The Namibian Eiseb Graben as an extension of the East African Rift: evidence from Landsat TM 5 imagery

H. Wanke
LFB Hydrogeology and Environment
Geological Institute of the University of Würzburg, Pleicherwall 1, 97070 Würzburg, Germany
E-mail: a.h.wanke@web.de

ABSTRACT

In this study four subparallel faults have been recognised in the Eiseb Block in the field and in Landsat TM 5 scenes. Their extension into Botswana's Gomare and Kunyere faults, which delineate the Okavango Rift/Botswana, has been traced. In the Eiseb Block abrupt termination of Kalahari dunes corresponds with northeast-southwest trending tectonic lineaments, whereas a second set of north-northwest to south-southeast orientated lineaments is evident from the orientation of rivers. The two systems intersect in the central part of the study area. Weighted lineament trends show peaks at northeast to southwest (41° to 50°) and north-northwest to south-southeast (151° to 160°). A field survey revealed small extensional faults of corresponding orientation. The fact that Kalahari dunes are displaced since their last active phase shows that the faulting is post-35 to 28 ka. However, the Eiseb Graben and associated lineaments seem to be a long-lived, probably reactivated structure that follows the pre-existing structures of the Damara inland branch, Karoo trough, and basin structures of the Kalahari.

Introduction

In the Eiseb Block of eastern Namibia four subparallel southwesterly trending faults can be clearly recognised in topographic maps, aerial photographs and in satellite images. Hegenberger (1982) described dunes in the lower Eiseb and Epukiro catchment to be structurally displaced by several lineaments that can be traced into the Gomare fault zone of the Okavango Rift. Miller and Schalk (1980) have indicated four faults (Figure 1) in the Geological Map of Namibia. However, no extension of these faults into Botswana is found in the latest version of the Botswana Geology Map (Key and Ayers, 2000).

The aim of this paper is to identify these four faults in the field and in Landsat TM 5 scenes, to establish their age and investigate their extension into Botswana. Further lineaments are mapped in the lower catchments of the Eiseb and the Epukiro Omuramba (ephemeral river) and are compared to structural data from the Okavango Delta. Subsequently a tectonic interpretation is made.

Interpretation of Landsat TM 5 Scenes

Two scenes of Landsat TM 5 have been used for the mapping of lineaments in the Eiseb Block: LTM 176-74 and LTM 176-75, date of acquisition 1984-07-02. More recent satellite images have been avoided to minimise interference with newly established human settlements and subsequent road development. After georeferencing the scenes, lineaments were mapped with channel combination 3-2-1 (true colour composite), 7-4-1, 7-5-4 and 7-3-1 on the blue, green and red channel of the processing software (TNTmips by MicroImages, 1996). Straight flood courses and the abrupt termination and displacement of dunes (Figure 2) are the most obvious features for the identification of lineaments. Well developed vegetation trends along lineaments, most likely resulting from groundwater flow lines which follow joints in the partly consolidated sediments of the Kalahari Group, have also been used. Joints that are used as groundwater routings are seen in wetter soil. Very distinctive features defining lineaments are meanders that have been disrupted and calcrete surfaces forming distinct elongated features.

The mapped lineaments are given in Figure 3 together with Landsat TM channel 1. Two major lineament orientations can be observed: north-northwest to south-southeast and northeast to southwest. While the the northeast to southwest trend is clearly defined by dune termination; the north-northwest to south-southeast trend is best defined by the orientation of rivers, *e.g.* the Omuramba Daneib and tributaries to the Rooiboklaagte. The two systems intersect in the central part of the study area.

The frequency distribution of lineaments in the Eiseb Block has been illustrated in a rose diagram (Figure 4). The peaks of the weighted lineament trends are at northeast to southwest (41° to 50°) and north-northwest to south-southeast (151° to 160°) with 88 % of the measured lineaments lying between 21° to 70° and between 131° to 170°. The most obvious trend from the study area, namely the orientation of dunes (Figure 3), has been left out in this interpretation as it is orientated by the paleowind direction and is thus not of tectonic origin.

In the satellite images it was observed that the dunes southeast of the Eiseb Lineament are smaller and lower than the dunes northwest of it. The dune separation is the same on both sides, as interdunes are wider

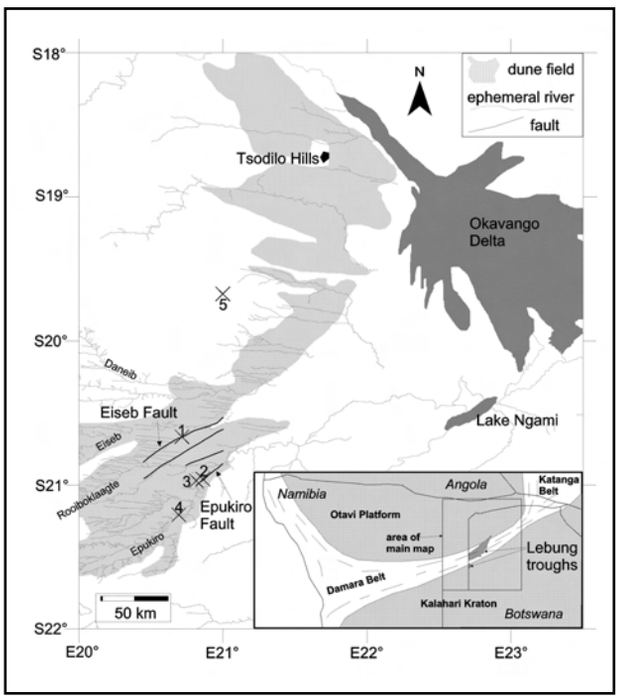

Figure 1. Locality map of the study area. The dune fields have been digitized from satellite imagery. The four faults in the Eiseb Block have been adopted from Miller and Schalk (1980). The insert in the lower right part of the figure gives an overview of the basement fabrics (modified after Daly *et al.* 1989) and the location of the Lebung (Karoo) troughs according to Key and Ayers (2000). Location X1 indicates Otjinanguruwe where the Eiseb fault scarp is accompanied by a shallow ridge of calcrete. Locations X2 to X5 where used to identify tectonic activity as the source of displacement and are referred to in the section "field observations".

southeast of the Eiseb Lineament. This might indicate filling of the interdune area due to enhanced accommodation space by a relative movement downward at the southeastern side. An alternative explanation for the narrow dune remnants on the southeastern side of the Eiseb fault is degradation of the original dunes by flooding. The flooding from the Okavango Delta (Figure 3) reached only the morphologically lower area southeast of the Eiseb fault. Both explanations are consistent with down-throw to the southeast, and thickness variations of at least 150 m of the Kalahari Group sediments (Klock, 2002) confirm this observation of subsidence between the Eiseb and the Epukiro faults.

Field observations

The Eiseb Lineament is easily recognisable in the topographic sheets of the area. In the field the fault-line scarp was found to separate a flat plain to the southeast from rising dunes towards the northwest. The fault-line scarp is partly accompanied by small ridges (~5 cm high) of calcrete (*e.g.* near Otjinanguruwe south20°39.92/east20°42.915, X1 in Figure 1).

Good exposures of lithified Kalahari sediments are rare in the study area and only few indicators of young tectonic activity were found. A small outcrop on the northern bank of the Omuramba Epukiro (south21°12.4/east20°41.6, X4 in Figure 1) showed a slight relative off-set down to the east where Kalahari silcrete layers are cut by a fault. This outcrop is located at a northwest-southeast trending lineament (indicated by a small black arrow in Figure 3). Associated with a basalt outcrop at the Botswana-Namibia-border (south19°40.39/east20°59.93, X5 in Figure 1), north of the Eiseb Block, a small extensional fault cutting through the basalt and the overlaying conglomerate is still visible in the covering red soil. Vertical displacement has been determined by lithostratigraphic correlation between the two banks of the Omuramba Epukiro: the sequence is displaced about 15 m down to the south (south20°57.54/east20°51.65, X2 in Figure 1). In the outcrop of the northern bank small displacements (Figure 5) have been observed in the top part of a limestone layer of the Eiseb Formation (Middle Kalahari Group). A north-northwest to south-southeast trending fault was found in the southern cliff of the Omuramba Epukiro (south20°58.20/east20°48.87, X3 in Figure 1) with a displacement of 1-2 m down to the west (Figure 6).

Taking into account that Karst features in the study area are relatively limited and small, it appears more likely that a displacement of 15 m has a tectonic origin. Displacement of such a large block as shown in Figure 6 is also likely to be a tectonic feature rather than a Karst feature.

Time of faulting

The northeasterly striking faulting must be recently active as dunes are displaced. The dunes in the lower catchments of Eiseb and Epukiro Omuramba are

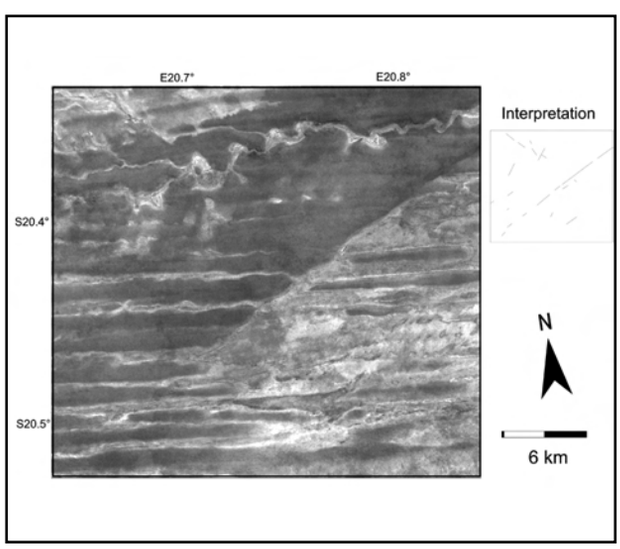

Figure 2. Selection of the lower Eiseb catchment in channel 1, LTM5 176-75, date of acquisition 1984/07/02 with interpretation of lineaments. Dunes are cut by northeast to southwest trending lineaments while the tributaries to the Omuramba in the upper left corner of the image follow northwest to southeast trending lineaments.

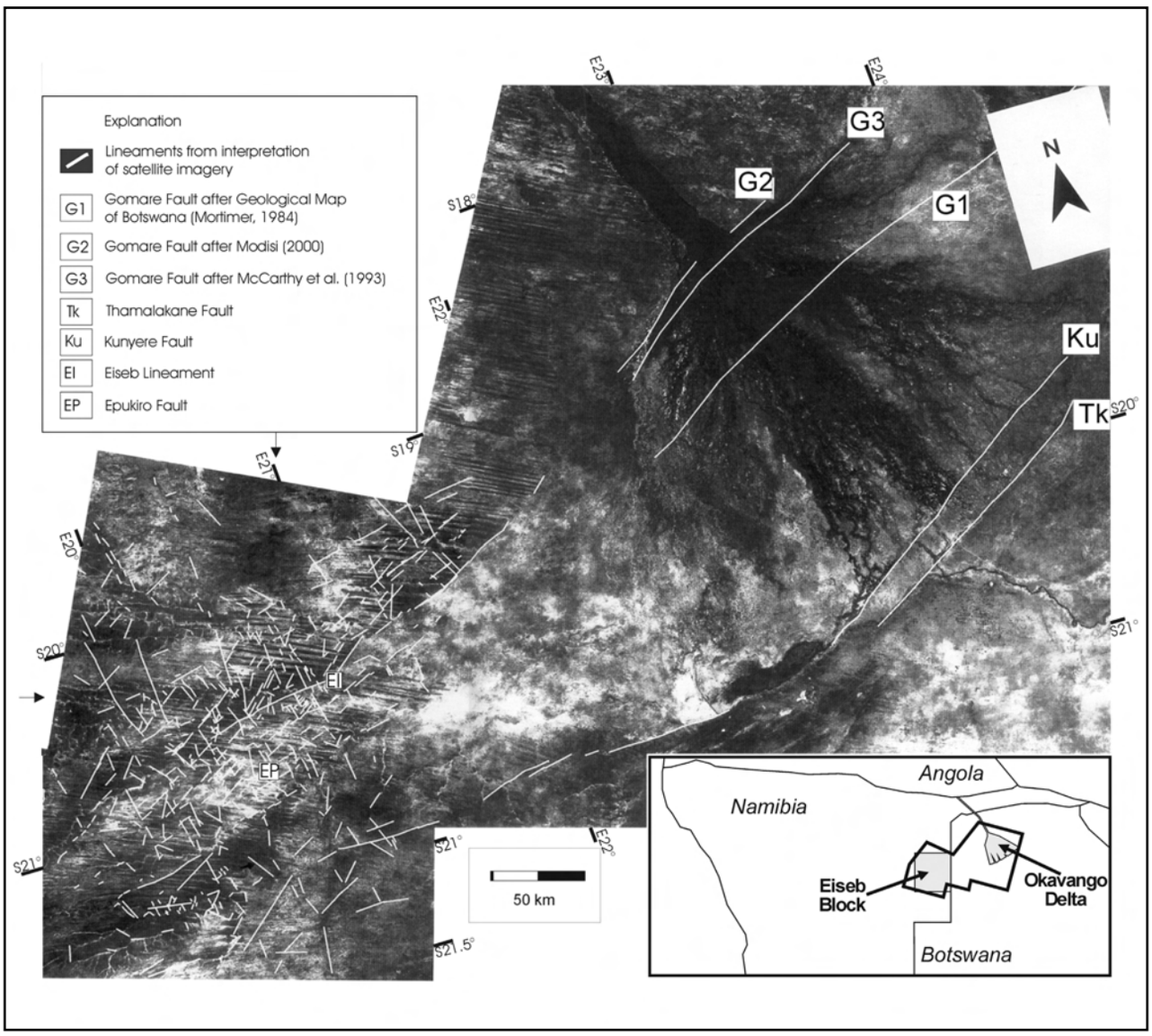

Figure 3. Interpretation of lineaments from satellite imagery for the Eiseb Block (left) and reported major faults from the Okavango Delta (right) with channel 1 of Landsat Thematic Mapper 5, scenes 176-74, 176-75 (date of acquisition 1984/07/02), 175-73, 175-74, 173-75 (date of acquisition 1984/06/09), 174-73 and 173-74 (date of acquisition 1984/07/04). The location of Figure 2 is indicated by arrows at the borders of the satellite image.

situated in the southern part of a dune field that reaches up to the Tsodilo Hills in Northwestern Botswana (Figure 1). The last activity of the dunes has been dated at 35 to 28 ka by Thomas *et al.* (2003). This is consistent with ages of surrounding dune fields, *e.g.* the Omatako dune field west of the study area with 43 to 21 ka (Thomas *et al.*, 2000). Latest fault activity is therefore constrained to be post-35 to 28 ka.

Regional correlation and interpretation

Major faults from the Okavango Delta also shown in Figure 3 are the Thamalakane Fault, the Kunyere Fault and the Gomare Fault. The first two faults are clearly identified as they follow the rivers they are named after. The assignment of the name Gomare Fault to fault lineaments shows some confusion in the literature. Three different faults in the northern part of the delta are named Gomare Fault after the town Gomare (or Gumare in some maps) at the delta's border. The southeastern most of the three faults (G1 in Figure 3) is taken from Mortimer (1984), the northwestern most (G3 in Figure 3) was named the Gomare Fault by McCarthy *et al.* (1993) and the fault G2 (Figure 3) was named the Gomare Fault by Modisi (2000) and Modisi *et al.* (2000). From the mapped pattern it was observed that the Gomare Faults G2 and G3 could be traced into Namibia towards the lineament that has been named the Eiseb Lineament by Hegenberger (1982). The Gomare Fault G1 is more likely to be traced into Namibia's Epukiro Fault. While the Kunyere Fault is traceable into Namibia, the Thamalakane Fault is not found west of Lake Ngami. The northeast to southwest trending Kunyere Fault bends towards east-northeast to south-southwest directions west of Lake Ngami.

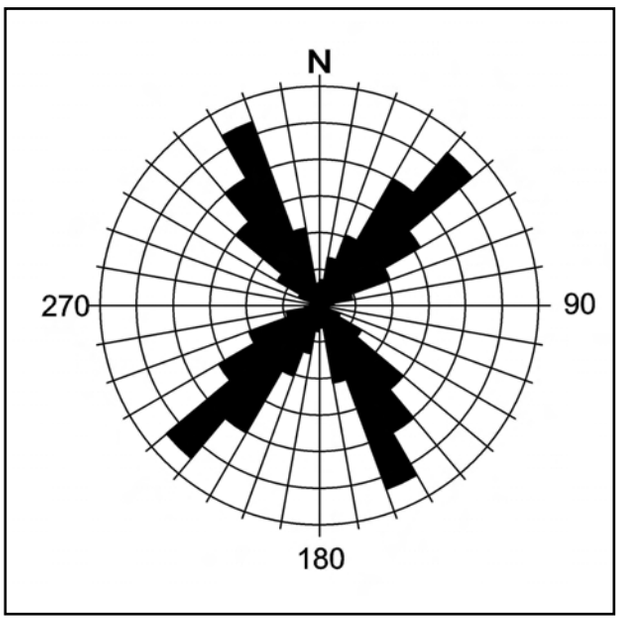

Figure 4. Frequency distribution of lineament trends for the Eiseb Block observed from satellite imagery interpretation. Lineaments have been weighted according to the length of traceability in the Landsat TM 5 imagery.

The dominant lineament trends in Figure 4 are consistent with observations from Hutchins *et al.* (1976), who found principal orientations of lineaments in the Okavango Delta, mapped by the use of Landsat imagery, between 140° to 160° (with 140° to 150° being the more frequent direction) and a second peak at 40° to 50°. The Kunyere and Thamalakane faults also follow the direction of approximately 40°. McCarthy *et al.* (1993) obtained slightly different results from the interpretation of SPOT images. The most common direction from their interpretation is east-southeast (100 to 110°) which they interpreted as traces of dune orientation and a Karoo dyke swarm and are thus not of primary tectonic origin. Apart from these features, their observed main directions are 60 to 70°, 120 to 140° and 150 to 160°. The 60 to 70° and 120 to 140° orientations are also observed in the Namibian study area, but they are evidently less significant than the 40 to 50° and the 150 to 160° peaks (Figure 4).

Reeves (1972) proposed incipient rifting in the Kalahari, and the Okavango Delta has been seen as the southwestern extension of the East African Graben System due to its seismic activities and similar sense of crustal extension (Scholz *et al.*, 1976; Fairhead and Henderson, 1977; McCarthy *et al.*, 1993). East-west extension of the African continent is believed to have reactivated ancient, northeasterly-trending basement structures and the Okavango Delta is interpreted as a large half-graben structure formed by this mechanism (McCarthy *et al.*, 1993). Modisi (2000) indicates continuation of the rift further to the north into the Caprivi Strip of Namibia and it is most likely that it can be traced further into Zambia and Lake Kariba (Mallick *et al.*, 1981; Scholz *et al.*, 1976). It seems likely from the observation of satellite imagery, thickness variations of the Kalahari Group and geophysical research by CSIR (1982) that the continuation of the half-graben structure

Figure 5. Interpreted photo of a limestone layer of the Eiseb Formation (Middle Kalahari Group) showing small displacements (S20°57.54/E20°51.65, X2 in Figure 1). This small displacements are associated with a larger displacement (allocated by lithostratigraphic correlation) of 15 m with this bank of the Omuramba Epukiro compared to the southern bank.

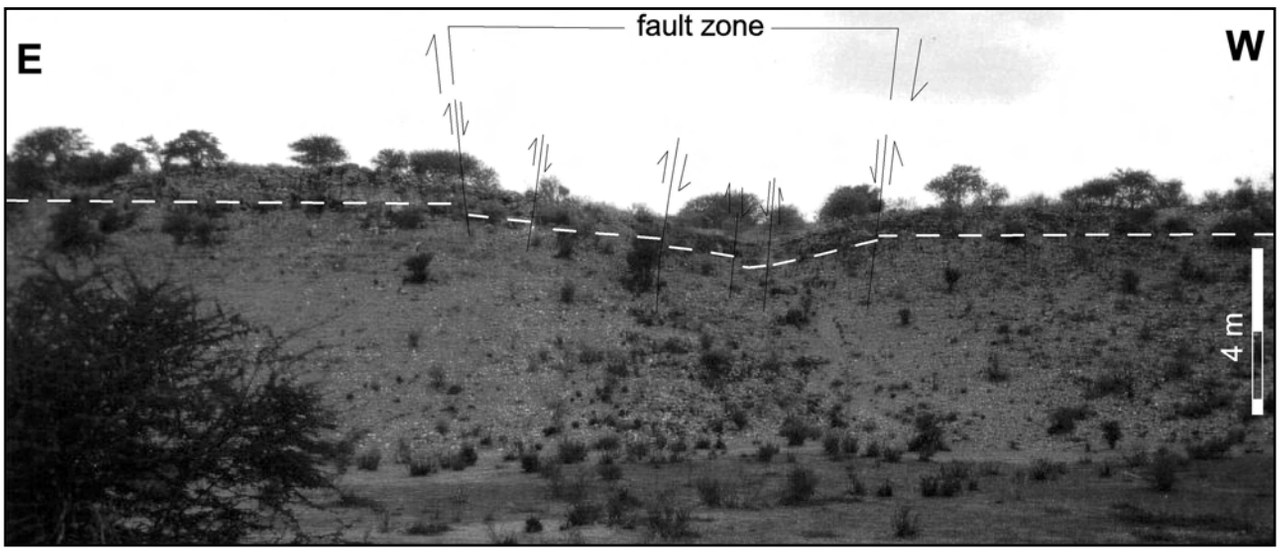

Figure 6. Interpreted photo of a north-northwest to south-soiutheast trending fault that was found in the southern cliff of the Omuramba Epukiro (S20°58.20/E20°48.87, X3 in Fig. 1) with a displacement of 1 to 2 m down to the west.

from the Okavango Delta can be traced into the Namibian Eiseb Graben. Hegenberger (1982) proposed that this structure follows a deep (lithospheric?) zone of weakness, also referred as a geophysical conductor, which was observed by De Beer and van Zijl (1975) and De Beer *et al.* (1976) with a magnetovariational study, and interpreted as a southwestward extension of the African Rift System. This structure is indicated to reach the Namibian border between 20° and 21° latitude with a northeast to southwest trend and then bend into east-west direction and, at a longitude of about E17° curve back to northeast to southwest direction. The bending of the conductor cannot be seen in the Gomare Fault (or Gomare fault system), but the southern edge (Kunyere Fault) of the postulated rift follows this trend (Figure 3).

Additionally the Eiseb Graben follows the trend of the established structures of the Damara inland branch (Figure 1). It also follows the Karoo troughs indicated as Lebung strata by Key and Ayers (2000). A thickness increase of at least 150 m in the Eiseb Graben compared to the surrounding area also indicates that the structure has been active during the deposition of the Kalahari Formation and not only of the Kalahari beds. Thus the Eiseb Graben appears to be a long-lived, probably reactivated structure that follows established trends.

The global seismic network does not indicate current earthquake activity in the area of the Eiseb Graben. Seismic data from Fairhead and Henderson (1977) show only activity at the Okavango rift and a single event northwest of the Eiseb Block. From the field observation, however, it is clear that tectonic activity has occurred and the displacement of dunes indicates Holocene activity. The global seismic network records events since only the past few decades, which is a relatively short time compared to the assumed age of last tectonic activity post-35 to 28 ka.

A possible explanation for the lack of seismic events in the last 25 years is the fact that fault systems are not always active along their entire length (*e.g.* San Andreas Fault [Allen, 1968]). An additional factor influencing the seismically less active Eiseb Graben in comparison to the Okavango Rift might be the lack of underground water. In the Okavango Delta, the groundwater is only a few meters deep, while the unsaturated zone in the Eiseb Block is up to 150 m thick (Klock, 2002). The presence of groundwater may increase tectonic activity due to the weakening effect that water has in fracture systems (*e.g.* Rutter, 1983).

Conclusions

In this study prominent lineaments off-setting Kalahari Dunes have been identified in the Eiseb Block. A tectonic origin for the lineaments is indicated by remote sensing, and field observations. Tectonism post-dates dune activity (post-35 to 28 ka). Despite the lack of recorded seismicity, there is therefore reasonable evidence for Holocene tectonic activity in the Eiseb area. Provided the Eiseb Block faults are correctly interpreted as a continuation of the Okavango half-graben into northeastern Namibia, the study area is predicted to be undergoing extension at the present day. The data and interpretations in this paper therefore suggest that the Eiseb Graben is a further southwest extension of the East African Rift.

References

Allen, C. (1968). The tectonic environment of seismically active and inactive areas along the San Andreas fault system. *In:* W. R. Dickinson and A. Grantz (Editors), Proceedings of Conference on Geologic Problems of the San Andreas fault system. *Stanford University Publications, Stanford, USA*, 70-82.

CSIR (Council for Scientific and Industrial Research) (1982). Geoelectrical survey in the Gam area and Eiseb Omuramba. Compiled by J. H. De Beer, J. Blume, J., A. Du Plooy and J. H. B. Kruidenier for the National Physical Research Laboratory to the Council for Scientific and Industrial Research,

Pretoria, South Africa, 75pp.

Daly, M.C., Chorowicz, J. and Fairhead, J. D. (1989). Rift basin evolution in Africa: the influence of reactivated steep basement sheer zones. *In:* M. A. Cooper and G. D. Williams (Editors), Inversion Tectonics, *Special Publication of the Geological Society of London*, **44**, 309-334.

De Beer , J. H. and van Zijl, J. S. V. (1975). An electrical conductivity anomaly and rifting in Southern Africa. *Nature*, **225**, 687-689.

De Beer , J. H., van Zijl, J. S. V., Huyssen, R. M. J., Hugo, P. L. V., Joubert, S. J. and Meyer, R. (1976). A magnetometer array study in South West Africa, Botswana and Rhodesia. *Geophysical Journal of the Royal Astronomical Society*, **45**, 1-17.

Fairhead, J. D. and Henderson, R. W. (1977). The seismicity of southern Africa and incipient rifting. *Tectonophysics*, **41**, T19-T26.

Hegenberger, W. (1982). The regional geology of northeastern South West Africa/Namibia. *Regional Geology Series, Geological Survey of Namibia*, 22pp.

Hutchins, D. G., Hutton, L. G., Hutton, S. M., Jones, C. R. and Loehnert, E. P. (1976). A summary of the geology, seismicity, geomorphology and hydrogeology of the Okavango Delta. *Bulletin of the Geological Survey of Botswana*, **7**, 1-27.

Key, R. M. and Ayres, N. (2000). Botswana Geology Map. *Journal of African Earth Sciences*, **30**, CD-ROM Supplement.

Klock, H. (2002). Hydrogeology of the Kalahari in north-eastern Namibia with special emphasis on groundwater recharge, flow modelling and hydrochemistry. *Hydrogeologie und Umwelt*, **31**, 1-196.

Mallick, D. I. J., Habgood, F. and Skinner, A. C. (1981). A geological interpretation of Landsat imagery and air photography of Botswana. *Institute of Geological Sciences Overseas Geology and Mineral Resources*.

McCarthy, T. S., Green, R. W. and Franey, N. J. (1993). The influence of neo-tectonics on water dispersal in the northeastern regions of the Okavango swamps, Botswana. *Journal of African Earth Sciences*, **17**, 23-32.

MicroImages (1996). TNTmips Version 5.4. MicroImages Inc., Lincoln, USA.

Miller, R. M. and Schalk, K. E. L. (1980). Geological Map of Namibia. *Geological Survey of Namibia*.

Modisi, M. P. (2000): Fault system at the southeastern boundary of the Okavango Rift, Botswana. *Journal of African Earth Sciences*, **30**, 569-578.

Modisi, M. P., Atekwana, E. A., Kampunzu, A. B. and Ngwisanyi, T. H. (2000). Rift kinematics during the incipient stage of continental extension: Evidence from the nascent Okavango rift basin, northwestern Botswana. *Geology*, **28**, 939-942.

Mortimer, C. (1984). Geological Map of Botswana. *Geological Survey of Botswana*.

Reeves, C. V. (1972). Rifting in the Kalahari? *Nature*, **237**, 95-96.

Rutter, E. H. (1983). Pressure solution in nature, theory and experiment. *Journal of the Geological Society of London*, **140**, 725-740.

Scholtz, C. H., Koczynsky, T. A. and Hutchins, D. G. (1976). Evidence for incipient rifting in southern Africa. *Geophysical Journal of the Royal Astronomical Society*, **44**, 135-144.

Thomas, D. S. G., O'Connor, P. W., Bateman, M. D., Shaw, P. A., Stokes, S. and Nash, D. J. (2000). Dune activity as a record of late Quaternary aridity in the northern Kalahari: new evidence from northern Namibia interpreted in the context of regional arid and humid chronologies. *Palaeogeography, Palaeoclimatology, Palaeoecology*., **156**, 243-259.

Thomas, D. S. G., Brook, G., Shaw, P., Bateman, M., Haberyan, K., Appleton, C., Nash, D., McLaren, S. and Davies, F. (2003). Late Pleistocene wetting and drying in the NW Kalahari: an integrated study from the Tsodilo Hills, Botswana. *Quaternary International*, **104**, 53-67.

Editorial handling: L. D. Ashwal