the classical definition of a rift system. Neither horizontal extension nor lithosphere thinning is found in the area, nor is there evidence of pronounced seismicity. Therefore, the OG should not be regarded as an incipient rifting zone. Several other tectonic structures diverge from the EARS western branch. These horsts and grabens are distributed in the extensive SWEA. We propose that this area is a deformation zone accommodating differential movements between the Nubian and Somalian, Victoria and Rovuma plates on one side and between the rigid Congo and Kalahari cratons within somewhat less stable Nubian plate on the other side. Coupling these two deformations leads to a maximum deformation on the Chicoma-Luangwa-Kariba branch, which decreases and disperses west of the Botswana border to disappear through Namibia. In Botswana, the OG may not be the most active area as the seismicity in the central Kalahari has been obscured by instrumental bias in the African seismic network until 2004. We thus propose to change the commonly used but genetically loaded name "Okavango Rift Zone" to a more geologically neutral, descriptive, "Okavango Graben".

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Allen, P.A., Allen, J.R., 2013. Basin Analysis : Principles and Application to Petroleum Play Assessment. Third edition ed., John Wiley & Sons.

Altamimi, Z., Métivier, L., Collilieux, X., 2012. Itrf2008 plate motion model. *Journal of Geophysical Research : Solid Earth* 117, 1–14. URL : <http://dx.doi.org/10.1029/2011JB008930>, doi :10.1029/2011JB008930. b07402.

Ballard, S., Pollack, H.N., Skinner, N.J., 1987. Terrestrial heat flow in Botswana and Namibia. *Journal of Geophysical Research : Solid Earth* 92, 6291–6300. URL : <http://dx.doi.org/10.1029/JB092iB07p06291>, doi :10.1029/JB092iB07p06291.

Begg, G., Griffin, W., Natapov, L., O'Reilly, S.Y., Grand, S., O'Neill, C., Hronsky, J., Djomani, Y.P., Swain, C., Deen, T., Bowden, P., 2009. The lithospheric architecture of Africa : Seismic tomography, mantle petrology, and tectonic evolution. *Geosphere* 5, 23–50. URL : <http://geosphere.gsapubs.org/content/5/1/23.abstract>, doi :10.1130/GES00179.1, arXiv:<http://geosphere.gsapubs.org/content/5/1/23.full.pdf+html>.

Blewitt, G., Kreemer, C., Hammond, W.C., Gazeaux, J., 2016. MIDAS robust trend estimator for accurate GPS station velocities without step detection. *Journal of Geophysical Research : Solid Earth* 121, 2054–2068. URL : <http://dx.doi.org/10.1002/2015JB012552>, doi :10.1002/2015JB012552. 2015JB012552.

- Boehm, J., Werl, B., Schuh, H., 2006. Troposphere mapping functions for GPS and very long baseline interferometry from European Centre for Medium-Range Weather Forecasts operational analysis data. *Journal of Geophysical Research : Solid Earth* 111, n/a–n/a. URL : <http://dx.doi.org/10.1029/2005JB003629>, doi :10.1029/2005JB003629. b02406.
- Bufford, K.M., Atekwana, E.A., Abdelsalam, M.G., Shemang, E., Atekwana, E.A., Mickus, K., Moidaki, M., Modisi, M.P., Molwalefhe, L., 2012. Geometry and faults tectonic activity of the Okavango Rift Zone, Botswana : Evidence from magnetotelluric and electrical resistivity tomography imaging. *Journal of African Earth Sciences* 65, 61 – 71. URL : <http://www.sciencedirect.com/science/article/pii/S1464343X12000167>, doi :<http://dx.doi.org/10.1016/j.jafrearsci.2012.01.004>.
- Campbell, G., Johnson, S., Bakaya, T., Kumar, H., Nsatsi, J., 2006. Airborne geophysical mapping of aquifer water quality and structural controls in the Lower Okavango Delta, Botswana. *South African Journal of Geology* 109, 475–494. URL : <http://sajg.geoscienceworld.org/content/109/4/475>, doi :10.2113/gssajg.109.4.475, arXiv:<http://sajg.geoscienceworld.org/content/109/4/475.full.pdf>.
- Chanard, K., Avouac, J.P., Ramillien, G., Genrich, J., 2014. Modeling deformation induced by seasonal variations of continental water in the Himalaya region : Sensitivity to Earth elastic structure. *Journal of Geophysical Research : Solid Earth* 119, 5097–5113. URL : <http://dx.doi.org/10.1002/2013JB010451>, doi :10.1002/2013JB010451.
- Chorowicz, J., 2005. The East African rift system. *Journal of African Earth Sciences* 43, 379 – 410. URL : <http://www.sciencedirect.com/science/article/pii/S1464343X05001251>, doi :<http://dx.doi.org/10.1016/j.jafrearsci.2005.07.019>. phanerozoic Evolution of Africa.
- Davies, J.H., 2013. Global map of solid Earth surface heat flow. *Geochemistry, Geophysics, Geosystems* 14, 4608–4622. URL : <http://dx.doi.org/10.1002/ggge.20271>, doi :10.1002/ggge.20271.
- De Wit, M., Vitali, E., Ashwal, L., 1995. Gondwana Reconstruction of the East Africa-Madagascar-India-Sri Lanka-Antarctica fragments revised. *Centennial Geocongress, extended abstracts* 1, 218–221.
- Du Toit, A., 1927. The Kalahari and some of its problems. *South African Journal of Science* 24, 88–101.
- Dugda, M.T., Nyblade, A.A., Julia, J., Langston, C.A., Ammon, C.J., Simiyu, S., 2005. Crustal structure in Ethiopia and Kenya from receiver function analysis : Implications for rift development in eastern Africa. *Journal of Geophysical Research : Solid Earth* 110, n/a–n/a. URL : <http://dx.doi.org/10.1029/2004JB003065>, doi :10.1029/2004JB003065. b01303.
- Fairhead, J., Girdler, R., 1969. How Far does the Rift System extend through Africa? *Nature* 221, 1018–1020. URL : <http://dx.doi.org/10.1038/2211018a0>, doi :10.1038/2211018a0.
- Forte, A.M., Quéré, S., Moucha, R., Simmons, N.A., Grand, S.P., Mitrovica, J.X., Rowley, D.B., 2010. Joint seismic-geodynamic-mineral physical modelling of African geodynamics : A reconciliation

- of deep-mantle convection with surface geophysical constraints. *Earth and Planetary Science Letters* 295, 329 – 341. URL : <http://www.sciencedirect.com/science/article/pii/S0012821X10001883>, doi :<http://dx.doi.org/10.1016/j.epsl.2010.03.017>.
- Gane, P., Oliver, H., 1953. South African earthquakes–1949 to December 1952. *Transactions of the Geological Society of South Africa* 61, 21–35.
- Girdler, R.W., 1975. The great negative Bouguer gravity anomaly over Africa. *Eos, Transactions American Geophysical Union* 56, 516–519. URL : <http://dx.doi.org/10.1029/E0056i008p00516>, doi :10.1029/E0056i008p00516.
- Griffin, W., O'Reilly, S.Y., Natapov, L., Ryan, C., 2003. The evolution of lithospheric mantle beneath the Kalahari Craton and its margins. *Lithos* 71, 215 – 241. URL : <http://www.sciencedirect.com/science/article/pii/S0024493703001142>, doi :<http://dx.doi.org/10.1016/j.lithos.2003.07.006>. a Tale of Two Cratons : The Slave-Kaapvaal Workshop.
- Gumbrecht, T., McCarthy, T., 2001. The topography of the Okavango Delta, Botswana, and its tectonic and sedimentological implications. *South African Journal of Geology* 104, 243–264. URL : <http://sajg.geoscienceworld.org.biblioplanets.gate.inist.fr/content/104/3/243.abstract>, doi :10.2113/1040243.
- Gummert, M., Lindenfeld, M., Wölbern, I., Rümpker, G., Celestin, K., Batte, A., 2015. Crustal structure and high-resolution Moho topography across the Rwenzori region (Albertine rift) from P-receiver functions. *Geological Society, London, Special Publications* 420. URL : <http://sp.lyellcollection.org/content/early/2015/02/09/SP420.4.abstract>, doi :10.1144/SP420.4, arXiv:<http://sp.lyellcollection.org/content/early/2015/02/09/SP420.4.full.pdf+html>.
- Haddon, I.G., 2005. The sub-Kalahari geology and tectonic evolution of the Kalahari Basin, Southern African. Ph.D. thesis. Faculty of Science, University of the Witwatersrand.
- Haddon, I.G., Erasmus, D.M., Roos, H.M., 1999. Isopach Map of the Kalahari Group.
- Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfes, D., Müller, B., 2010. Global crustal stress pattern based on the world stress map database release 2008. *Tectonophysics* 482, 3 – 15. URL : <http://www.sciencedirect.com/science/article/pii/S0040195109004132>, doi :<http://dx.doi.org/10.1016/j.tecto.2009.07.023>. *frontiers in Stress Research*.
- Herring, T., King, R.W., Floyd, M., McClusky, S., 2015. Introduction to GAMIT/GLOBK, Release 10.6. Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology.
- International Seismological Centre, 2016. On-line Bulletin. International Seismological Center. Thatcham, United Kingdom. [Http ://www.isc.ac.uk](http://www.isc.ac.uk).

- Kachingwe, M., Nyblade, A., Julià, J., 2015. Crustal structure of Precambrian terranes in the southern African subcontinent with implications for secular variation in crustal genesis. *Geophysical Journal International* 202, 533–547. URL : <http://gji.oxfordjournals.org/content/202/1/533.abstract>, doi :10.1093/gji/ggv136, arXiv:<http://gji.oxfordjournals.org/content/202/1/533.full.pdf+html>.
- Khoza, T.D., Jones, A.G., Muller, M.R., Evans, R.L., Miensopust, M.P., Webb, S.J., 2013. Lithospheric structure of an Archean craton and adjacent mobile belt revealed from 2-D and 3-D inversion of magnetotelluric data : Example from southern Congo craton in northern Namibia. *Journal of Geophysical Research-Solid Earth* 118, 4378–4397. doi :{10.1002/jgrb.50258}.
- Kinabo, B., Atekwana, E., Hogan, J., Modisi, M., Wheaton, D., Kampunzu, A., 2007. Early structural development of the Okavango rift zone, NW Botswana. *Journal of African Earth Sciences* 48, 125 – 136. URL : <http://www.sciencedirect.com/science/article/pii/S1464343X07000258>, doi :<http://dx.doi.org/10.1016/j.jafrearsci.2007.02.005>. the East African Rift System : Dynamics, Evolution and Environment The East African Rift System : Development, Evolution and Resources.
- Laske, G., Masters, G., Ma, Z., Pasyanos, M., 2013. Update on CRUST1.0 - A 1-degree Global Model of Earth's Crust, in : EGU General Assembly Conference Abstracts, pp. EGU2013–2658. URL : <http://igppweb.ucsd.edu/~gabi/rem.html>.
- Le Gall, B., Tshoso, G., Jourdan, F., Féraud, G., Bertrand, H., Tiercelin, J., Kampunzu, A., Modisi, M., Dymment, J., Maia, M., 2002. $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology and structural data from the giant Okavango and related mafic dyke swarms, Karoo igneous province, northern Botswana. *Earth and Planetary Science Letters* 202, 595 – 606. URL : <http://www.sciencedirect.com/science/article/pii/S0012821X0200763X>, doi :[http://dx.doi.org/10.1016/S0012-821X\(02\)00763-X](http://dx.doi.org/10.1016/S0012-821X(02)00763-X).
- Lepersonne, J., 1974. Carte géologique du Zaïre, échelle 1 :2.000.000.
- Leseane, K., Atekwana, E.A., Mickus, K.L., Abdelsalam, M.G., Shemang, E.M., Atekwana, E.A., 2015. Thermal perturbations beneath the incipient Okavango Rift Zone, northwest Botswana. *Journal of Geophysical Research-Solid Earth* 120, 1210–1228. doi :{10.1002/2014JB011029}.
- Linol, B., 2013. Sedimentology and sequence stratigraphy of the Congo and Kalahari basins of south-central Africa and their evolution during the formation and break-up of west Gondwana. Ph.D. thesis. Nelson Mandela Metropolitan University.
- Lyard, F., Lefevre, F., Letellier, T., Francis, O., 2006. Modelling the global ocean tides : modern insights from fes2004. *Ocean Dynamics* 56, 394–415. URL : <http://dx.doi.org/10.1007/s10236-006-0086-x>, doi :10.1007/s10236-006-0086-x.
- Macgregor, D., 2015. History of the development of the East African Rift System : A series of interpreted maps through time. *Journal of African Earth Sciences* 101, 232 – 252. URL : <http://www.sciencedirect.com/science/article/pii/S1464343X14003240>, doi :10.1016/j.jafrearsci.2014.09.016.

- Malservisi, R., Hugentobler, U., Wonnacott, R., Hackl, M., 2013. How rigid is a rigid plate? Geodetic constraint from the TrigNet CGPS network, South Africa. *Geophysical Journal International* 192, 918–928. URL : <http://gji.oxfordjournals.org/content/192/3/918.abstract>, doi :10.1093/gji/ggs081, arXiv:<http://gji.oxfordjournals.org/content/192/3/918.full.pdf+html>.
- McCarthy, T., 2013. The Okavango Delta and its place in the geomorphological evolution of Southern Africa. *South African journal of geology* 116, 1–54. URL : <http://sajg.geoscienceworld.org/content/116/1/1.abstract>, doi :10.2113/gssajg.116.1.1, arXiv:<http://sajg.geoscienceworld.org/content/116/1/1.full.pdf+html>.
- Miensopust, M.P., Jones, A.G., Muller, M.R., Garcia, X., Evans, R.L., 2011. Lithospheric structures and Precambrian terrane boundaries in northeastern Botswana revealed through magnetotelluric profiling as part of the Southern African Magnetotelluric Experiment. *Journal of Geophysical Research-Solid Earth* 116, 1–21. doi :{10.1029/2010JB007740}.
- Milesi, J.P., Frizon de Lamotte, D., De Kock, G.S., 2010. Carte tectonique de l’afrique. URL : <http://www.sudoc.fr/160194628.1> :10 000 000.
- Miller, R.M., Pickford, M., Senut, B., 2010. The geology, palaeontology and evolution of the Etosha pan, Namibia : Implications for terminal Kalahari deposition. *South African Journal of Geology* 113, 307–334. URL : <http://sajg.geoscienceworld.org/content/113/3/307>, doi :10.2113/gssajg.113.3.307, arXiv:<http://sajg.geoscienceworld.org/content/113/3/307.full.pdf>.
- Modisi, M., 2000. Fault system at the southeastern boundary of the Okavango Rift, Botswana. *Journal of African Earth Sciences* 30, 569 – 578. URL : <http://www.sciencedirect.com/science/article/pii/S0899536200000397>, doi :[http://dx.doi.org/10.1016/S0899-5362\(00\)00039-7](http://dx.doi.org/10.1016/S0899-5362(00)00039-7). 50th Anniversary of the Geological Survey.
- Modisi, M., Atekwana, E., Kampunzu, A., Ngwisanyi, T., 2000. Rift kinematics during the incipient stages of continental extension : Evidence from the nascent Okavango rift basin, northwest Botswana. *Geology* 28, 939–942. URL : <http://geology.gsapubs.org/content/28/10/939.abstract>, doi :10.1130/0091-7613(2000)28<939:RKDTIS>2.0.CO;2, arXiv:<http://geology.gsapubs.org/content/28/10/939>.
- Muller, M., Jones, A., Evans, R., Grütter, H., Hatton, C., Garcia, X., Hamilton, M., Miensopust, M., Cole, P., Ngwisanyi, T., Hutchins, D., Fourie, C., Jelsma, H., Evans, S., Aravanis, T., Pettit, W., Webb, S., Wasborg, J., 2009. Lithospheric structure, evolution and diamond prospectivity of the Rehoboth Terrane and western Kaapvaal Craton, southern Africa : Constraints from broadband magnetotellurics . *Lithos* 112, Supplement 1, 93 – 105. URL : <http://www.sciencedirect.com/science/article/pii/S0024493709002631>, doi :<http://dx.doi.org/10.1016/j.lithos.2009.06.023>. proceedings of the 9th International Kimberlite Conference9th International Kimberlite Conference.
- Nyblade, A., Dirks, P., 2006. Africaarray newsletter. URL : <http://africaarray.psu.edu/publications/newsletters/2006>

- Pinna, P., Marteau, P., Becq-Giraudon, J.F., Manigault, B., 1987. Carta Geológica. República Popular de Moçambique. 1/1.000.000.
- Podgorski, J.E., Green, A.G., Kalscheuer, T., Kinzelbach, W.K., Horstmeyer, H., Maurer, H., Rabenstein, L., Doetsch, J., Auken, E., Ngwisanyi, T., Tshoso, G., Jaba, B.C., Ntibinyane, O., Laletsang, K., 2015. Integrated interpretation of helicopter and ground-based geophysical data recorded within the Okavango Delta, Botswana. *Journal of Applied Geophysics* 114, 52 – 67. URL : <http://www.sciencedirect.com/science/article/pii/S0926985115000051>, doi :<http://dx.doi.org/10.1016/j.jappgeo.2014.12.017>.
- Reeve, W., Thieme, J., Johnson, R., 1981. Geological map of Zambia. 1 :1,000,000.
- Reeves, C., 1972a. Earthquakes in Ngamiland. *Botswana Notes and Records* 4, 257–261.
- Reeves, C.V., 1972b. Rifting in the Kalahari? *Nature* 237, 95–96. URL : <http://dx.doi.org/10.1038/237095a0>, doi :10.1038/237095a0.
- Saria, E., Calais, E., Stamps, D.S., Delvaux, D., Hartnady, C.J.H., 2014. Present-day kinematics of the East African Rift. *Journal of Geophysical Research : Solid Earth* 119, 3584–3600. URL : <http://dx.doi.org/10.1002/2013JB010901>, doi :10.1002/2013JB010901.
- Scholz, C.H., Koczyński, T.A., Hutchins, D.G., 1976. Evidence for Incipient Rifting in Southern Africa. *Geophysical Journal International* 44, 2135–144. URL : <http://gji.oxfordjournals.org/content/44/1/135.full.pdf+html>, doi :10.1111/j.1365-246X.1976.tb00278.x.
- Sengör, A.M.C., Burke, K., 1978. Relative timing of rifting and volcanism on Earth and its tectonic implications. *Geophysical Research Letters* 5, 419–421. URL : <http://dx.doi.org/10.1029/GL005i006p00419>, doi :10.1029/GL005i006p00419.
- Simiyu, S.M., Keller, G.R., 1997. An integrated analysis of lithospheric structure across the East African plateau based on gravity anomalies and recent seismic studies. *Tectonophysics* 278, 291 – 313. URL : <http://www.sciencedirect.com/science/article/pii/S0040195197001091>, doi :[http://dx.doi.org/10.1016/S0040-1951\(97\)00109-1](http://dx.doi.org/10.1016/S0040-1951(97)00109-1).
- Singletary, S.J., Hanson, R.E., Martin, M.W., Crowley, J.L., Bowring, S.A., Key, R.M., Ramokate, L.V., Direng, B.B., Krol, M.A., 2003. Geochronology of basement rocks in the Kalahari Desert, Botswana, and implications for regional Proterozoic tectonics. *Precambrian Research* 121, 47 – 71. URL : <http://www.sciencedirect.com/science/article/pii/S0301926802002012>, doi :[http://dx.doi.org/10.1016/S0301-9268\(02\)00201-2](http://dx.doi.org/10.1016/S0301-9268(02)00201-2).
- Stagman, J., 1991. Provisional geological map of Zimbabwe. Original map from 1977 revised in 1991.

- Steinberger, B., Buitter, S., Medvedev, S., Tetreault, J., 2010. The mantle under Africa : An overview of global and regional tomography models, lithosphere thickness models and their effect on present-day and past dynamic topography.
- The International Gravimetric Bureau, 2012. Iag geodesist's handbook. *Journal of Geodesy* 86, 946–950.
- Tregoning, P., van Dam, T., 2005. Effects of atmospheric pressure loading and seven-parameter transformations on estimates of geocenter motion and station heights from space geodetic observations. *Journal of Geophysical Research : Solid Earth* 110, n/a–n/a. URL : <http://dx.doi.org/10.1029/2004JB003334>, doi :10.1029/2004JB003334. b03408.
- Tregoning, P., Watson, C., Ramillien, G., McQueen, H., Zhang, J., 2009. Detecting hydrologic deformation using GRACE and GPS. *Geophysical Research Letters* 36, n/a–n/a. URL : <http://dx.doi.org/10.1029/2009GL038718>, doi :10.1029/2009GL038718. l15401.
- Tugume, F., Nyblade, A., Julià, J., van der Meijde, M., 2013. Precambrian crustal structure in africa and arabia : Evidence lacking for secular variation. *Tectonophysics* 609, 250 – 266. URL : <http://www.sciencedirect.com/science/article/pii/S0040195113002825>, doi :<http://dx.doi.org/10.1016/j.tecto.2013.04.027>. moho : 100 years after Andrija Mohorovicic.
- Wilson, B., Dincer, T., 1976. An introduction to the hydrology and hydrography of the Okavango Delta., in : Society, B. (Ed.), *Symposium on the Okavango Delta*, Gaborone, Botswana. pp. 33–48.
- Wu, J.E., McClay, K., Whitehouse, P., Dooley, T., 2009. 4d analogue modeling of transtensional pull-apart basins. *Marine and Petroleum Geology* 26, 1608 – 1623. URL : <http://www.sciencedirect.com/science/article/pii/S0264817208001177>, doi :<http://dx.doi.org/10.1016/j.marpetgeo.2008.06.007>.
- Youssof, M., Thybo, H., Artemieva, I., Levander, A., 2013. Moho depth and crustal composition in Southern Africa. *Tectonophysics* 609, 267 – 287. URL : <http://www.sciencedirect.com/science/article/pii/S004019511300543X>, doi :<http://dx.doi.org/10.1016/j.tecto.2013.09.001>. moho : 100 years after Andrija Mohorovicic.
- Yu, Y., Liu, K., Moidaki, M., Reed, C., Gao, S., 2015a. No thermal anomalies in the mantle transition zone beneath an incipient continental rift : evidence from the first receiver function study across the Okavango Rift Zone, Botswana. *Geophysical Journal International* 202, 1407–1418. URL : <http://gji.oxfordjournals.org/content/202/2/1407.abstract>, doi :10.1093/gji/ggv229, arXiv:<http://gji.oxfordjournals.org/content/202/2/1407.full.pdf+html>.
- Yu, Y., Liu, K.H., Reed, C.A., Moidaki, M., Mickus, K., Atekwana, E.A., Gao, S.S., 2015b. A joint receiver function and gravity study of crustal structure beneath the incipient Okavango Rift, Botswana. *Geophysical Research Letters* 42, 8398–8405. URL : <http://dx.doi.org/10.1002/2015GL065811>, doi :10.1002/2015GL065811. 2015GL065811.

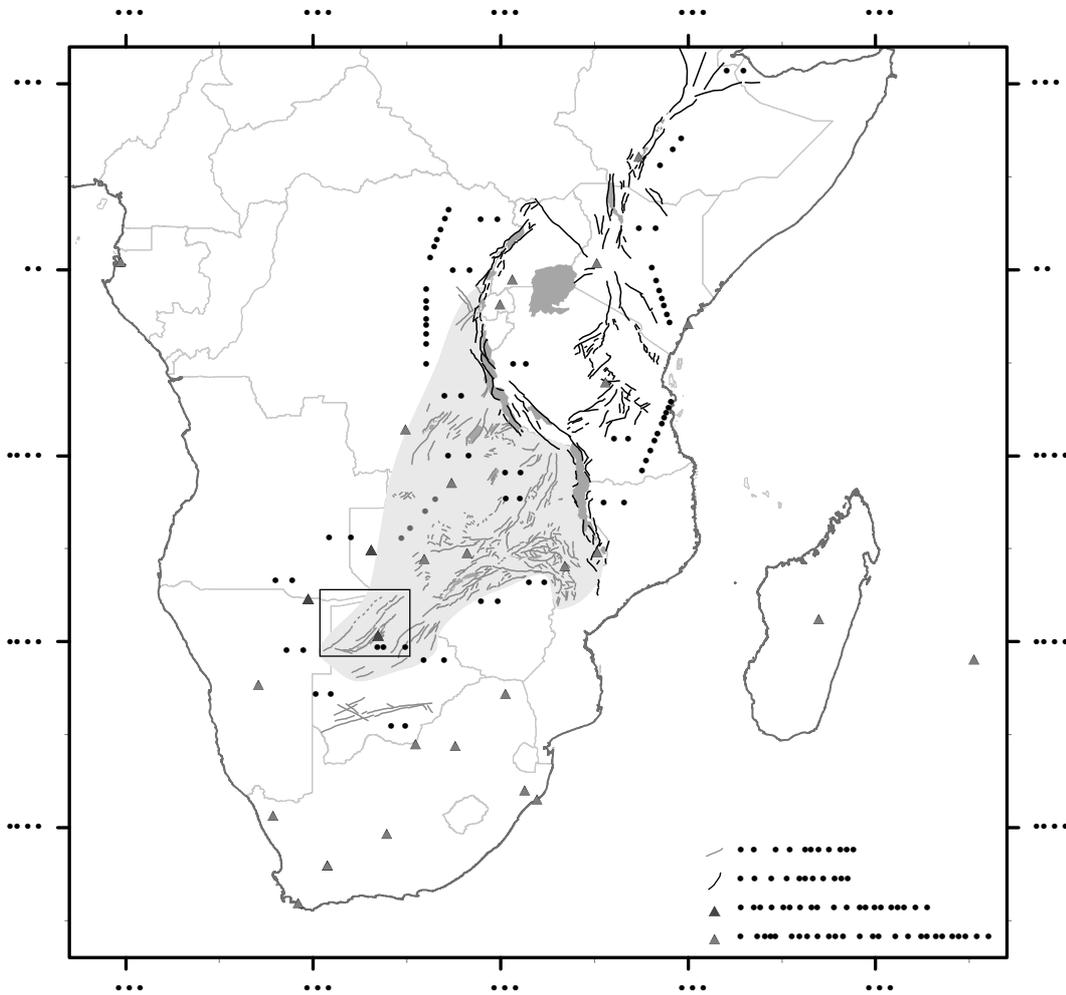


FIGURE 1: Location of the Okavango Graben and the three studied permanent Africa Array GPS stations (MA : MAUA, MO : MONG, RU : RUND). 26 GPS stations complete the network. The EARS and SWEA (South Western Extension Area) main faults are compiled from Lepage (1974); Reeve et al. (1981); Pinna et al. (1987); Stagman (1991); Haddon (2005); Kinabo et al. (2007); Milesi et al. (2010). The SWEA extent is filled with light gray. Af : Afar Depression, Al : Lake Albert, Ba : Lake Bangweulu, Ct : Chicora trough, CK : central Kalahari, Ka : Lake Kariba, Ki : Lake Kivu, Kr : Kenyan rifts, Lu : Luangwa Valley, Ma : Lake Malawi, MER : Main Ethiopian Rift, Mk : Makgadikgadi Pans, Mw : Lake Mweru, Ta : Lake Tanganyika, Td : Tanzanian divergence, Up : Upemba trough, Zf : Zoetfontein fault.

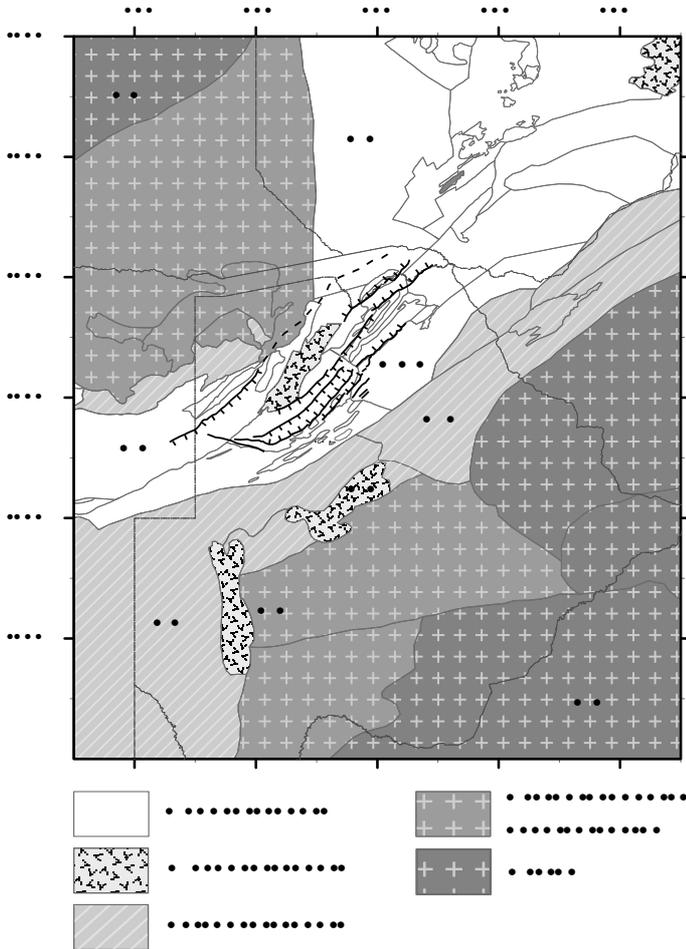


FIGURE 2: Structural crust model compiled from Singletary et al. (2003); Haddon (2005); Kinabo et al. (2007); Muller et al. (2009); Begg et al. (2009); Miensoopust et al. (2011); Khoza et al. (2013); Youssof et al. (2013). Archean thick cratons surround younger weaker orogenic belts. CC : Congo Craton, Db : Damara belt, GCb : Ghanzi-Chobe belt, Kb : Kibarian belt, KC : Kalahari Craton, Kh : Kheis belt, Mb : Magondi belt, Ob : Okwa block, Rt : Rehoboth terrane.

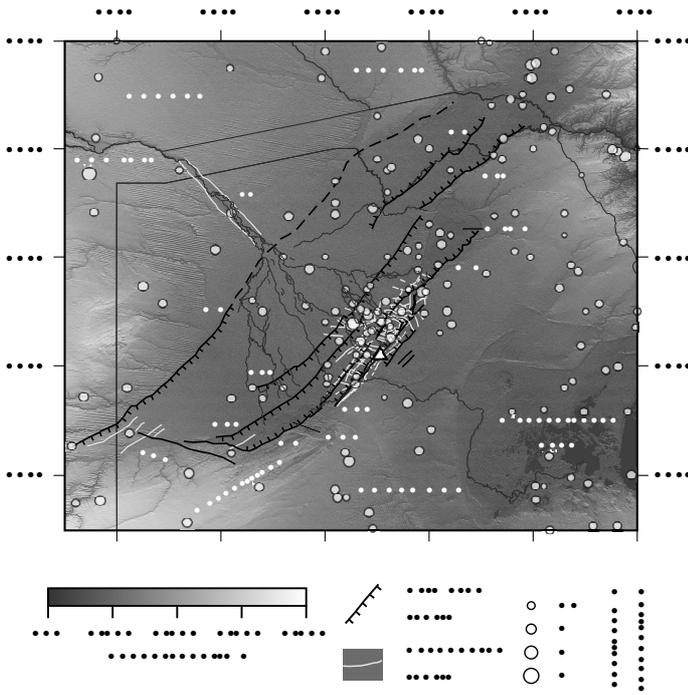


FIGURE 3: Topographical map (SRTM30) showing location of the main faults (modified from Campbell et al. (2006); Kinabo et al. (2007)), seismic activity and inundated areas. C. : Chobe fault, G. : Gumare fault K. : Kunyere fault, Le. : Lecha fault, Li : Linyanti fault, M. : Mababe fault, M.D. : Mababe Depression, N.L. : Lake Ngami, P. : Panhandle, SSZ : Sekaka Shear Zone, Th. : Thamalakane fault, Ts. : Tsau fault.

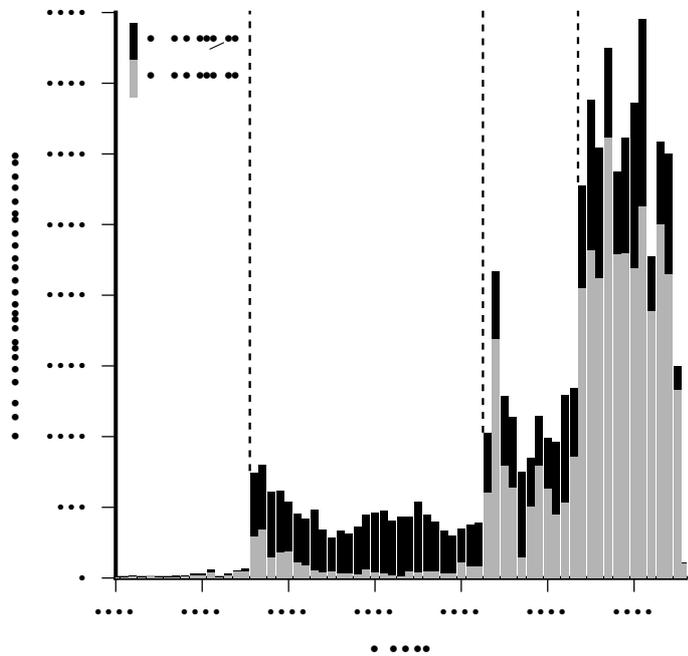


FIGURE 4: Number of recorded earthquakes per year from ISC database (from 0°E, 18.7°N to 51.7°E, 38°S and from the 16/03/1901 to the 06/02/2016). Dotted lines mark the dates of significant improvements in seismic instrumentation in Africa.

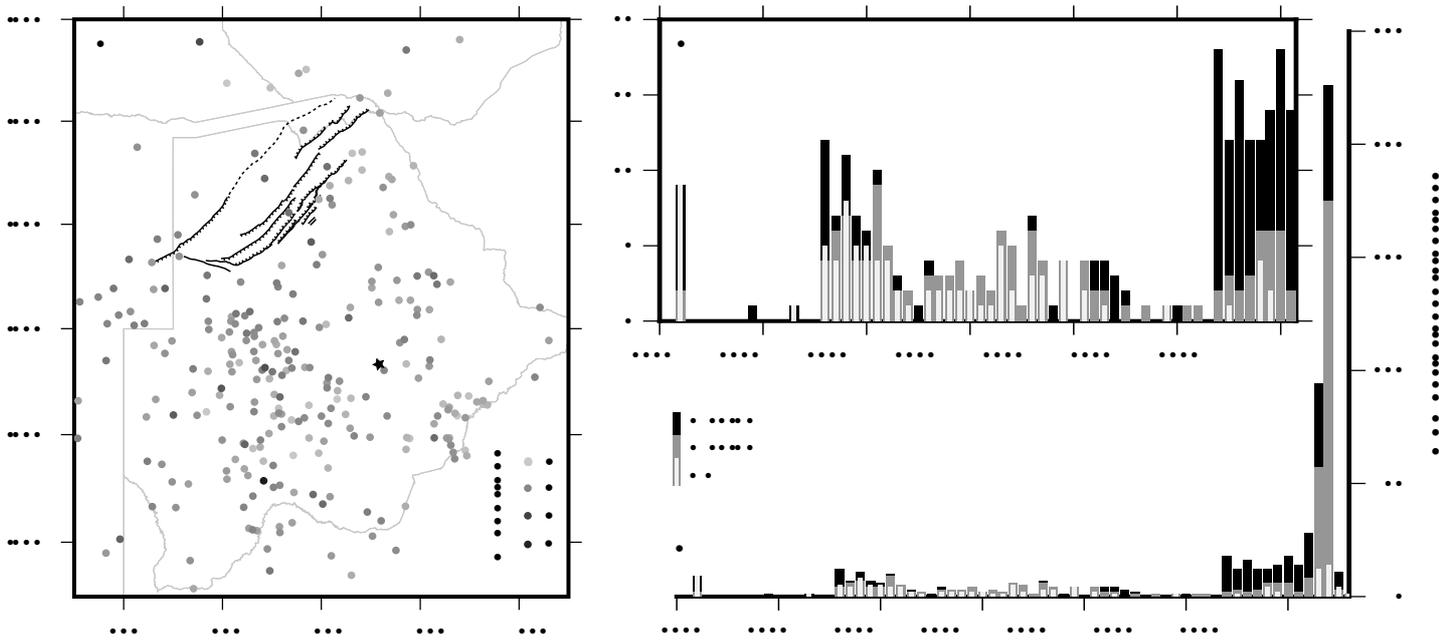


FIGURE 5: Seismicity in Botswana. A : Location of earthquakes from August 2013 to December 2014. The black star shows location of the recent M6.5 earthquake. B : Number of events per year in Botswana and the OG (International Seismological Centre, 2016). C : Zoom on previous graph, note the expanded scale. *Annot. : Location of the M6.5 earthquake has been added.*

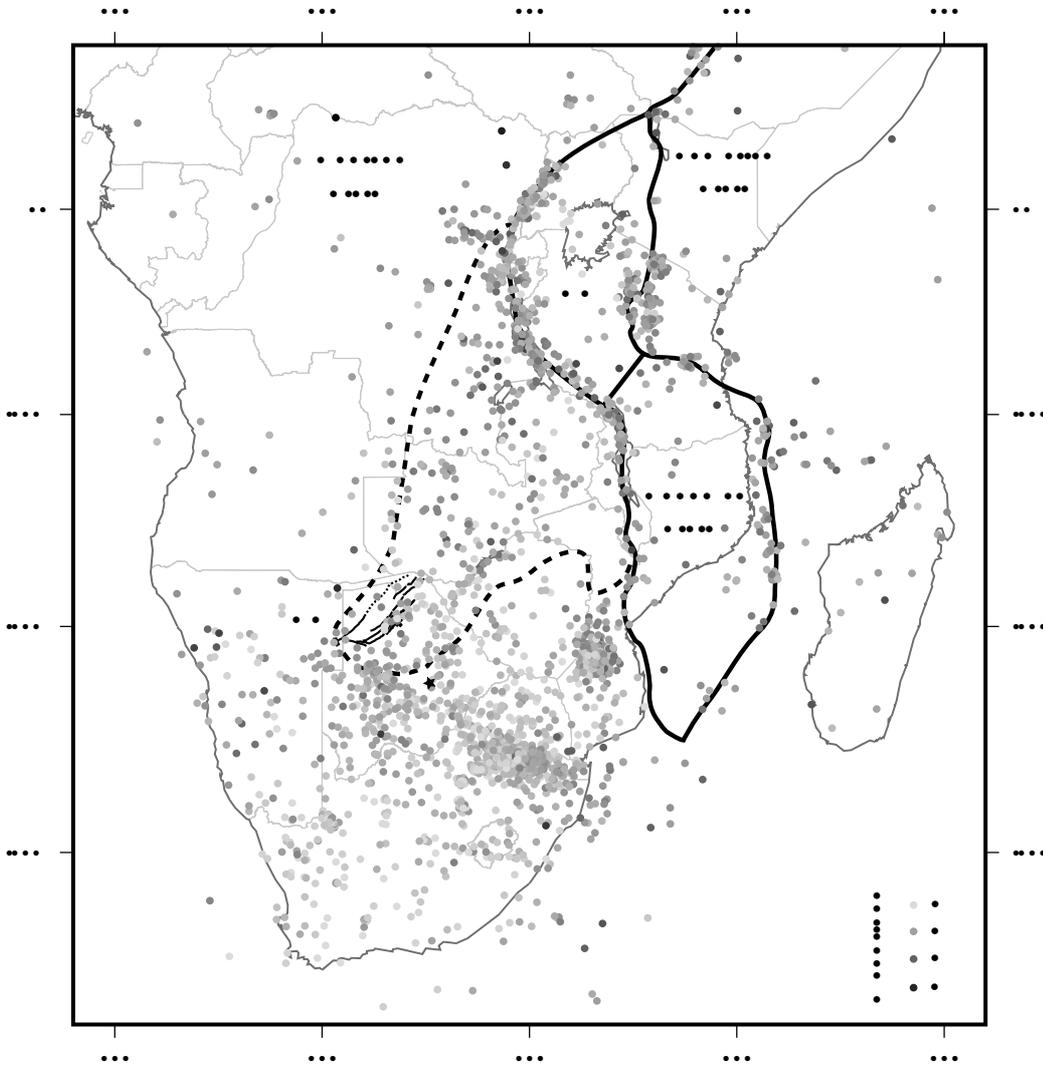


FIGURE 6: Recorded earthquakes from 2004 to 2016, with magnitude over 3 (International Seismological Centre, 2016). The black star indicates the location of the recent M6.5 earthquake (*Annot. : Location of the recent earthquake has been added.*). Plates boundaries are from Saria et al. (2014).

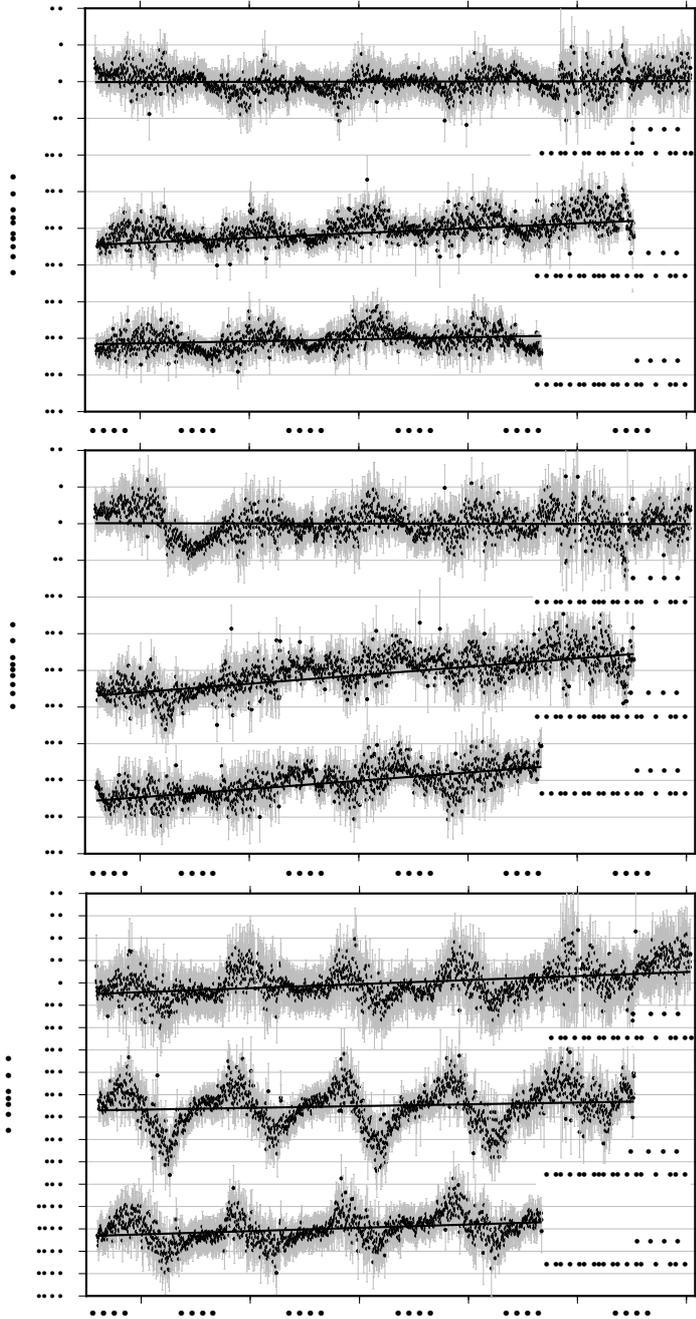


FIGURE 7: Time series from the Africa Array permanent GNSS stations records. Raw rates calculated by GLOBK are indicated under station name for each component; linear trends are drawn with straight lines. North and east components are shown detrended with MAUA's rate, vertical positions are plotted without correction.

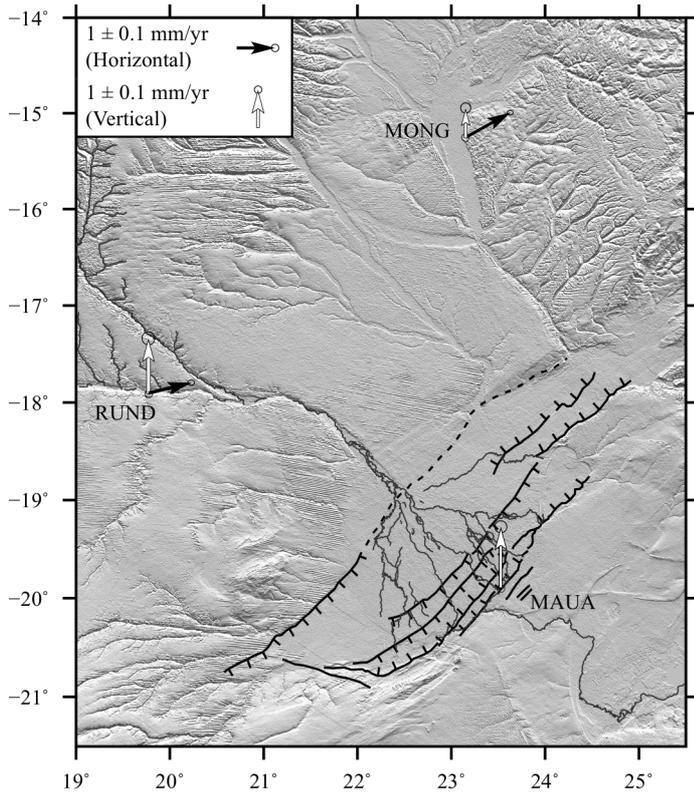


FIGURE 8: Displacements of the three permanent GNSS stations. Horizontal rates are shown in black arrows, relatively to MAUA. Vertical rates are shown in white arrows. Background shows hillshade based on SRTM30.

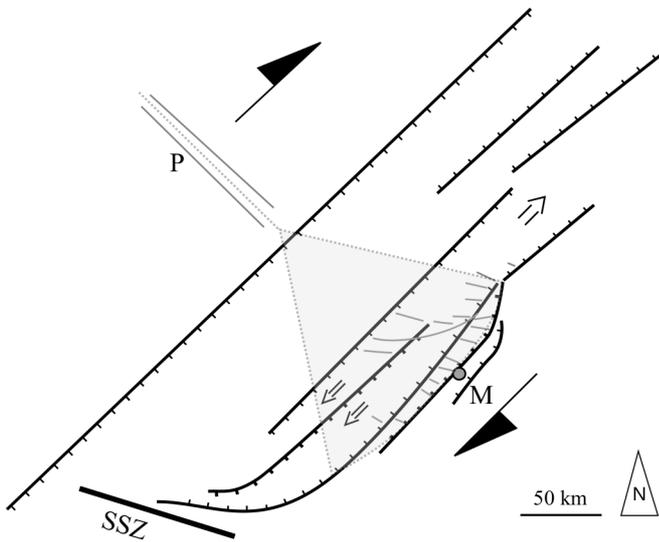


FIGURE 9: Synthetic structural model for the OG showing strike-slip displacement astride the graben and extension on the secondary fault set, in the interslip of the primary fault set. The grey area shows the extent of the Okavango Delta. M : Maun, P : Panhandle. The grey area represents the extent of the Okavango Delta.

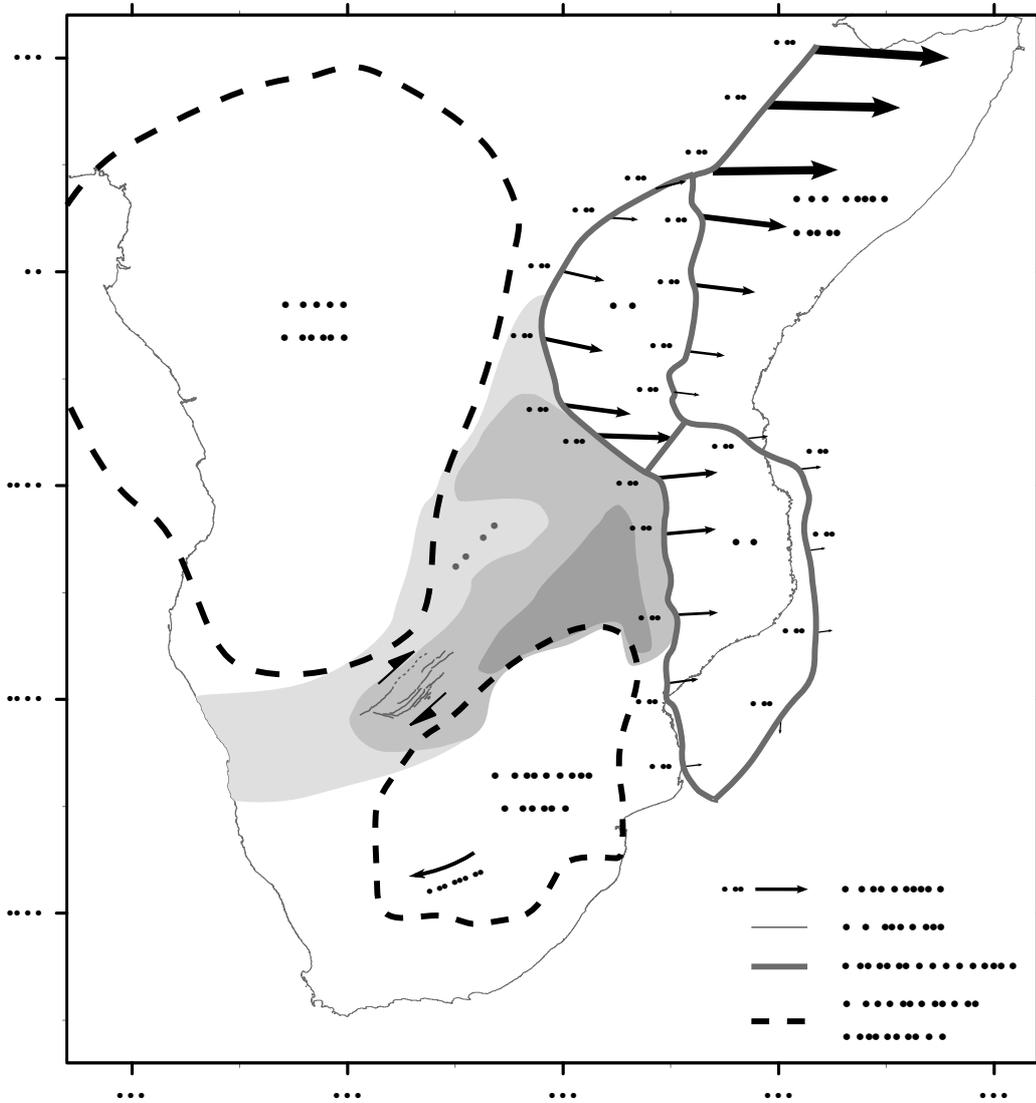


FIGURE 10: EARS block limits and velocities (in mm/y, relative to adjacent blocks) from Saria et al. (2014), South Africa velocity relative to the Nubian plate from Malservisi et al. (2013). In the SWEA, increasing saturation represents observed fault density and hence probably increased deformation, revealing the distribution of the lithospheric weakness and conjugated influences of the southern Africa displacement and the EARS opening. RP : Rovuma plate, VP : Victoria plate.

Graphical abstract

