

Seismicity and neotectonic uplift in the Augrabies Falls National Park, Namaqualand, Northern Cape, South Africa

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Abstract Gneissic rocks in the Augrabies Falls National Park are part of the Proterozoic Namaqua-Natal mobile belt. Finding neotectonic evidence in old terranes is always not an easy task. In South Africa, the mid-Miocene is believed to be the beginning of neotectonics. This study investigated the occurrence and recurrence of earthquake activity, occurrence of faulting, jointing, uplift, and potholes in the gneisses cropping out around the Augrabies Falls area that may account for neotectonics. A historic seismic event obtained from the United States Geological Survey (USGS), and seismic epicenters downloaded in October 2015 from IRIS earthquake browser and overlaid on a satellite image with digitised faults and lineaments, indicates that the area is seismically active and is a zone of seismic risk. Potholes occurring today on a dry surface at approximately 613 m above sea level are a direct consequence of the Griqualand-Transvaal neotectonic uplift, which generated a major fault along which water flows continuously. It is concluded that the Augrabies Falls National Park area is a zone of neotectonics. This zone should not be considered for the storage of nuclear wastes.

Keywords Seismicity · Neotectonic · Uplift · Groundwater · Lineament

1 Introduction

The Augrabies Falls in the Northern Cape Province are hosted in the Riemvasmaak gneiss of Proterozoic age.

Neotectonics in this province is marked by a recurrent seismic activity and the tectonic uplift. Brandt (2011) highlighted that the Augrabies area is located on the boundary of the Kaapvaal Craton, the Kheis orogenic belt, and the Namaqua-Natal mobile belt. Moreover, the area is characterized by the occurrence of numerous faults, shear zones, folds, etc. The falls were thought to be formed about 1.8 million years ago, progressively cutting back eastwards along faults in the pink gneiss (Werger and Coetzee 1977). However, there has never been a plausible explanation about the formation of the fault in the gneiss.

All these zones of weakness (faults and shear zones) may be subject to reactivation. The commencement of neotectonics in southern Africa has never been established (Friese et al. 2006). According to Burke (1996), the beginning of neotectonic activity in southern Africa is envisaged to have started with the Oligocene at ~35 Ma, which coincides with the African continent becoming stationary over the so-called African Superplume. Burke (1996) emphasised that the behaviour of the African Plate has changed during the Oligocene at ~35–30 Ma and many, if not all, of the phenomena that have characterized Africa over the past ~35–30 Ma have been induced by the cessation of plate motion (i.e. a reduction to below a velocity of ~10 mm/a). Andreoli et al. (1996) proposed neotectonic activity in South Africa to have been initiated in the Miocene (~25 Ma). The works of Andreoli et al. (1996) as well as Viola et al. (2005) highlighted that seismicity in southern Africa is driven by regional stresses originating from large-scale features that include intra-continental rifts, large-scale topographic elevations (such as the border of Lesotho and South Africa north of the Eastern Cape Province), and the network of mid-oceanic ridges. At present, neotectonics in southern Africa is increasingly associated with two large deviatoric stress

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fields: one with a predominant extensional NNE trend corresponding to the East Africa Rift System, and a second one, the Wegener Stress Anomaly (WSA) characterized by a NW-WNW compressive trend (Zoback et al. 1989). According to Viola et al. (2005), the Wegener Stress Anomaly is anomalous because the continental margin of the SE Atlantic should be of the passive margin and extensional type in terms of plate tectonics. Furthermore, the WSA is characterized by the Andersonian strike-slip fault regime (σ_2 vertical, σ_1 and σ_3 horizontal). Bird et al. (2006) found that the orientation of the Wegener Stress Anomaly varies from NNW-SSE in Namaqualand, west Namibia, and the adjacent southeast Atlantic offshore, to NW/WNW-SE/SSE in the southern Cape, the Bredasdorp basin, and in the Witwatersrand basin. Talwani (2014) and Mooney et al. (2012) highlighted that an inventory of $M \geq 4.5$ intraplate earthquakes showed that they are preferentially located in old rift structures and at boundaries of cratons.

Meissner and Wever (1986) indicated that epicenters of intracontinental earthquakes are concentrated on lineaments. Intersections also control earthquake sequences by loading or unloading stresses on adjacent or intersecting faults (King et al. 1994).

Titus et al. (2009) quoting Andreoli et al. (1989, 1990, etc.) indicated that there is a striking match between the tectonic fabric of the southeast Atlantic and southwest Indian Ocean on the one hand and the tectonic fabric of the African subcontinent on the other. A number of major oceanic transform faults or fractured zones such as the Cape/False Bay, the Agulhas-Falkland Fractured Zone, the Trans Indian/Ceres Prince Edward, and the Mozambique/Madagascar fractured zones (Fig. 1) continue into the on-shelf and on-shore joints/faults of the South African continent. Titus et al. (2009) in their study of aquifers in Namaqualand found that a set of NNE-SSW striking fault/fracture zones represents continental continuations of oceanic transform faults. Andersen and Ainslie (1994) argued that stress orientation can be related to visible structures and to kinematic pattern; moreover, once the orientation of the present-day stress field is determined, it is possible to predict which pre-existing structures are favourably oriented for reactivation of strike-slip or normal motion.

Two surface neotectonic uplifts in South Africa took place in the last five million years (Partridge et al. 2010; Partridge and Maude 2000): the Amatole-Swaziland (formerly Ciskei-Swaziland) along the east coast, and the Griqualand-Transvaal uplift that affected the Augrabies Falls (Fig. 1). Artyushkov and Hofmann (1986) mentioned that in southern Africa the uplift took place in the early Miocene (up to 300 m) and in the late Pliocene and Pleistocene (up to 900 m). This uplift is controlled by the

NNE-SSW trending Miocene-Pliocene Griqualand-Transvaal axis. The term “uplift” in this study is related to the definition given by Molnar and England (1990) who indicated that what matters most is the uplift of the Earth’s surface relative to sea level, which is the change in elevation. Dobson et al. (2010) proposed three competing evolutionary models for the surface uplift: (1) the major phase of surface uplift occurred in the late Cretaceous, (2) the major phase of surface uplift occurred at ~ 30 Ma, and (3) ~ 900 m of the modern topography being generated rapidly 100 m/Ma in the Plio-Pleistocene (c. 3 Ma).

2 General geology of Augrabies Falls area

The Augrabies Falls area metamorphic rocks comprise the Riemvasmaak orthogneiss, which is hosted in the Koranaland Group, Kakamas Terrane. Werger and Coetzee (1977) mentioned the occurrence of rocky hills in the central portion formed by dark quartz-rich granulite. Most of the area is composed of biotite granite gneiss. The landscape is made up of granite and metagabbros, and the metagabbros is composed of dark minerals (amphibole, biotite). Because of the granitic domes, exfoliation jointing is also predominant in the area. Brandt (2011) highlighted that the Augrabies gneiss consists of quartz, microcline, and plagioclase with varying amounts of biotite and hornblende and with rare opaque minerals (apart from allanite which is a common accessory mineral). The gneissic texture and fabric is conspicuously uniform throughout the area. Brandt (2011) also indicated that the Augrabies Gneiss is well exposed and indeed forms the rock type into which the main Augrabies Falls and canyon have been cut. The Augrabies Falls area is also characterized by faults, micro-faults, and parallel joint sets. Werger and Coetzee (1977) indicated that exfoliating domes are created by chemical weathering stress along sub-horizontal joints, which causes thin slabs of rock to detach from the rock surface. According to Werger and Coetzee (1977), the main incision of the peneplain to form the Orange River gorge and the evolution of the Augrabies Falls are associated with the continental surface uplift during the late Tertiary with a recent river terrace occurring along the Orange River.

3 Methodologies

The methodologies in this study include the analysis of recent seismic events in the area of study, digitalisation of faults and lineaments from a satellite image, and field observations. Reports from different sources were also taken into account for this study and have helped decipher

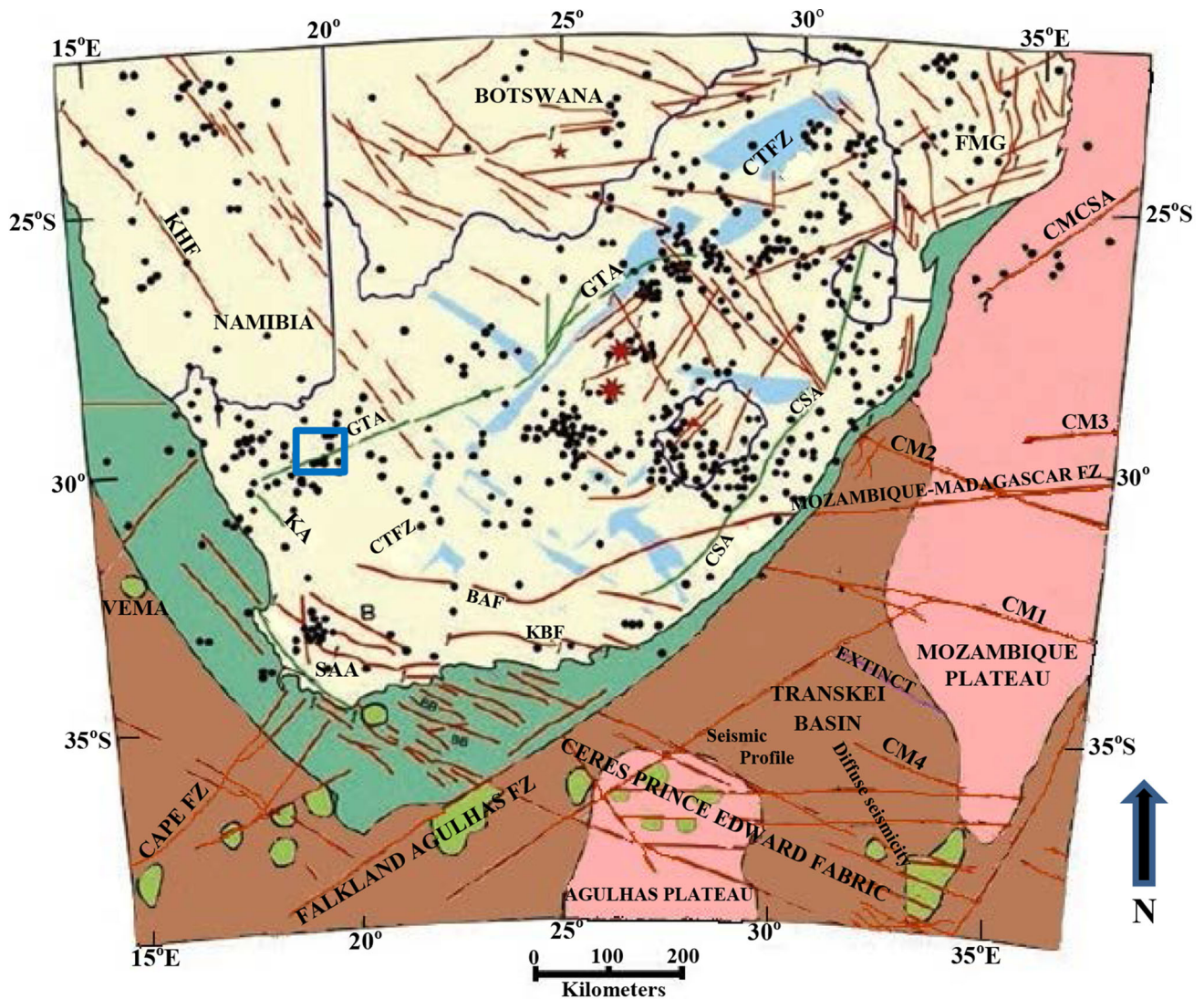


Fig. 1 Seismic epicenters in relation to Post-Karoo tectonic framework of South Africa and nearby regions (Andreoli et al. 1996, modified and coloured by Friese et al. 2006). Yellow and dark green continental crust, red oceanic crust invaded by oceanic basalt, brown oceanic basalt crust, light green offshore volcanic domain, blue lineament belts, ET eastern Transvaal, GA Gauteng Province, KN Kwazulu-Natal Province, NT Northern Transvaal, KFB Koega-Bavianskloof fault, FMG Funhalouro-Mazenga Graben, KHF Kuiseb-Hebron fault, CTFZ Cape-Tzaneen fracture zone, BB Bredasdorp Basin, green lines surface uplift axis, KA Kamesberge axis, SAA Saldnha-Aghulas axis, GTA Griqualand-Transvaal axis, CSA Ciskei-Swaziland (now Amatole-Swaziland) axis, BAF Beattie Anomaly Fracture, CMCSA Central Mozambique Channel Seismic Axis, f-f neotectonic faults active since the Miocene, dashed lines lineaments/possible neotectonic faults, red stars localities affected by catastrophic Pleistocene earthquakes, red triangle proposed neovolcanic center of Lesotho, BB Bredasdorp Basin. Blue square study area. Source of seismic data: Fernández and du Plessis 1992)

the occurrence of earthquake activity, and accordingly of neotectonics in the Augrabies Falls area. Remote sensing was also used to infer the occurrence of major structures in the area. An L 4-5 TM best satellite image dated of 2011 from Landsat Archive of the area was downloaded for free from EarthExplorer, United States Geological Services (USGS). This satellite image was exported to ArcGIS 10.1 to digitise faults and lineaments, over which recent seismic epicenters downloaded from IRIS Earthquake Browser in September 2015 were overlaid.

4 Results

4.1 Field observations

Field observations confirmed the occurrence of the surface uplift that took place in the last five million years; potholes exposed on a dry surface and the conspicuous fault along which the water flows from the falls are indicative of the neotectonic uplift. The Augrabies Falls gneiss displays typical oriented minerals characteristics of regional

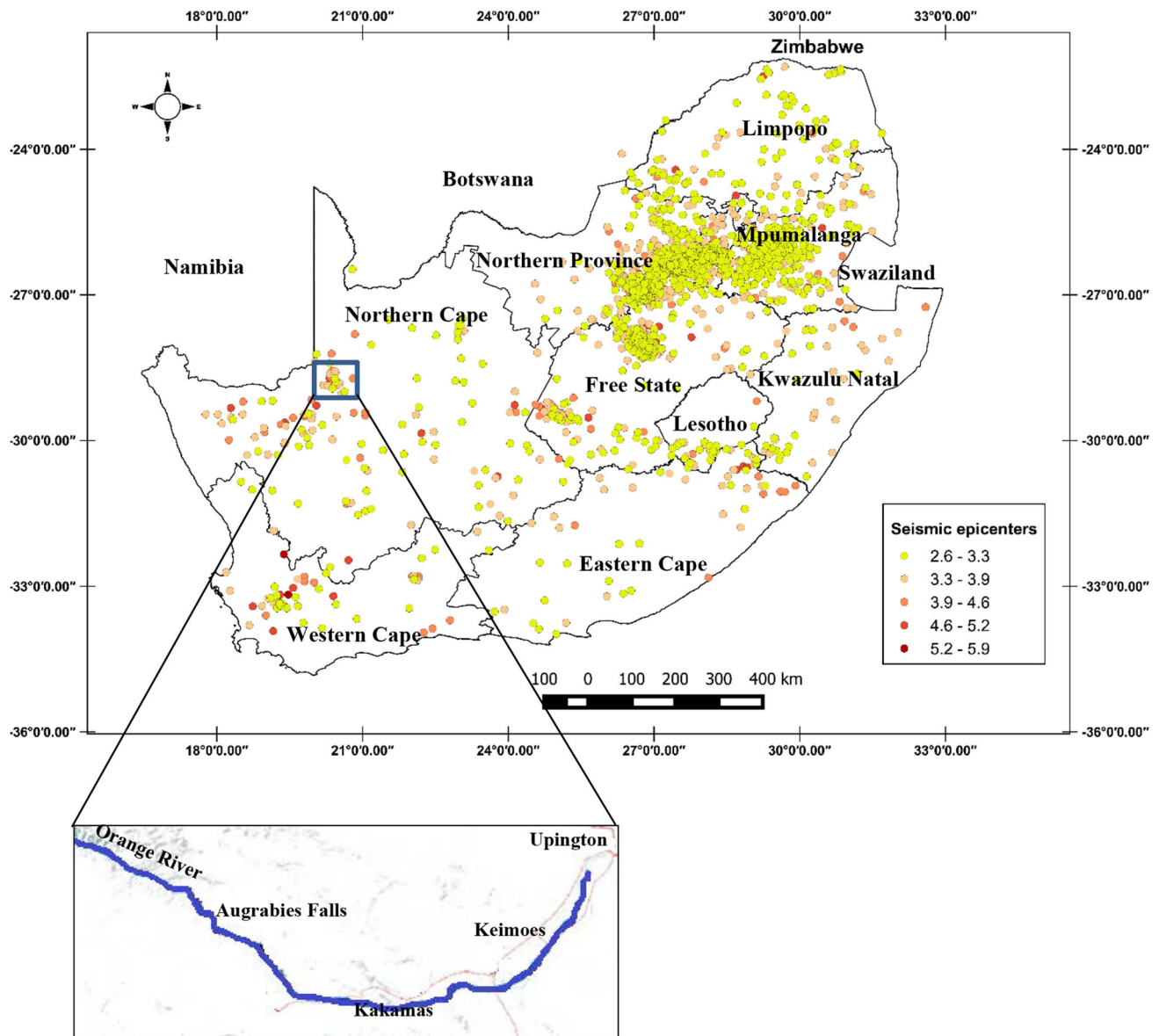


Fig. 2 Recent seismic epicenters distribution of South Africa (October 2015). The *rectangular* in the figure above is the study area and is enlarged as the map below. *Source of seismic epicenters:* IRIS Earthquake Browser

metamorphism. This orientation is highlighted by the presence of dark minerals (biotite, hornblende) and light minerals (quartz, plagioclase); therefore, the protolith would probably be a granite. The foliation is oriented N170°E, is almost constant in all the area, and may be related to a northeast-southwest directed compression. Few pegmatite dykes of Proterozoic age occur in the Riemvasmaak orthogneiss cropping out in the Augrabies Falls area, and these pegmatite dykes may be related to a plutonic granitoid. These pegmatites are late Proterozoic event, because if they were part of the granite protolith, they would have been sheared or metamorphosed as the granite has been changed into gneiss.

4.2 Seismic data

The area around the Augrabies Falls is beset by recurrence of seismic activity (Figs. 2, 3). The Orange River (Fig. 2) may flow along a zone of weakness, possibly an extensional fault. In stable continental regions, earthquakes are generally due to accumulation of stress in a pre-existing zone of weakness in response to plate tectonic or other forces. Many epicenters near the Orange River are indicative of stress build-up. Clustering of seismic epicenters (Figs. 2, 3) is characteristic of continental intraplate earthquakes. These clusters of seismic epicenters can be associated with local stress build-up associated with higher

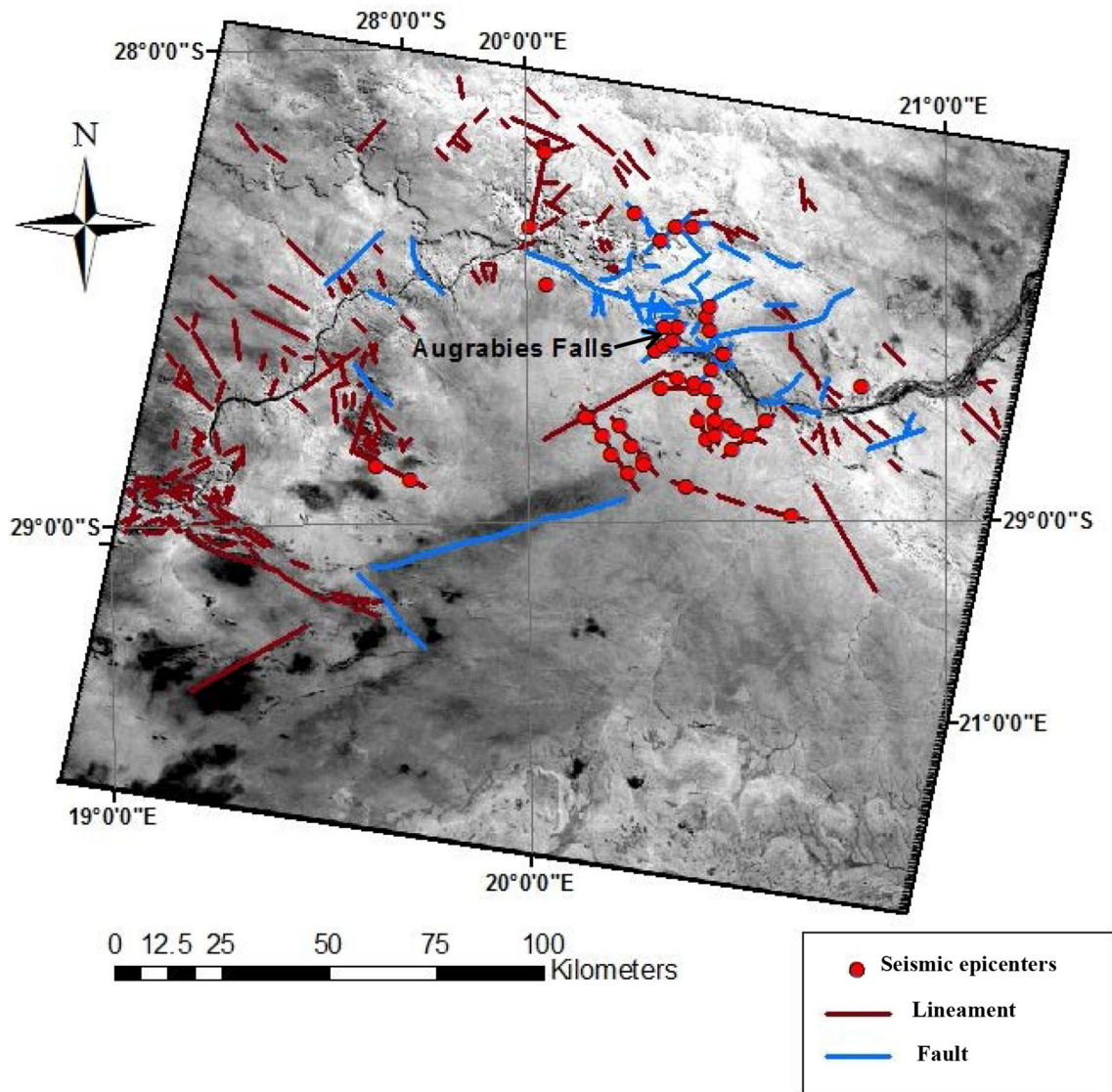


Fig. 3 Satellite image with digitised faults and lineaments with seismic epicenters. *Source of seismic epicenters:* IRIS Earthquake Browser

strain rates. Hypocentral depths from data acquired from the USGS are very shallow and are concordant with continental intraplate earthquake characteristics; all the events have a hypocentral depth of 5 km. According to the data received from the USGS, seven earthquakes occurred around the Augrabies Falls area with the magnitude varying from 4.1 to 4.6 on the Richter scale in 2011 (Table 1). The Augrabies Falls area is also characterized by stress release evidenced by small clustering of seismic epicenters (Fig. 3). In this figure, many seismic epicenters were connected by lineaments, characterized by continental intraplate earthquakes, as it is the case of South Africa. The intersection of many faults in this area can explain the occurrence of seismicity.

To better observe markers that can be used to identify neotectonics in a given area, attention should be focused on beheaded new rivers, springs, hot springs, or recent soils' offset that can indicate recent movement along faults. These recent indurated soils are commonly known as "pedocretes". Terms generally used for pedocretes are calcretes, ferricretes, silcrettes, etc. If these pedocretes are affected by fractures or faults, then they can be used as indicators for neotectonics. For continental intraplate earthquake, one can also consider a region of high topography like the border of the countries of South Africa and Lesotho. Topography and crustal density heterogeneities may induce stress in the lithosphere. In stable continental regions, earthquakes generally reflect accumulation of

Table 1 Seismic data of the Augrabies Falls area. *Source:* United States Geological Survey (USGS)

Date (a-mo-d)	Time (h:min:s)	Magnitude	Depth (km)
2011-12-18	18:07:06	4.3	5
2011-04-06	23:34:53	4.6	5
2011-02-21	21:19:12	4.6	5
2011-01-25	02:39:53	4.4	5
2011-01-13	17:36:55	4.4	5
2011-01-12	06:14:20	4.2	5
2011-01-07	12:56:42	4.1	5

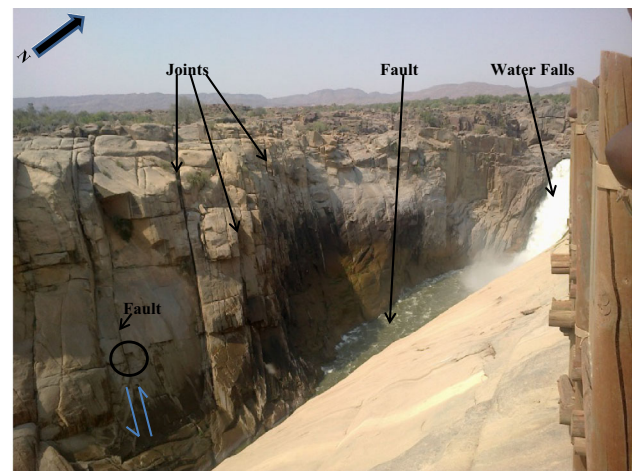
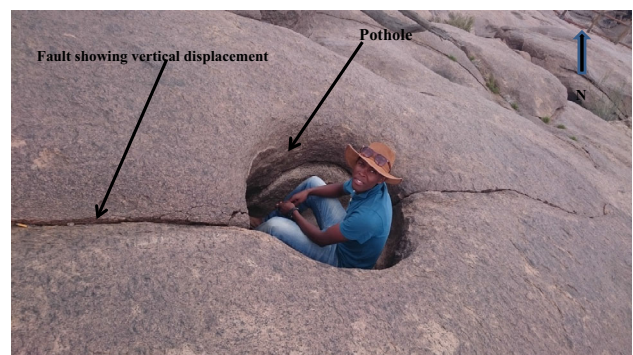
stress generally in a pre-existing zone of weakness in response to plate tectonic forces (Talwani 2004). These local stress concentrators can take the form of intersecting faults, fault bends, and buried plutons. In South Africa, recent tectonic surface uplift can also be used to infer neotectonics.

4.3 Augrabies Falls faulting, lineaments, and potholes: evidence of the Griqualand-Transvaal neotectonic axis of surface uplift

4.3.1 Faulting and lineaments

In the Northern Province of South Africa, this surface uplift caused major faulting and formed the Augrabies Falls (Fig. 4). It is noteworthy to indicate that water in the Augrabies Falls flows through metamorphic rocks. The flow of water in the Augrabies Falls can be explained by the presence of the fault as a result of the surface uplift. Moreover, from the satellite image, it appears that many faults and lineaments are concentrated along the Orange River, which can probably be a fault that is possibly being reactivated due to recurrent seismicity in the area. Faults and lineaments around it are possibly splays. On the other hand, high density of lineaments (Fig. 3 left) is indicative of possible neotectonics.

The presence of joints almost oriented E-W and cutting the fault at high angle suggests that there is a minor local stress perturbation in the area that generated them (Fig. 4), the major stress field being the Wegener Stress Anomaly. These joints probably formed after the generation of the fault, because they have an orientation different from the one of the fault. Parallel joints are good indicators for the indication of stress field orientation; generally, parallel joints dovetail the orientation of the great compressional stress σ_1 and non-parallel joints are however good for hydrogeology and engineering. Neotectonics in this area is also confirmed by the presence of a fracture that can be assimilated to a fault because of an evident vertical dip-slip movement (Fig. 5). Conjugate joints are also visible in the Augrabies Falls area. Conjugate joints are good to infer the

**Fig. 4** The Augrabies Falls and water flowing in the fault zone, joints strike at a high angle to the fault. The circle shows a displacement of a horizontal joint by a vertical joint that was reactivated**Fig. 5** A fracture showing a dip-slip movement and cutting across a pothole

orientation of the great and least principal local stresses. σ_1 bisects the acute angle and σ_3 the obtuse angle. As shown in Fig. 6, conjugate joints show extension in the direction of the least stress. A deduced strain ellipse shows elongation in the direction of the least stress and shortening in the direction of the compressional stress.

4.3.2 Potholes

Some potholes at an elevated height (617 m above sea level) are visible on a dry surface (Fig. 6). A plausible explanation for the occurrence of these potholes is as follows: (1) the flow of water at an exceedingly very high energy regime because the orthogneisses hosting the Augrabies Falls are very indurated; (2) some of these potholes have a diameter and a depth of approximately 1 m; with such dimensions, the water would have flowed for a very long period of time to produce such structures in a very indurated rock. Potholes occur when water is flowing, but at the Augrabies Falls area nowadays these

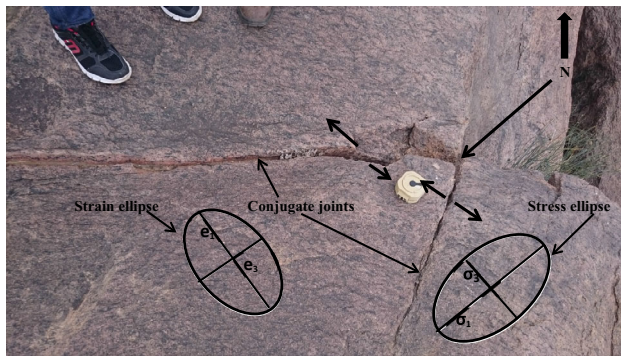


Fig. 6 Example of conjugate joints in the Augrabies Falls orthogneiss; the longer diameter in the stress ellipse indicates the direction of σ_1 and the shorter diameter the direction of σ_3 . The strain ellipse is deduced from the local stresses acting during generation of conjugate joints

potholes are exposed on a dry surface with no water flow at high altitude as mentioned above. If there is no water flow, and at such high altitude, this can be the result of the Griqualand-Transvaal neotectonic uplift that took place in the Quaternary. The fault and joints are shown in Fig. 4 and the potholes in Fig. 5. The fault in Fig. 5 probably occurred later after the major uplift event. This fault cuts across a pothole, which has acted as a stress release zone. Potholes were formed first, secondly the neotectonic surface uplift took place exposing the pothole, and lastly the stress around the pothole was released causing the rock to crack. This fault can also, to a certain extent, be an indication of on-going surface uplift because of the dip-slip component. The area of the Augrabies Falls is definitely beset by neotectonics.

5 Discussion and conclusions

Two major factors that cause neotectonics in the area of the Augrabies Falls in the Northern Cape Province in South Africa are (1) the recurrent seismic activity and (2) the surface uplift along the Griqualand-Transvaal axis. The recurrence of seismicity around the Augrabies Falls can be related to the intersection of faults (Fig. 3). King (1986) stated that fault intersections control seismic occurrences over many years, thus providing locations for the initiation and cessation of ruptures, and controlling the size of the earthquakes. Intersections also control earthquake sequences by loading or unloading stresses on adjacent or intersecting faults (King et al. 1994). Many epicenters around the Orange River are clustered and are considered as areas of stress concentration. Brandt (2011) highlighted that the Augrabies area is highly deformed with faults that can be considered as zones of weakness. Zoback and Healy (1984), however, noted that the concentration of seismicity

on fault zones is also apparent away from the present plate boundaries inside the continents. When old lineaments are reactivated under a new stress regime, the preference of stress release along them is indicative of their mechanical weakness. Clustering of epicenters in the area, hypocentral depths of the seven seismic events (Table 1), and high lineament density are in line with intraplate continental earthquakes' characteristics. Talwani (1999) mentioned that, unlike earthquakes at plate boundaries, intraplate earthquakes tend to be spatially clustered in relatively small regions, which are locations of very local stress build-up and higher strain rates. Seismic epicenters in southern Africa from 1620 to 1993 (e.g. Fernández and du Plessis 1992) display clusters that can be associated to areas of stress concentration (Figs. 2, 3). Jackson and Blewett (1993), Carnelbeek and Iranga (1996), and Nyblade et al. (1996) indicated that the hypocentral depths are generally shallow for intraplate continental earthquakes. The higher density of lineaments (Fig. 4) can be an indication that neotectonics is active in the area. Kumanan (2001) found in India that lineament density maxima zones and lineament intersections were buffered out as possible neotectonic zones.

Arguments of Werger and Coetzee (1977) suggested that the Augrabies Falls were cutting back eastwards along faults in the pink gneiss seem uncertain to reconcile. The fault along which the water flows from the falls can be justified by the Griqualand-Transvaal axis surface uplift; this is in agreement with Andreoli (pers com) who indicated, for instance, that the surface uplift of the Amatole-Swaziland (formerly Ciskei-Swaziland) axis that occurred during the Mio-Pliocene might have generated some fractures in the Karoo aquifers. The fault along which the water flows from the falls is an expression of the Griqualand-Transvaal axis of the surface uplift that took place in the Miocene-Pliocene-Pleistocene epoch. Gneisses are known to be bad aquifers because of their hardness, poor porosity, and poor permeability. Because of the surface uplift, the metamorphic rocks broke easily with a surface expression of joints and faults. Ransome and de Wit (1992) made mention of the differential uplift of ca 30 m experienced by the region around the mouth of the Orange River relative to the Saldanha Bay area.

Another evidence of the uplift is the presence of potholes. Potholes are formed in an area where the riverbed is uneven. The water may encounter a protuberance and swirls around it in a whirlwind pattern; or the water in the swirling current around a pebble can make it to move in a circular path. These potholes around the Augrabies Falls are nowadays visible on a dry surface in the gneisses at a height of approximately 617 m above sea level. This is in favour of the argument that the water was flowing over the bed of a river and led to the formation of these potholes;

the absence of water flow or a river nowadays is a consequence of the surface uplift. In southern Africa, the uplift took place in the early Miocene (up to 300 m) and in the late Pliocene and Pleistocene (up to 900 m) with no stretching or shortening of the crust. According to Artyushkov and Hofmann (1986), this is indicative of a plume material in some regions that ascended from below and rapidly spread along the base of the lithosphere, and eroded the mantle lithosphere in vast areas beneath the continents. In regions with hot asthenosphere, a strong weakening of the mantle lithosphere which allows its erosion can be associated with the high temperature of the plume material. In regions where the asthenosphere is at moderate temperature, weakening of the mantle lithosphere can result from infiltration of volatiles from the plume material.

Mitrovica et al. (2000) reported that Southern Africa is being uplifted by a large-scale positively buoyant plume within the mid-lower mantle. On the basis of geological observations, they estimated residual topography and average Cenozoic uplift rate to be 300–600 m and 5–30 m/Myear, respectively, for Southern Africa. The Augrabies Falls area is not a stable area to be considered for the storage of nuclear wastes because of the recurrent seismicity and possible reactivation of old fractures, which can act as conduits for water that can carry nuclear wastes and contaminate the groundwater.

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