Seismotectonic analysis of the Anker area, Kunene region north-western Namibia

M. Sitali · B. Manzunzu · V. Midzi · S. Shipena ·
B. Lushetile

Received: 27 October 2020 / Accepted: 21 January 2022 / Published online: 22 February 2022
© The Author(s) 2022

Abstract Recently, a swarm of seismic events occurred within the Kunene region (NW of Namibia) with magnitude values going up to M_L 4.6. Some of the events alarmed the Anker community and have become of national interest. In order to understand the source of this seismic activity, the Geological Survey of Namibia (GSN) and the Council for Geoscience (CGS) of South Africa installed a temporary network of 10 seismic stations in the Anker area to monitor seismicity for a period of 3 months from 20 June to 24 September 2018. More than 1600 micro-seismic events were recorded and located within

the boundaries of the array, which was roughly 50 km×50 km. The stations were installed in a 50 km×50 km radius to have an accurate overlap of the network coverage and also by the spatial distribution of the known seismicity in the study area. The magnitude of the events ranged from M_L – 1.1 to 3.6 and occurred at depths of less than 20 km. To improve the location of earthquakes, a new velocity model was developed using high-quality seismic dataset recorded by the temporary network. The seismic data was used to determine a minimum 1-D velocity model, which was used for the relocation of the earthquakes using the double difference method. The relocated solutions provided information to explain the seismotectonics of the region and establish the source of the current seismic swarm. Lineaments were mapped using magnetic data to identify the sources of the seismicity. Focal mechanism analysis of some of the events indicates the area is highly faulted with predominantly normal faulting.

Highlights

- The study aimed at determining the cause of the sudden earthquake occurrence in Anker.
- The 2018 seismic swarm in Anker area is the first to be ever recorded in the Namibian seismology.
- The recorded earthquake's cluster aligns in the same direction as the regional tectonic structure (Kaoko Belt).
- The study area is dominated by normal faulting. Findings from the study indicate that the area falls under a stable continental region (SCR).
- The experienced seismic activity in the area is believed to be linked to a reactivation of pre-stressed faults.

M. Sitali (✉) · S. Shipena · B. Lushetile
Geological Survey of Namibia, Windhoek, Namibia,
South Africa
e-mail: Mako.Sitali@mme.gov.na

B. Manzunzu · V. Midzi
Engineering and GeoHazards Unit, Council
for Geoscience, Pretoria, South Africa

Keywords Anker · Seismicity · Temporary network · Seismic swarm · Namibia

1 Introduction

The occurrence of intraplate earthquakes has been a major concern for seismic hazard analysis studies (e.g. Gupta and Johnston 1998; Calais et al. 2016; Manzunzu et al. 2017; Allen, 2020; Labidi

et al. 2021). Of late, a number of these events have occurred in areas that have not shown any sign of stress transfer (e.g. Midzi et al. 2018; Calais et al. 2016). Of note is the 2006 Machaze earthquake which occurred in Mozambique and ruptured a 60 km surface fault and the 2017 Botswana earthquake which occurred in an area that had no history of seismic occurrence. These events pose a major challenge to the estimation of seismic hazard for a region (Labidi et al. 2021). It has been suggested that major earthquakes in SCR regions may not only depend on a long-term tectonic loading under a regional, essentially time invariant, tectonic stress field, but instead they can also be determined by small transient stress changes in a crust close to failure equilibrium (Calais et al. 2016). The background tectonic stress field in the lithosphere has been observed to be effectively modulated by very small stress changes and strain rates ~ 100 Pa/year (100 times less than plate motion rates). Their driving mechanism may also be attributed to external, non-tectonic origin thereby triggering some localised earthquakes (Luttrell et al. 2007; Luttrell and Sandwell, 2010). Regardless of the specific transient stress change that brings a fault to failure, the resulting rupture mechanism will however be consistent with the regional tectonic stress field as was observed in many other studies (e.g. Manzunzu et al. 2017; Midzi et al. 2018).

Seismicity in Namibia is generally low with exceptional moderate magnitude events that occur occasionally (Mangongolo and Hutchins, 2008). The recent occurrence of five moderate earthquakes recorded by the Namibian Seismological Network with magnitudes ($4.0 < M_L < 4.6$) in May 2018 in the Anker area, north-western Namibia raised concerns on the possible source of seismic events, whether the events could be precursors to a major earthquake, and their impact on the community. However, the region has limited both seismic stations and detailed geological information to identify the causative source of these events. At the time of the study, there was no functional seismic station in the Kunene region and generally, there is insufficient earthquake records in Namibia to determine the source of the seismic swarm. The events were felt widely around the epicentral region and were recorded by a network of permanent stations monitored by the Geological Survey of Namibia (GSN) as well as other regional stations.

Seismic swarms have been observed to occur differently in terms of the extent and intensity of occurrence (Llenos et al. 2009; Hill et al. 1975; Smith et al. 2004; Hainzl and Ogata, 2005). The occurrence of seismic swarms is often associated with response to fault creep, fluid or magmatic events (Hill et al. 1975; Smith et al. 2004; Hainzl and Ogata, 2005; McGuire et al. 2005; Vidale and Shearer, 2006; Vidale et al. 2006), and has been exploited for evaluating earthquake triggering models in magmatically dominated environments (e.g. Dieterich et al. 2000; Toda et al. 2002). Analysis of seismic swarms requires a dedicated local high-density network capable of picking up even the smallest events that are due to micro stress transfer. In many cases, a general extent of the causative source is known and the network configuration is such that it covers the extent of the source. However, in regions like Anker where faults are not well mapped and their activity is not known, it is difficult to associate seismic swarms with specific faults. In 2018, the GSN and the Council for Geoscience (CGS) installed a temporary network of seismic stations to monitor the seismic swarm to help model the seismotectonics of the area. This knowledge is useful in seismic hazard studies as well as for decision-making. In this study, we present accurately located seismic events of the Anker seismic swarm recorded by a temporary network of seismic stations. Focal mechanism solutions are determined for selected good quality events. The results were used in modelling the seismotectonics of the region. In comparison to events of similar nature in other regions, we discuss the results of this study including the fault rupture geometry in the stable continental region (SCR) context, bearing in mind the possible seismic hazard implications.

2 Geology of the study region

Large areas of the Namibian geology exposed onshore are associated with the Late Proterozoic Pan-African orogenic cycle (Miller, 1983; Porada, 1989; Gray et al. 2006). The origin of orogenic systems of northern Namibia is connected to the break-up of Gondwana during the Late Proterozoic and Early Phanerozoic (Prave, 1996; Trompette, 1997). It forms part of the much larger Pan-African orogenic system that surrounds and transects the African continent

(Porada, 1989). The conclusions of many studies on geodynamic models have been proposed for the intracontinental branch of the Pan-African Damara Orogen which assumes subduction processes of either continental or ocean floor. The study area is situated within the triple junction and Neoproterozoic rocks of the Pan-African Kaoko and Damara mobile belts as well as the Congo Craton (Fig. 1) mainly dominates its geology. Due to the collisional suture between the Congo and the Kalahari cratons that is associated with rifting which the intracontinental Damara Belt represents, makes the geology as well as the faulting system complex and hence tectonic stress changes

might also be taking place although at a very slow rate typical of intracontinental regions. The mobile belts evolved through successive phases of intracontinental rifting, spreading and subduction as well as deformation that is characterised by open folding which decreases in intensity towards the north and east (Miller, 2008). The intracontinental Damara belt represents the collisional suture between the Congo and Kalahari cratons and chronicles a complete history from rifting and associated rift sedimentation and volcanism, via an oceanic stage and marine sedimentation through to convergence and final collision (Miller, 1983; Porada, 1989; Gray et al. 2006). Major

Fig. 1 Simplified geological map of north Namibia showing the major tectonic units. The Epupa complex (EC), the Kamanjab Inlier (KI) and the Grootfontein Inlier (GI) occur along

the margin of the Congo Craton (marked by the stippled line). TTM, Tsumkwe–Tarikora Massif; AI, Abbabis Inlier; RSI, Rehoboth Sinclair Inlier (After Miller 1983; Gray et al., 2006)

structures show predominantly two trends associated with the Damara (SW-NE trend) and the Kaoko mobile belts (NNW-SSE trend) many of which have been reactivated (Miller, 1983; Wanke, et al. 2000). The Kaoko mobile belt is a sinistral transpressional belt that is characterised by prominent sets of NNW-SSE striking, westerly dipping normal faults, with a down to the west sense of displacement (Durr and Dingeldey 1996; Maloof 2000; Passchier et al. 2002; Goscombe et al. 2003a,b), whereas the Damara belt is a divergent orogen that formed during high-angle convergence between the Congo and Kalahari cratons (Miller, 1983; Porada et al. 1983). The junction between the southern Kaoko belt and the Damara belt is the distinctive Ugab Zone with complex fold interference (Coward, 1983; Porada et al. 1983; Maloof, 2000; Passchier et al. 2002; Goscombe et al. 2004). The Congo Craton is composed of the Kamanjab Inlier, in the Kunene region, the Epupa complex and

Grootfontein Inlier (Fig. 1), the three units are composed of metasedimentary sequence and volcanic intrusive granites and gneiss (Frets 1969; Porada, 1974; Becker 2006a, b, c; Miller, 2008).

3 The Kunene earthquake swarm

Seismicity in Namibia is generally low with a few isolated events within known seismogenic zones as delineated by Mangongolo and Hutchins (2008). In their findings, the Kamanjab region is not mentioned and this may be due to lack of seismic data at the time. However, of late, the region has shown some increase in seismicity that has caused a scare to the general population. In order to fully understand a seismic sequence, a network of seismic stations that can locate as many events as possible is needed close to the epicentral area, using the right configuration

Fig. 2 Location map of Anker temporary seismic stations (red dots) covering a rectangular area of approximately 50 km × 50 km

to constrain the location and focal mechanism solutions. This is because the accurate location of seismic events is controlled by the network geometry, available phases, arrival-time reading, suitable knowledge on the crustal structure and related velocity model (Pavlis, 1986; Gomberg et al. 1990; Waldhauser and Ellsworth, 2000). The Anker community reported an increase in frequency of seismic events that were felt since the beginning of 2018. In order to understand the source of these seismic swarms, the GSN and the CGS of South Africa installed a temporary network of 10 seismic stations to monitor the events for 3 months from 20 June to 24 September 2018 (Fig. 2). The seismometers used during the experiment were Trillium Compact 120s sensors.

More than 1600 microseismic events were recorded and located within the boundaries of the array roughly 50 km × 50 km (Fig. 3). The recorded data were analysed using the SEISAN software (Ottemöller et al.

2018) to determine the source parameters. The local magnitude scale developed by Saunders et al. (2013) for South Africa was used because it is the same scale that is currently being used by the GSN for magnitude determination in Namibia. The magnitude of the events ranges from -1.1 to $3.6 M_L$ with depth reaching up to 15 km. The map (Fig. 3) shows two clusters of seismicity with a general directional trend of NW–SE although there is a slight distinction between the upper and the lower clusters. The upper cluster is trending NNW–SSE and the lower cluster is trending in a more NW–SE and it is diffusely distributed (Fig. 4). The upper seismic cluster follows the direction of regional tectonic structures of the Kaoko mobile belt. The majority of lineaments from the magnetic data (Fig. 4) indicate lineaments in the same direction, which may be an indication that these deep sitting faults maybe unstable hence resulting in an increase in microseismicity in the study area.

Fig. 3 Map showing the seismic events in the Anker area from the temporary seismic network. Also shown are the known lineaments and structures obtained from the interpretation of aeromagnetic data

4 Development of the local velocity model

Due to the limited number of seismic events recorded in Namibia, there is no locally developed velocity model for use in earthquake location. Rather, routine location at the GSN uses the Midzi et al. (2010) model developed for South Africa. However, for this study, because of the localised nature of the hypocentral distances for the analysed earthquakes, it was decided to recompute a new local 1-D velocity model in order to improve the earthquake locations. The computation of the local velocity model was conducted through a travel time inversion process that is implemented in the VELEST software (Kissling et al. 1994) using the data collected from the temporary network of stations. The program performs a simultaneous inversion for both velocity and hypocenter parameters by calculating a minimum 1-D velocity model which represents

the least squares solution of the travel time residuals (Ellsworth, 1977; Kissling et al. 1994, 1995).

A selected high-quality seismic dataset was used for the velocity model inversion and to ensure accuracy in the results, only events located by at least eight stations were selected for processing. A modified version of the model by Midzi et al. (2010), which is currently being used in the analysis of data by the GSN, was used as the starting model. The model was modified by changing the thicknesses of the layers in the upper crust to about 2 km, whilst those in the lower crust were set at about 4 to 5 km. This was done to try to resolve optimum layer thicknesses, since the inversion is only done for the velocities and not for layer thickness. Smaller layer thickness values were selected for the upper crust because layer velocities vary more than in the lower crust. The starting model was iteratively refined to establish a reliable model geometry and velocity intervals in preparation

Fig. 4 Map showing magnetic lineaments in the Kamanjab sheet, enclosing the Anker area indicated with a black star

for an updated a priori 1-D velocity model which was then used as the initial model for the final inversion process. In the final inversion process, travel time data were jointly inverted to obtain a 1-D velocity model (Fig. 5). This solution was then used for relocation of the analysed seismic events as well as for focal mechanism computation for selected earthquakes in the Anker region.

5 Relocation of the recorded seismic events

To better understand the seismotectonic model for the Anker region, the earthquakes recorded by the temporary network were relocated using the double difference method (Waldhauser and Ellsworth, 2000). This method minimises the residuals between observed and theoretical travel time differences for pairs of earthquakes at each station whilst linking together all observed event-station pairs. Absolute P- and S-wave travel time differences were used, although the location method can also incorporate the cross-correlation of differential travel time measurements. Only well-recorded events with at least eight stations were relocated using the newly developed velocity model.

The spatial distribution of the original and relocated earthquakes in the region with depths of events is shown

in Fig. 6. The main change in the distribution of relocated events is the disappearance of the two separated clusters of events. Rather, there is now one large cluster of events collocated with the original southern cluster. The clustering appears to have increased (Fig. 6), implying improved locations of events. Three distinct clusters are observed in the depth profile (Fig. 6b) all dipping in a westerly direction. The shallower part is to the eastern side and has depth between 0 and 20 km. The western deeper cluster has depth between 10 and 25 km.

After the relocation process, the earthquakes can be observed to follow a similar trend observed in Fig. 3 of NW–SE trend although they seem to cluster around the Anker region. There are no detailed structural mapping studies done for the study area to corroborate our observation; however, the regional tectonic setting within this region shows typical trends obtained in this study. The NW–SE trend is associated with the Kaoko mobile belt, a prominent geological structure in northern Namibia and known seismic zone (Mangongolo and Hutchins, 2008).

6 Focal mechanism computation

Focal mechanism solutions for some of the cluster earthquakes were determined using the FOCMEC program

Fig. 5 The velocity model developed for the Anker region. Dashed line represents the initial velocity model by Midzi et al. (2010). The red line represents the final velocity model

which implements the first motion polarity method (Snoko et al. 1984). Phases were picked using the SEISAN software (Ottemöller et al. 2018). The basic idea is that the polarity of the first P-wave arrival varies between seismic stations at different directions from an earthquake. The first motions define the four quadrants, two compressional and two dilatational, and the

division between the quadrants occurs along the main fault plane and an auxiliary plane that is perpendicular to the main fault plane. Each event selected had at least eight clear polarities. The fault plane solutions vary in type of faulting but normal faulting appears to dominate (Fig. 7 and Table 1). However, many of the solutions had a left-lateral strike-slip component to them. In a few

Fig. 6 Results of the earthquake relocations for the events in the Anker region recorded by the temporary network deployed by the GSN and CGS from June to September 2018. **a** shows the spatial distribution of the seismic events recorded by the

temporary network (green circles) as well as the relocated events (blue circles), **b** shows the depth profile for the relocated events along profile A–B in **a**

cases, reverse faulting mechanisms were also observed. This suggests that the area is highly faulted with faults oriented in all directions as shown in Fig. 7.

7 Seismotectonic analysis

The seismotectonic context of northern Namibia is typically of a SCR characterised by low rate of crustal deformation and temporally and spatially

diffuse distributed seismicity (Mangongolo and Hutchins, 2008). This makes it difficult to associate any recorded seismicity to faults. Though no known fault could be clearly linked to the Anker swarm, it is possible that the events are linked to the regional triple junction due to the Kaoko and Damara mobile belts. The junction is characterised by faults oriented in both NW–SE and NE–SW directions. Seismic swarms have been associated with either transient stress changes, fluid migration or magmatic activities

Fig. 7 Focal mechanism solutions obtained in this study and associated with tectonic lineaments (yellow lines) in the study area. Blue beach balls represent normal faulting, red represent reverse faulting and black beach balls are for strike-slip faulting

Table 1 Focal mechanism solutions for the earthquakes analysed in this study

Year	Month	Day	Hour	Minute	Second	Latitude	Longitude	Depth	Magnitude	Strike	Dip	Rake
2018	6	21	3	1	26.1	−19.780	14.548	0.0	1.1	138.42	71.25	−68.83
2018	6	21	12	12	5.7	−19.814	14.557	5.0	0.6	303.22	67.48	−45.90
2018	6	21	13	23	50.8	−19.743	14.548	13.3	0.8	218.57	40.00	0.00
2018	6	21	13	23	51.5	−19.730	14.523	5.0	0.8	63.17	54.07	−37.45
2018	6	21	16	5	37.8	−19.816	14.570	9.3	0.5	322.55	54.07	37.45
2018	6	21	16	5	37.8	−19.813	14.574	9.5	0.5	8.74	77.76	−54.06
2018	6	21	16	35	45.9	−19.762	14.545	10.9	0.4	324.00	35.00	−90.00
2018	6	21	16	35	46.0	−19.771	14.545	10.1	0.4	46.07	67.48	−45.90
2018	6	21	19	1	55.0	−19.821	14.580	5.1	0.1	187.69	83.59	−39.57
2018	6	21	22	1	45.4	−19.782	14.529	11.2	0.8	219.69	54.07	37.45
2018	6	21	22	31	52.3	−19.745	14.563	11.9	0.4	180.00	75.00	−90.00
2018	6	21	23	41	18.2	−19.760	14.559	11.5	0.4	285.74	79.45	44.01
2018	6	22	1	0	49.3	−19.818	14.592	5.8	0.3	116.83	54.07	37.45
2018	6	22	1	29	15.0	−19.813	14.577	5.2	0.3	180.00	45.00	−90.00
2018	6	23	0	16	17.2	−19.713	14.564	11.1	1.1	126.69	73.73	11.79
2018	6	23	0	16	18.3	−19.788	14.580	7.4	0.8	128.21	68.37	−34.50
2018	6	23	0	16	17.3	−19.722	14.572	13.3	0.4	140.73	65.60	−32.73
2018	6	23	0	34	29.1	−19.810	14.556	11.6	0.8	218.57	40.00	0.00
2018	6	24	0	53	52.3	−19.795	14.542	9.0	0.8	300.00	40.00	−90.00
2018	6	24	3	12	54.9	−19.777	14.554	10.4	0.8	148.93	67.48	−45.90
2018	6	24	3	15	4.6	−19.783	14.559	11.0	0.8	300.00	40.00	−90.00
2018	6	24	3	38	23.1	−19.799	14.580	5.3	0.1	218.57	40.00	0.00
2018	6	24	4	3	45.0	−19.809	14.552	9.0	0.7	260.00	40.00	−90.00
2018	6	24	5	15	54.5	−19.807	14.549	7.5	0.7	180.00	60.00	−90.00
2018	6	24	5	40	25.7	−19.787	14.535	8.0	0.7	167.14	40.00	0.00
2018	6	25	0	2	47.4	−19.800	14.555	9.8	0.9	354.65	67.48	−45.90
2018	6	25	0	33	38.2	−19.812	14.554	6.7	0.5	63.17	54.07	−37.45
2018	6	25	1	12	22.5	−19.793	14.559	14.4	0.8	353.53	82.36	49.57
2018	6	25	1	17	16.4	−19.796	14.544	10.6	0.8	4.64	64.34	−16.10
2018	6	25	1	21	12.7	−19.816	14.582	4.4	0.1	353.53	82.36	49.57
2018	6	25	1	49	43.1	−19.818	14.563	12.8	0.7	220.89	41.41	−40.89
2018	6	28	0	19	18.8	−19.792	14.551	12.3	0.8	116.31	64.34	−16.10
2018	6	28	0	19	19.1	−19.790	14.554	11.5	0.8	288.00	90.00	60.00
2018	6	28	0	19	18.9	−19.776	14.553	13.4	0.7	147.37	27.99	43.22
2018	6	28	0	20	31.7	−19.853	14.626	25.8	0.5	236.31	64.34	−16.10
2018	6	28	0	20	35.3	−19.787	14.527	9.3	0.6	320.00	90.00	0.00
2018	6	28	0	33	57.9	−19.788	14.555	12.7	0.9	37.45	54.07	−37.45
2018	6	28	0	43	1.8	−19.441	14.690	40.8	0.4	348.21	73.73	53.31
2018	6	28	2	15	16.4	−19.770	14.541	8.5	1	148.93	67.48	−45.90
2018	6	28	2	16	25.2	−19.792	14.572	5.3	0.1	140.73	65.60	−32.73
2018	6	28	2	20	59.4	−19.929	14.977	0.0	0.9	116.83	54.07	37.45
2018	6	28	2	25	18.8	−19.810	14.588	6.2	1.5	97.50	67.48	−45.90
2018	6	28	2	42	34.9	−19.789	14.579	6.4	0.2	270.00	30.00	−90.00
2018	6	28	3	23	29.8	−19.780	14.541	10.7	1	90.00	60.00	0.00
2018	6	28	3	23	30.0	−19.763	14.520	6.3	0.8	330.00	15.00	−90.00
2018	6	28	3	33	12.6	−19.768	14.550	12.1	0.8	324.00	90.00	60.00

Table 1 (continued)

Year	Month	Day	Hour	Minute	Second	Latitude	Longitude	Depth	Magnitude	Strike	Dip	Rake
2018	6	28	3	51	32.0	−19.809	14.551	9.8	0.9	260.00	40.00	−90.00
2018	6	28	8	23	38.0	−19.783	14.538	11.2	0.7	350.00	90.00	0.00
2018	6	28	8	31	18.4	−19.816	14.556	6.1	0.4	333.45	52.32	−59.07

(Hill et al. 1975; Dieterich et al. 2000; Vidale and Shearer 2006). However, in this area, neither of those activities is evident.

Results from the focal mechanism analysis indicate that regional tectonic stresses are predominant although it was not possible to associate with localised structures and lineaments. The current seismic swarm may be either a result of stress transfer within a set of faults that are rupturing in response to heterogeneous stress fields or the presence of pre-existing crustal weaknesses within which deformation is localised and possibly triggered by loading, unloading or non-tectonic sources (e.g. Calais et al. 2016; Manzunzu et al. 2017). This can accommodate localised seismic swarms as seen to occur in the region. Although the Kaoko and Damara mobile belts have not shown significant movement since Precambrian, the occurrence of the seismic swarm showing localised movement of the faults. Another possible explanation for the occurrence of different faulting mechanisms at the same place and time (Fig. 7) is that events might be taking place on non-optimally oriented faults or are caused by block faulting. The Anker area lies at the confluence of two tectonic regimes, the Damara belt that trends NE–SW and the Kaoko belt trending NW–SE. The presence of steep shear zones in this region that are typically inherited from Pan-African orogenic belts in this part of Southern Africa (Wanke et al. 2000) may aid in transient stress changes. However, intraplate regions often lack surface rupture linked to an individual earthquake making it hard to identify active faults. Intraplate regions deform slowly and it is difficult to identify surface geological features related to the seismic foci with any sort of precision, and therefore, only a few events can be correlated to the surface geology, making them hard to study (Gangopadhyay and Talwani, 2003). Further studies on fault interaction and static stress transfer need to be conducted in order to understand the occurrence of this seismic swarm.

8 Conclusions

More than 1600 microseismic events were recorded using a temporary network of 10 stations deployed for a period of 3 months. The magnitude of these events ranges from −1.1 to 3.6 M_L which occurred down to a depth of 15 km. The locations of these events were used to try and associate the seismicity to the local tectonic structures. In this study, a new average crustal velocity model was computed for the Anker local area and used for relocating the earthquakes. The new velocity model is based on extensive good quality local earthquake data which resulted into significant improvements in swarm earthquake locations. Relocation of the earthquakes indicates a NW–SE trend in seismicity which is consistent with the orientation of the Kaoko mobile belt. However, the study region lies at the junction of two mobile belts and focal mechanism solutions suggest that rupture mechanisms can be associated with both mobile belts. A mixture of focal mechanism solutions was obtained from this study indicating the complexity of the localised faulting in the area. Seismicity might be linked to reactivation of pre-stressed faults within the region due to changes in stress conditions. The seismotectonics of the Anker region might be under the influence of regional tectonic structures. Future work need to be undertaken in order to find best solution of the source of these seismic swarms in the study area.

Acknowledgements The authors would like to acknowledge the support given by the CGS in providing the temporary seismic stations for recording the seismicity in the Anker region. We are also in debt to the GSN for the support and logistics throughout the data collection process. We would also like to thank specifically the geophysics team at the Geological Survey of Namibia and the Seismic Technical Team of the Council for Geoscience for their immense contribution in data acquisition. The authors are also grateful for the assistance given by Mr. Ewereth Muvangua for his contribution on geological information and Ms. Kombada Mhopjeni in proofreading our manuscript.

Funding The research was funded by the Government of the Republic of Namibia (Ministry of Mines and Energy) and the Government of the Republic of South Africa (Council of Geoscience) in a form of a joint research project.

Data availability Data can be shared with any interested parties upon request.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Allen TI (2020) Seismic hazard estimation in stable continental regions. *Bull N Z Soc Earthq Eng* 53(1):22–36
- Becker T (2006a) Sheet 1914CB Atlanta. Geological map of Namibia, Geological Series Scale 1:50 000. Ministry of Mines and Energy, Geological Q47 Survey of Namibia
- Becker T (2006b) Sheet 1914DA Bruno. Geological map of Namibia, Geological Series Scale 1:50 000. Ministry of Mines and Energy, Geological Survey of Q47 Namibia
- Becker T (2006c) Sheet 1914DB Kamanjab. Geological map of Namibia, Geological Series Scale 1:50 000. Ministry of Mines and Energy, Geological Survey of Q47 Namibia
- Calais E, Camelbeeck T, Stein S, Liu M, Craig TJ (2016) A new paradigm for large earthquakes in stable continental plate interiors. *Geophys Res Lett* 43 <https://doi.org/10.1002/2016GL070815>
- Coward MP (1983) The tectonic history of the Damara Belt. In: Miller, R.G. (Ed.), *Evolution of the Damara Orogen of South West Africa/Namibia*, 11. *Geol Soc South Afr Spec Pub*, pp. 409–421
- Dieterich J, Cayol V, Okubo P (2000) The use of earthquake rate changes as a stress meter at Kilauea Volcano. *Nature* 408:457–460
- Durr SB, Dingeldey DP (1996) The Kaoko Belt (Namibia): part of a late Neoproterozoic continental-scale strike-slip system. *Geology* 24(6):503–506
- Ellsworth WL (1977) Three-dimensional of the crust and mantle beneath the island of Hawaii. PhD thesis, Massachusetts Institute of Technology
- Frets DC (1969) Geology and structure of the Huab-Welwitschia area South West Africa, Doctoral dissertation, University of Cape Town
- Gangopadhyay A, Talwani P (2003) Symptomatic features of intraplate earthquakes. *Seismol Res Lett* 74:863–883
- Gomberg JS, Shedlock KM, Roecker SW (1990) The effect of S-wave arrival times on the accuracy of hypocenter estimation. *Bull Seism Soc Am* 80:1605–1628
- Goscombe B, Hand M, Gray D (2003a) Structure of the Kaoko Belt, Namibia: progressive evolution of a classic transpressional orogen. *J Struct Geol* 25(7):1049–1081
- Goscombe B, Hand M, Gray DR, Mawby J (2003b) The metamorphic architecture of a transpressional orogen: the Kaoko Belt, Namibia. *J Petrol* 44:679–711
- Goscombe BD, Cees W, Passchier CW, Hand M (2004) Boudinage classification: end-member boudin types and modified boudin structures. *J Struct Geol* 26:739–763
- Gray DR, Foster DA, Goscombe B, Passchier CW, Trouw RAJ (2006) $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology of the Pan-African Damara Orogen, Namibia with implications for tectono-thermal and geodynamic evolution. *Precambrian Res* 150:49–72. <https://doi.org/10.1016/j.precamres.2006.07.003>
- Gray DR, Foster DA, Meert JG, Goscombe BD, Armstrong R, Trouw RAJ, Passchier CW (2008) A Damara Orogen perspective on the assembly of southwestern Gondwana. *Geological Society, London, Special Publications* 294(1):257–278
- Gupta HK, Johnston AC (1998) Stable continental regions are more vulnerable to earthquakes than once thought. *EOS*, 79 (27)
- Hainzl S, Ogata Y (2005) Detecting fluid signals in seismicity data through statistical earthquake modeling. *J Geophys Res* 110:B05S07. <https://doi.org/10.1029/2004JB003247>
- Hill DP, Mowinckel P, Peake LG (1975) Earthquakes, active faults, and geothermal areas in the Imperial Valley. *California, Science* 188:1306–1308
- Kissling E, Ellsworth WL, Eberhart-Phillips D, Kradolfer U (1994) Initial reference models in local earthquake tomography. *J Geophys Res* 99:19635–19646
- Kissling E, Kradolfer U, Maurer H (1995) Program VELEST user's guide—short introduction. Institute of Geophysics, ETH Zurich
- Kleinhanns IC, Fullgraf T, Wilsky F, Nolte N, Fliegel D, Klemd R, Hansen BT (2015) U-Pb zircon ages and (isotope) geochemical signatures of the Kamanjab Inlier (NW Namibia): constraints on Palaeoproterozoic crustal evolution along the southern Congo craton. *Geological Society, London, Special Publications* 389(1):165–195
- Labidi M, Whitney B, Drouet S (2021). Seismic activity in stable continental regions. In *EGU General Assembly Conference Abstracts* (pp. EGU21–8273).
- Llenos A, McGuire JJ, Ogata Y (2009) Modelling seismic swarms triggered by aseismic transients. *Earth Planet Sci Lett* 281:59–69
- Luttrell K, Sandwell D (2010) Ocean loading effects on stress at near shore plate boundary fault systems. *Journal of Geophysical Research: Solid Earth* 115(B08):411–414

- Luttrell K, Sandwell D, Smith-Konter B, Bills B, Bock Y (2007) Modulation of the earthquake cycle at the southern San Andreas Fault by lake loading. *Journal of Geophysical Research: Solid Earth* 112(B08):411–415
- Maloof AC (2000) Superposed folding at the junction of the inland and coastal belts, Damara Orogen, Namibia. In: Miller, R.McG. (Ed.), Henno Martin commemorative volume, vol. 12. *Commun. Geol. Surv. Namibia*, pp. 89–98
- Mangongolo A, Hutchins DG (2008) Seismicity of Namibia from 1910 to 2006. In: Miller, R. (Ed.), *Geology of Namibia*. Geological Survey of Namibia, Windhoek 3, 27–1 – 27–7
- Manzunu B, Midzi V, Mangongolo A, Essrich F (2017) The aftershock sequence of the 5 August 2014 Orkney earthquake (M_L 5.5), South Africa. *J Seismol* 21(6), pp.1323–1334.
- McGuire JJ, Boettcher M, Jordan TH (2005) Foreshock sequences and short-term earthquake predictability on East Pacific Rise transform faults. *Nature* 434:457–461
- Midzi V, Saunders I, Brandt MB, Molea T (2010) 1-D velocity model for use by the SANSN in earthquake location. *Seismol Res Lett* 81(3):460–466
- Midzi V, Saunders I, Manzunu B, Kwadiba MT, Jele V, Mantsha R, Marimira KT, Mulabisana TF, Ntibinyane O, Pule T, Rathod GW, Sitali M, Tabane L, van Aswegen G, Zulu BS (2018) The 03 April 2017 Botswana M6.5 earthquake: preliminary results. *J Afr Earth Sc* 143:187–194
- Miller, R.McG., 1983. The Pan-African Damara Orogen of South West Namibia/Africa. In: Miller, R.G. (Ed.), *Evolution of the Damara Orogen of South West Africa/Namibia*, vol. 11. Special Publication of the Geological Society of South Africa 11, 431–515.
- Miller, R.M., 2008. *The geology of Namibia* (Vol. 1, pp. 7–1). Ministry of Mines and Energy, Geological Survey.
- Ottmöller L, Voss P, Havskov J (2018) SEISAN earthquake analysis software for Windows, Solaris. Department of Earth Sciences, University of Bergen, Linux and MACOS
- Passchier CW, Trouw RAJ, Ribeiro A, Paciullo FVP (2002) Tectonic evolution of the southern Kaoko belt. *Namibia Journal of African Earth Sciences* 35(1):61–75
- Pavlis GL (1986) Appraising earthquake hypocenter location errors: a complete, practical approach for single-event locations. *Bull Seism Soc Am* 76:1699–1717
- Porada H (1989) Pan-African rifting and orogenesis in southern to Equatorial Africa and eastern Brazil. *Precambrian Res* 44:103–136
- Porada H, Ahrendt H, Behr HJ, Weber K (1983) The join of the coastal and intracontinental branches of the Damara Orogen, Namibia, South West Africa. In: Martin H, Eder FW (eds) *Intracontinental fold belts*. Springer, Berlin, pp 901–912
- Porada, H.R., 1974. The Khoabendus Formation in the area northwest of Kamanjab and in the southeastern Kaoko veld, South West Africa. *Mem. geol. Surv. S. Afr., S.W.Afr. Ser.*, 4, 23 pp
- Prave AR (1996) Tale of three cratons: tectonostratigraphic anatomy of the Damara Orogen in northwestern Namibia and the assembly of Gondwana. *Geology* 24:1115–1118
- Saunders I, Ottmöller L, Brandt MBC, Fourie CJS (2013) Calibration of an M_L scale for South Africa using tectonic earthquake data recorded by the South African National Seismograph Network: 2006 to 2009. *J Seismolog* 17(2):437–451. <https://doi.org/10.1007/s10950-012-9329-0>
- Smith KD, von Seggern D, Blewitt G, Preston L, Anderson JG, Wernicke B, Davis J (2004) Evidence for deep magma injection beneath Lake Tahoe, Nevada-California, *Science* 305:1277–1280
- Snoke J.A., J.W. Munsey, A.G. Teague and G.A. Bollinger, 1984. A programme for focal mechanism determination by combined use of polarity and SV-P amplitude ratio data, *Earthquake Note*, 55, 15pp.
- Toda S, Stein RS, Sagiya T (2002) Evidence from the AD 2000 Izu islands earthquake swarm that stressing rate governs seismicity. *Nature* 419:58–61
- Trompette R (1997) Neoproterozoic (~ 600 Ma) aggregation of Western Gondwana: a tentative scenario. *Precambr Res* 82(1–2):101–112
- Vidale J. E. and Shearer P. M. 2006, A survey of 71 earthquake bursts across southern California: exploring the role of pore fluid pressure fluctuations and aseismic slip as drivers, *Journal of Geophysical Research*, 111, B05312. <https://doi.org/10.1029/2005JB004034>
- Vidale, J.E., Boyle, K.L. and Shearer, P.M., 2006. Crustal earthquake bursts in California and Japan: their patterns and relation to volcanoes. *Geophysical research letters*, 33(20).
- Waldhauser F, Ellsworth WL (2000) A double-difference earthquake location algorithm: method and application to the Northern Hayward Fault. *California, Bulletin of the Seismological Society of America* 90(6):1353–1368
- Wanke A, Stollhofen H, Stanistreet IG, Lorenz V (2000) Karoo unconformities in NW Namibia and their tectonic implications. *Communications of the Geological Survey of Namibia* 12:259–268

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.