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The seismotectonics of Southeastern Tanzania: Implications for the propagation of the eastern branch of the East African Rift

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ABSTRACT

Seismicity patterns and focal mechanisms in southeastern Tanzania, determined from data recorded on temporary and permanent AfricaArray seismic stations, have been used to investigate the propagation direction of the Eastern branch of the East African Rift System southward from the Northern Tanzania Divergence Zone (NTDZ). Within the NTDZ, the rift zone is defined by three segments, the Eyasi segment to the west, the Manyara segment in the middle, and the Pangani segment to the east. Results show that most of the seismicity (~75%) extends to the south of the Manyara segment along the eastern margin of the Tanzania Craton, and at ~6–7° S latitude trends to the SE along the northern boundary of the Ruvuma microplate, connecting with a N–S zone of seismicity offshore southern Tanzania and Mozambique. A lesser amount of seismicity (~25%) is found extending from the SE corner of the Tanzania Craton at ~6–7° S latitude southwards towards Lake Nyasa. This finding supports a model of rift propagation via the Manyara segment to the southeast of the Tanzania Craton along the northern boundary of the Ruvuma microplate. However, given the limited duration of the seismic recordings used in this study, the possibility of another zone of extension developing to the south towards Lake Nyasa (Malawi) cannot be ruled out. Focal mechanisms along the boundary between the Victoria and the Ruvuma microplates and offshore southeastern Tanzania show a combination of normal and strike slip faulting indicating mainly extension with some sinistral motion, consistent with the mapped geologic faults and a clockwise rotation of the Ruvuma microplate.

1. Introduction

The southward propagation of the Eastern branch of the East African Rift System (EARS) through Kenya and into northern Tanzania, where the rift zone splits into three segments, the Eyasi segment to the west, the Manyara segment in the middle, and the Pangani segment to the east, has been well studied (e.g., Dawson, 1992; Ebinger et al., 1997; Foster et al., 1997) (Fig. 1). Southeastern Tanzania is situated at the southern end of this so-called Northern Tanzania Divergence Zone (NTDZ) (Fig. 1), where the nature of the seismicity, the stress regime and the locus of rifting are, by contrast, less well understood. Southeastern Tanzania encompasses the boundaries between the proposed Victoria and Ruvuma microplates, which are rotating in counterclockwise and clockwise directions, respectively, with respect to the Nubian Plate (Calais et al., 2006; Stamps et al., 2008; Saria et al., 2013, 2014; Fernandes et al., 2013; De'prez et al., 2013). It has been suggested that the Eastern branch may connect with the Davies Ridge offshore via the northern edge of the Ruvuma microplate (O'Donnell et al., 2013) (Fig. 1). It also has been suggested that the Eastern branch may connect to the Western branch of the EARS via a transverse fault zone along the margin of the Tanzania Craton (Le Gall et al., 2004) (Fig. 1). Alternatively, Mougenot et al. (1986) suggested that the Eastern branch might not extend through southeastern Tanzania but instead may be propagating along the Pangani rift across northeastern Tanzania (Fig. 1).

The seismicity and stress regime in northern Tanzania have been studied in great detail to understand extension within the NTDZ (Wohlenberg, 1969; Fairhead and Girdler, 1971; Sykes and Landisman, 1974; Bâth, 1975; Fairhead and Girdler, 1969; Nyblade et al., 1996; Langston et al., 1998; Macheyeki et al., 2008; Mulibo and Nyblade, 2009; Albaric et al., 2009), but seismicity in southeastern Tanzania has not been similarly investigated and remains poorly understood. This is mainly because until recently there have been few seismic networks within the area to record local seismicity. In this paper, data from temporary and permanent seismic stations in and surrounding southeastern Tanzania operated between 2009 and 2011 are used to investigate seismicity and the regional stress regime, and to elucidate from them the propagation direction of the Eastern branch of the rift system south of the NTDZ.

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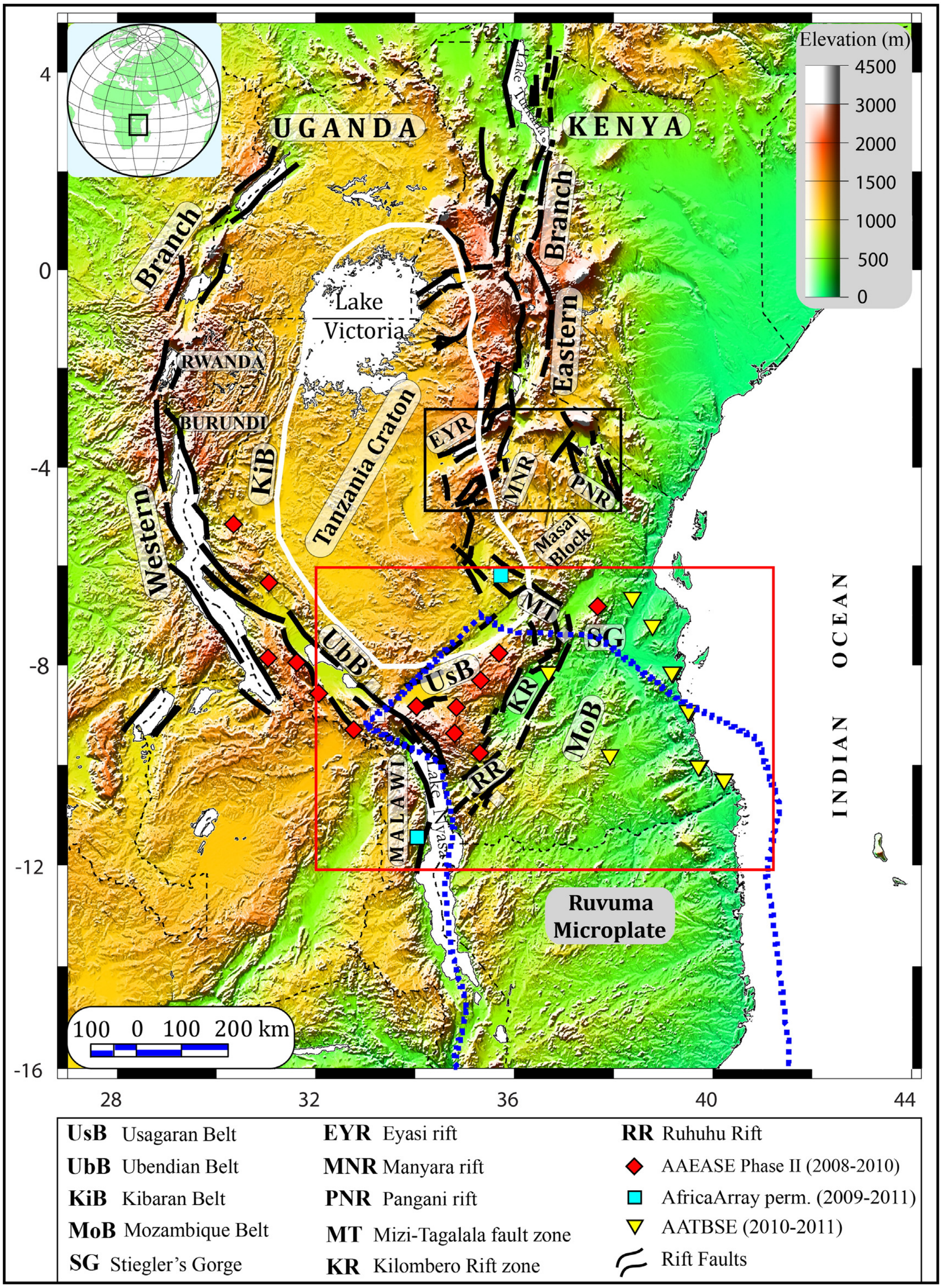

Fig. 1. Topographic map of East Africa showing the regional geology, including the Tanzania Craton (bold outline), the Proterozoic mobile belts surrounding the craton, the major Cenozoic rift faults and the three rift segments of the Northern Tanzania Divergence Zone (NDTZ). Seismic stations used are also shown. The black box shows the NDTZ, the red box shows the region that is enlarged in Figs. 2 and 5, and the blue dashed line shows the boundary of the Ruvuma microplate. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Background

2.1. Geology and tectonic setting

The topography and the major tectonic provinces of the study area are shown in Figs. 1 and 2, which include the area to the south and southeast of the Tanzania Craton along the southeastern side of the East African Plateau. The Tanzania Craton forms the core of the Precambrian tectonic framework of eastern Africa and is flanked by several Proterozoic mobile belts (Figs. 1 and 2). To the south and southeast of the craton lie the Ubendian and Usagaran Belts, respectively (Lenoir et al., 1994; Theunissen et al., 1996). The eastern part of the Usagaran Belt and the Tanzania Craton is bordered by the Mozambique Belt, which covers much of the study area and is characterized by north-south

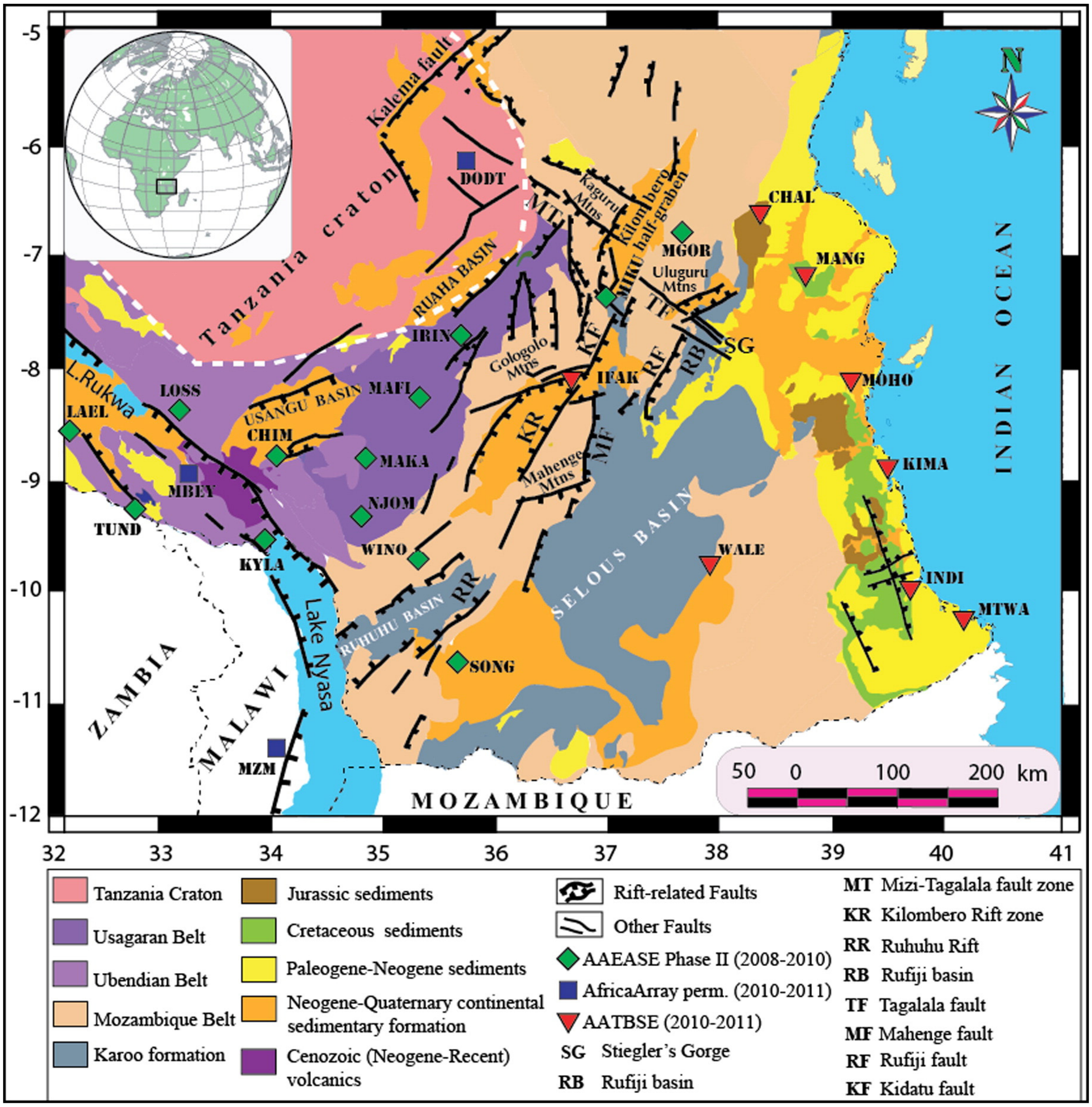

Fig. 2. Map showing the geology of the study area and the location of stations used. Geological features are from Le Gall et al. (2004) and Pinna et al. (2004). Major Karoo basins include KR, RR, RB, and the Selous Basin.

oriented structures formed from west-vergent thrusting onto the Tanzania Craton (e.g., Muhongo et al., 2001; Boger and Miller, 2004; Fritz et al., 2005; Tenczer et al., 2007).

The Precambrian tectonic framework has been affected by two major rifting episodes, Karoo (Permian–Jurassic) and the Cenozoic development of the East African rift system (Figs. 1 and 2). The Karoo rifting resulted in the formation of rift basins trending NE–SW (Fig. 2). In the study area, the Karoo rift basins are located within the Mozambique Belt and are mainly filled by alluvial deposits and sedimentary rocks of Permian and Triassic age (Wardlaw, 1999; Wopfner, 2002) (Fig. 2). To the north and west of the Karoo basins lies the Karoo border zone characterized by a series of faults separating the Karoo from the relatively uplifted basement of the Proterozoic Usagaran mobile Belt (e.g., Catuneanu et al., 2005). The dominant structural features in the study area are reflected by morphological features, some of which are believed to be active, associated with faults and topographic lineaments trending in sub N–S, NNE–SSW and NE–SW to NW–SE directions (Le Gall et al., 2004; Pinna et al., 2004) (Fig. 2). Some of the faults within the Karoo rift basins have been overprinted by younger Neogene to Holocene faults (Le Gall et al., 2004).

The Cenozoic EARS forms two branches, the Western branch and the Eastern branch (Fig. 1). The Western branch, which is more seismically active than the Eastern branch, is comprised of several en echelon fault-bounded rift basins, some of which have developed within or adjacent to Karoo rifts, resulting in the reactivation of some older Karoo faults (e.g., Chorowicz, 2005). The Eastern branch, which developed within the Mozambique Belt and partly along the eastern side of the Tanzania Craton, traverses from the Afar triple junction southward through Ethiopia, Kenya and Tanzania. Within central and southern Kenya, the Eastern branch forms a narrow, well-defined, 50- to 80-km-wide north-south oriented rift zone, but in northeastern Tanzania the rift structures diverge into a ~300-km-wide zone of block faulting (Dawson, 1992; Ebinger et al., 1997; Foster et al., 1997), forming three separate segments of normal faulting that define the Northern Tanzania Divergence Zone.

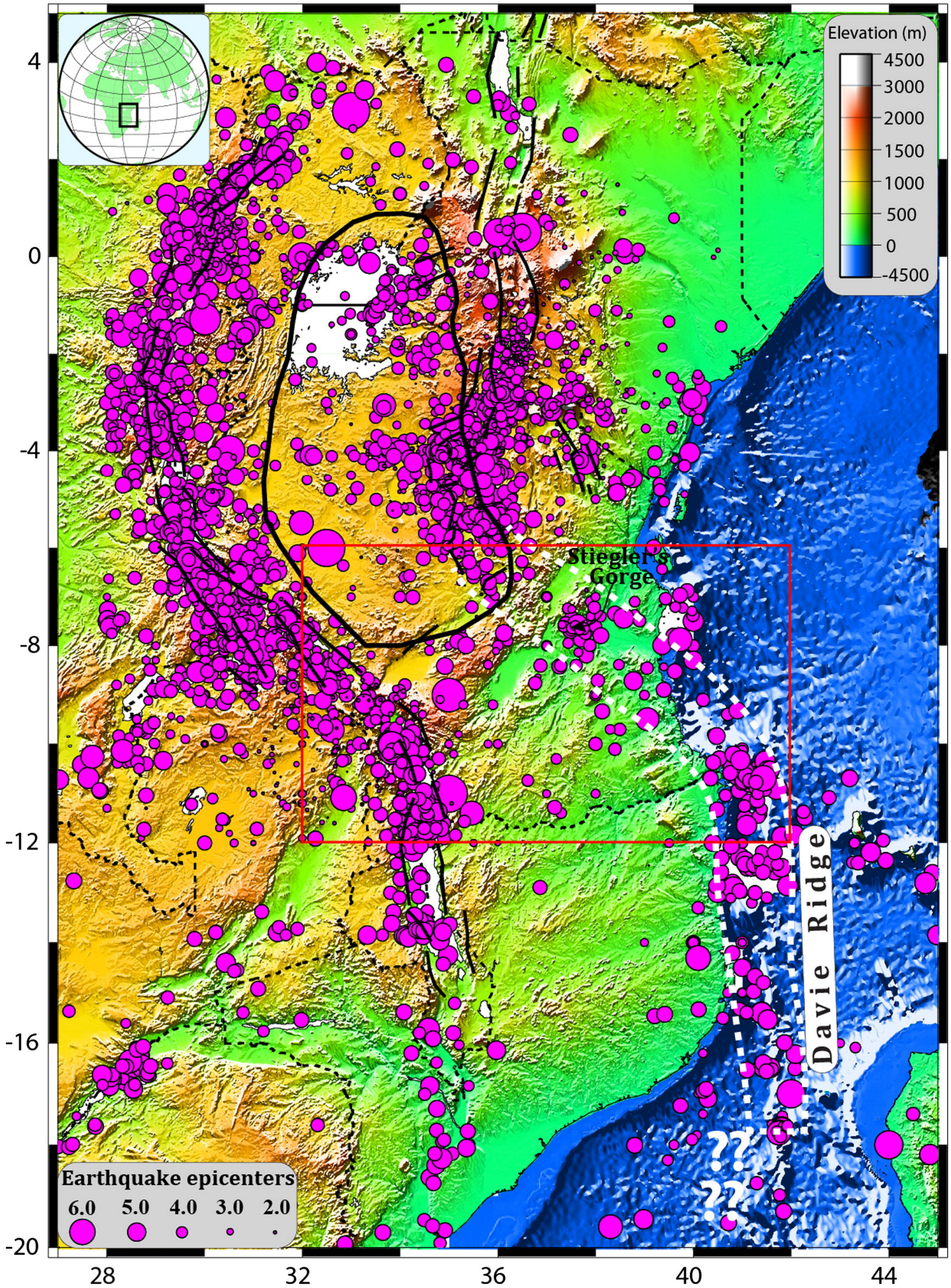

Fig. 3. Map showing seismicity (magnitude 2 to 6.5) for the East African rift system compiled from the International Seismological Center (ISC) catalogue for the period between 1900 and 2011. The white dashed outline shows the proposed propagation direction of the Eastern branch of the EARS. The geology is the same as in Fig. 1. The red box shows the region that is enlarged in Fig. 5. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

As mentioned previously, the three segments of the NTDZ include the Eyasi rift to the west, the Manyara rift in the middle, and the Pangani rift to the east (Ebinger et al., 1997; Foster et al., 1997) (Fig. 1). These segments are characterized largely by ~100-km-long and ~50-km-wide half graben structures bounded by distinct escarpments (Foster et al., 1997). The divergence of the rift in northern Tanzania may result from the presence of thick cratonic lithosphere extending beneath the Mozambique Belt (Ebinger et al., 1997; Tesha et al., 1997; Nyblade and Brazier, 2002). The Manyara and Pangani rifts form the boundaries of the Masai block, which is considered to have acted as a barrier to Cenozoic rifting (Ebinger et al., 1997) (Fig. 1).

Three interpretations have been proposed by O'Donnell et al. (2013); Le Gall et al. (2004); Mougenot et al. (1986) for the propagation of the Eastern branch away from the NTDZ. Using slip vectors from earthquakes along the coast of Tanzania and northern Mozambique and in the Lake Nyasa rift, Calais et al. (2006); Stamps et al. (2008);

Table 1
Velocity model used for event location from Langston et al. (2002).

Layer thickness (km)	P-wave Vel. (km/s)	S-wave Vel. (km/s)	Density (g/cm^3)
10	5.84	3.38	2.33
10	6.26	3.62	2.5
10	6.68	3.86	2.67
7	7.09	4.1	2.84
Half space	8.28	4.74	3.31

Fernandes et al. (2013) and Saria et al. (2013, 2014) proposed the existence of a Ruvuma (Rovuma) microplate extending across southeastern Tanzania and northern Mozambique that is rotating clockwise with respect to the Nubian Plate (Fig. 1). The northwestern boundary of the microplate was drawn along a belt of moderate seismicity and young faulting in the Usangu-Ruaha-Kilombero grabens (Le Gall et al., 2004; Ebinger, 2009) (Fig. 2). Using surface wave tomography, O'Donnell et al. (2013) imaged a low-velocity region in the upper mantle beneath southeastern Tanzania striking to the southeast of the NTDZ, suggesting a southeastwards propagation of the Eastern branch approximately coincident with the proposed location of the northern edge of the Ruvuma microplate (Fig. 1).

Le Gall et al. (2004), using detailed morphostructural interpretations of SRTM-DEM, remote sensing, aeromagnetic and geological data suggested that the Eastern branch south of the NTDZ propagates via the Manyara rift segment along the eastern margin of the Tanzania Craton and links with the Western branch at the northern end of the Lake Nyasa (also known as Lake Malawi) rift basin. They argued that rifting through southeastern Tanzania is accommodated on three related fault systems, the northwest-southeast striking Mizi-Tagalala transverse fault zone, Kilombero rift and the Ruhuhu rift (Figs. 1 and 2).

In contrast to the proposals by O'Donnell et al. (2013) and Le Gall et al. (2004); Mougenot et al. (1986), using seismic data from extensional basins offshore northern Tanzania, suggested that the Eastern branch does not extend into southeastern Tanzania and instead propagates along the Pangani rift across northeastern Tanzania (Fig. 1). This interpretation is similar to the O'Donnell et al. (2013) interpretation in that the Eastern branch connects offshore Tanzania to the Davie Ridge, but the Pangani rift lies well to the north of the low velocity zone in the upper mantle imaged by O'Donnell et al. (2013).

2.2. Seismicity and stress regimes

Seismicity maps of East Africa produced over the past few decades show that most of the seismicity is confined to the rift zones (Fig. 3) (e.g., Fairhead and Girdler, 1969; Wohlenberg, 1969; Bungum and Nnko, 1984; Shudofsky et al., 1987; Kebede and Kulhanek, 1991; Iranga, 1992; Nyblade et al., 1996; Langston et al., 1998). The highest seismicity rates in the Eastern branch occur in northern Tanzania, encompassing the Eyasi and Manyara rift segments. The seismicity pattern in southeastern Tanzania does not clearly demarcate the location of the rift (Fig. 3). A high number of small to moderate magnitude ($5.6 < m_b > 2.0$) earthquakes have been reported in southeastern Tanzania within the Stiegler's Gorge area of the Rufiji basin (Bungum and Nnko, 1984), and when combined with the seismicity in Fig. 3, suggests that the rift might be propagating to the southeast. However, there is also some seismicity along the southeastern margin of the Tanzania Craton suggesting that rifting might be continuing almost due south.

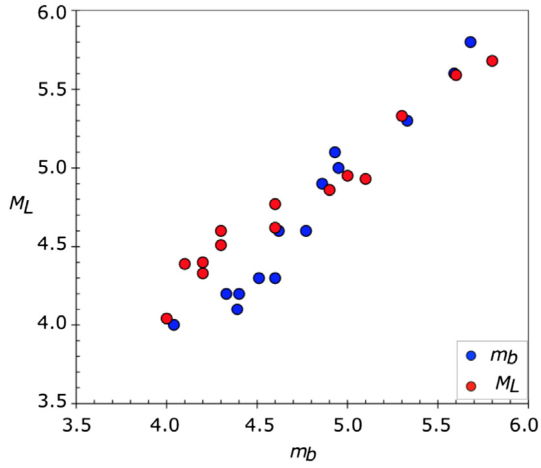

Fig. 4. A plot of m_b vs M_L for selected events.

Table 2
Comparison of M_L and m_b for selected moderate events.

Date			Time			Latitude	Longitude	m_b[a]	M_L
Year	Mon.	day	h	min	s	(°)	(°)		
2009	3	24	2	10	39	−11.63	34.56	4.0	4.0
2009	8	10	22	53	9	−10.43	34.37	4.6	4.6
2009	10	7	6	19	47	−7.00	35.97	4.2	4.3
2009	10	14	5	36	30	−10.90	34.38	4.1	4.4
2009	11	5	4	9	5	−9.84	33.90	4.3	4.5
2009	11	8	17	12	47	−8.86	32.88	4.2	4.4
2009	12	6	17	35	0	−9.91	33.89	5.6	5.6
2009	12	6	18	27	40	−9.83	33.91	5.1	4.9
2009	12	7	18	14	57	−9.88	33.82	5.0	5.0
2009	12	8	3	7	20	−9.91	33.80	5.8	5.7
2009	12	12	2	25	27	−9.77	33.86	5.3	5.3
2010	2	13	15	19	11	−10.75	33.69	4.6	4.8
2010	4	26	11	53	48	−5.36	35.82	4.9	4.9
2011	3	8	20	30	35	−11.50	34.50	4.3	4.6

[a] m_b is from the ISC catalogue.

Studies of the depth distribution of seismicity within the East African rift, including the southeastern extent of the Manyara rift segment, have reported events throughout the upper and lower crust (e.g., Bungum and Nnko, 1984; Shudofsky et al., 1987; Nyblade and Langston, 1995; Foster and Jackson, 1998; Langston et al., 1998). Well-constrained focal depths from waveform analyses using teleseismic and regional data for events in the Eastern branch show nucleation depths extending down to 30–40 km in northern Tanzania (Nyblade and Langston, 1995; Foster and Jackson, 1998; Mulibo and Nyblade, 2009; Albaric et al., 2009; Yang and Chen, 2010), and 15 km in central Tanzania (Mulibo and Nyblade, 2009; Craig et al., 2011).

Focal mechanisms have been used in many studies to investigate the stress regime in the EARS. Results for the Eastern branch suggest extension directions either E–W, roughly perpendicular to the EARS trend (Fairhead and Stuart, 1982; Delvaux and Barth, 2010) or NW–SE, somewhat oblique to the EARS trend (Strecker et al., 1990). In northern and central Tanzania, focal mechanisms show a range of stress orientations including NNW–SSE, NE–SW, NW–SE, and sub E–W (Bungum and Nnko, 1984; Shudofsky, 1985; Brazier et al., 2005; Macheyeki et al., 2008; Mulibo and Nyblade, 2009). The focal mechanisms to the southeast offshore eastern Tanzania and along the Davie Ridge indicate normal faulting with E–W, N–S or NW–SE extension (Grimison and Chen, 1988; Yang and Chen, 2010; Craig et al., 2011). Bathymetric features indicate that the deformation is spread over a broad region (Chen and Grimison, 1989).

3. Data and methodology

3.1. Data

This study uses broadband seismic data from temporary and permanent networks in Tanzania operated under the AfricaArray program (Figs. 1 and 2). The stations were equipped with 24-bit Reftek data recorders, Streckeisen STS-2 or Guralp 3T, ESP and 40T broadband seismometers, and GPS clocks. Three component data were recorded

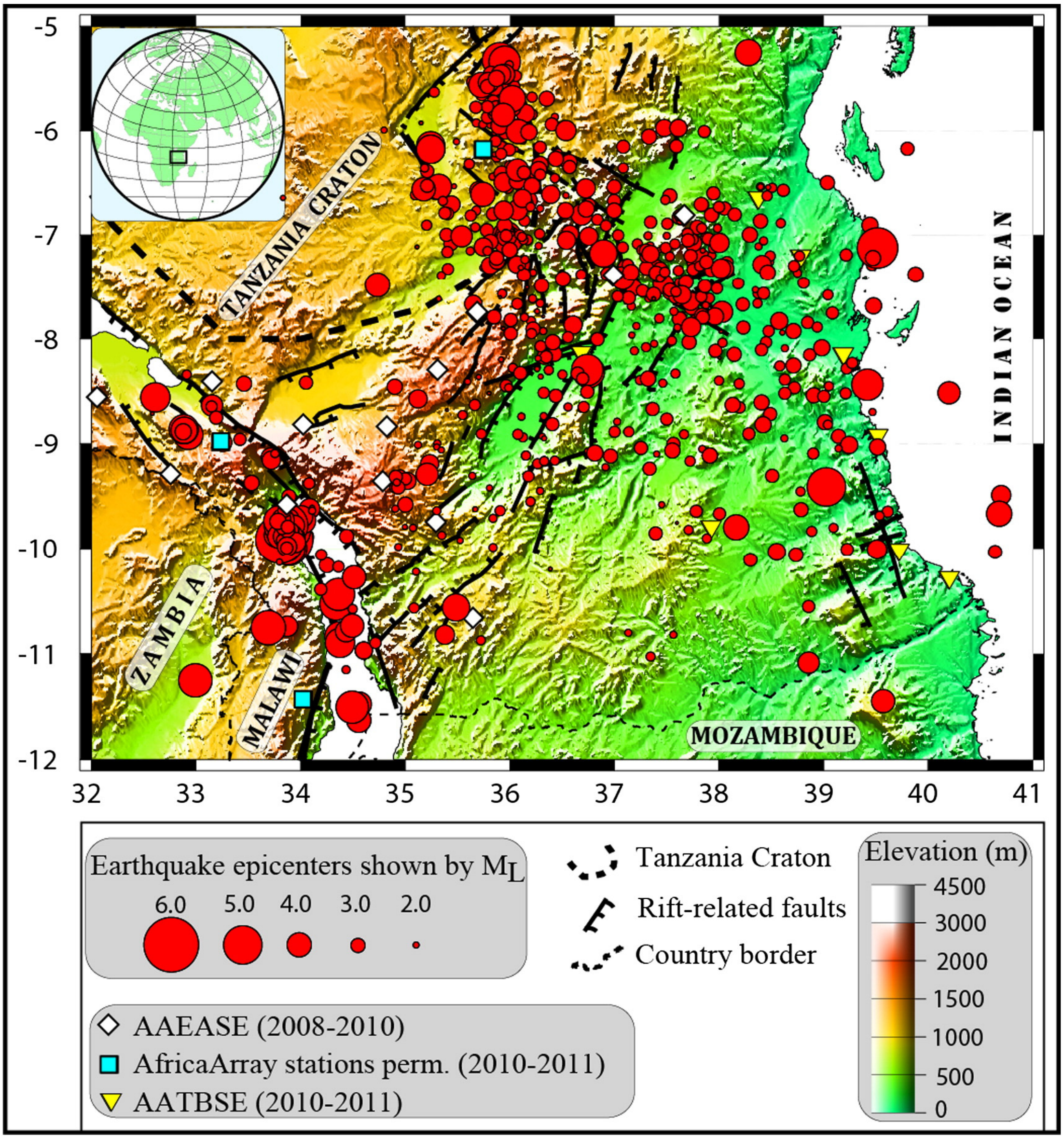

Fig. 5. Map showing seismicity in southeastern Tanzania located in this study. The geology is the same as in Fig. 2.

continuously at 40 samples per second. The data used are from two overlapping temporary deployments, each running for a 1.5-year period. The first deployment consisted of 20 stations of the AfricaArray eastern Africa broadband seismic experiment (AAEASE), deployed in southwestern and southeastern Tanzania from January 2009 to July 2010. The second deployment consisted of 8 stations of the AfricaArray Tanzania basin seismic experiment (AATBSE), installed from February 2010 to July 2011 in southeastern Tanzania and along the coast (Figs. 1 and 2). The overlapping time window between the two deployments is 6 months. Most of the data used in this study are from the overlapping time period and from the year after the demobilization of the first deployment. Data from permanent AfricaArray stations within the study area also have been used (Fig. 1). A listing of stations used is provided in the supplemental material.

3.2. Earthquake location

The arrival times of P-waves clearly recorded by 4 or more stations were hand picked for use in event location. All data were filtered using a Butterworth 1–5 Hz band-pass filter prior to picking arrival times. The uncertainty in visually picking the P arrivals is ~0.1 s. S arrival times were not used in the location process, as it was difficult to pick them on most of the records due to their low signal to noise ratio. The P-wave picks that resulted in residuals between 1.0 s and 1.5 s were down weighted by 50 to 75% in the location algorithm, while those with residuals greater than 1.5 s were not used. Events with an average P travel time residual of ≤1.0 s were kept for interpretation.

An absolute earthquake location code, HYPOELLIPSE, was used to locate the events (Lahr, 1999). The location algorithm in HYPOELLIPSE is based on the minimization of the root mean square (RMS) residuals obtained from phase arrival times (Lahr, 1999). The technique involves an iterative process, which minimizes the change in observed and calculated arrival times using a least squares approach. Uncertainty in the event locations obtained arises primarily from picking arrival times and the velocity model. A 1D regional velocity model from Langston et al. (2002), which is an average model for Precambrian terrains in Tanzania, was used in the location procedure (Table 1). The 90% confidence error ellipses obtained from the location procedure indicate that uncertainties in epicentral locations do not exceed 5 km and that uncertainties in the source depth do not exceed 5 km.

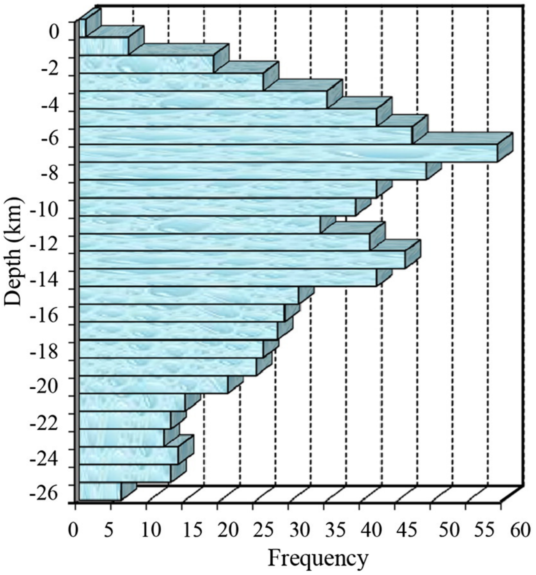

Fig. 6. Depth distribution of seismicity plotted on histogram for events located in this study.

3.3. Magnitude computation

Horizontal component waveforms were used to calculate local magnitude (M_L) for each event. This was done by using the maximum amplitudes on the horizontal components with the local magnitude scale developed for East Africa by Langston et al. (1998). Before reading the amplitudes, the instrument responses of the seismometers were removed and replaced with the response of a Wood–Anderson seismometer (Kanamori and Jennings, 1978). The displacement ground motions on the Wood–Anderson torsion seismograph were then used to determine the coefficients of the empirical formula as given in the Richter (1935, 1958) M_L relation below:

$$M_L = \log A - \log A_0 + S \quad (1)$$

where *A* is the maximum signal amplitude of the horizontal seismogram, and *S* denotes the coefficient for the empirical station correction. A_0 represents the distance correction which is given by Hutton and Boore (1987) below, defined such that an earthquake of $M_L = 3.0$ contains a peak amplitude of 1 mm at an epicentral distance of 100 km.

$$-\log A_0 = n \log (r/100) + K(r-100) + 3.0 \quad (2)$$

n and *K* are parameters related to the geometrical spreading and anelastic attenuation, and *r* is the hypocentral distance in kilometers.

The distance and station corrections used in computing M_L come from the local magnitude scale developed for East Africa using data recorded by the Tanzania broadband seismic experiment in 1994–1995 (Langston et al., 1998). The distance correction is defined as

$$-\log A_0 = 0.776 \log(r/17) + 0.000902(r-17) + 2.0. \quad (3)$$

The station corrections from the 1994–1995 deployment in Tanzania (Langston et al., 1998) were small (0.007–0.068), and therefore an average of these corrections (0.04) was adopted for use in this study. Using the average station correction to recompute the M_L for the 1994–1995 events yielded on average a difference in the magnitudes of only 0.025. Comparing the M_L with m_b listed in the PDE catalogue for some moderate events (Table 2; Fig. 4) yields a difference in the range of 0.01 to 0.3.

3.4. Focal mechanisms

Focal mechanisms have been computed for selected events along the proposed boundary between the Victoria and Ruvuma microplates in southeastern Tanzania. Moderate sized events ($M_L \geq 4.0$) and smaller events with magnitude $M_L \geq 2.9$ that showed clear first-motion P polarities were used. Fault plane solutions were computed using the first-motion P polarities and the FOCMEC program (Snoke, 2003). The program performs a grid search for all combinations of strike, dip and rake to find all sets of nodal planes that match a given set of phase polarities. We only used P-polarities, along with an increment of 2°, in the grid search. A total of 20 events were analyzed, and focal mechanisms for 15 events were obtained for which variations in the strike, dip and rake for all the solutions obtained was ≤10°. The average solution for these 15 events are reported and used in our interpretation.

4. Results

4.1. Seismicity and depth distribution

A total of 763 events across southeastern Tanzania were located and are shown in Fig. 5 (see supplementary material for event catalog). Most of the events have a magnitude between $M_L = 5.0$ and $M_L = 2.0$. Of the 763 events, 67 events can be found in either the National Earthquake International Center (NEIC) or International Seismological Center (ISC) catalogues. Twenty-seven events appear in both catalogues. Most of the events appearing in NEIC and ISC catalogues are located in the Lake Nyasa Rift and are aftershocks of the 19 December 2009 Karonga event (m_b 6.0).

The spatial distribution of the events in the region shows that the events are distributed throughout southeastern Tanzania but concentrated (1) along the southeastern margin of the Tanzania Craton, and (2) in a region extending from the southeastern end of the craton through Stiegler's Gorge towards the coast. Limited seismicity is observed in a region extending from Stiegler's Gorge to the southwest (Fig. 5). The temporal distribution of the events does not show any correlation within the region, and the pattern of seismicity during the entire recording period is distributed along the entire length of the study area. Given the similar spacing between the seismic stations used for this study compared to the network used by Langston et al. (1998), the spatial distribution of seismicity shown in Fig. 5 largely reflects the distribution of events larger than about magnitude 2 to 2.5.

Most of the seismicity occurs along or near to mapped faults (Fig. 5). The seismicity along the margin of the Tanzania Craton is located in an area with sub NE–SW and NW–SE fault orientations (Figs. 2 and 5). Southeast of the craton, ~75% of the seismicity follows a southeastward pattern into the Stiegler's Gorge area and then continues towards the coast. From the southeastern corner of the craton and from Stiegler's Gorge, a lesser amount (~25%) of seismicity is found to the south and southwest, towards Lake Nyasa. The depth distribution of the events is shown in Fig. 6. The numbers of earthquakes decrease with depth, and approximately 75% of the hypocenters are shallower than 15 km depth. On a larger scale, the combined seismicity from this study and events from the ISC from between 1900 and 2011 shows that the seismicity pattern in the Manyara segment of the Eastern branch extends from the southeastern margin of the craton in a southeasterly direction towards the coast (Fig. 7).

4.2. Focal mechanisms

Focal mechanisms with nodal planes obtained by averaging the full range of solutions obtained from the grid search are given in Table 3 and shown in Fig. 7. The full range of solutions along with first motion P-wave polarities are shown in Fig. 8. The mechanisms along the

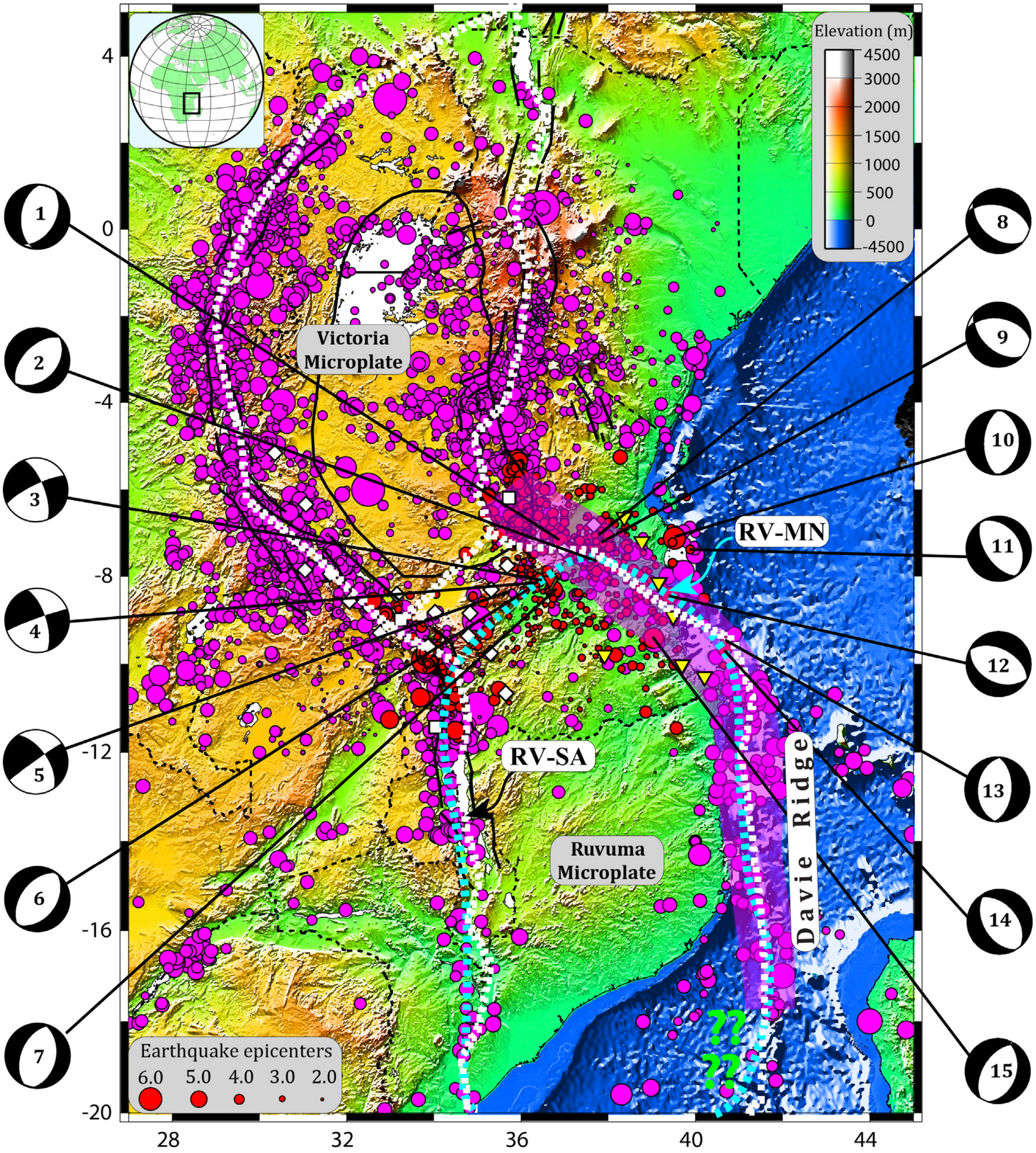

Fig. 7. Map showing seismicity (magnitude 2 to 6.5) for the East African rift system located in this study (red circles) and those compiled from the International Seismological Center (ISC) catalogue for the period between 1900 and 2011 (pink circles). White dashed line (RV-SA) shows the Ruvuma microplate boundary from Saria et al. (2013). Magenta line (RV-MN) indicates a new proposed boundary for the Ruvuma microplate from this study. The transparent outline shows the proposed propagation of the Eastern branch of the EARS along the northern boundary of the Ruvuma microplate. The geology is the same as in Fig. 1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

boundary between the Victoria and Ruvuma microplates show a combination of normal and strike slip faulting. The normal faulting occurs along fault planes striking in sub north to northeast and southwest directions, whereas the strike slip mechanisms are consistent with sinistral motion and the clockwise rotation of the Ruvuma microplate (Calais et al., 2006; Stamps et al., 2008; Saria et al., 2013, 2014). The mechanisms offshore southeastern Tanzania show predominantly normal faulting (Fig. 7). The nodal planes in this region strike north-south to northwest-southeast, with extension in sub east-west to northeast-southwest directions.

5. Discussion

In summary, the two main findings from the seismicity pattern are; (1) most of the seismicity along the eastern margin of the craton extends from ~6–7° S to the southeast through Stiegler's Gorge towards the coast and (2) there is a more limited amount of seismicity along the southeast corner of the craton extending towards Lake Nyasa. The depth distribution of the seismicity shows a peak at 7 km depth with events occurring as deep as ~25 km (Fig. 6). Focal mechanisms from selected events along the boundary between the

Table 3
Focal mechanisms solutions for selected events.

	Date			Time			Latitude	Longitude	Depth	M_L	Focal mechanism		
No.	year	mon	day	h	min	s	(°)	(°)	(km)		Strike (°)	Dip (°)	Rake (°)
1	2011	6	5	0	18	29	−7.1751	36.8990	2.40	4.3	29.98	43.37	−72.38
2	2010	6	19	9	1	3	−7.6197	37.7018	6.40	3.5	224.00	53.00	−90.00
3	2010	6	20	0	37	57	−8.1383	36.4304	10.30	3.2	243.62	77.80	−21.99
4	2010	7	10	14	31	53	−8.1699	36.3523	19.50	3.0	249.98	85.34	−22.55
5	2010	7	5	23	32	20	−8.3635	35.7074	13.50	3.0	234.33	87.50	−29.91
6	2010	6	17	12	54	1	−8.3247	36.1045	8.60	2.9	217.00	49.00	−90.00
7	2009	11	29	17	19	51	−8.3124	36.7592	17.00	4.5	202.43	48.28	−81.95
8	2009	9	10	11	24	23	−7.0712	37.7563	8.50	3.3	131.22	44.71	−70.02
9	2009	8	27	18	7	34	−7.2376	37.8101	7.60	4.0	132.72	48.65	−65.69
10	2011	6	10	8	27	5	−7.1187	39.5190	6.70	5.2	182.00	55.00	−90.00
11	2010	3	6	15	52	12	−7.3766	39.8810	17.70	3.2	327.00	34.00	−90.00
12	2011	3	25	10	3	13	−8.4349	39.4224	21.40	4.6	296.67	49.00	−90.00
13	2010	5	17	5	24	57	−9.4869	40.7001	14.30	3.5	170.37	40.37	−79.86
14	2011	5	25	5	18	36	−9.6606	40.6800	9.10	4.1	150.67	46.30	−81.69
15	2010	8	3	19	40	37	−9.4062	39.0320	7.30	5.0	212.66	51.41	−90.00

Victoria and Ruvuma microplates show a combination of normal and strike slip motion.

The depth distribution of earthquakes obtained in this study is comparable to many previous studies in East Africa. As noted briefly in the background section, the maximum depth of ~25 km with a peak at 7 km depth is similar to previous studies, which show a range of source depths including many events that have nucleated within both the upper and lower crust (Shudofsky et al., 1987; Nyblade and Langston, 1995; Zhao et al., 1997; Foster and Jackson, 1998; Langston et al., 1998; Camelbeeck and Iranga, 1996; Brazier et al., 2005; Mulibo and Nyblade, 2009; Tugume and Nyblade, 2009). Thus, the depth distribution of seismicity obtained in this study is not unprecedented.

What are the implications of these findings for the propagation of the Eastern branch of the EARS and the sense of motion along the boundary between the Victoria and Ruvuma microplates? The Manyara rift segment is where the Eastern branch in northern Tanzania is most active seismically. The seismicity in this segment extends along the craton to ~6–7° S. South of this point, most of the seismicity occurs in a region striking to the southeast, with only ~25% of seismicity extending to the south (Figs. 5 and 7). Based on these results, the seismicity associated with the Manyara rift segment indicates that the Eastern branch likely extends to the southeast towards the coast. This finding is in agreement with the tomography model of O'Donnell et al. (2013), which also suggests a southeasterly trend to the Eastern branch in Tanzania.

As mentioned previously, recent plate kinematic studies (Calais et al., 2006; Stamps et al., 2008; Saria et al., 2013, 2014) identify a microplate, the Ruvuma microplate (model RV-SA; Fig. 7), located in southeastern Tanzania and northern Mozambique that is rotating clockwise with respect to Nubia at an angular velocity of 0.118 deg/My. The seismicity pattern observed in this study is generally consistent with the location of the northern boundary of the Ruvuma microplate (Fig. 7), suggesting that the Eastern branch is propagating to the southeast along the northern boundary of the microplate. The northwestern boundary of the Ruvuma microplate is also generally consistent with the seismicity pattern, but it could be shifted slightly to the southeast to align better with the locus of seismicity (model RV-MN, Fig. 7).

The focal mechanisms for selected events along the boundary between the Victoria and the Ruvuma microplates are also consistent with the proposed Ruvuma microplate motion. Results from focal mechanisms show a combination of normal faulting and strike slip motion consistent with the clockwise rotation of the Ruvuma microplate (Calais et al., 2006; Stamps et al., 2008; Saria et al., 2013, 2014). The combination of a strike-slip component of movement and normal faulting indicates that the boundary between the Victoria and Ruvuma plate is extensional with some sinistral motion. The normal faulting mechanisms in this region are also consistent with mapped faults (Le Gall et al., 2004).

This interpretation of the seismicity pattern and propagation direction of the Eastern branch is different from the interpretations proposed by Le Gall et al. (2004) and Mougenot et al. (1986). As reviewed previously, Le Gall et al. (2004) proposed a structural connection between Western and Eastern branches of EARS south of the Tanzania Craton via a fault system that includes the Mamizi, Kilombero, and Ruhuhu rifts (Fig. 1). While some seismicity occurs in that region, as is shown in this and previous studies (see Fig. 3), the region is not as seismically active as the area identified in this study along the northern margin of the Ruvuma microplate, at least within the time period of the data used in this study. In other words, the structural linkage between the Eastern and Western branches proposed by Le Gall et al. (2004) does not appear to be as seismically active as the northern margin of the Ruvuma microplate. While extension could be progressing in both a southerly and a southeasterly direction from the Manyara rift segment in the NTDZ, the results of this study suggest that the main direction of rift propagation is to the southeast along the northern boundary of the Ruvuma microplate. With regard to the Mougenot et al. (1986) interpretation, a similar conclusion can be reached, as Fig. 7 shows considerably more seismicity along the northern boundary of the Ruvuma microplate in southeastern Tanzania than in northeastern Tanzania along the Pangani rift.

6. Summary

From our analyses, it has been found that ~75% of the seismicity follows a southeasterly trend from the southern end of the Manyara rift segment in the NTDZ along the southeastern corner of the Tanzania Craton, continuing through Stiegler's Gorge towards the coast. In contrast, a lesser amount of seismicity (~25%) occurs in a southerly direction towards Lake Nyasa. This finding suggests that the Eastern branch of the EARS is propagating mainly to the southeast from the Manyara rift, probably along the northern boundary of the Ruvuma microplate. However, the possibility of a zone of extension developing to the south towards Lake Nyasa (Malawi) cannot be ruled out, especially given the short-term deployment of seismic stations used in this study. Focal mechanisms along the boundary between the Victoria and the Ruvuma microplates show a combination of normal faulting and strike slip motion indicating extension with a sinistral component of motion, consistent with mapped geologic faults and the clockwise rotation of the Ruvuma microplate.

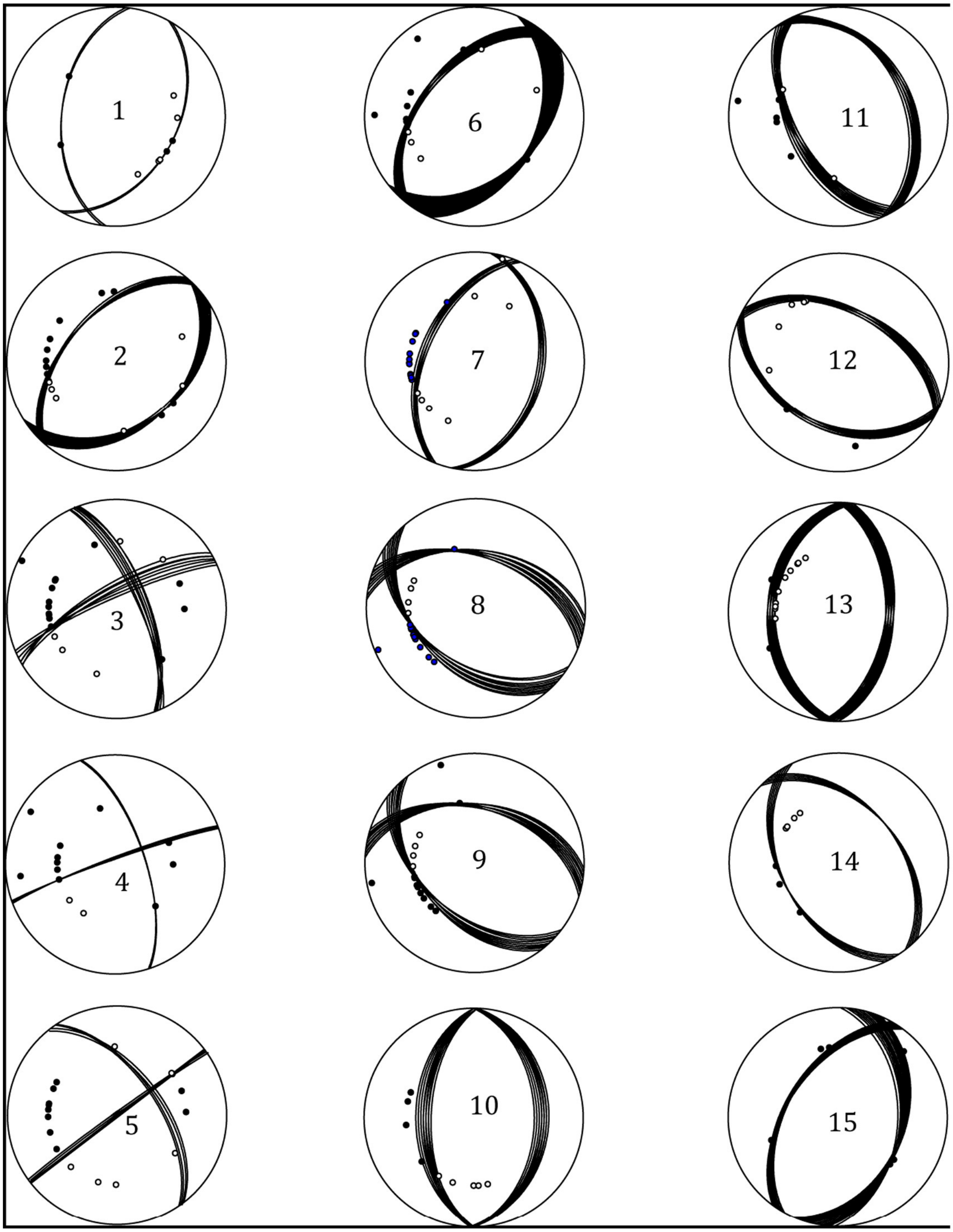

Fig. 8. Focal mechanisms solution from first motion P-wave polarities. The black circles show compressional first motions and open circles indicate dilatational first motions. Event numbers correspond to those given in Fig. 7 and Table 3.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.tecto.2016.02.009.

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