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COMMUNICATIONS OF THE GEOLOGICAL SURVEY OF NAMIBIA

VOLUME 28
2025

CONTENTS

Papers:

Reports:

Notes:

Cover image: Oblique satellite image of the Cuvelai Basin of Namibia and Angola: notable features are the wide channels of the Cuvelai, the complex of Omadhiya Lakes, many large salt pans, and the great expanse of Etosha Pan; the country border is represented by the indicated diagonal line across the bottom left corner (adapted from Google Earth, courtesy of J. Mendelsohn)

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Seismicity of North-western Namibia during the Period 01 January to 31 May 2012

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Abstract :- The aim of this study was to investigate the seismicity of north-western Namibia, which correlates with a zone of predicted long-term average high strain rates. Consequently, the local seismicity was monitored over a five month-period (01 January – 31 May 2012) to determine how seismically active the area actually is. During this time a total of 281 earthquakes, 149 of which were aftershocks, with local magnitudes from -0.4 to 4.7 M_L were recorded. Analysis centred upon events surrounding the earthquake which occurred on March 24, 2012 (origin time 4:43:52, location -20.127° S / 14.461° E, depth of 0.1 km and magnitude 4.7 M_L) approximately 60 km northwest of Khorixas, in order to identify precursors, if any, as well as the sequence of aftershocks. The present investigation revealed a new seismic zone characterised by smaller magnitude earthquakes, named here the Kamanjab Seismic Zone. The study is part of the WALPASS project which deployed 40 temporary seismic stations on- and offshore north-western Namibia from October 2010 to November 2012. Its goals were to image the lithosphere and deeper upper mantle in the ocean-continent transition beneath the passive continental margin of northern Namibia, and to detect seismic anomalies.

Keywords :- Seismicity; Earthquake; Kamanjab Seismic Zone

Introduction

Seismicity in Namibia is considered to be low to moderate (Fig. 1), the first earthquake having been recorded in 1910. Before the establishment of the Namibian Seismological Network (NSN) in 2002, the country only had two seismic stations, located in Tsumeb and Windhoek, which were operated by the United States Geological Survey (USGS) and the World-wide Standardised Seismological Network (WWSSN), respectively (Mangongolo and Hutchins, 2008). This sparse seismic network meant that only larger earthquakes were documented, while smaller ones that are easily attenuated, remained undetected. Although, by 2010 the NSN had increased to eight permanent seismic stations, this was still inadequate for a huge country like Namibia, with a low population density. For this reason, the WALPASS (Walvis Ridge Passive Source Seismic Experiment) Project was initiated by GFZ (Deutsches GeoForschungsZentrum), which deployed 12 ocean-based (OBS) and 28 land-based (LBS) temporary broadband seismic stations between October 2010 and November 2012, offshore and onshore north-western Namibia (Fig. 2). The project was aimed, firstly, at imaging the structure of the crust and upper mantle beneath the passive continental margin of northern Namibia and, secondly, at finding seismic anomalies related to the postulated hotspot track from the continent out into the South Atlantic Ocean along the Walvis Ridge (Heit *et al*., 2012). In addition, the data generated by this project was used to study and analyse the seismic activity of north-western Namibia.

Geological Setting

The study area spans a portion of the Damara mobile belt, which consists of a coastal arm (Kaoko Belt) and a NE-SW striking intracontinental arm (Damara Belt *sensu stricto*; e. g. Porada, 1979). The coastal Kaoko Belt and the intracontinental Damara Belt are genetically individual orogens joined together during the amalgamation of Western Gondwana (Porada, 1989; Fig. 3). The two orogens have distinct structural trends and styles. While the Kaoko Belt with its NNW-trending structural grain resulted from oblique, south-westerly subduction of the Congo Craton beneath the South American Craton, the ENE-trending Damara Belt developed during collision of the south-eastern Kalahari and north-western Congo Craton (Gray *et al*., 2008). Both, the Kaoko and Damara Belt consist of a number of distinct, fault- or thrust-bounded tectonostratigraphic zones characterised by deformation style, metamorphic grade and lithology (Fig. 4), with the junction of the two branches, southwest of Khorixas, displaying complex deformation patterns (Gray *et al*., 2008). The south-west African passive margin originates from the break-up of the Gondwana supercontinent, which in western Gondwana began during the Early Cretaceous (Ewart *et al*., 1998).

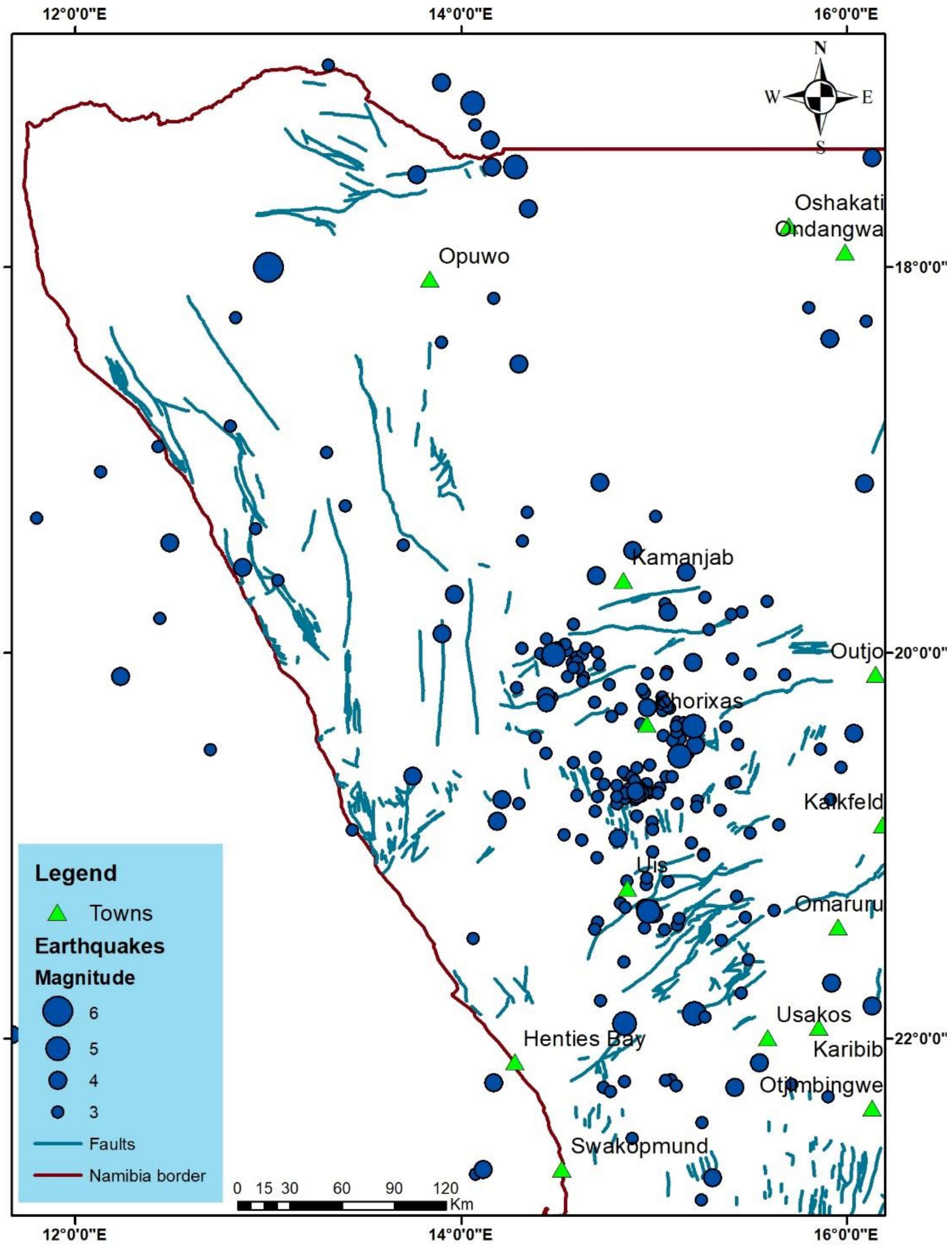

Figure 1. Seismicity of north-western Namibia (International Seismology Centre, ISC)

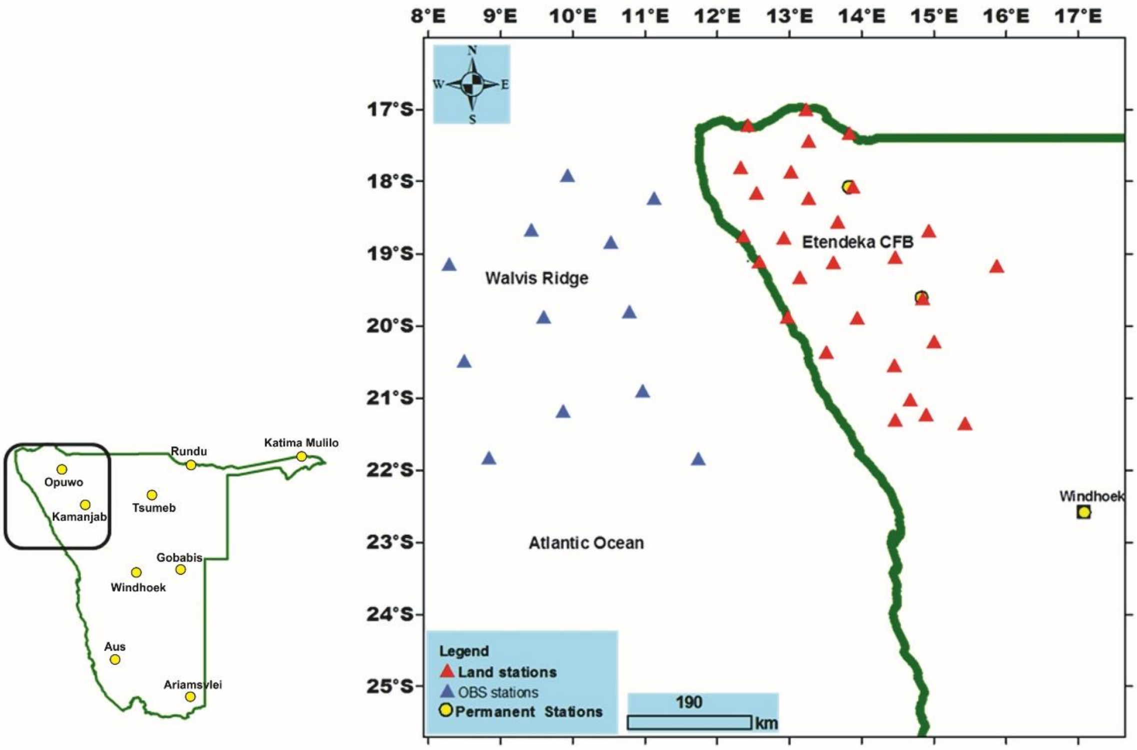

Figure 2. Temporary seismic network deployed by the WALPASS project showing the 12 ocean-based (OBS) and 28 land-based (LBS) stations; left: NSN permanent stations (yellow dots) and extent of the study area

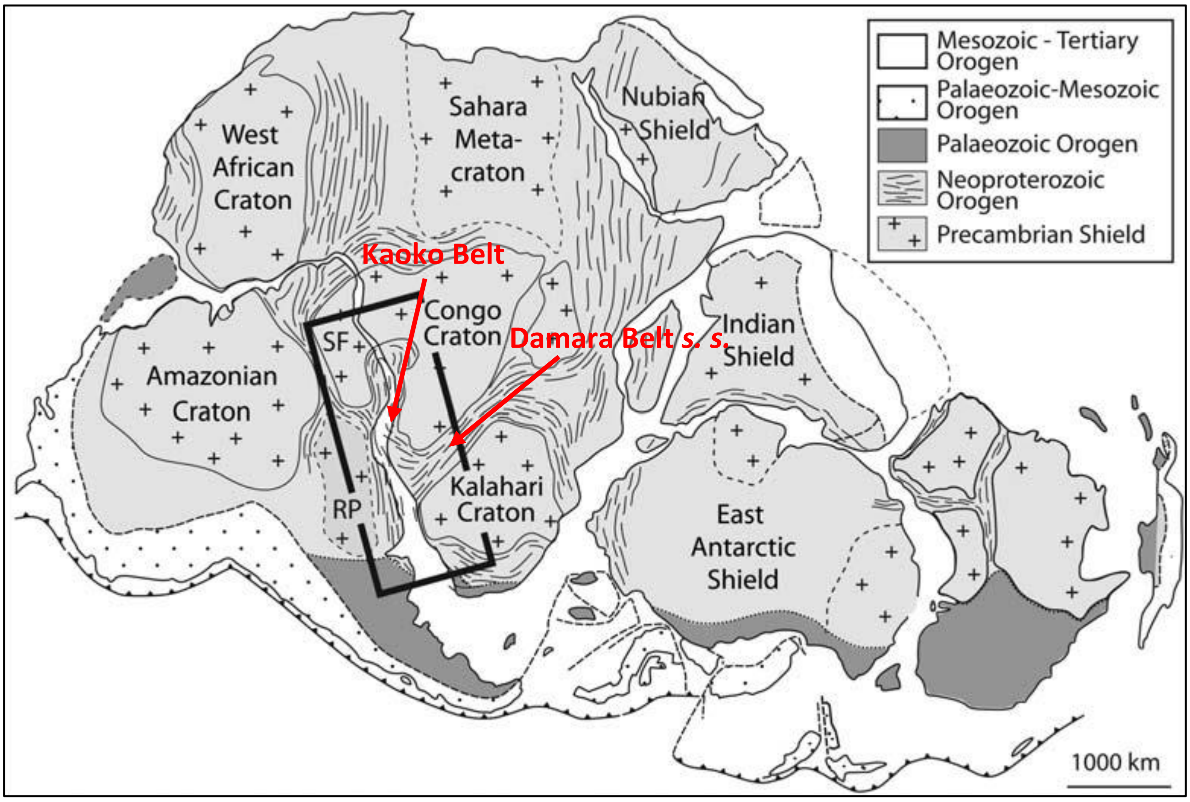

Figure 3. Schematic map of the Gondwana supercontinent showing the positions of cratons and orogenic belts (after Gray *et al*., 2008)

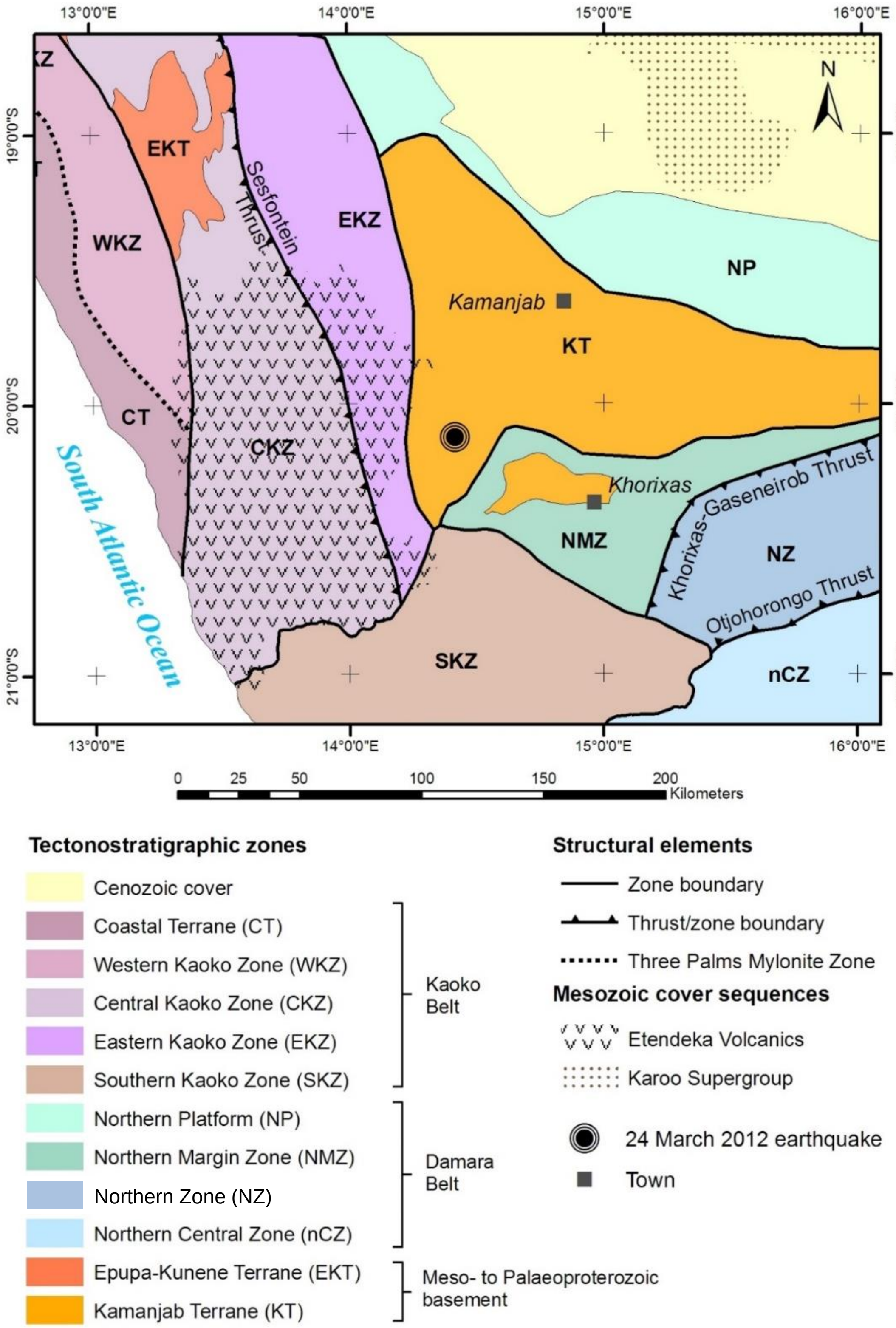

Figure 4. Location of the 24 March 2012 earthquake in relation to the tectonostratigraphic framework of north-western Namibia: the epicentre is situated within the Palaeoproterozoic Kamanjab basement inlier consisting of metamorphosed volcanic, sedimentary and intrusive rocks, near the juncture of the Neoproterozoic Damara and Kaoko orogenic belts. During the Damara Orogeny the area underwent complex multiphase deformation, with some of the lineaments and structures being rejuvenated during the Mesozoic and break-up of the Gondwana Supercontinent (Miller, 2008).

Regional seismicity

Seismicity studies in Namibia relating epicentre locations to known geological faults and fault systems were conducted by Mangongolo and Hutchins (2008), based on historical seismic data from the Council for Geoscience (South Africa), the United States Geological Survey, the International Seismological Centre (UK), the Goetz Observatory (Zimbabwe) and the newly established Seismological Network of Namibia. They concluded that most seismic events occurred along the escarpment separating the central highlands from the coastal plains and in topographically high-lying zones of the Damara and Namaqua orogenic belts, in association with major fault systems. These topographically high regions are part of the Wegener Stress Anomaly (WSA), which extends from south-western Angola to South Africa (Bird *et al*., 2006; Fig. 5).

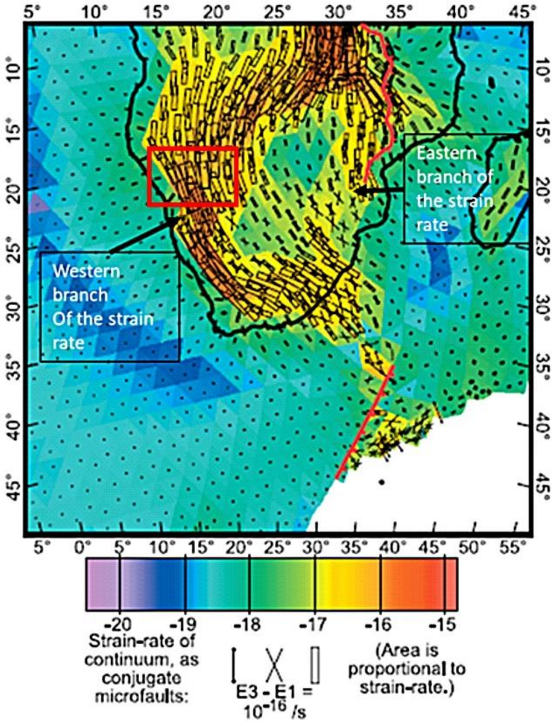

Figure 5. Predicted long-term average strain rates in the study area (red rectangle; after Bird *et al*. (2006); symbols show orientation of the strain rate tensor

Bird *et al*. (2006) carried out modelling experiments to determine the causes of stress in southern Africa and neotectonics of the lithosphere, using the Shell software (Kong and Bird, 1995). Out of eight models tested, the AF-SO-013 model (Fig. 7) was the most preferred, as there was a high correlation between the strain rate field and instrumental seismicity. This model predicts that the Wegener Stress Anomaly is represented by a SW-NE compressive horizontal principal stress direction (σ_{2H}), exceeding the NW-SE compression (σ_{1H}); it further predicts a dominant normal faulting and minor thrusting stress regime for the study area (Fig. 6).

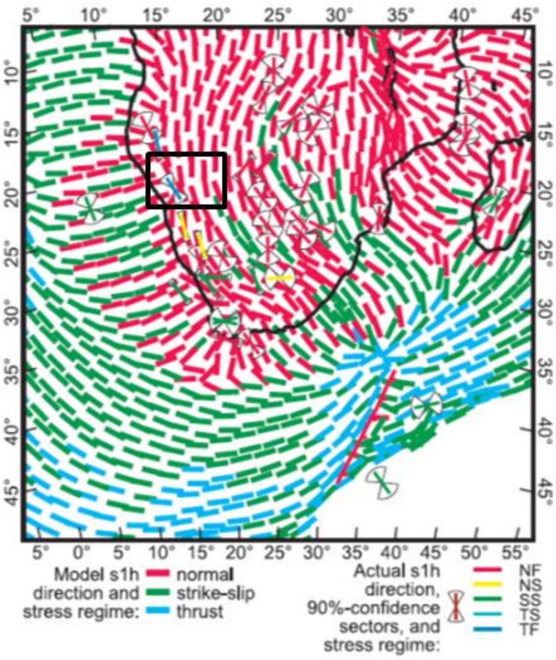

Figure 6. Mostly compressive horizontal principal stress direction from the preferred model AF-SO-013 (Fig. 7), shown as thrust regime in southern Africa and Madagascar (Bird *et al*., 2006); black polygon indicates the study area

The WSA is thought to be the result of ridge-push from the South-west Indian Ridge caused by unbroken lithosphere resistance to rotation between the Somalia and Africa Plates (Bird *et al*., 2006; Fig 7). The strain rate and stress direction of the western branch connects to a western arc extending through Angola, Namibia and South Africa, while the eastern branch joins with a less active south-eastern fan passing through offshore northern Mozambique (Fig. 5).

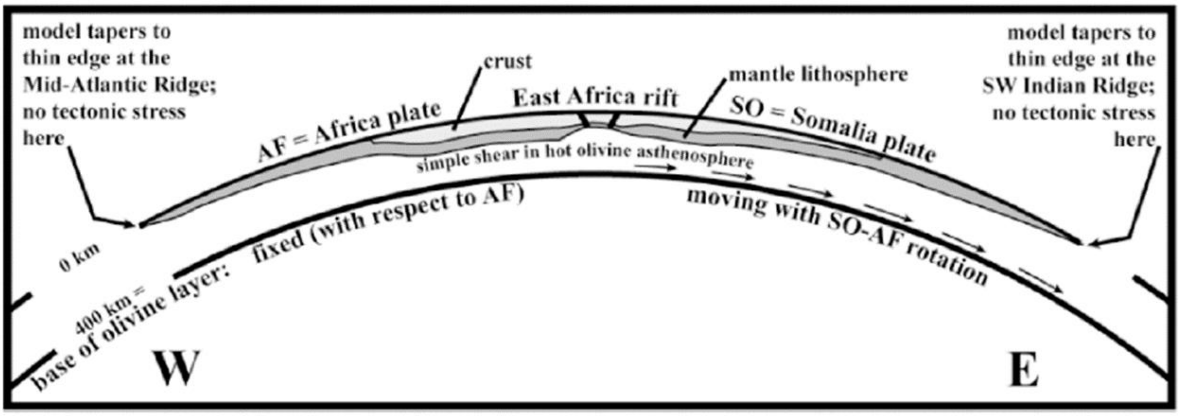

Figure 7. Schematic cross-section through the preferred model AF-SO-013 along an east-west great circle, showing a divergent flow assumed to drive relative rotation of the Somalia Plate with respect to the Africa Plate (Bird *et al*., 2006; cross-section not to scale)

Location methods and velocity models

In the present study the HYPOCENTER software (Lienert and Havskov, 1995; Lienert *et al*., 1986), which combines most features of the HYPO71 and HYPOINVERSE software, was employed. This software calculates the location (x,y,z) and origin time (t_0) for a single event by tracing the rays through a given 1-D velocity model (both direct and refracted waves), and adjusting earthquake parameters using a conventional least-squares approach (Gubbins, 2004).

To improve the accuracy of hypocentre locations, known blasts at the Navachab, Rössing and Langer Heinrich Mines were used to test for the optimal velocity model. Two velocity models, i. e. a crustal model, which is the 1-D global velocity model in the SEISAN software (Havskov and Ottemoller, 1999), and the 1-D IASP91 velocity model were tested. Mine events with at least five clearly observable P and S arrivals were selected, with an average of 10 phase readings for each event. Events with root mean square (rms) residuals larger than 1 s and standard location errors (horizontal error – ERH; vertical error - ERZ) larger than 3 km were rejected. The tests showed that the IASP91 velocity model located the mine blasts more precisely than the crustal model.

Results

The seismicity pattern of north-western Namibia determined by the current study is similar to that observed by Mangongolo and Hutchins (2008). However, in addition to the Windhoek Graben - Okahandja Lineament and the North-western Seismic Zone, a new zone was identified west of Kamanjab, referred to here as the Kamanjab Seismic Zone (Fig. 8). Of the 281 earthquakes recorded during the period January to May 2012 the majority occurred within this zone, including the main 24 March earthquake. Events decrease away from the main quake, but isolated occurrences are observed to the south and north (Fig. 9).

The main event during the study period was relocated with better accuracy on account of the improved seismic station distribution: occurring at 4:43:52 on 2012/03/24, it was located at 20.127° S, 14.461° E and depth 0.1 km. The average uncertainties in the determination of hypocentre location were 5.48 km in the horizontal and 5.42 km in the vertical direction due to the limitations of manually picking P and S waves of small magnitude events. The area of occurrence is sparsely populated, with the nearest town Khorixas situated some 60 km to the southeast. Other populated places at some distance from the epicentre are Palmwag, ~40 km to the northwest, Kamanjab, ~70 km to the northeast and Fransfontein, ~60 km due east. The farthest location from which repercussions were reported is Henties Bay, some 220 km to the south. There was no report of injury or death associated with the event, only relatively minor damage to property such as broken windows and falling dishes.

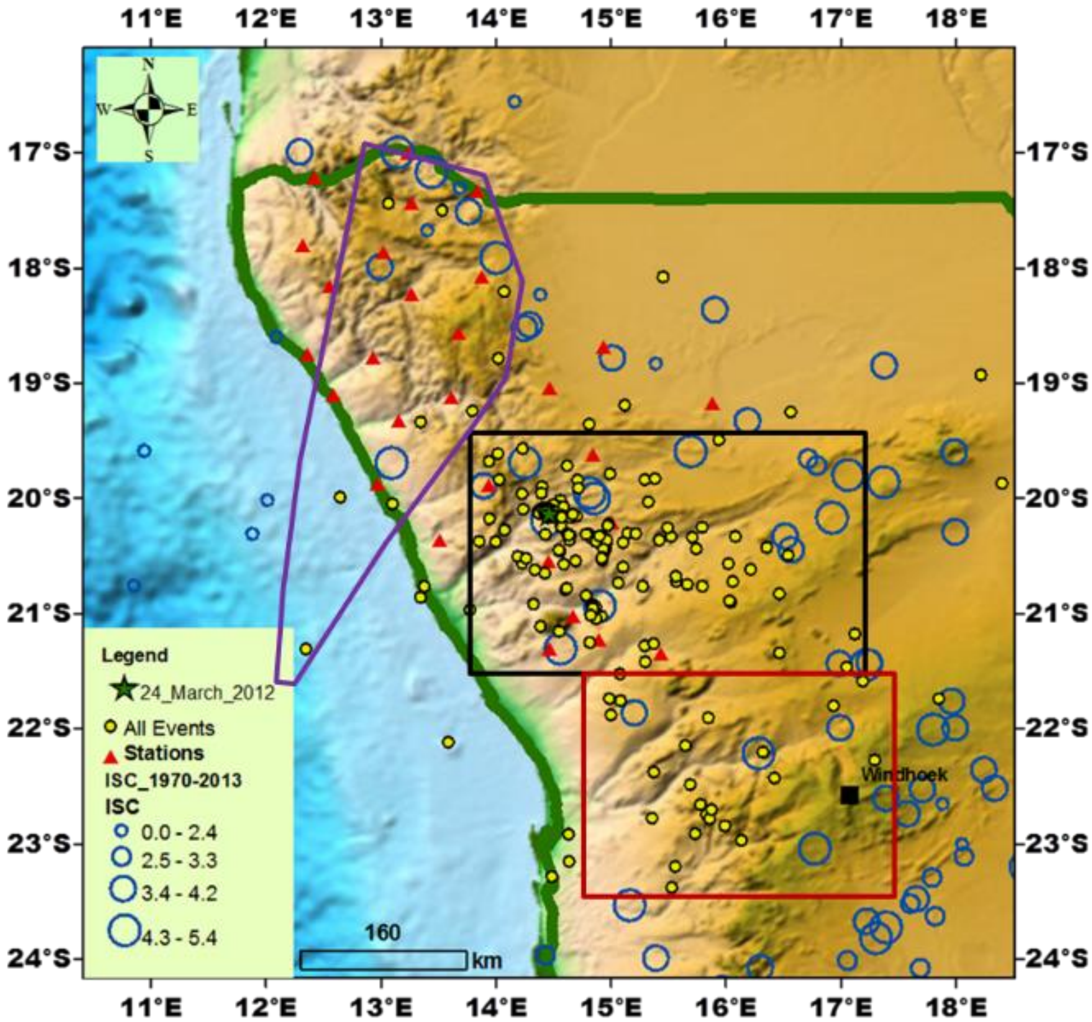

Figure 8. Seismicity in relation to known active seismic zones in Namibia: north-western seismic zone (purple polygon); Windhoek Graben and Okahandja Lineament (red rectangle); Kamanjab Seismic Zone (black rectangle). Red triangles denote temporary seismic stations; ISC events are represented by open circles. The fact that few events have been recorded in the north-western part of the network may be attributed to a lower earthquake frequency and/or sparse seismic recording stations.

Kamanjab Seismic Zone

A rectangle (measuring 392 km²; Fig. 9) within the newly identified Kamanjab Seismic Zone was chosen in order to determine local magnitudes, frequency distribution (Fig. 10) and focal plane solutions (Fig. 11). A total of 111 events occurred in this zone during the study period, with the earliest earthquake recorded on 27th February and the last on 19th May 2012. Apart from the main 4.7M_L event, most earthquakes were very minor, with the smallest recorded at -0.4 M_L and the second largest at 3.9 M_L. The local magnitude scale is calculated as $\log A - 2.48 + \log \Delta$, where A is the amplitude of the signal and Δ the epicentral distance (Lay and Wallace, 1995). In the case of very small earthquakes, with small amplitudes and short epicentral distances, the local magnitude will be negative, because of logarithm of smaller numbers and a regional scale factor that is already negative. Small earthquakes produce seismic waves that can only be detected by modern seismographs. Figure 9 shows a NW-SE alignment of the earthquakes recorded during the study period, indicating the location of causative faults which, however, do not correspond with any mapped structures. It is concluded, therefore, that the causative faults either do not find expression at the surface, or that available geological mapping in the area is not sufficiently detailed.

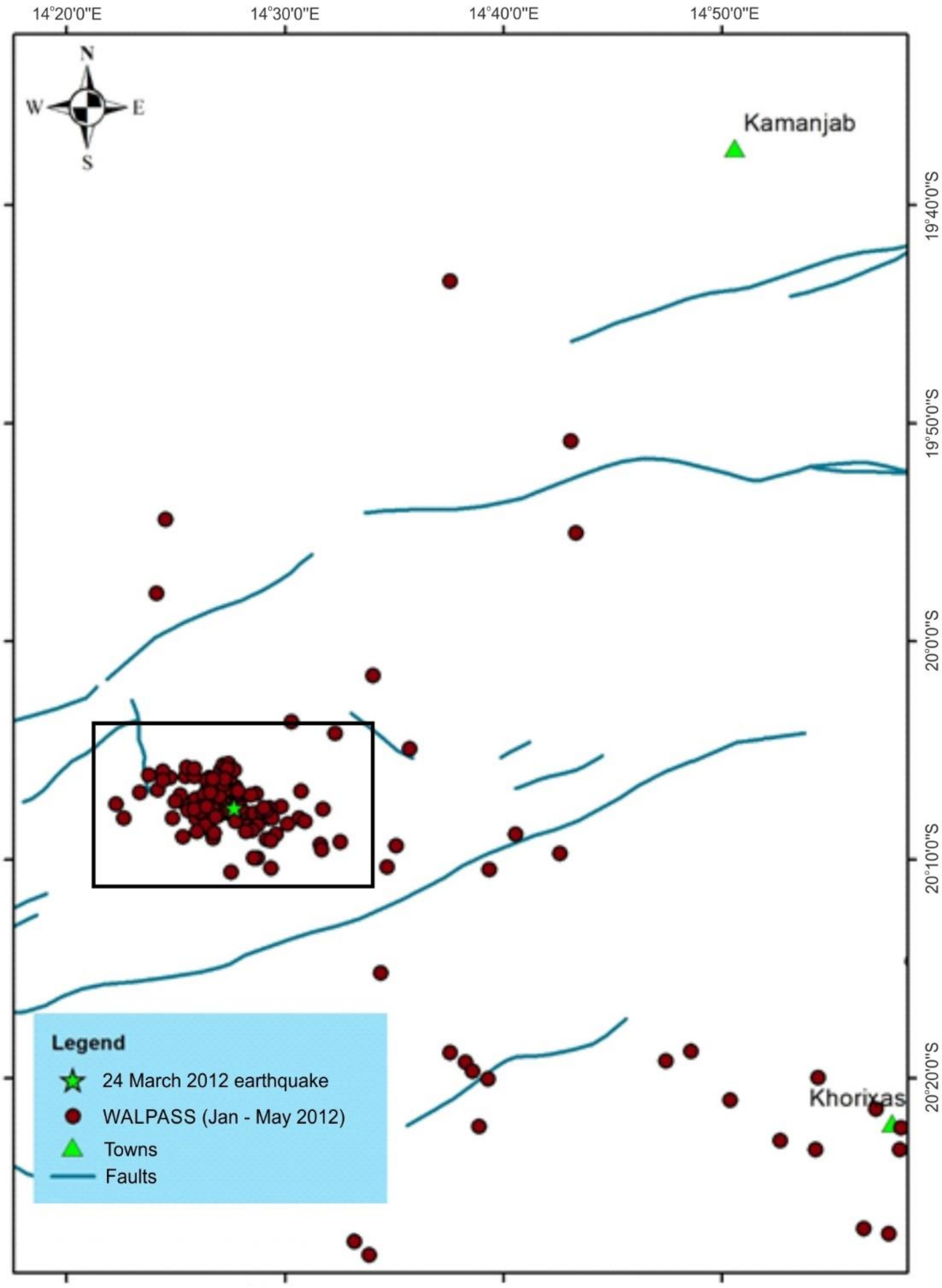

Figure 9. Close-up of events within the Kamanjab Seismic Zone showing a NW-SE oriented cluster (black rectangle) and mapped faults around the seismic zone; green star = location of the main 24 March earthquake

Frequency-Magnitude distribution

The Gutenberg - Richter relation provides a statistical distribution of earthquake magnitudes and is described by a power law (Gutenberg and Richter, 1944):

$$\log_{10} N = a - bM$$

where N is the number of earthquakes in a group having magnitudes larger than M, **a** is a constant and **b** is the slope of the log-linear relation.

In our study, the b-value, which represents the percentage of existing stress to the final breaking stress within the fault (Scholz, 1968), was 0.75 (Fig. 10), which is low compared to values typical for seismically active regions (≥ 1). This may be indicative of a stable crustal region with less fractured crust, or else of an incomplete earthquake catalogue leading to biased results. For the WALPASS project the cut-off was M_L 1.8, below which events could not be reliably detected.

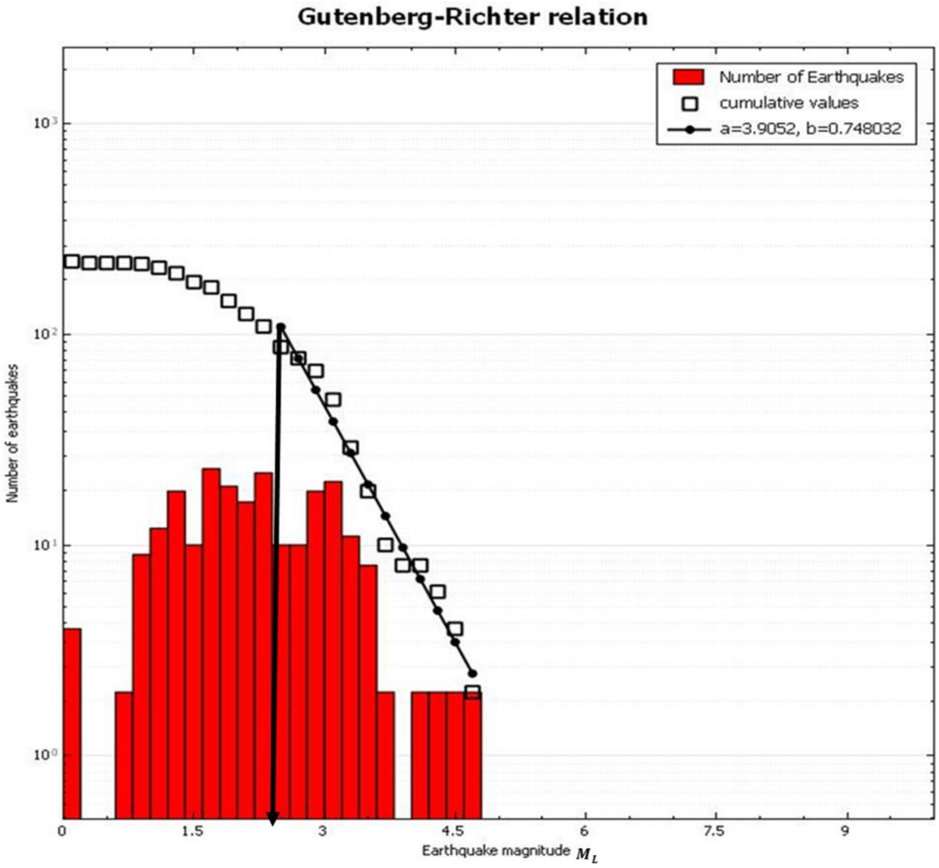

Figure 10. Frequency - magnitude correlation of events in the Kamanjab Seismic Zone showing 1.8 M_L cut-off

Fault plane solutions

Focal mechanisms give the fault plane orientation and slip direction of seismic events, and provide information about the investigated fault and the stress field in which it occurs (Hardebeck and Shearer, 2003). The focal mechanism solution of the main 24 March 2012 earthquake obtained from P arrivals indicates normal faulting (Fig. 11a). Eighteen stations were used with good signal to noise ratios. The focal mechanism solution yielded strike = 0°, dip = 34° and rake = 90°, pointing to a shallow normal fault dipping to the east and striking north-south. Generally, major faults and lineaments in the study area are oriented in NW-SE direction (Gray *et al*., 2008); however, near the study area faults tend to stike NE-SW (Fig. 9).

The second event, which occurred on 24 March 2012 at 05:02 has a focal solution with strike = 59°, dip = 44° and rake = -66°, suggesting a transtensional stress regime (Fig. 11b), which is not in agreement with Grey *et al*. (2008), who stated that most of the Damara Belt is dominated by craton-bound, imbricate thrust shear zone systems with complex fold interference trending NNW. Chetty (2017) asserts that transpression and transtension are strike-slip deformations that deviate from simple shear and are widespread in orogenic belts. These stress regimes occur at local and regional scale but typically at plate boundaries. The third event happened on 24 March at 06:05 and has a focal solution with strike = 138°, dip = 51° and rake = 53°, which indicates a transpressional stress regime (Fig. 11c).

All focal mechanism solutions show different stress regimes, with the main event indicative of normal faulting. In contrast to expectations, it was found that the aftershocks did not have the same focal mechanism solutions, i. e. the same radiation patterns as the mainshock (Fig. 12). The reason could be that the aftershocks did not occur along the same fault as the mainshock (Barth *et al*., 2008), as might be the case in a structurally complex area such as the junction of two orogenic belts.

The complex deformation and fracture patterns at the juncture of the Kaoko and Damara Orogenic Belts would be expected to result in a heterogeneous velocity structure, affecting focal solutions of shallow earthquakes and presenting challenges to their interpretation.

More focal mechanism solutions, through calculation of higher degree moment tensors and a grid search of stress models, are needed to constrain and select an appropriate focal mechanism (Barth *et al*., 2008; Stein and Wysession, 2009).

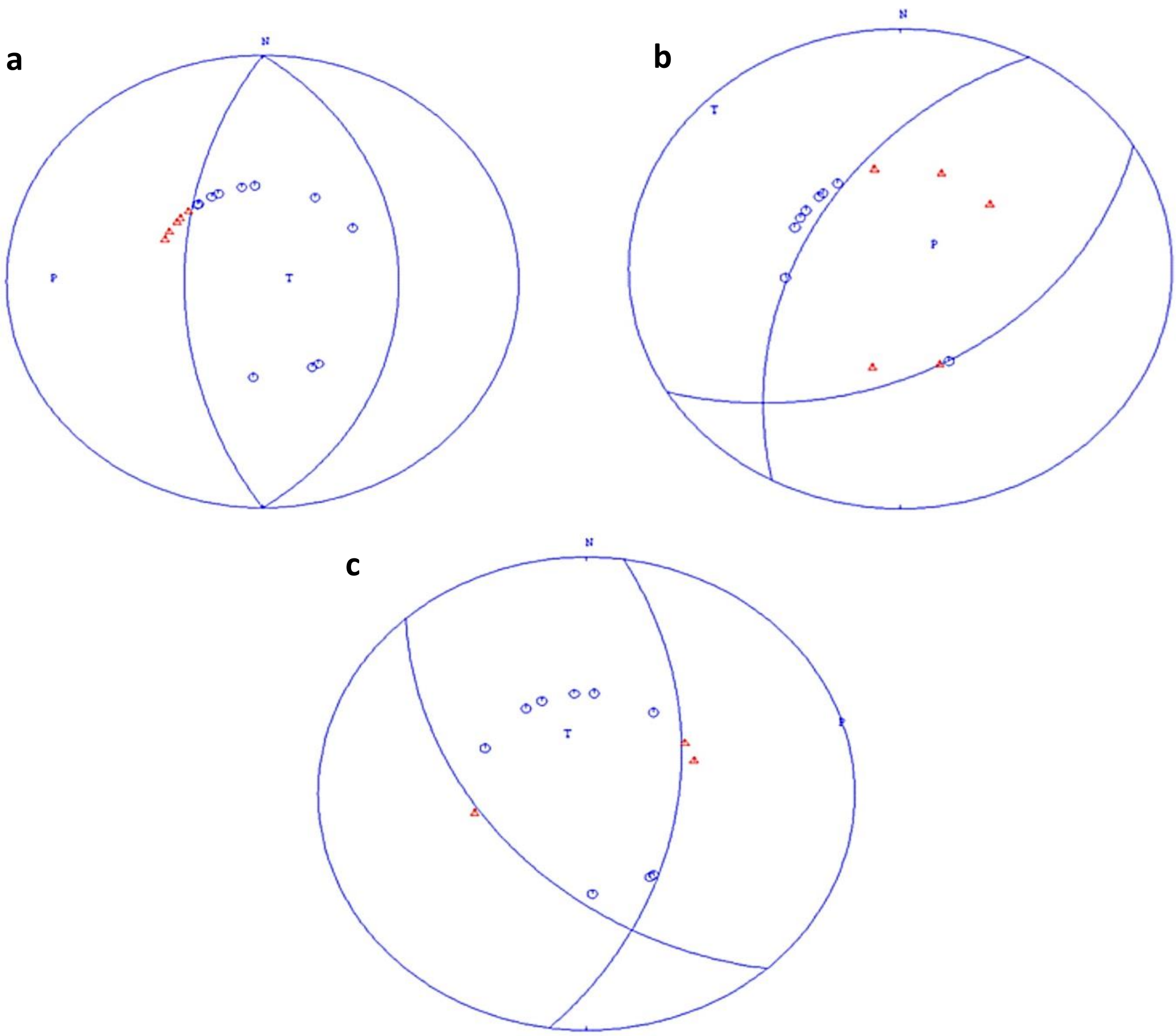

Figure 11. Focal mechanisms of the main 24 March 2012 earthquake: a) at 04:43 showing normal faulting, and an eastward dip; b) at 05:02 showing a transtensional stress regime; c) at 06:05 showing a transpressional stress regime. The red triangles show first motion as compressions (P); blue circles show dilations (T).

Discussion

Foreshocks and aftershocks

116 events occurred before and 165 after the mainshock on 24 March 2012, including those in the Kamanjab Seismic Zone. However, the qualification of an earthquake or tremor as an aftershock requires the specification of time and space windows. Accordingly, a rectangle was drawn around the study area based on the proximity of events to the mainshock and possible seismic event patterns (Fig. 9). Events occurring within this rectangle were analysed to determine foreshocks and aftershocks of the mainshock. 53 foreshocks and 119 aftershocks occurred in the demarcated area, with most of them aligning in NW-SE direction. Foreshocks in appear to have started rupturing early in January 2012 with an increase in frequency, suggesting that the mainshock and the region of foreshock are within the same sequence of cascading ruptures triggered by a common mechanism (Schuh and Böhm, 2011). In addition, several foreshocks were observed around the

mainshock, which, together with the above-mentioned foreshocks, may be associated with stress build-up in and around the fault prior to the main rupture (Fig. 13).

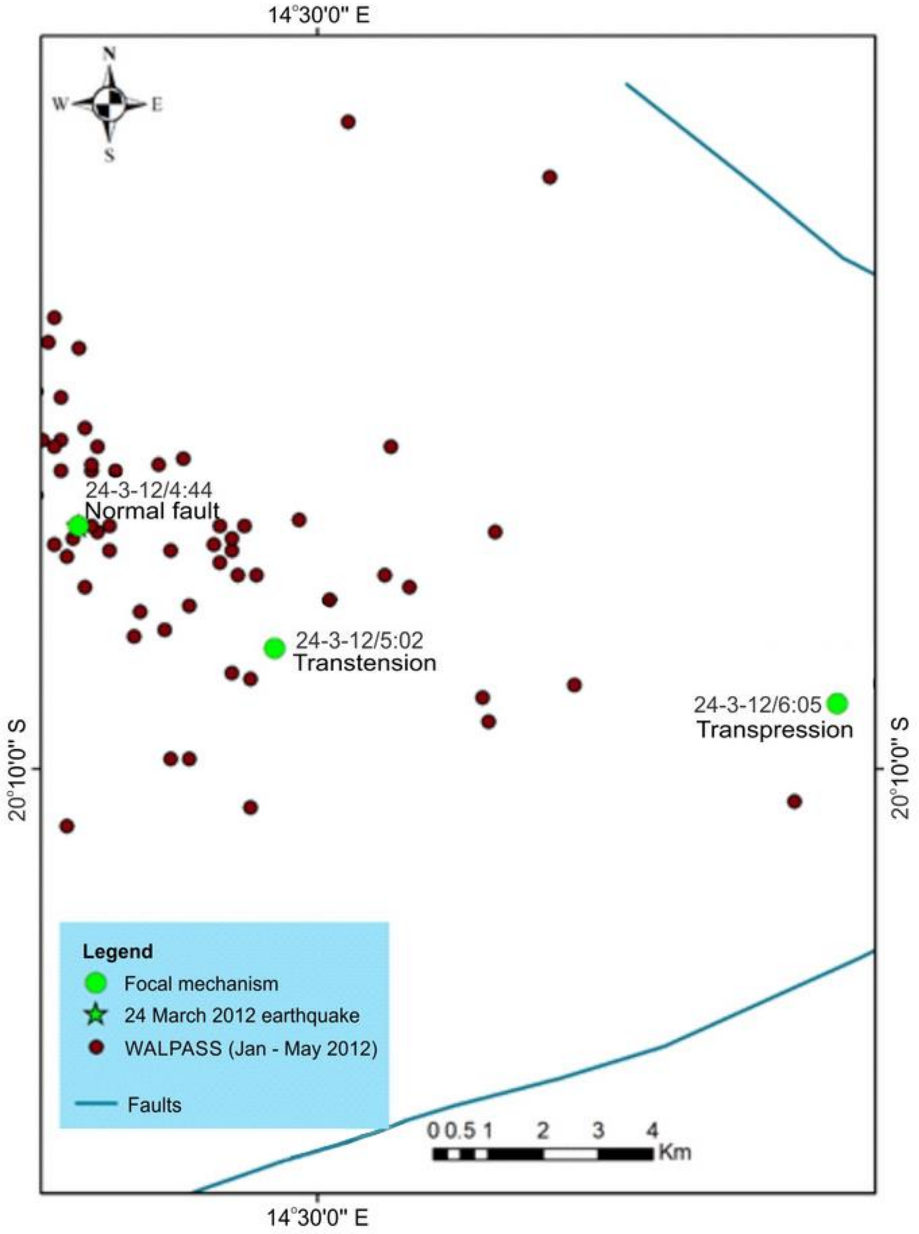

Figure 12. Location of focal mechanism solutions of the 24 March 2012 earthquake (green circles), indicating date, time and stress regime of the event.

Aftershocks occur on planes of weakness in regions of increased post-seismic stress, at the edge of unbroken barriers and in regions of rapid transition from high to low slip around the mainshock (Das and Henry, 2003). In this study, most aftershocks occurred within 10 km of the mainshock rupture, indicating regions of increased stress as a result of the main earthquake. These aftershocks are aligned along the cluster identified in figure 9. Aftershocks larger than 3.5 M_L were plotted, and four of them occurred on the same day as the mainshock. These events are located at the periphery of the cluster (Fig. 14), indicating areas of increased stress. Most of the larger events show a NW-SE linear trend to the north of the mainshock. It is thought that these aftershocks are the result of incomplete rupture, and of the fault(s) readjusting by relieving elastic strain. Most aftershocks are located around the mainshock (Fig. 14).

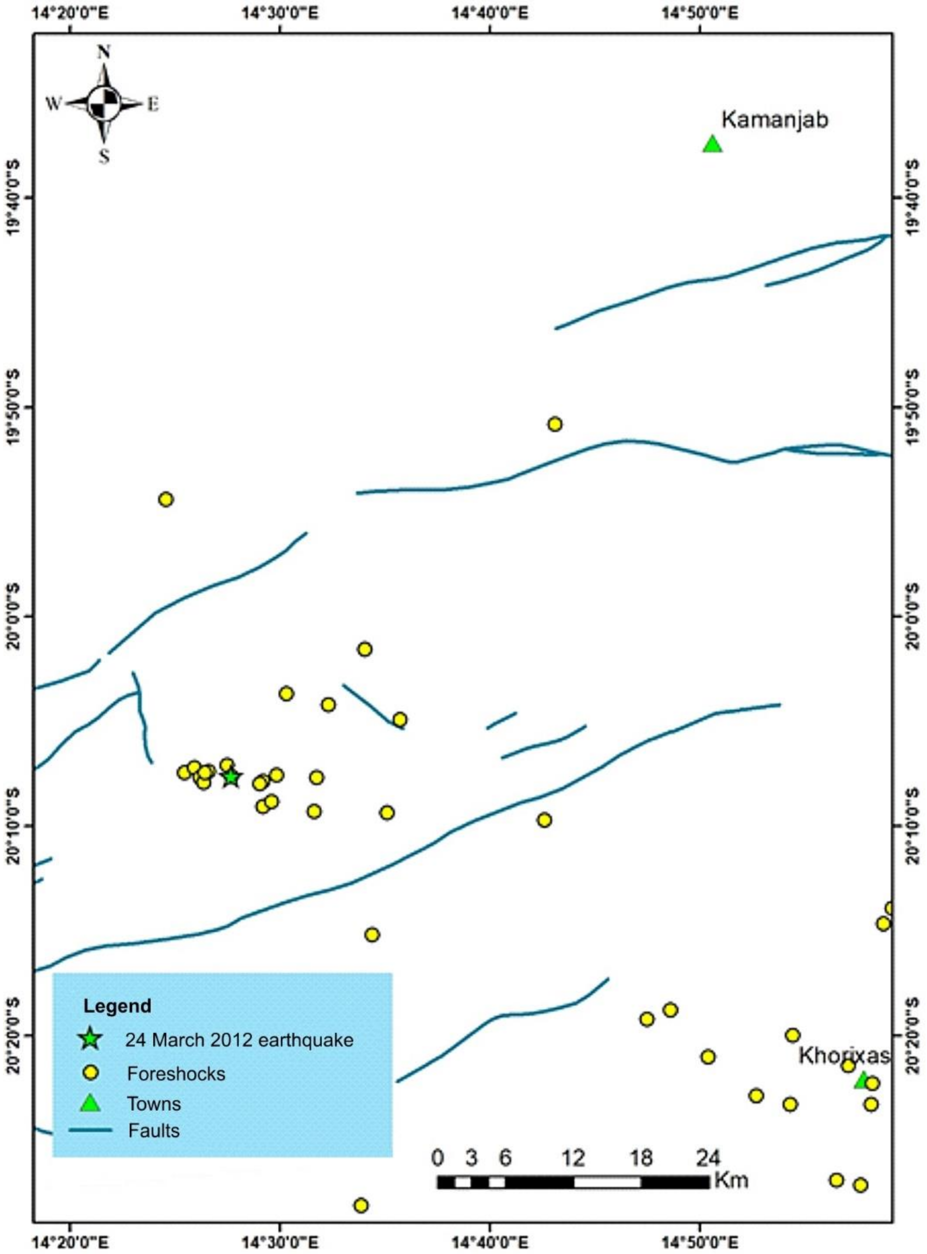

Figure 13. Foreshocks in relation to the main event (green star) showing NW-SE orientation

Regional strain correlation

Judging from the seismicity recorded during the five-month period under consideration, the seismic hazard in north-western Namibia is much higher than predicted by Bird *et al*. (2006), although these observations may not be representative of long-term activity. Study of the entire two year-dataset of the WALPASS project's duration might give a better indication of the latter. However, there is a very strong correlation between the strain rate model predicted and events registered, confirming that seismicity in this region is higher than recorded by current instrumentation.

The AF-SO-013 model prediction in terms of stress and strain in the study area is consistent with our results. Therefore, the above model could be considered as a reliable first order indicator of stress patterns in southern Africa, especially in areas where instrument records are lacking, as, for example, in southern Angola.

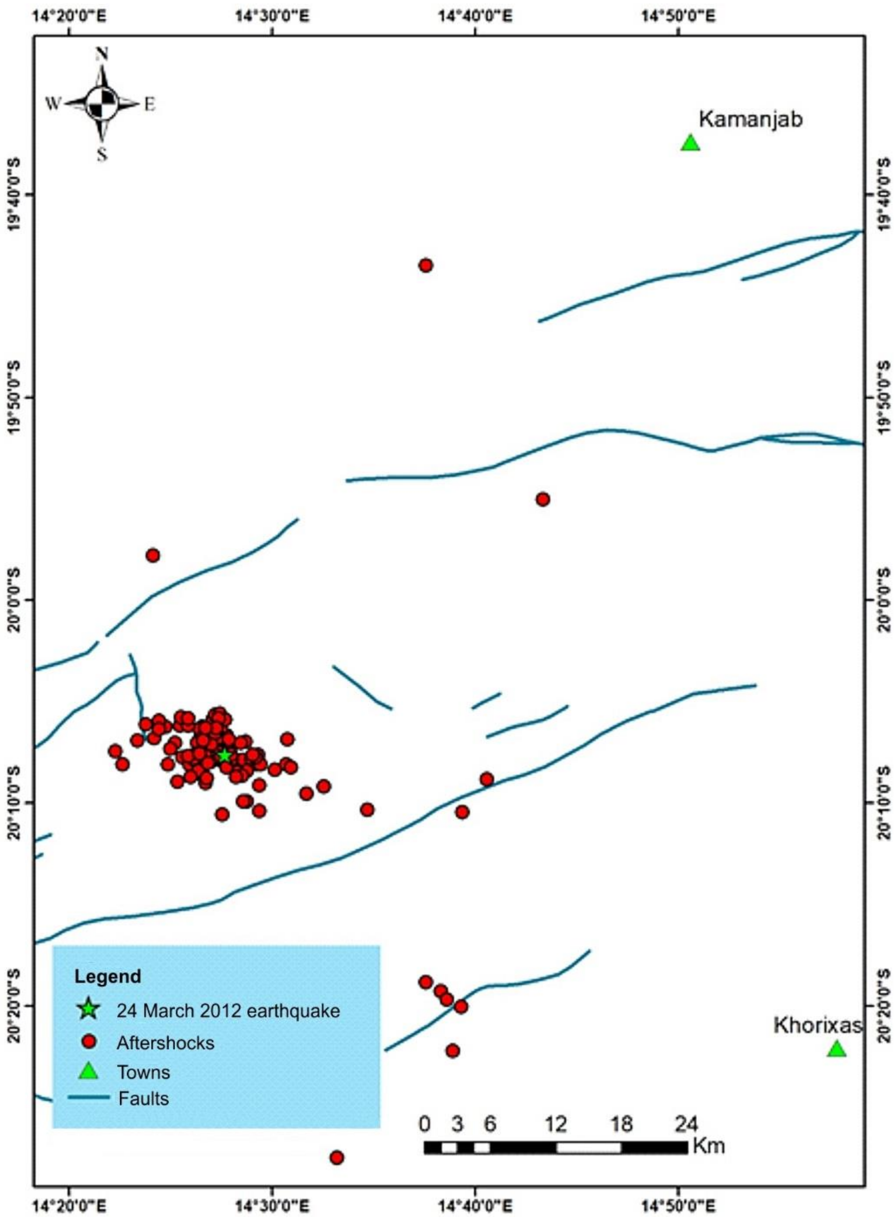

Figure 14. Aftershocks in relation to the main event (green star) extending in a NW-SE orientation

Conclusion

Seismicity observed during the study period indicates a higher earthquake frequency than previously recorded by the NSN stations, with local magnitudes ranging from -0.4 to 4.7 in the newly recognised Kamanjab Seismic Zone. The historic low seismicity records can therefore be attributed to insufficient permanent stations in the area, as most earthquakes with local magnitudes of ≤ 3 M_L are too small to be detected by the current station layout. Two clusters, oriented NE-SW and NW-SE, within the Kamanjab Seismic Zone, are likely due to complex faulting, and indicative of directions of high recent stress within the Palaeoproterozoic basement of the Kamanjab Inlier. Recorded foreshocks heralded the main event on 24th March 2012, with a rupture pattern of seismic activity extending from south-east of the mainshock towards the Kamanjab Seismic Zone, and alternating periods of quiescence and high activity.

There is a marked correlation between the recorded seismicity in the study area and the predicted strain model that connects the western branch of the East Africa Rift System to Angola, Namibia and South Africa (Fig. 5). However, since only five months of data were used in this analysis, a further study of local events over the entire two-year duration of the WALPASS project would be needed to verify the existence of a higher seismicity and tectonic stress patterns in north-western Namibia than is indicated by the recordings of the current permanent station network.

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Enigmas of Angola's and Namibia's Cuvelai Basin and its Etosha Pan

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Abstract :- Southern Africa is host to two major inland river basins, the Okavango and the Cuvelai. Research on the landscape history of the Cuvelai has been patchy leaving many aspects of the basin's functioning and structure poorly understood. This paper offers a collection of observations and ideas highlighting unusual features that obscure our understanding of the Cuvelai and its Etosha Pan. Among them are questions concerning the basin's geographic limits, its sub-basins and their functioning, possible tectonic influences on deltas and the Kunene River, the effects of easterly winds, the settlement patterns of people, lunette dunes, springs and geomorphological processes around Etosha Pan, as well as environmental concerns. We hope that these questions whet the enquiring appetites of students and scientists to unravel more of the unusual structure and functioning of this rare environment.

Keywords :- Cuvelai, Dust, Etosha Pan, Kalahari Basin, Kunene River, Lunette dunes

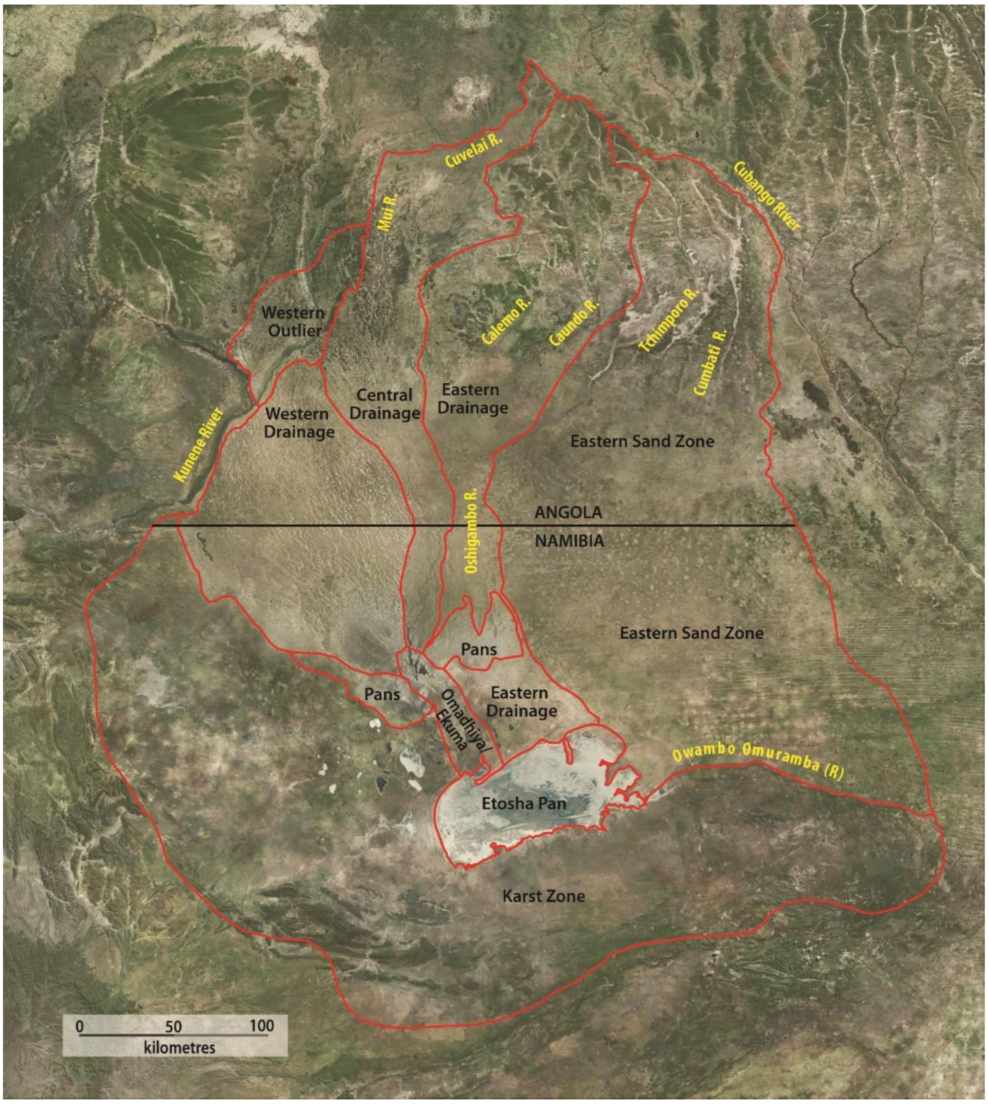

Figure 1. The Cuvelai Basin, its major zones and features, and a possible Western Outlier discussed below

Introduction

Inland deltas occur on all continents but relatively few formed recently during the last 65 million years (Bridgland *et al*., 2020). Southern Africa is host to two such global inland deltaic systems, the Okavango Basin in Angola, Namibia and Botswana, and the Cuvelai Basin in Angola and Namibia. Because of their recent geological history, both basins have good potential in providing examples of markers, integrators and actors of climate change at work on Earth. They also demonstrate ecosystem and environmental services that shape human settlement in the region. However, systematic and sustained studies of parts of the Cuvelai Basin and its functioning are lacking.

Research in the Cuvelai Basin dates back a century (e. g. Jaeger, 1926; Schwarz, 1920; Wellington, 1938) but it has been uneven. Collectively, we have spent some six decades exploring the Cuvelai Basin on the ground, in aerial surveys and with the use of satellite images and other data sets. This work has included studies of the basin's people, Etosha Pan, drainage systems, dust, fossils and geomorphology (e. g. Calunga *et al.,* 2015; Hipondoka, 2005; Hipondoka *et al.,* 2004, 2006, 2013; Hamunyela *et al.,* 2022; Kempf and Hipondoka 2003; Mendelsohn *et al.*, 2000, 2015; Mendelsohn and Weber, 2011; Mendelsohn and Mendelsohn, 2019; Pickford *et al*., 2009; Van der Waal *et al.,* 2021; Wanke *et al.,* 2018). Our explorations have yielded observations on peculiar features and raised questions that seem significant, curious, or surprising, and that highlight conditions and issues deserving enquiry and explanation. The purpose of this paper is to present these observations and questions in the hope that students and scientists will examine them so that the functioning of this unusual part of the world is better documented, understood and managed. We hope, too, that the paper provides a reasonable introduction to the Cuvelai Basin and its literature.

The Cuvelai Basin is an unusual feature of the African landscape, its combination of topographical, sedimentary, hydrological and socio-economic features probably giving it unique world status. Topographically, the basin extends west to east between the Kunene (called Cunene in Angola) and Cubango (also called the Okavango) rivers in Angola and across a shallow basin in Namibia, where its southern limits are bounded by a range of karst hills (Fig. 1). From north to south, elevations drop from 1450 m above sea level to 1080 m asl. Much of the basin has little or no surface drainage. The only water courses that flow with any frequency are those in the Western, Central and Eastern Drainage Zones, which consist of many channels that merge and diverge along their course from north to south. Most channels converge on the Omadhiya Lakes from where water may flow south along the Ekuma River into the Cuvelai's ultimate end – the Etosha Pan. The Cuvelai is thus endorheic, all surface water disappearing, as it seeps into the soil or evaporates from the channels, the Omadhiya Lakes and Etosha Pan. Tens of thousands of small pans, usually dry, which only fill with water sporadically after heavy local rains, dot the landscape across the middle of the basin between ~17° and 19° southern latitude.

The broad, shallow Cuvelai Basin described above is distinct from the more confined hydrological Cuvelai Drainage made up of the Western, Central and Eastern Drainage zones (Fig. 1.) This distinction should be born in mind throughout this article. Most of the Cuvelai Drainage's channels are in Angola, where they are called *chanas* as opposed to *iishana* in Namibia.

A Western Outlier?

To our knowledge, all geographers and other academics have described the Cuvelai Drainage as located east of the Kunene River in Angola. However, from fieldwork and studies of satellite imagery it now seems to us that a section of an original Cuvelai Drainage may lie west of the Kunene (Figs 1, 2). Surface water in this section flows along *iishana* first south and then south-east into the Kunene River. The vegetation, soils and structure of these drainage lines appear the same as in the adjacent main Western Drainage. Moreover, the location and number of *iishana* immediately west and east of the Kunene are similar, suggesting that they might once have been connected.

Similarities across the Kunene River are most obvious in the southern half of the area (Fig. 2). We are uncertain how far the similarities extend further north where the land is more wooded, drainage lines are more defined, and far fewer people reside. A tentative northern border is indicated by the dashed line in Fig. 2. If this supposition is correct, the Kunene River likely cut its way south across this section of the basin, perhaps ending its earlier flow to the south-east in the Cuvelai Basin, where it probably formed the Kunene mega-fan (Gärtner *et al*., 2023). Such a redirection of the Kunene's flow may be associated with uplift across a broader part of Angola, as postulated below (see page 22).

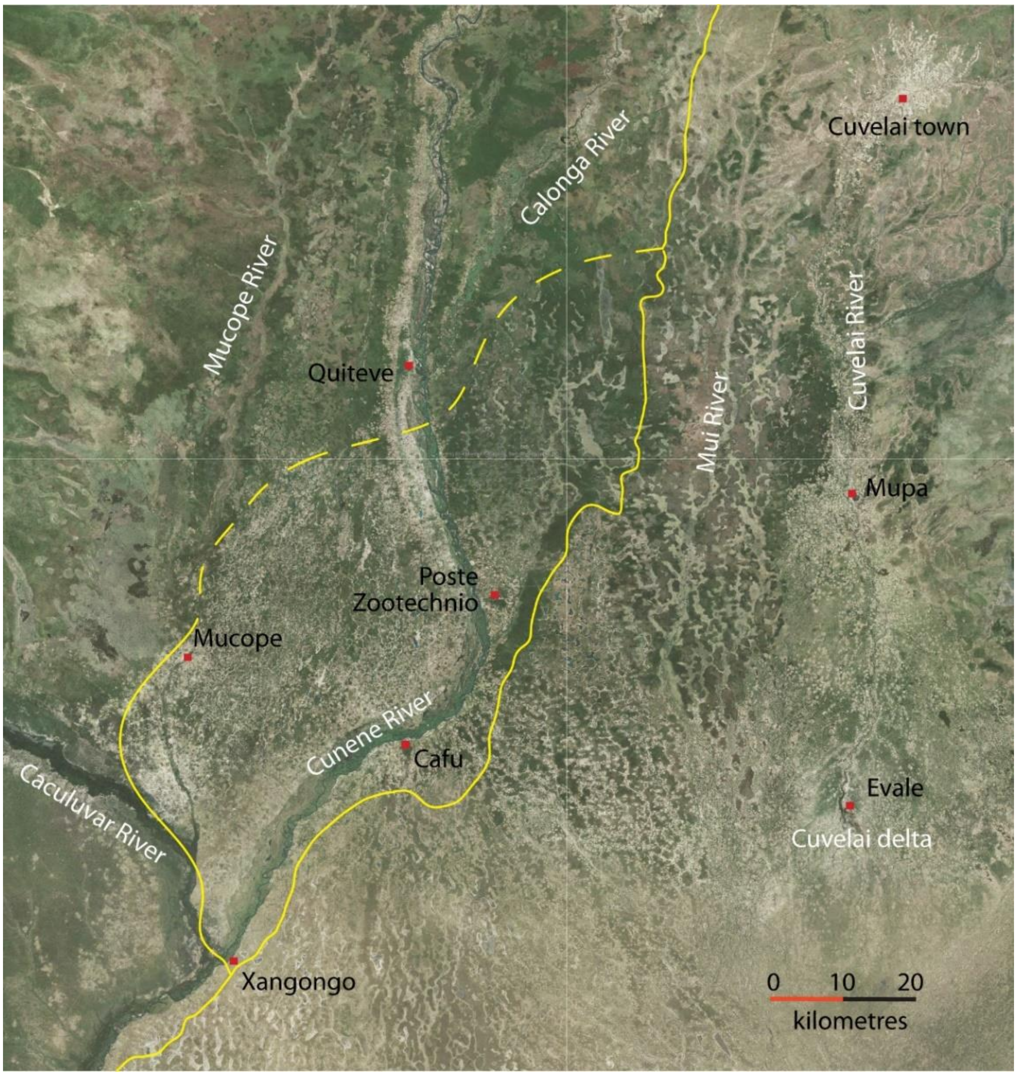

Figure 2. Probable section of the Cuvelai west of the Kunene (Cunene) River

Drainage zones

Of the three (western, central and eastern) major parts of the Cuvelai Drainage (Fig. 1), only two regularly carry water in *iishana* south into Namibia. These are the Western and Central Drainages, which differ in several ways. *Iishana* in the Western Drainage are broad, often several hundred metres wide, and the entire drainage collects water from an extensive area, about 100 km across at its widest. Water in the Western Drainage flows slowly, much of it flooding expanses alongside or away from *iishana*. Few trees line these *iishana,* which have more saline soils than those of the Central Drainage, where the *iishana* are narrow, often less than 100 metres across, less saline, and frequently bordered by riparian woodland, predominantly *eemwandi* or jackal berry *(Diospyros mespiliformis)*. Water flows are faster and the entire Central Drainage covers no more than 50 km at its widest point.

The sharpest transitions between the two zones are to be seen between Ongwediva and Oshakati and just east of Ongenga. The narrow, fast-flowing, freshwater *iishana* of the Central Drainage begin as small tributaries, which coalesce into larger channels that later diverge and merge repeatedly on their way south. By contrast and enigmatically, the *iishana* of the Western Zone begin immediately east of the Kunene River in broad pan-like channels, which continue to the south-east in that form, at times also merging with and again diverging from other broad, slow-flowing *iishana*. How water courses can begin and remain broad seems to us puzzling. This is the case all along the Western Drainage's margin just above and adjacent to the Kunene River (Fig. 1).

Some channels of the Western and Central Drainages merge to the west of Ondjiva. Reasons for the differences between the zones and how they reflect past events in the Cuvelai deserve study. We also encourage studies to examine the chemistry and structure of sediments in the *iishana* since they are likely to show the provenance of surface flows.

The Eastern Drainage is much more ephemeral than the drainages to the west. Its catchment consists largely of deep aeolian sands which absorb rainwater rapidly. Significant flows down its drainage lines are rare, perhaps occurring roughly every ten years. The two main water courses are the Calemo and Caundo rivers. Still further east is the Eastern Sand Zone, where surface water is limited to the narrow courses of the upstream reaches of the Tchimporo River. The Cumbati River is usually dry and not – or no longer – connected to any of the other watercourses in the Cuvelai Basin.

Seasonal wetlands and pans

The importance of Etosha Pan as an ephemeral wetland which sporadically supports thousands of breeding flamingos is well known (Lindeque and Archibald, 1991). Little, however, is known about the ecology of other ephemeral wetlands in the Cuvelai Drainage. These consist of hundreds of braided *iishana* channels and tens of thousands of small freshwater pans (Arendt *et al*., 2021; Fig. 3), sixty-six larger saline pans, and substantial expanses of saline grasslands that are flooded periodically (Fig. 3). At times these wetlands are used for breeding by at least sixty species of aquatic birds that move across southern Africa (Lindeque and Archibald, 1991; J. M. Mendelsohn, pers. obs., Fig. 4), but the extent of the contributions made by the pans to populations of African aquatic avifauna remains unknown.

Figure 3. Some of the thousands of pans that occasionally fill with local rain (photograph taken south of the Oshakati – Okahao road)

When filled, Arendt *et al*. (2021) estimated that some 190,000 pans may hold 1.9 km^3 of water. For the medium flood of 2017, Wanke *et al*. (2018) estimated a combined average discharge of over 200 m^3/s during the flood peak in *iishana*. At the time, this estimate was nearly half the discharge of around 500 m^3/s of the nearby Kunene River at Ruacana (Namibia Hydrological Services, 2017).

Figure 4. Thousands of cattle egrets (*Bubulcus ibis*) breeding in a temporary pan inundated during the huge flood (locally known as an *efundja*) in March 2011 (photograph: Helge Denker)

East Winds

While much of the Cuvelai has been moulded by its water courses, prevailing winds from the east have also done much to fashion the landscape and determine where people live. This is most evident in the lunette dunes that lie west of small pans in the central-eastern areas of the basin, mostly just north of the Angola-Namibia border (Fig. 5a). People predominantly live and farm immediately west of the pans, probably because the soils here are more fertile due to aeolian sands being mixed with fine alluvial sediments scoured off the pans by east winds (Mendelsohn and Mendelsohn, 2019). The same process likely explains why most people live and grow crops just west of old drainage lines in this area (Fig. 5b). In southern Angola areas immediately west of rivers are favoured for settlement to such a degree that most roads along major rivers were built directly to their west, for example, along the Kunene River between Matala and Quiteve, the Cubango from Kuvango to Katwitwi, and the Cuito and Longa Rivers from Cuito Cuanavale to Dirico, and from Longa to Nankova, respectively. A recent paper by Jolivet *et al*. (2023) explores the effects of east winds on rivers across south-east Angola and north-east Namibia.

Likewise, homesteads and fields are usually first established on higher ground immediately west of *iishana* (Fig. 5c), while subsequent houses and fields are started elsewhere on the raised ridges (*omitunda*). The practice of having the main entrance of Aawambo homesteads face east is rooted in the tradition that a 'virgin *omutunda* should be tamed by entering it from the east' (K. Hishoono, pers. comm.).

Deltas and the alignment of the Kunene and nearby rivers

Across the Cuvelai Basin between the towns of Xangongo and Caiundo is a line (Fig. 6), where rivers either spread into deltas (Mui – Fig. 7 - and Cuvelai) or into open expanses of grass-lands that are periodically inundated when fed by flows in the Calemo, Caundo, Tchimporo and Cumbati Rivers; the latter are visible as pale grey areas in Fig. 1. In very wet years water may flow from the grasslands south-westwards to form the Oshigambo River (Fig. 9).

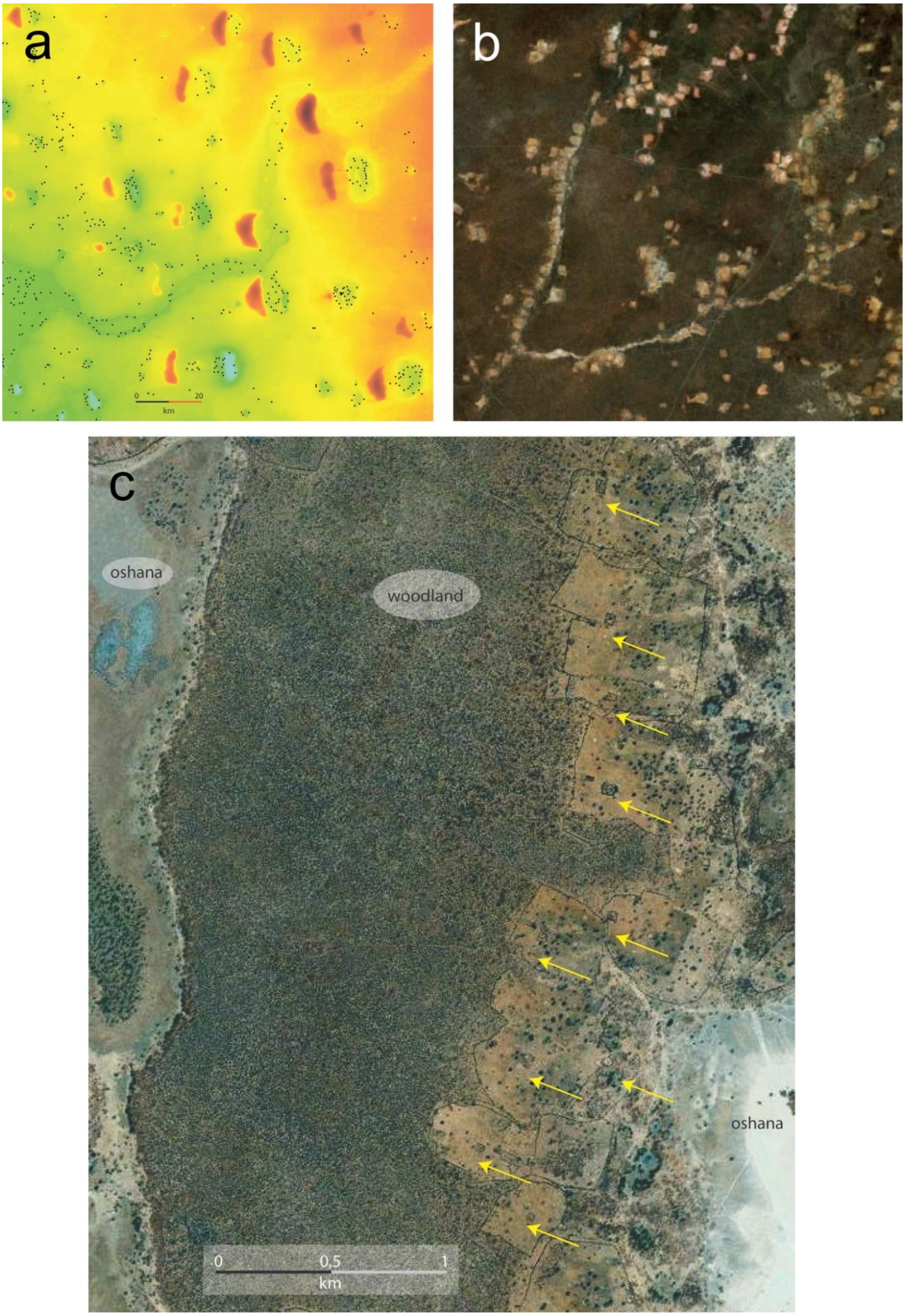

Figure 5. (a) Lunette dunes west of pans surrounded by houses (dots) (seen in Google Earth at 17.24° S, 16.64° E, (b) houses and fields west of drainage line (17.51° S, 16.93° E), and (c) houses (marked by yellow arrows) and fields west of an *oshana* (17.13° S, 15.33° E)

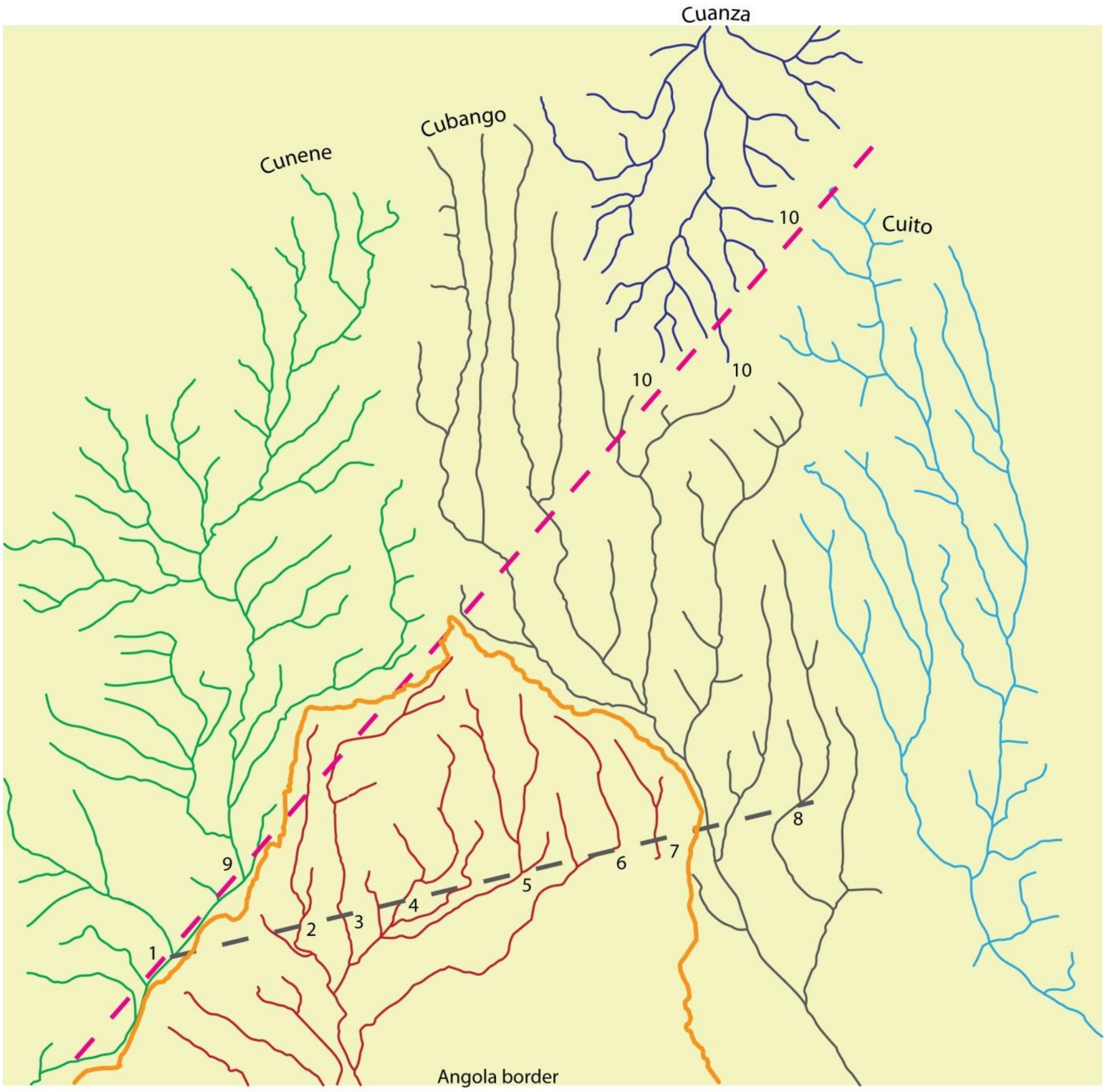

Figure 6. Deltas and axes in and around the Cuvelai Basin in Angola. The dashed grey line marks the axis from where the Caculuvar River joins the Kunene River at Xangongo (1) to the Mui River delta (2), Cuvelai River delta (3) and the flexures of the Calemo (4), Caundo (5), Tchimporo (6), Cumbati (7) and Cuatir (8) rivers. The dashed red line marks a possible flexure which may have diverted the Kunene River in a south-westerly direction (9), as well as breaking the drainage (10) between the Cuanza River (now flowing north) and the Cubango and Cuito Rivers which flow south.

An additional axis extends across this part of southern Angola, which runs along the course on to which the Caculuvar and Kunene Rivers appear to have been deflected, perhaps from their previous south-easterly trajectories. Notably, the same axis extends along the watershed that separates the north-flowing Cuanza River from rivers that flow south, the biggest being the Cuelei and Cuebe Rivers of the Cubango River Basin, and the Cuito and Cuanavale Rivers of the Cuito River Basin. The same appears to have happened further east to the Lungue-Bungo and Lumege Rivers of the Zambezi River Basin. The development of this watershed has been attributed to tectonic uplift (R. Swart, pers. comm.), which deflected the Cuanza northwards from its previous trajectory to the south.

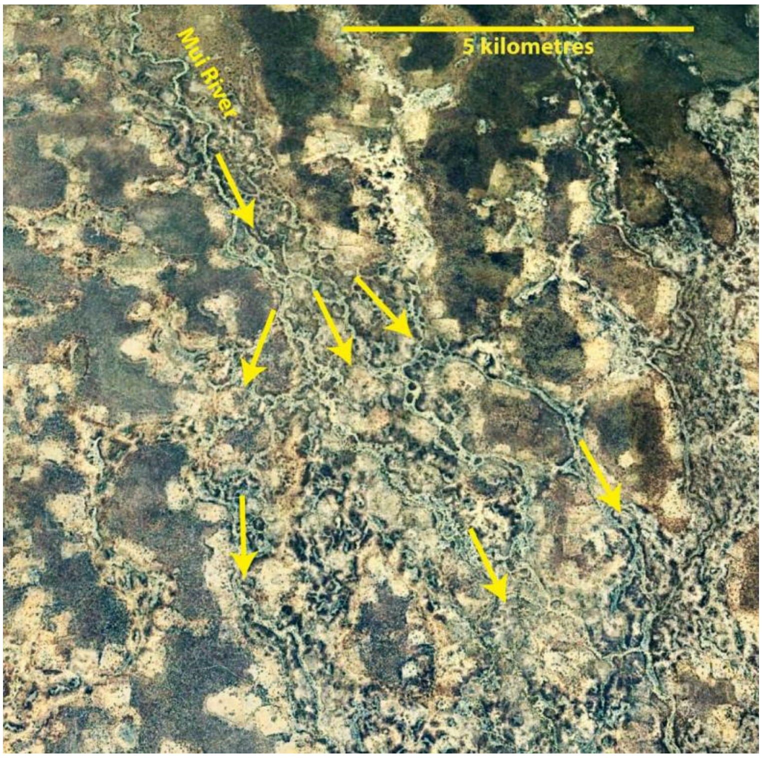

Figure 7. Delta of the Mui River as seen in Google Earth at 16.50° S and 15.55° E

A river on a ridge

Rivers normally flow in valleys. Like a normal river, the Cuvelai River runs from its source along the bottom of an incised valley, where tributaries join it on both banks. This is the Cuvelai's structure up to the town of Mupa. From there to the town of Evale the Cuvelai runs on top of a gentle ridge that drops away a few metres to the east and to the west (Fig. 8). South of Evale the Cuvelai branches into a delta. We surmise that the ridge was formed by the progradation of the Cuvelai River delta, which led to it progressively moving south as channels of the delta pushed south on top of alluvial sediments that had been deposited previously.

The channels that now flow off the sides of the ridge between Mupa and Evale merge further to the south with *iishana* coming from the Mui River delta (Fig. 7), the Cuvelai delta, and with *iishana* from the west and east (Fig. 8). Lying in the centre of this zone of convergence, Ondjiva often suffered major flood damage before embankments were built to force flood waters to flow around this large town (Calunga *et al*., 2015).

Palaeolake Kunene

It is widely agreed that the upper Kunene River once flowed into the Cuvelai Basin (e. g. Schwarz, 1920; Wellington, 1938). The same is true of the proto-Caculuvar River, and perhaps even some westerly flows of the Cubango River. All three of these large rivers may therefore have contributed sediments to fill and form today's Cuvelai Basin. In those times, much of the basin was probably a lake (Stuart-Williams, 1992).

Although Etosha Pan is the terminal sump of the Cuvelai System, the deepest point is actually in the Omadhiya Lakes, located 60 km upstream of Etosha Pan. The Omadhiya Lakes are some 2 m below the beds of the north-western section of Etosha Pan. As a result, water only flows into Etosha Pan in exceptional flood years. Surprisingly, water from Omadhiya Lakes may also spill-over and reach Etosha Pan through the Oshigambo River as captured in a satellite image taken 12 April 2011 (Fig. 9). Also, the depth of the lake beds regulates the funnelling of *iishana* from a maximum width of 150 km between Olushandja

Dam and Edundja, eventually to converge at Omadhiya Lakes. In turn, the Omadhiya Lakes are controlled by neotectonics (Kempf and Hipondoka, 2003), which are also considered responsible for the downstream section of the Oshigambo River being severed from its mid-section south of Onathinge, between ca. 18.17° S, 16.09° E and 18.26° S, 16.08° E. This severed section extends over 10 km.

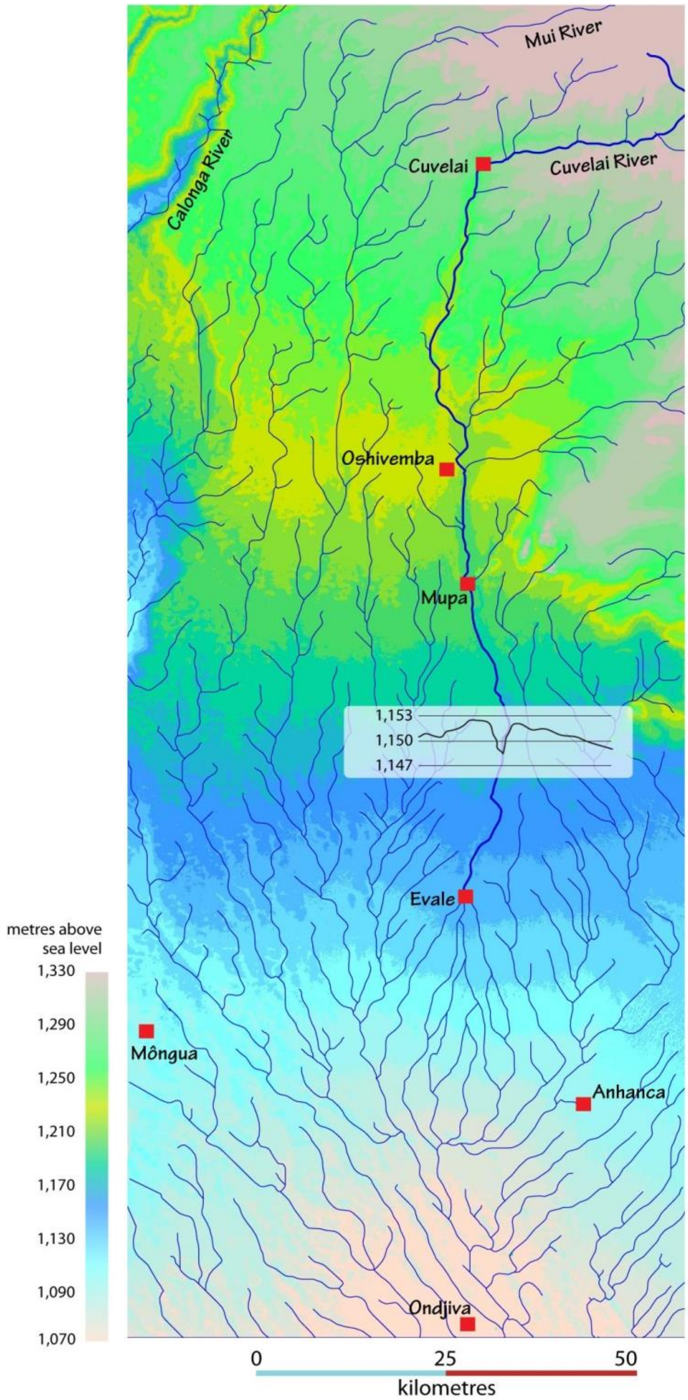

Figure 8. The course of the Cuvelai River from north of Cuvelai, to Mupa, Evale and Ondjiva. Drainage lines flow into the Cuvelai north of Mupa, while others flow away from the Cuvelai River between there and Evale. From west to east, midway between Mupa and Evale, elevations across the Cuvelai River rise from ca. 1150 to 1153 m a. s. l., then drop to 1147 in the Cuvelai River and rise again to 1152 m before sloping down to ca. 1148 m a. s. l. in the east.

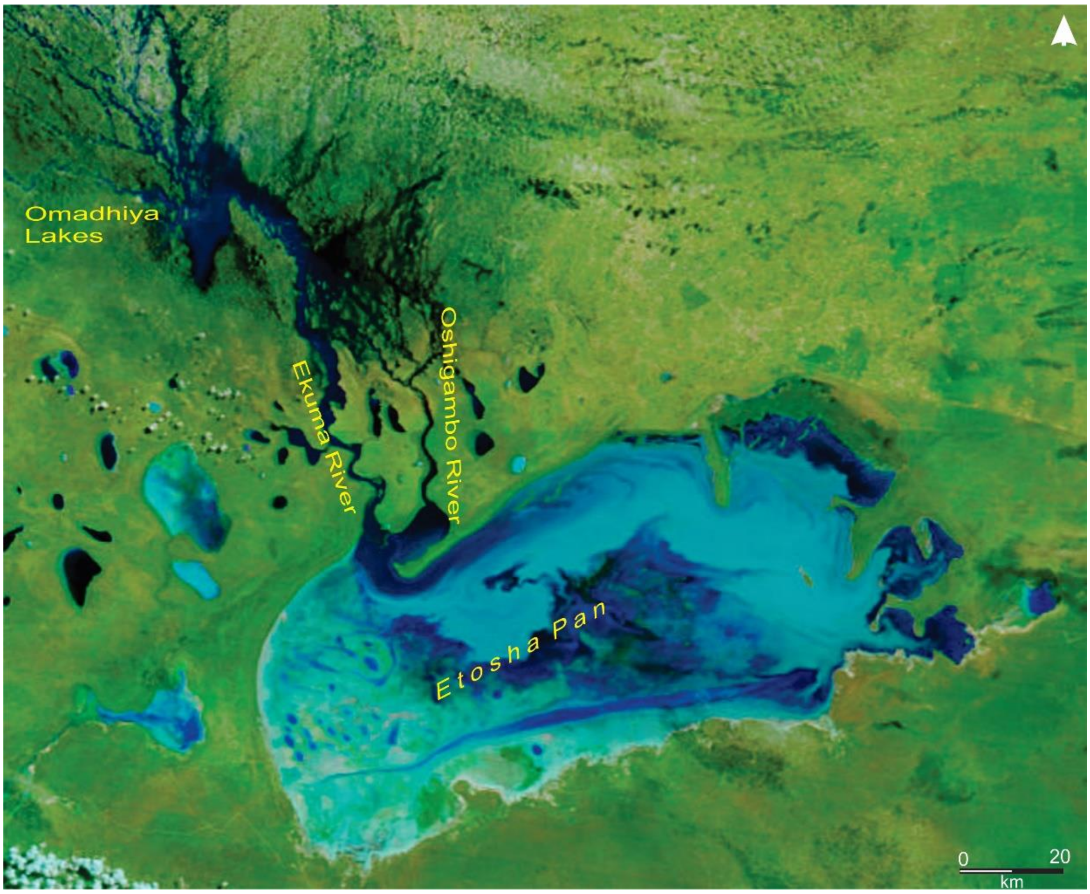

Figure 9. Water reaching Etosha Pan through both the Ekuma and Oshigambo Rivers from Omadhiya Lakes (image source: NASA. https://earthobservatory.nasa.gov/images/50100/flooding-across-northern-namibia)

Etosha's lunette dunes

The prevailing north-easterly wind at Etosha is assumed to have been in force for at least the last 140 ka (Buch *et al*., 1992). It is further assumed that the elliptical shape of Etosha Pan and the orientation of its main axis resulted from lake currents under the influence of this dominant north-easterly wind. However, the setting of the dunes fringing the western margin suggests that their sediments largely originated from the Ekuma Delta. Subsequently, the sediments were redistributed along the western beach face by counter-clockwise lake currents. Like in coastal environments, winds deposited these beach sediments along the shoreline as coastal dunes. In the process, Adamax Pan became separated by these dunes from Etosha Pan. Groundwater seepage beneath these dunes occasionally reaches Etosha Pan from Adamax north of Okondeka, which is a contact spring fed from the same source.

Dust plumes from Etosha Pan's surface add little to the formation of these dunes. This is inferred from the setting or characteristics of the i) current shoreline, ii) remnants of sand ridges rising as islands within the pan, and iii) clay sediment from the pan surface being transported further than the immediate surroundings. The base of the dune adjacent to the Ekuma Delta started as a composite feature with coarser material (Fig. 10). Within a short distance, the base splits into two major ridges, whose material becomes increasingly finer towards their tail-ends at Okaukuejo. The dune base thus starts north of the north-western pan margin and the ridges terminate before reaching the south-western margin of the pan. These two settings suggest that a significant proportion of the coarser material could not be transported further from its source in the Ekuma Delta. The position of the base of the sand ridge is also not aligned with the pan's surface or the dominant, north-easterly wind vector. In contrast, the sand ridge is absent to the south along the last 10 km of the western pan margin which lies to windward of the north-easterly wind.

Logan Island (Fig. 10) is the most

prominent remnant of the sand ridges located west in Etosha Pan. Because of its endorheic nature, the pan contracts and expands depending on the inflow. Logan Island is thus a remnant of an earlier shoreline that was eroded when the pan expanded. The sediments of Logan Island overlie the clay bed that characterises the rest of the pan. The clay layer under Logan Island is situated at the same elevation level as the adjacent clay of the pan.

Although fluvial input to the pan is known to regulate the availability of erodible sediment from the pan (Bryant, 2003), satellite images show evidence for dust uplifted from Etosha Pan and transported over tens of kilometres as far as the Atlantic Ocean by the north-easterly winds (Wiggs *et al.,* 2022). Some of the significant dust plumes pass over the dune-free south-western pan margin. The absence of a collective geomorphic imprint of the dust plumes also points to the limited influence wind has today on the development of these dunes.

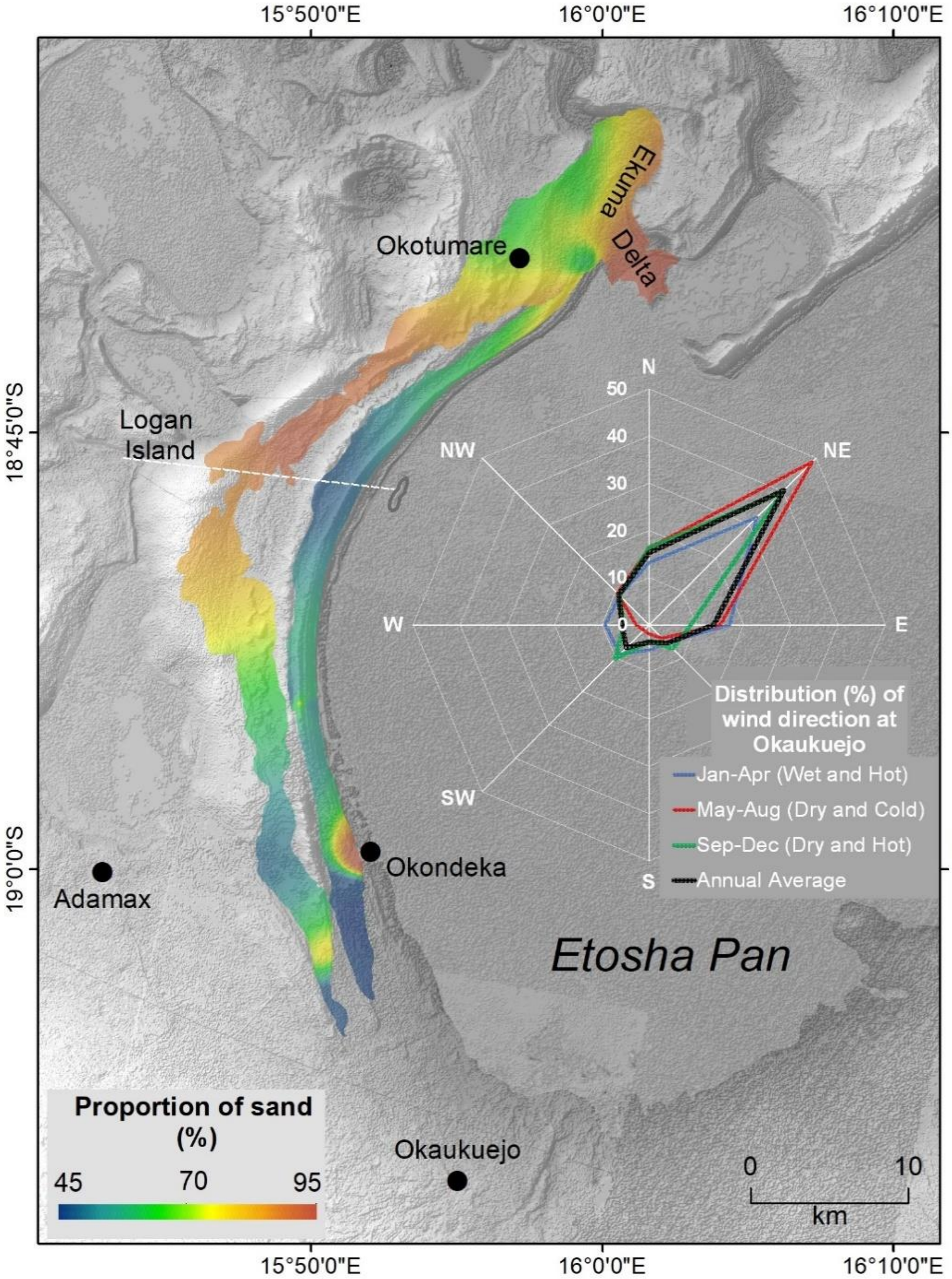

Figure 10. Proportions of sand in lunette dunes along the western margin of Etosha Pan

Raised artesian springs

A spring in the middle of Etosha Pan rests on a mound that rises about two metres above the surrounding pan surface (Fig. 11). The mound is built purely of mud, a result of dust being trapped in the moisture of the spring. Several other springs resting on mounds occur south of Etosha Pan, but these are built of carbonate precipitates from the springs' water (Miller, 2001). Of these the Gobaub spring south of Halali is a prominent example.

Figure 11. Spring in the middle of Etosha Pan a) from a distance, and b) up close from the top

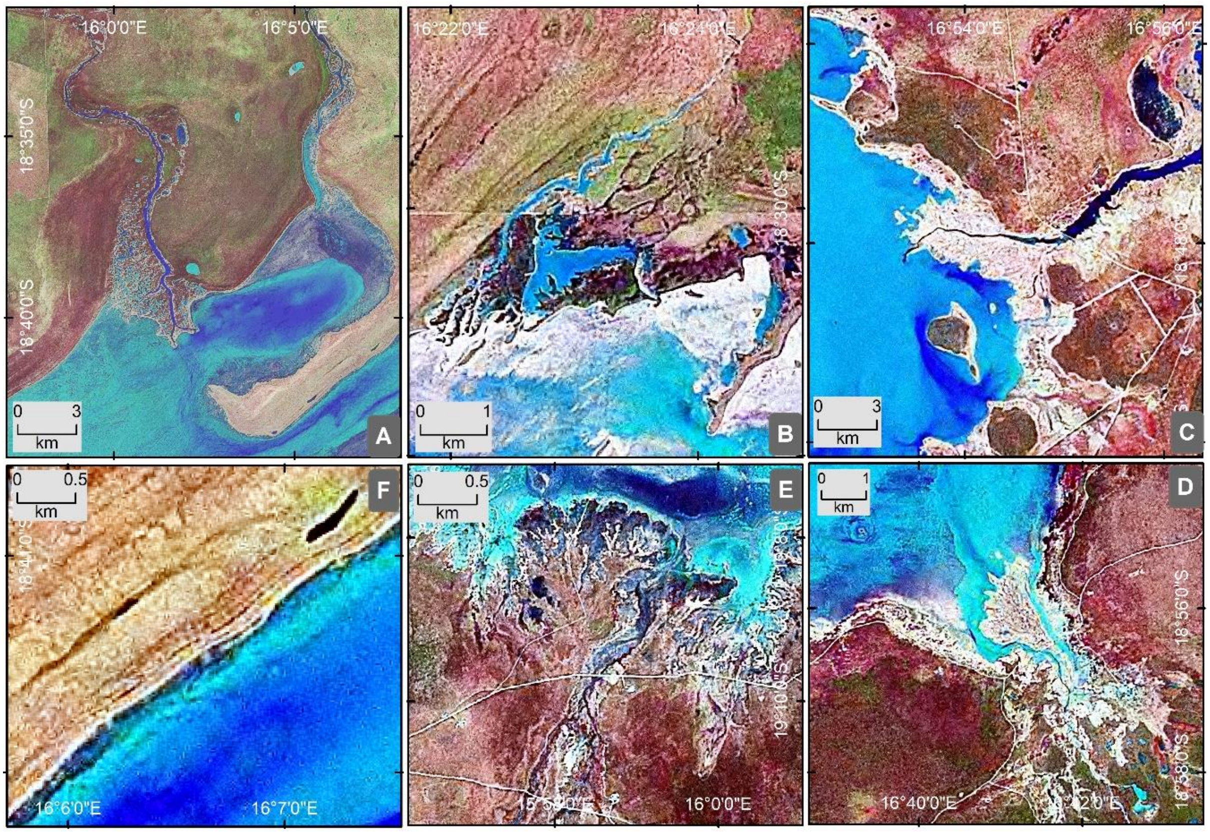

Figure 12. Selected deltas, fan deltas and a section of Oshigambo Peninsula. A) Ekuma Delta (left) and the absence of a delta at Oshigambo River (right), despite its prominence, B) Niipele, C) Fisher's Pan channel, D) Springbokfontein channel, E) Gaseb channel and F) beach sand ridges of the Oshigambo Peninsula. The illuviation of these sand ridges exposes a variety of fossils, including fragments of a sitatunga (Hipondoka *et al*., 2006) – the most amphibious antelope on the planet (Skinner and Smithers, 1990).

Geomorphological processes and footprints at Etosha Pan

Wave action eroded the rugged and steep scarps in the eastern and southern pan margins. Similarly, through deposition wave action shaped the northern Oshigambo Peninsula and western pan margin. Deposition of sediment in the west and eroding wave action in the east contributed to the eastward gradient of the pan.

Although Etosha Pan is one of the two (beside the Kuiseb River system) leading dust sources in Namibia (Vickery *et al.,* 2013), the river deltas, fan deltas and illuviation in the northern, eastern and southern margin of the pan give it more a fluvial footprint.

Ekuma is the only bird's foot delta, suggesting that it was formed under the influence of weak waves and currents, the river flow being stronger. The rest of the deltas in Fig. 12 bear hallmarks of modifications by waves and currents. For example, Niipele, Fisher's and Springbokfontein are all deflected counterclockwise synchronous with the current direction. None of the sediments from these deltas have been dated to establish their chronology.

People of the Cuvelai

There is a notable and close relationship between the Cuvelai Drainage and the Aawambo (in Namibia) or Ambo (Angola) people who speak the same or closely related languages, have similar traditions, rules, farming and livestock keeping practices, villages and homes. Other groups living in low densities in the basin are !Xun, Hai‖Om, Aandongona, Damara, Herero, Ganguela and Nyaneka-Humbe. Many Aawambo have in recent decades moved to live and work elsewhere in Namibia or Angola, or from traditional rural villages to modern towns within the basin.

These emigrants generally maintain close associations with their rural family homes, to such an extent that many households can be termed trans-local, with family members living in quite different parts of the country contributing goods and money to their original family homesteads (Erkkilä *et al*., 2022). The relationships between these urban and rural household members appear to be stronger in Namibia than in Angola for reasons that are unknown and puzzling.

The close relations between Aawambo living either side of the Angola/Namibia border are another notable feature. Most Namibians are descended from grand-, great grand- or older Angolan parents, and many families retain links with members either side of the border. Many Angolan children school in Namibia, and many Angolans regularly visit Namibia for health care and to buy and sell goods. There are also great numbers of Angolans, many of them young, working informally for households on the Namibian side as domestic workers or tending livestock or crops. Conversely, it is estimated that tens of thousands of Namibian cattle belonging to Ovakwanyama owners graze seasonally or even permanently in Angola, especially in the Oshimolo area.

Some villages are bisected by the international border, where residents freely cross the cutline that separates Angola from Namibia (a good example is the village of Onehova visible on Google Earth at 17.393° S, 16.578° E). Most trade between residents of the two countries happens close to the border, especially in and around Santa Clara and Oshikango. Outapi, Onandjaba and Eenhana are other vibrant centres of cross-border trade, while smaller centres of trade are at Ongenga, Okongo and Ondobe. These examples demonstrate the close linkages between Aawambo in Namibia and Angola.

For many years satellite images revealed a conspicuous difference between the Angolan and Namibian sides of the Cuvelai, especially in its densely populated drainage areas (Fig. 13). The Namibian side was distinctly paler and brighter than the Angolan, because more trees had been cleared by the higher number of people resident in Namibia. The Angolan side appeared darker as it had more trees and fewer people and fields. The difference in population density began in the 1930s, when many Angolan Ambo began moving to Namibia (then South-West Africa), largely in response to harsh conditions levied on Angolans in the form of taxation and forced labour (Kreike, 1996; Hayes, 1992). Migration south continued, in later years due to civil war in Angola and the attractive services and economic conditions in

Namibia. At the same time, a large stretch on either side of the cutline was cleared of fields in the 1970s as the war for Namibia's liberation intensified.

In both countries most people cluster in and near the network of ephemeral drainage lines, at population densities much higher than in the surrounding areas (Mendelsohn and Weber, 2011). Historically, people settled among the *iishana*, where a mix of aeolian and alluvial sediments provided relatively fertile soils and because hand-dug wells provided access to fresh water year-round from shallow perched aquifers. Many people also live around arable soils and shallow aquifers amongst the thousands of small pans south-east and south-west of the major surface drainage zones (Arendt *et al*., 2021; Hamunyela *et al*., 2022). By contrast, potable water close to the surface is scarce in the poor aeolian soils that dominate the enclosing areas of the wider Kalahari Basin of which the Cuvelai is a part (Thomas and Shaw, 1991).

Figure 13. Satellite images taken in 1989 (left) and 2019 (right): the 1989 image shows a distinct difference between the darker Angolan and paler Namibian sides of the Cuvelai drainage zones. That distinction, caused by more land being cleared of trees in Namibia, has steadily diminished in recent years as Angola caught up with clearing its land for fields, while some woodland has recovered in Namibia (pers. obs.). The yellow arrow shows the grounds of the Ogongo Agricultural College, the only substantial area of the Cuvelai Drainage in Namibia not to have been cleared of woodland. Both images are from Google Earth with equivalent colour and contrast enhancement.

Environmental concerns

We use this opportunity to draw attention to some concerns regarding the environmental health of the Cuvelai Basin. The first is the accumulation of considerable volumes of human, plastic and other waste around major towns. Much of the waste lies in *iishana* from where it will be carried downstream during floods to be deposited around towns to the south and in the Omadhiya Lakes and Etosha Pan. A study of perennial and ephemeral rivers in Namibia found more micro-plastic particles in the Cuvelai's *iishana* system than in other rivers (Faulstich *et al.,* 2022).

Another concern requiring investigation is the use of dichlorodiphenyltrichloro-ethane (DDT) in mosquito control programmes to suppress the spread of malaria. This insecticide was first introduced in the basin in 1965 (Hansford, 1975; cited in Kamwi, 2005). Although DDT was banned in the 1970s due to its toxicity, it is still produced and given exemption for usage in controling malaria in Namibia (Burgos-Aceves *et al.,* 2021; Kamwi, 2005). The International Agency for Research on Cancer (IARC, 2015) classified DDT as a possible carcinogen in humans. More recently, exposure to DDT through pollution of water and soil resources has been documented to impact reproductive and immune systems with estrogen-disrupting action in humans and wildlife (Burgos-Aceves *et al.,* 2021).

During *efundja* floods great numbers of fish are found and often caught in *iishana* and the Omadhiya Lakes, which prior to the flood may have been dry for years. Where these fish come from is not fully known. Some come from the Kunene River (Van der Waal *et al.,* 2021), but others probably come from sources not connected with this river. Presumably these are fish that aestivate or hatch from eggs in the soil, perhaps in damp depressions. Identifying and protecting these refugia is important, not only for the survival of the fish but also for the nutritional and economic value provided by harvested fish.

Elderly residents often say that water flows in the Cuvelai are nowadays slower and wider than before, a possible consequence of sediments accumulating in the channels and making them shallower. Flood waters thus extend over larger areas and last longer than when these people were young. The sediments are said to have eroded off nearby fields and areas stripped of plant cover by livestock. These rapid changes reportedly have occurred because of the increase in land clearing, soil erosion accelerated by non-conservation tillage practices and livestock numbers. To our knowledge, these ideas have not been tested. If found to be correct, measures to alleviate flooding due to sediment accumulation could be investigated.

Some recent and little known literature

Useful information about the Cuvelai Basin is to be found in the following major, but often relatively unknown publications:

FISH: Van der Waal (1991), Van der Waal *et al.* (2021)

GEOGRAPHY: Feio (1966), SINFIC (2005), Mendelsohn *et al*. (2000, 2015), Mendelsohn and Weber (2011), Mendelsohn and Mendelsohn (2019)

GEOLOGY AND GEOMORPHOLOGY: Thomas and Shaw (1991), Buch *et al*. (1992), Miller (1997), Bryant (2003), Hipondoka (2005), Miller *et al*. (2010), Vickery *et al*. (2013), Wiggs *et al*. (2022), Gärtner *et al*. (2023)

HISTORY: Siiskonen (1990), Williams (1991), Hayes (1992), Kreike (1996, 2009), McKittrick (1996, 1997, 1998, 1999, 2002, 2003, 2006), McKittrick and Shingenge (2002), Gewald (2003)

HYDROLOGY and FLOODS: Stengel (1963), Lindeque and Archibald (1991), Kempf and Hipondoka (2003), Anon (2009), Shifidi (2014), Persendt *et al*. (2015), Wanke *et al*. (2018), Niipare *et al*. (2020), Arendt *et al*. (2021), Hamunyela *et al*. (2022)

LIVELIHOODS: Siiskonen (1990), Calunga *et al*. (2015), Erkkilä *et al*. (2022), Erkkilä (in press)

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The Regional Geochemical Sampling Programme of Namibia (RGSP): Evaluating pXRF Results from Area 2116 Okahandja

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Abstract: - Systematic geochemical soil and stream sediment sampling by the Geological Survey of Namibia (GSN) commenced in 1999. The Regional Geochemical Sampling Programme follows the Final Report of the IGCP (International Geological Correlation Programme) Project 259. Its aim is to establish a National Baseline Geochemical Database of elements in the anthropogenically undisturbed geosphere. Baseline geochemical surveys have applications in mineral exploration, land use planning, agriculture, medical geology, and many other fields. 2850 stream sediment and soil samples, including 159 duplicates, were collected at pre-selected locations in the area covered by 250 k map sheet 2116 Okahandja. Preliminary geochemical data were obtained by analysing the fine fraction (<180 µm) by portable XRF (Niton Energy Dispersive XRF) at the GSN laboratory to assess the effectiveness of this method in regional surveys. Spatial distribution maps for Cu and Fe in soil and stream sediments were compiled with ESRI ArcGIS software, and interpreted in terms of underlying country rock and morphology.

Keywords: - Geochemical mapping, baseline study, copper, iron

Introduction

The Geological Survey of Namibia has been conducting a nationwide regional geochemical mapping programme for over two decades, starting in 1999. The purpose of the project is to develop a geochemical database of most elements in the geosphere, untampered by human activities, although much of the ground is farming land. To date, sampling of eight and a half 1:250 000 map sheets has been completed (Fig. 1), with over 21 000 samples collected in an area covering approximately 170 000 km^2 or slightly more than 20% of the country. The Okahandja map sheet, located in central Namibia, north of the capital Windhoek, was sampled in 2003/4. A total of 2850 samples was collected, with an average sample density of approximately one sample per 7-8 km^2. The analytical data of these samples will be useful across many sectors, such as land use planning, mineral exploration, medical geology, agriculture and environmental monitoring. The purpose of this report is to establish a method of presentation of the data obtained, as well as to evaluate the usefulness of pXRF in regional geochemical surveys intended to produce baseline data. Of the 43 elements analysed (Ag, Al, As, Au, Ba, Bi, Ca, Cd, Cl, Co, Cr, Cs, Cu, Fe (tot), Hf, Hg, K, Mg, Mn, Mo, Nb, Ni, P, Pb, Pd, Rb, Re, S, Sb, Sc, Se, Si, Sn, Sr, Ta, Te, Th, Ti, U, V, W, Zn, Zr), copper and iron were selected as test cases because of their comparative abundance, and relatively low minimum detection limits of ± 20 ppm and 50 ppm, respectively, on the analytical instrument chosen.

Topography and Survey Design

Area 2116 Okahandja encompasses some highly variable terrain. Altitudes between 1600 m and 1800 m are being attained in the south-eastern part, while isolated inselbergs rise several hundred metres above the surrounding plains in the west. The lowest elevations are recorded in the south-west (<1200 m) and north-east (<1400 m), where the terrain drops off to the Namib Plains and the Kalahari Sandveld, respectively. The greatest topographic prominences are Omatako (2286 m), followed by Otjihaena (2108 m) and Mt. Etjo (2082 m) in the north-western sector. The map area is drained by the ephemeral Swakop, Khan and Omaruru Rivers, which flow westwards to the Atlantic coast, and their tributaries. The Omatako River rises in the Omatako Mountains and drains towards the Kalahari. All water-courses within the area flow only for short periods during a good rainy season, but – excluding exceptionally dry seasons - contain subsurface water at shallow depths throughout the year (Linus and Schreiber, 2017).

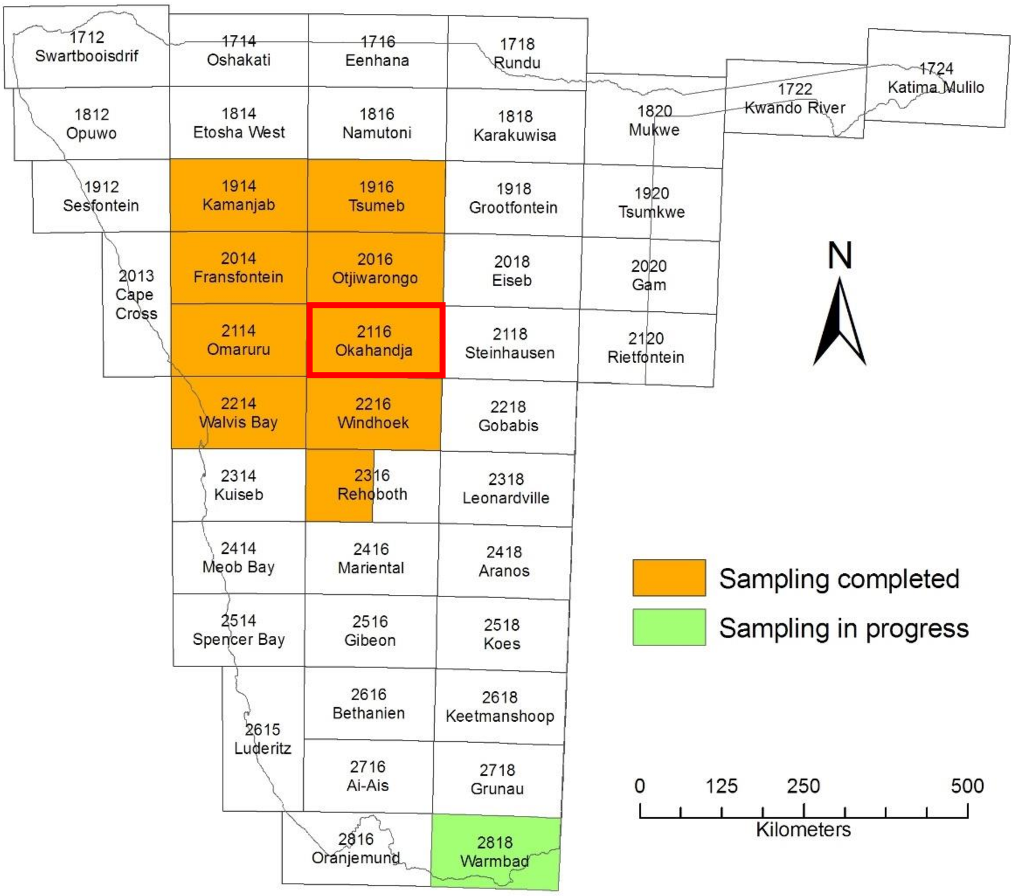

Figure 1. Index of 250 k map sheets showing the current status of the Regional Geochemical Sampling Programme (RGSP), with eight and a half sheets completed and one more in progress; area 2116 Okahandja is marked by the red box.

In the western, hilly part of the area (2116; Fig. 2) the drainage system is well-developed, and samples were taken mostly from second and third order streams, with a few from main drainage channels (i. e. Khan, Omaruru, Swakop, Omatako Omuramba) as control samples, and to detect potential anomalous values missed. Stream sediment sample locations were selected with the aim to cover drainage areas of approximately 10 km^2 or less per sample. Soil samples were taken to infill areas between drainages in the western part, while in the flat-lying east of the map area (area 2117; Fig. 2), where drainage channels are poorly developed or absent, soil samples predominate at a spacing of roughly one sample per 10 km^2.

While most stream sediment samples (except those within main drainages) were selected to detect the geochemical composition of areas drained by small seasonally flowing streams, the soil samples reflect *in situ* weathering and leaching of the underlying bedrock. However, where the Kalahari overburden exceeds 10 m in the north-eastern sector of the map sheet (Fig. 2), little expression of the buried rocks can be expected to show in surface samples, as is borne out by the analytical results (Figs 9, 13).

Altogether 2691 locations were sampled within the survey area. Of these 1492 were from stream sediments or drainages (~55.5%), which constituted the preferred sample medium, as being representative of a larger terrain, while 1199 were soil samples (44.5%). In the western half of the map sheet (area 2116) the proportion of drainage to soil samples was 1272 : 220 (excluding duplicates), while in the east (area 2117), where drainages are less well defined and often barely distinguishable from the surrounding soil cover, soil samples dominate over drainage samples 762 : 437 (excluding duplicates), the latter taken mostly from the south-western part (area 2117C; Fig. 2). For this reason, interpretation and visualisation of the analytical results is based on stream sediment samples in the western half of the area, and on soil samples in the east.

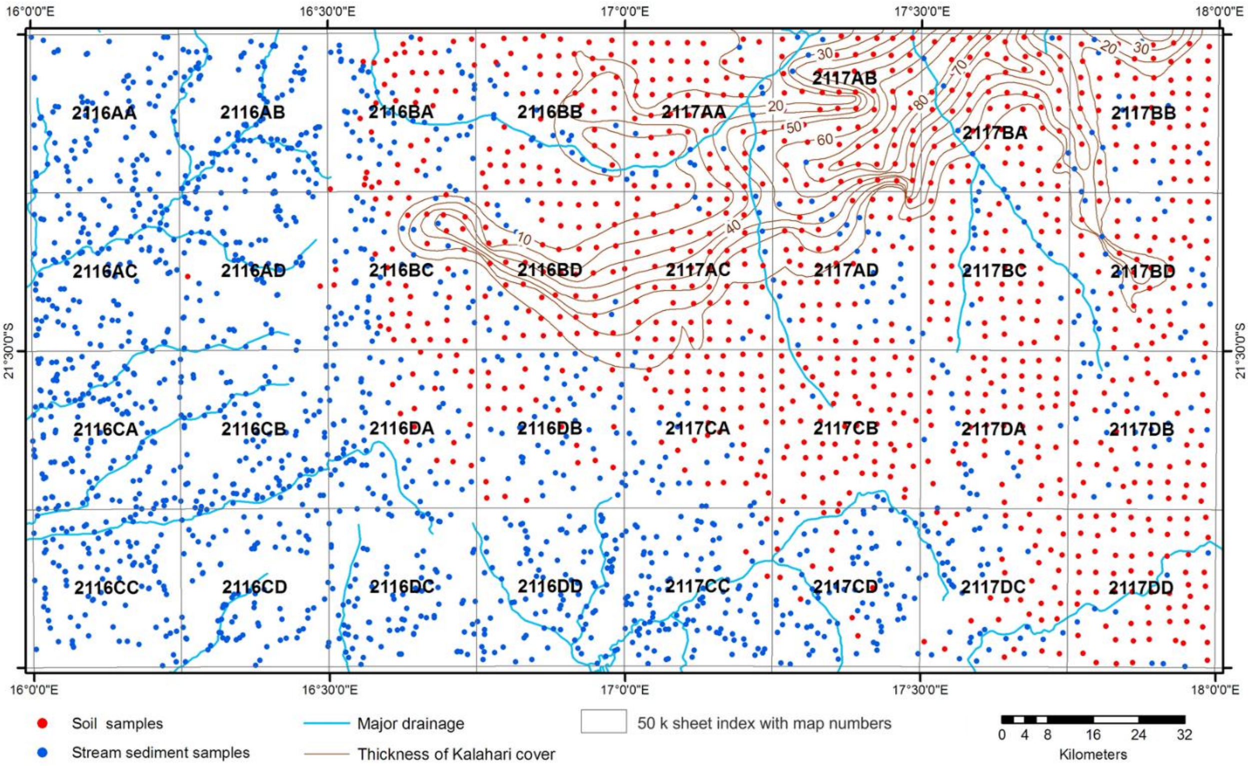

Figure 2. Survey layout showing positions of soil and stream sediment samples, major drainages and Kalahari isopachs

Sampling method

The RGSP is based largely on the recommendations of IGCP Project 259, also known as the "Blue Book", which outlines sampling protocols, sample handling, storage, analytical requirements and techniques for geochemical mapping in various environments. At each pre-selected sample location identified during the planning phase, five sample pits of ca. 25-30 cm depth were dug, and a composite sample obtained and screened. Two samples were collected, i. e. a coarse (<2 mm fraction) sample was placed in a 5 kg polystyrene bag, and a fine (<180 micron fraction) sample was stored in a 60 g polystyrene bag (Fig. 3). To avoid contamination, only wooden and plastic tools were used to collect and screen the samples. New gloves were used at each site to be worn during the major sampling stages, and the screening mesh was decontaminated by passing material from each new site before processing the actual sample. The samples were then riffle split and homogenised to obtain portions for analysis and archiving. All samples are stored at the GSN facilities in Windhoek.

Figure 3. Sample collection from a drainage channel showing the two size fractions collected

Sample Preparation and Analysis

Geochemical analysis of the samples from the Okahandja area was focused on the fine fraction (<180 microns). A representative portion of each sample was pulverised to < 64 µm, using a planetary Agate Ball Mill (Fig. 4) for a duration of 120 seconds. Subsequently, a well homogenised sample was placed into a sample cup with a thin mylar film at the base. As during the sampling process, a fresh pair of gloves was used for handling each new sample to avoid contamination. Geochemical analysis was carried out by a handheld Thermo Scientific Niton Energy Dispersive XRF (Niton XL3t GOLDD) spectrometer at the GSN laboratory in 2018. Each sample was analysed by placing the sample cup on the stage of the ED-XRF, which was run for 150 seconds (Fig. 4). Detection limits are shown in Fig. 5.

Figure 4. Sample preparation in an Agate Ball Mill (left) and analysis by Niton ED-XRF (right)

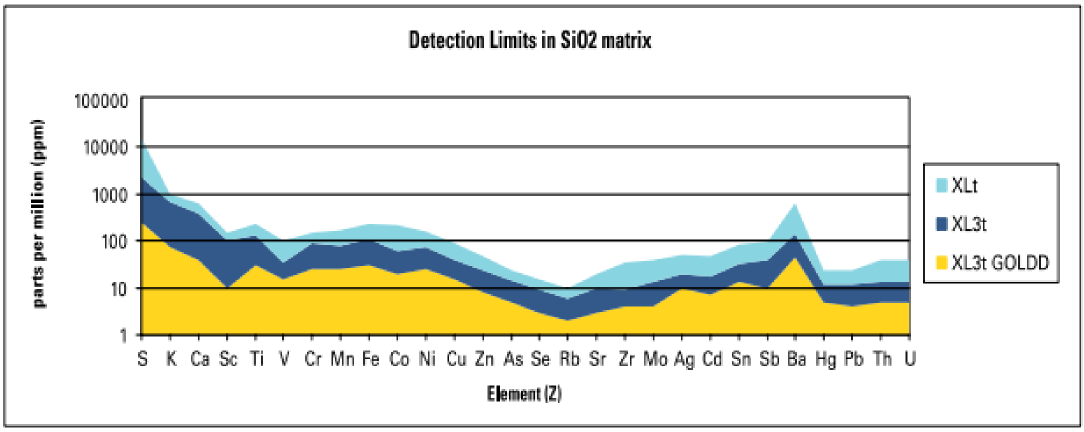

Figure 5. Detection limits of the XL3t GOLDD as compared to other models

Quality Control

The RGSP is supported by several internationally recognised Certified Reference Materials (CRMs) acquired from various institutions, i. e. Chinese manufactured standards (NCS DC 77301-3) for soil samples and Canadian originated standards (STSD_1-4) for stream sediments. Furthermore, two locally developed standards, SSTD-1 and a blank standard containing pure quartz, were used as part of the QC protocol. Duplicate and CRM samples were routinely inserted into the batches after every twentieth sample. Various QC plots of Standards and CRMs were created in Microsoft Excel to test for accuracy and precision of the analytical data (Fig. 6). In addition, evaluation of CRMs, blanks and local standards was carried out through Shewatt control charts (Piercey, 2014) and XY plots.

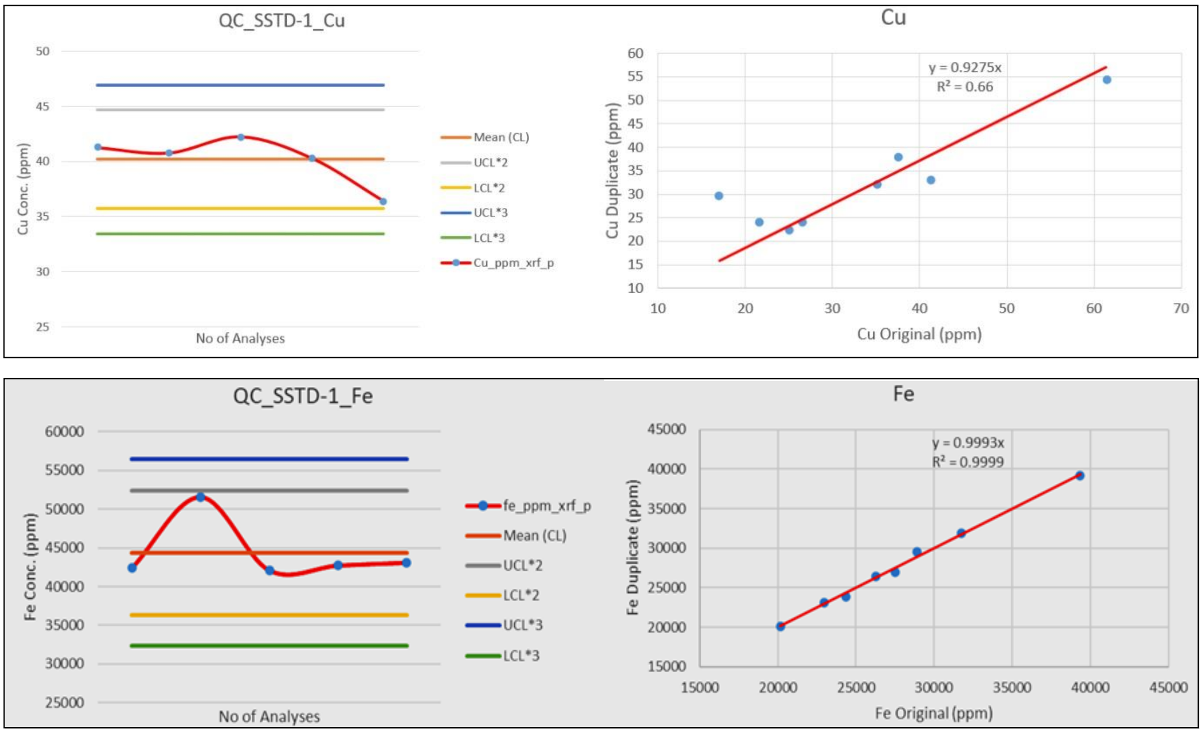

Figure 6. Control charts for copper and iron using the SSTD-1 standard to check accuracy (left); XY plot using duplicate samples for testing precision (right)

Data Visualisation

To visualise the results, basic exploratory analysis methods provided by ESRI ArcGIS software were used. To evaluate distribution trends in the data (e. g. normal, unimodal or bimodal distribution), both histograms (Figs 9, 11, 13, 15) and quantile-quantile plots (Fig. 7) were employed. Since geochemical data hardly ever show a normal distribution, the data were normalised using a logarithmic transformation before a spatial visualisation of distribution patterns was attempted. Following transformation, graduated symbol and gridded maps were produced to show the distribution of copper and iron within the survey area, the latter based on the inverse distance weighting technique (Figs 8 to 15).

Spatial Distribution of Copper

General

Copper (Cu) has an atomic number of 29, an atomic mass of 63 and two main oxidation states, i. e. +1 and +2. It has two naturally occurring isotopes (^{63}Cu and ^{65}Cu), with relative abundances of 69.17% and 30.83%, respectively (Albanese *et al*., 2015; Salminen, 2005). Copper forms sulfide minerals such as chalcopyrite ($CuFeS_2$) and Covellite (CuS) under reducing conditions, hydroxides and carbonate minerals, such as malachite [$Cu_2CO_3(OH)_2$)] under oxidising conditions, and can also occur in its native/metallic state as copper nuggets (Albanese *et al*., 2015; Salminen, 2005; Koljonen, 1992). Copper occurrences, many of which have been mined on a larger or smaller scale, are widespread throughout Namibia and present in almost all major lithostratigraphic units.

Copper has a higher affinity for mafic (40–60 ppm) and ultramafic rocks (40 ppm); in intermediate (20 ppm) and granitic rocks (12 ppm) it is found more rarely (Wedepohl, 1978). Black shales contain ~50 ppm Cu (Albanese *et al*., 2015; Reimann and De Caritat, 1998; Salminen, 2005), while quartzo-feldspathic and carbonate rocks contain only 5–15 ppm (Albanese *et al*., 2015; Salminen, 2005). The average concentration of copper in the earth's crust is 68 ppm (Salminen, 2005), while the average concentration in world soils ranges from 13 to 30 ppm (Adriano, 2001; Salminen, 2005). Copper is an essential nutrient for plant and animal growth at concentration levels of 5 to 30 ppm (Adrees *et al*., 2015) and 15 to 60 ppm (Koljonen, 1992), respectively. Less may lead to deficiency symptoms, whereas higher concentrations result in toxicity.

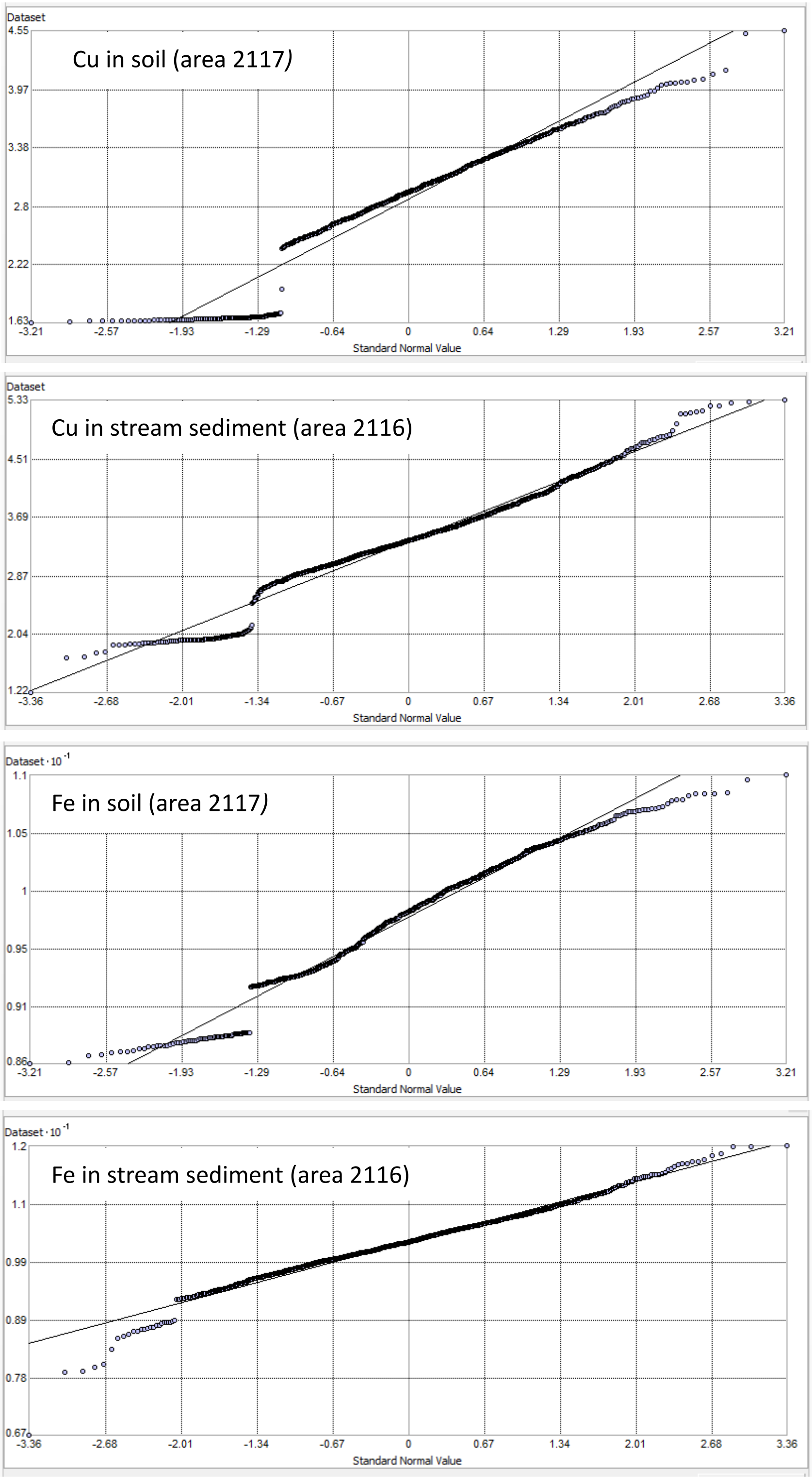

Figure 7. Normal Q-Q plots showing distribution trends in the various data sets: Cu in soil (Figs 8, 9); Cu in stream sediment (Figs 10, 11); Fe in soil (Figs 12,13); Fe in stream sediment (Figs 14,15)

Copper in soil (eastern map sheet; Area 2117)

The spatial distribution of copper in soils depends on climatic, geological and structural factors, as well as anthropogenic activities (Ballabio *et al*., 2018). In the eastern part of the Okahandja map sheet, analysed copper in soil values range from 5 to 91 ppm, with an average of 21 ppm, and a median of 19 ppm, which is comparable to average crustal values reported by Koljonen (1992) and Adriano (2001).

The area is largely covered by surficial sediments (sand, gravel, calcrete), interspersed with isolated outcrops of Damara-age metasediments (mica schist, marble, quartzite) and intrusives (pegmatite, granite, amphibolite); even more rarely high-grade metamorphic rocks of the Abbabis Complex, which forms the oldest stratigraphic unit in the area, are exposed.

The spatial distribution of copper is generally low, but variable across area 2117 (Figs 8, 9). Highest values occur in the south-east, where amphibolites and quartzo-feld-pathic gneisses of the Ekuja Basement Dome (Abbabis Metamorphic Complex) outcrop in the vicinity of the Omitiomire copper occurrence (Kitt *et al*., 2016), and around the Onjona-Eleksie Nappe Complex, consisting of paragneiss, quartzite and minor amphibolite. Younger Damara-age amphibolites intrusive into Kuiseb Formation mica schists south of the nappe complex also are likely sources of copper.

Copper in soil values decrease towards the north, concomitant with an increase of Kalahari cover over bedrock. Concentrations between 18 and 40 ppm occur in areas underlain by Damara metasediments; lowest values of less than 16 ppm are recorded in the north, where the thickness of the Kalahari overburden locally reaches 80 m, thus reducing the likelihood of geochemical bedrock anomalies finding expression in surface samples.

Copper in stream sediments (western map sheet; Area 2116)

The spatial distribution of copper in the western part of the map, where only stream sediment samples are considered in our analysis, is generally higher, averaging 34 ppm (4.5 – 197 ppm). Contrary to the comparatively low copper contents of granitic rocks postulated by Wedepohl (1978), elevated values are observed in samples representing drainages underlain by Damara-age granitoids, specifically the porphyritic Salem biotite granite, which dominates the southern part of the area, with smaller outcrops to the north-west (Figs 10, 11). Above-average concentrations also occur where hills and ranges formed by dolerite intrusions rise several hundred metres above the surrounding plains, which are underlain by deeply weathered Damara granite. Lowest values are measured in the north-east, where the Neoproterozoic Damara rocks are overlain by a thick cover of Karoo and Kalahari sediments.

Spatial Distribution of Iron

General

Iron (Fe; element 26 in the periodic table) has a molecular weight of 55.847, a melting point of 1535°C, a boiling point of 2800°C, and a specific gravity of 7.874. Four stable isotopes are found in nature: ^{54}Fe, ^{56}Fe, ^{57}Fe and ^{58}Fe. Iron commonly exists in one of three oxidation states: Fe^0 (elemental iron), Fe^{2+} (ferrous iron) and Fe^{3+} (ferric iron). It is the fourth most abundant element in the earth's crust after oxygen, silicon and aluminium, and accounts for over 5% of the crust’s mass. Its average crustal abundance is 7% (Williamson, 1998), while the W.H.O. maximum allowable limit for iron is 5% (Ogunlana *et al*., 2020). Iron is an essential element for almost all living organisms as it drives metabolic processes, including oxygen transport, DNA synthesis and photosynthesis in plants. If the concentration of available (soluble) iron, which is only a small fraction of the total Fe content in soils and stream sediments, is less than 50 ppm, deficiency symptoms result, while toxic effects may be observed where it exceeds 500 ppm. Iron is present in primary minerals, in the crystal lattices of clays and in weathered soils. An important feature of iron is its ability to combine with other metals to form a variety of alloys for a host of different uses and applications.

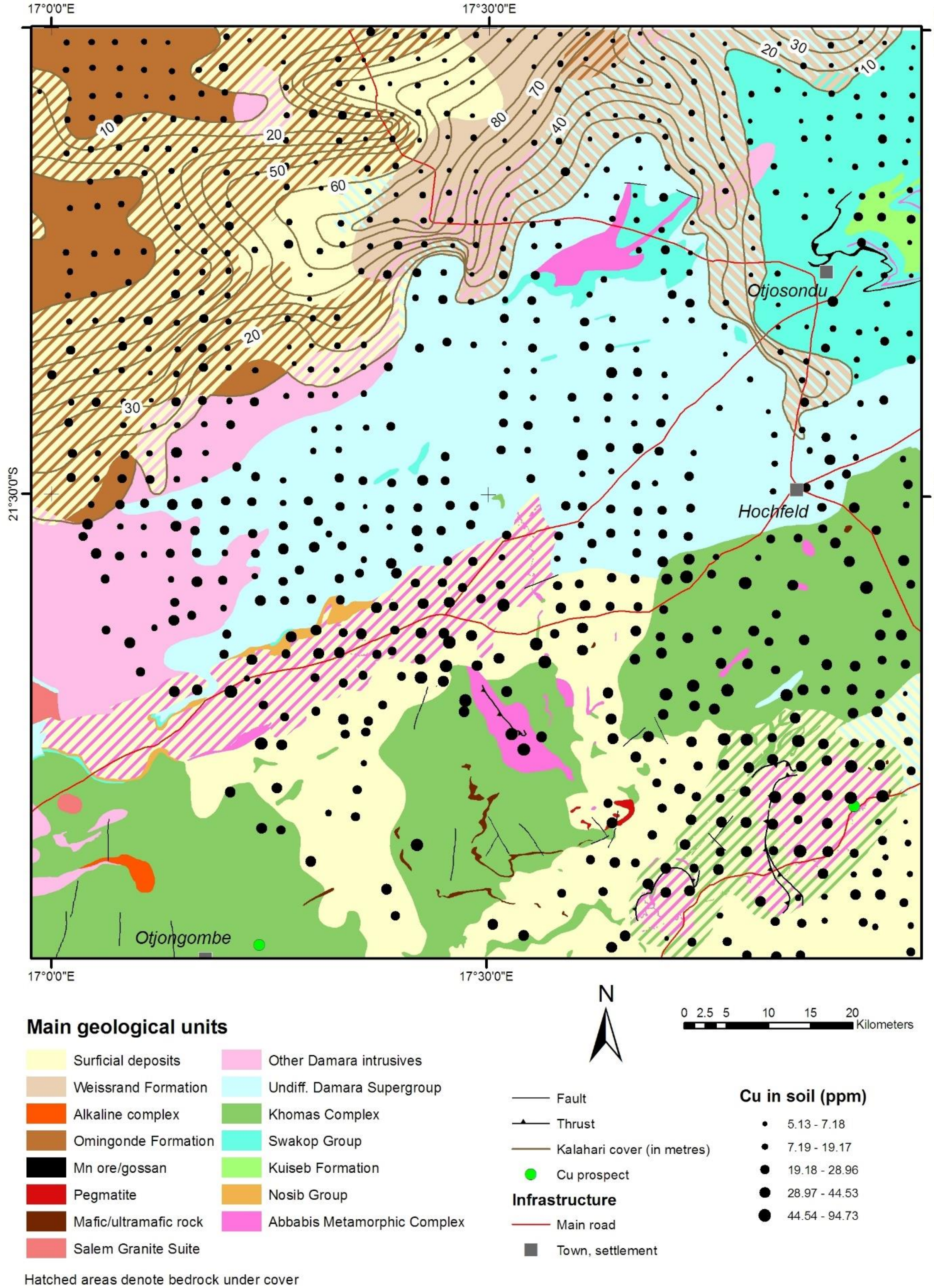

Figure 8. Graduated symbol visualisation displaying copper in soil concentrations in the eastern half of the Okahandja map sheet (area 2117), superimposed on a simplified geological map showing main lithological units, structures and copper prospects

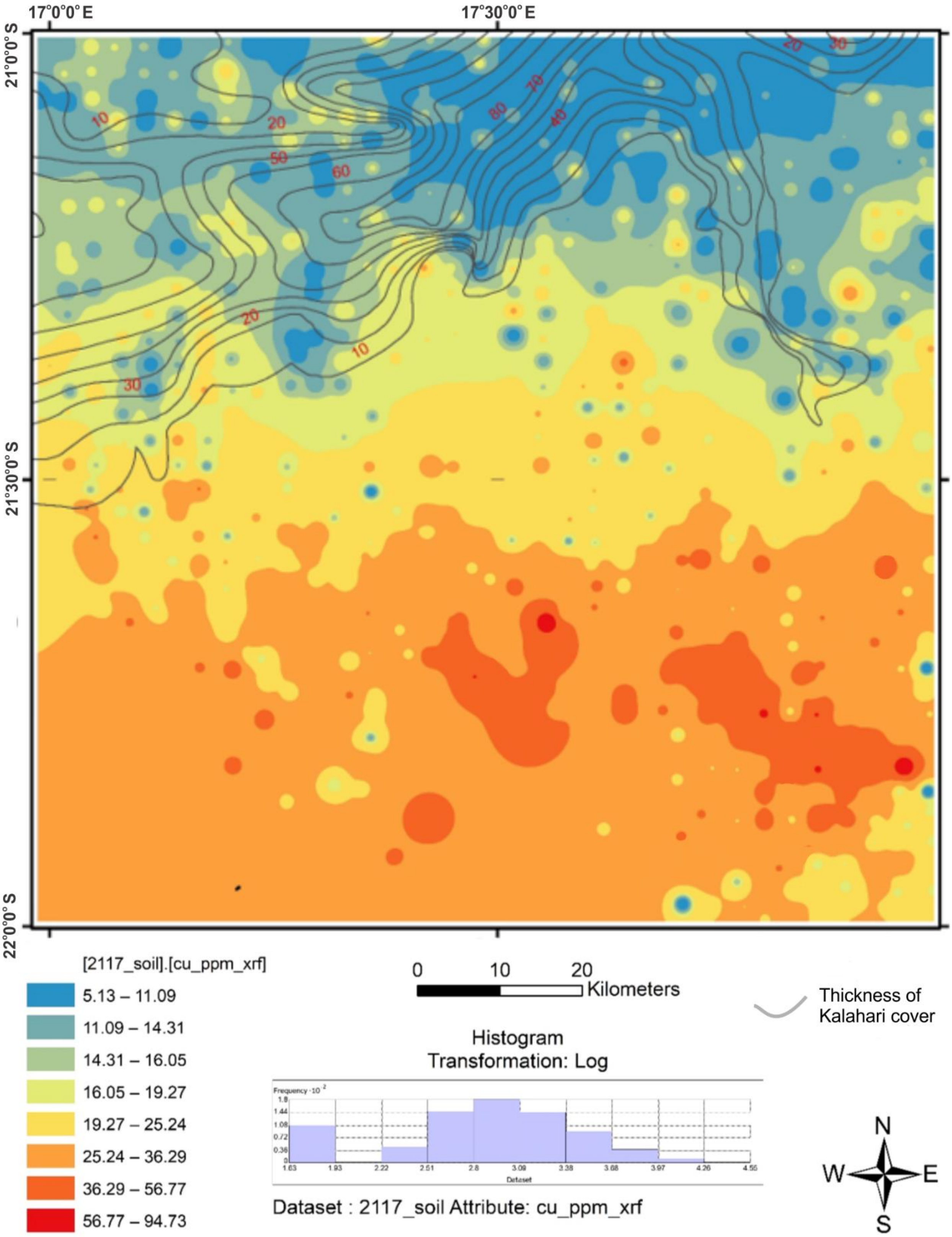

Figure 9. Gridded map of copper in soil concentrations based on inverse distance weighting (IDW) in the eastern half of the Okahandja map sheet (area 2117), showing a marked north-south trend; the histogram gives the distribution of abundances.

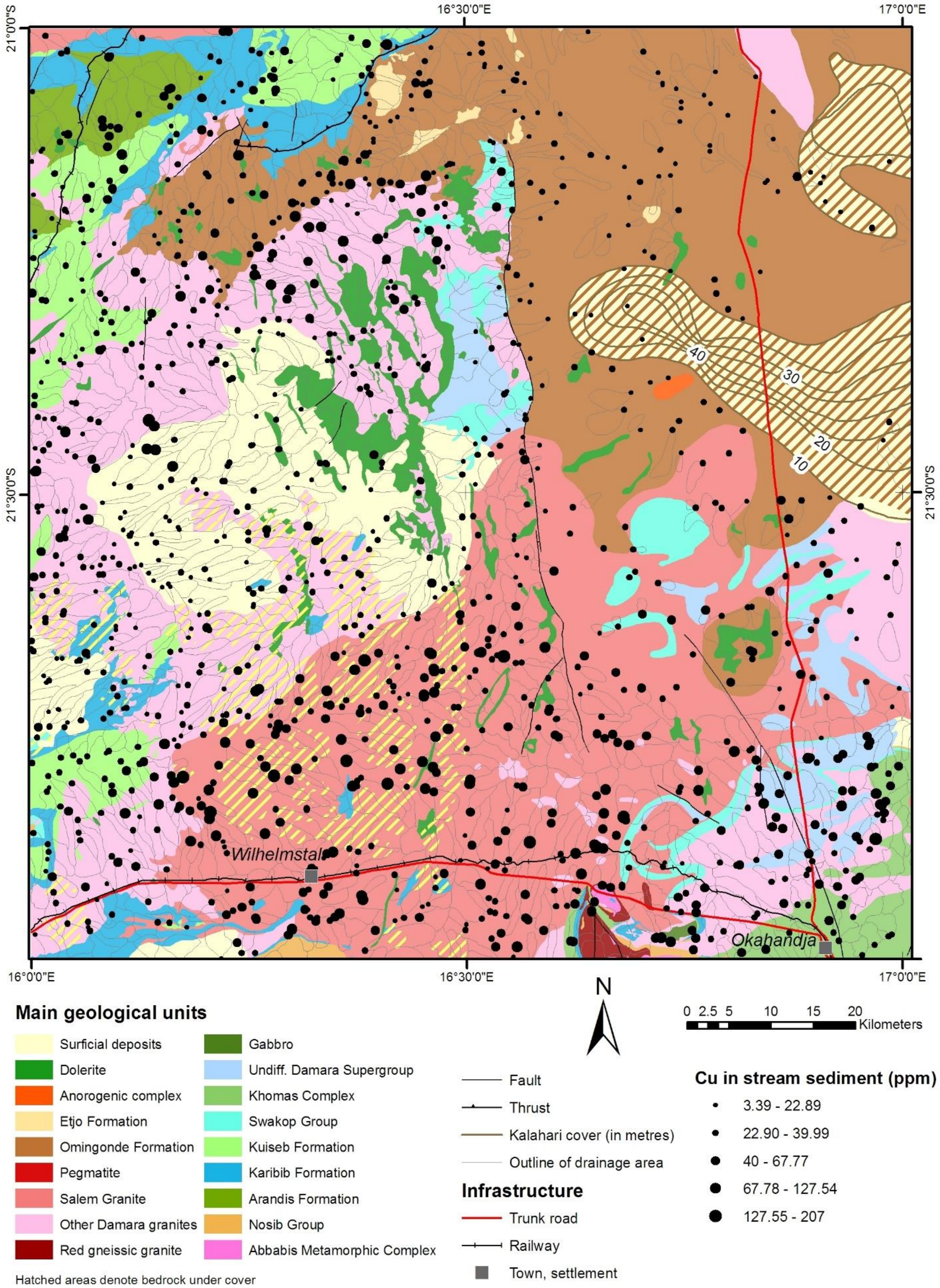

Figure 10. Graduated symbol visualisation displaying copper in stream sediment concentrations in the western half of the Okahandja map sheet (area 2116), superimposed on the simplified geological map showing main lithological units and structures

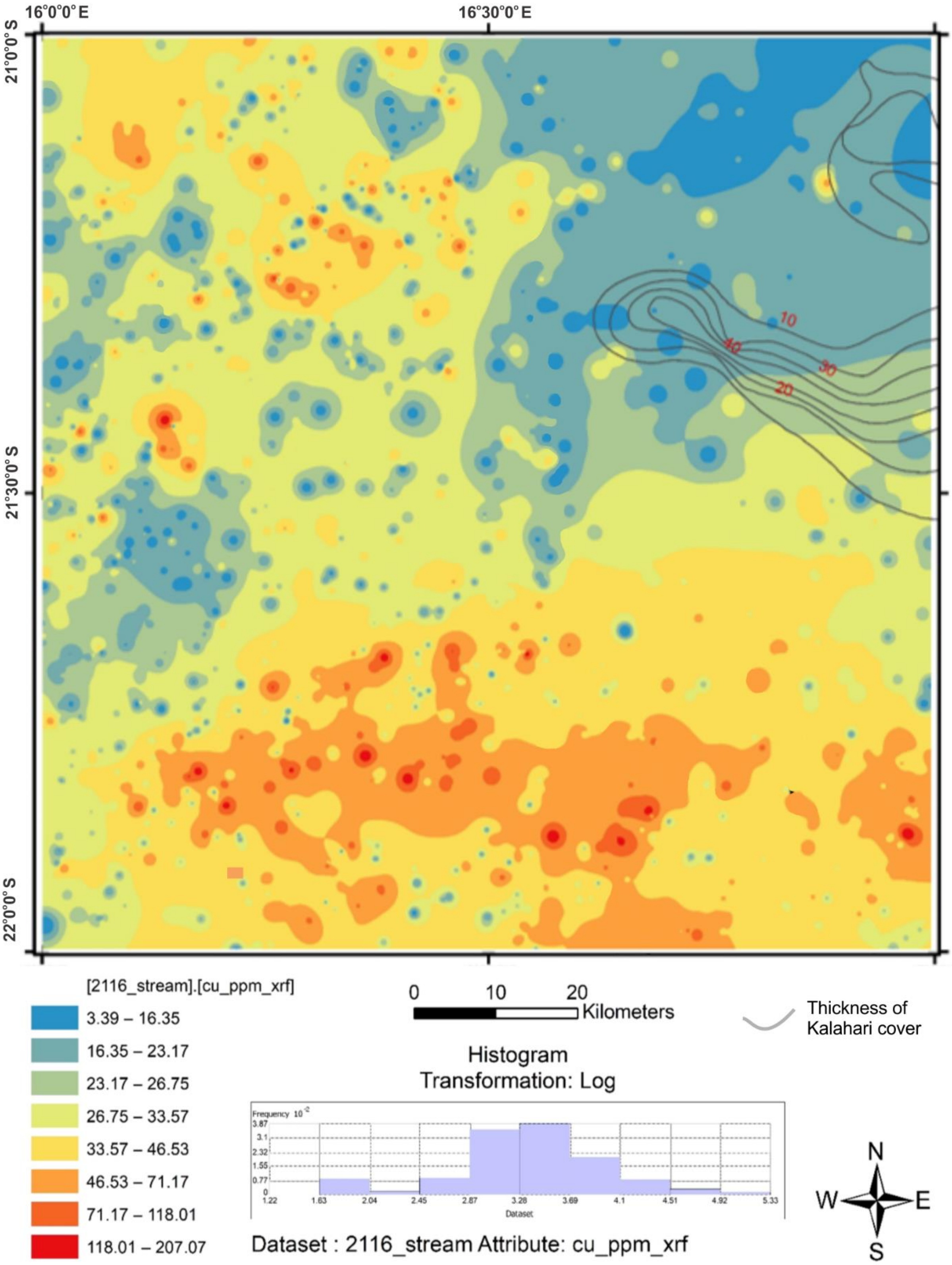

Figure 11. Gridded map showing copper in stream sediment concentrations based on inverse distance weighting (IDW) in the western half of the Okahandja map sheet (area 2116); the histogram gives the distribution of abundances.

Iron in soil (eastern map sheet; Area 2117)

In the eastern half of the area, Fe concentrations in soil samples range from 5286 ppm (0.53%) to 58216 ppm (5.82%), with an average of ~2%. This figure is below the documented Fe concentration in both the upper continental crust (3.3 %) and in world soils (3.5%; Koljonen, 1992).

The highest values of >33500 ppm are encountered in the southern central part (Figs 12, 13), which is underlain by mica schists and marbles of the upper Swakop Group (Damara Supergroup), intruded locally by amphibolites and pegmatites. Basement gneisses of the Abbabis Metamorphic Complex seem to have yielded somewhat lower Fe concentrations to the soil during weathering (~26000 to 33500 ppm; SE corner of the area). As with copper, iron concentrations drop steadily towards the north, which may be attributed to the increasing Cenozoic overburden, consisting of unconsolidated to semi-consolidated sediments of the Kalahari Group and Karoo-age mudstones and sandstones, evidently low in the two elements under consideration.

Iron in stream sediments (western map sheet; Area 2116)

Measured iron concentrations in stream sediments of the western part of the map sheet range from 851 ppm to the 169800 ppm (or 16.98 %), with an average concentration of 3.4%, which is higher than the respective average in soil samples in the east (2%), and close to the upper continental crust average of 3.3%. The overall distribution pattern is similar to that of copper in the same area, with highest concentrations occurring in the south and northwest (Figs 14, 15).

Samples representing catchments underlain by granitic rocks, specifically the biotite (Fe, Mg phyllosilicate) – rich granitoids of the Salem Suite, tend to show greater concentrations than those deriving from drainages dominated by metasedimentary rocks. Once again lowest values are observed in areas of thick Karoo and/or Kalahari cover in the northeast.

Summary and conclusions

This report presents generalised spatial distribution maps of copper and iron within area 2116 Okahandja. On account of local topography only stream sediment samples were considered in the western part (area 2116), while in the largely sand-covered eastern portion (area 2117) only soil samples were used. In the latter area, copper and iron in soil show much lower absolute and average values than the stream sediment samples in the west, which represent drainages of hilly areas with rock outcrops. In the east highest concentrations occur in the vicinity of scarce basement outcrops (Abbabis Metamorphic Complex), while in the west, areas underlain by granitic or mafic intrusives show elevated values. The distinct N-S trend in both copper and iron concentrations in area 2117 may be jointly ascribed to bedrock composition and Kalahari overburden, which increases in a northerly direction (Figs 9, 13). Apart from the rock types outcropping in or underlying the sampled area and thickness of Kalahari/Karoo cover, anthropogenic activities in this agricultural region may account for local highs, although care was taken to collect samples away from roads and fences, and other possible sources of contamination. Potentially toxic copper concentrations in stream sediments were measured north of the main road and railway between Okahandja and Wilhelmstal (Fig. 10), possibly due to polluting effects.

Analytical results were also compared to known crustal abundances. This showed copper and iron in soil samples of area 2117 on average to be lower than the documented values for upper continental crust and world soils, while concentrations of the same elements in the west, where stream sediments were analysed, are within small margins of the above values.

This case study shows that pXRF analysis, while having relatively high lower limits of detection (Fig. 5) compared to conventional analytical methods (XRF/ICP), provides a fairly reliable picture at regional scale of the distribution of comparatively abundant elements, such as Fe and Cu. However, it is unsuitable for elements of low abundance (e. g. gold) because of too high lower limits of detection.

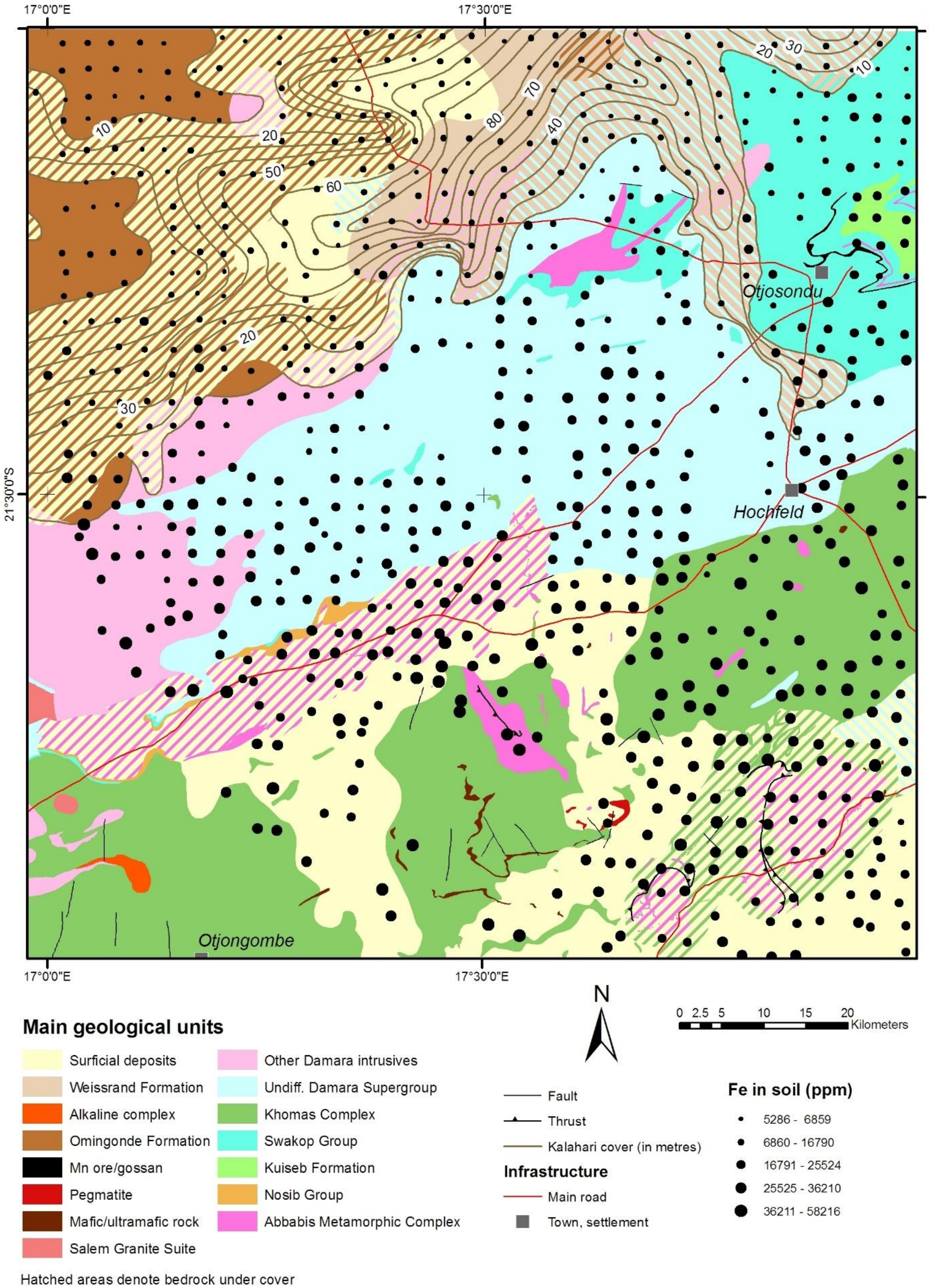

Figure 12. Graduated symbol visualisation displaying iron in soil concentrations in the eastern half of the Okahandja map sheet (area 2117), superimposed on the simplified geological map showing main lithological units and structures

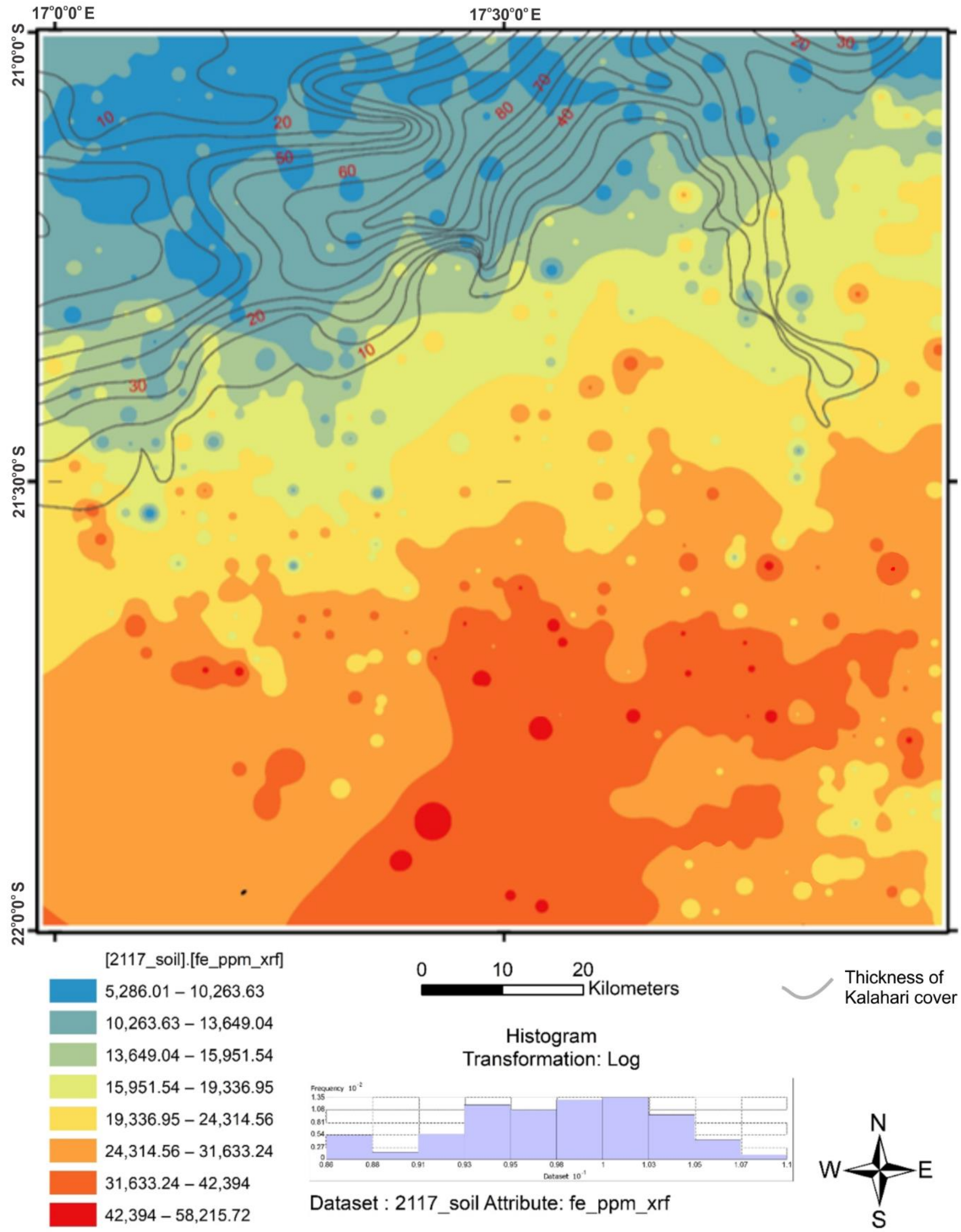

Figure 13. Gridded map showing iron in soil distribution based on inverse distance weighting (IDW) in the eastern half of the Okahandja map sheet (area 2117), showing a marked north-south trend; the histogram gives the distribution of abundances.

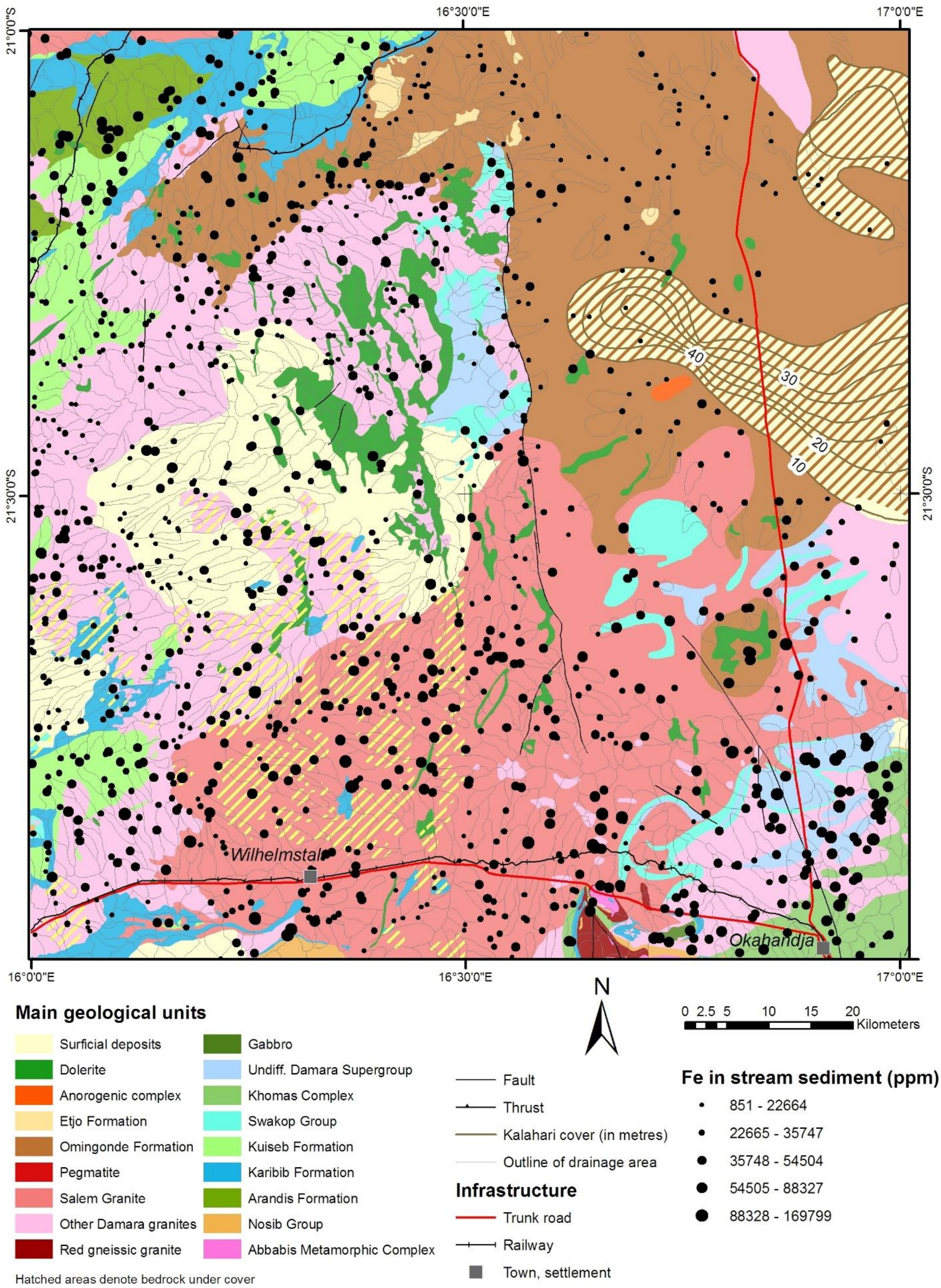

Figure 14. Graduated symbol visualisation displaying iron in stream sediment concentration in the western half of the Okahandja map sheet (area 2116), superimposed on the simplified geological map showing main lithological units and structures

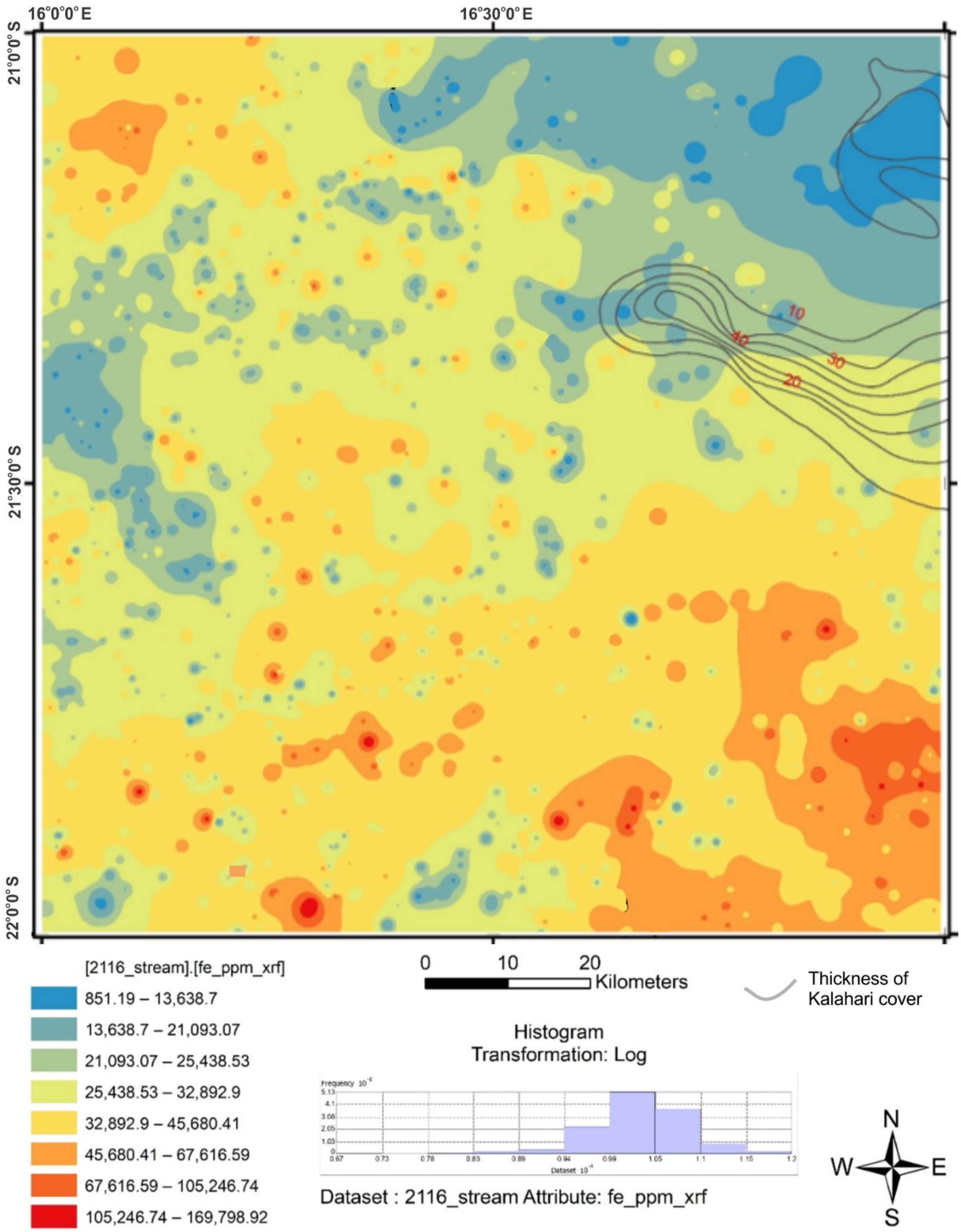

Figure 15. Gridded map showing the distribution of iron in stream sediment based on inverse distance weighting (IDW) in the western half of the Okahandja map sheet (area 2116); the histogram gives the distribution of abundances.

With regard to the chosen visualisation methods, graduated symbols showing relative abundance of the analysed elements (Figs 8, 10, 12, 14) realistically reflect anomalous values in relation to the underlying geology, which can be explored in more detail by mineral exploration companies, land use planers, health authorities and other stakeholders. An even clearer picture of overall element distribution is provided by gridded maps, based on statistical methods (Figs 9, 11, 13, 15), in areas of high sample density; however, such interpolations have to be used with caution where samples are few and far between, as in the south-west of area 2117 (Fig. 2). Here, meaningful interpretive results can only be obtained from the stream sediment samples dominating this sector, rather than the few scattered soil samples.

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Mineral Potential of the South-eastern //Karas Region: an Overview

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Abstract :- To complement the Southern Namibian Mapping Programme (Nguno and Macey, 2024), an investigation of the mineral potential of the south-eastern //Karas Region was conducted simultaneously with the field work as an incentive for further exploration. Until the year 2000, the former Sperrgebiet (now Tsau//Khaeb National Park) was reserved solely for exploration and mining of precious stones (alluvial diamonds) along the Atlantic seaboard and Orange River, rendering the huge area between Oranjemund and Lüderitz underexplored with respect to other commodities. That such potential exists is indicated by major mining operations just outside its borders, i. e. the Skorpion Zn and the Rosh Pinah Zn-Pb-Ag Mines, which are part of a major base metal province. The Gergarub Zn-Pb-Ag deposit, situated some 15 km northwest of Rosh Pinah on farm Spitskop 111, constitutes such an unexploited resource, within this province. Other past and present mining operations in the project area (Figs 1 and 2) include the Aukam Graphite, Tin and Fluorite Mines, as well as several dimension stone quarries.

Keywords :- Mineral exploration, Mineral potential, Sperrgebiet

Geology of the project area

The oldest rocks in the area belong to the Palaeo- to Mesoproterozoic Namaqua - Natal Metamorphic Province, which forms a ca. 400 km wide mobile belt along the southern and south-western margins of the Archaean Kaapvaal Craton. They encompass pre- (Sperrgebiet and Richtersveld Magmatic Arcs; Fig. 1), syn- (Kakamas and Aus Domains; Fig. 1) and late to post-tectonic (rare element pegmatites) rocks relative to the Namaqua high-grade tectonothermal event at ~1200 m.y. (e. g. Miller, 2008a), which forms part of the Rodinia Supercontinent assembly. West of Helmeringhausen, the Namaqua rocks are overlain by the Mesoproterozoic volcano-sedimentary Konkiep Group of the Sinclair Supergroup (Fig 1).

The Mesoproterozoic basement is intruded by the Neoproterozoic Richtersveld Igneous Suite, a northeasterly trending line of intrusives extending from the Richtersveld in South Africa to southern Namibia, which heralded the break-up of Rodinia and the development of a rift basin, in which the late Neoproterozoic metasedimentary and metavolcanic rocks of the Gariep Supergroup were deposited (Fig. 1). The ubiquitous Gannakouriep dykes intruded pre-Gariep basement as well as basal Gariep units throughout south-western Namibia and adjoining parts of South Africa during the rifting phase, while the alkaline plutons of the Kuboos – Bremen Igneous Province, which extends from the north-western Richtersveld (South Africa) to the Karas Mountains in Namibia, post-date metamorphism and deformation related to the formation of the Gondwana Supercontinent in the Gariep Belt.

In the eastern part of the project area the metamorphic rocks are overlain by the younger sedimentary successions of the Nama Group and Karoo Supergroup (Fig. 1), which during the Jurassic were extensively intruded by dolerite sills and dykes connected to the breakup of Gondwana. Cretaceous to Palaeogene intrusives, including phonolites, carbonatites and rare kimberlites, together with the unconsolidated to semi-consolidated surficial sediments of the Kalahari and Namib Groups, form the youngest stratigraphic units in the area.

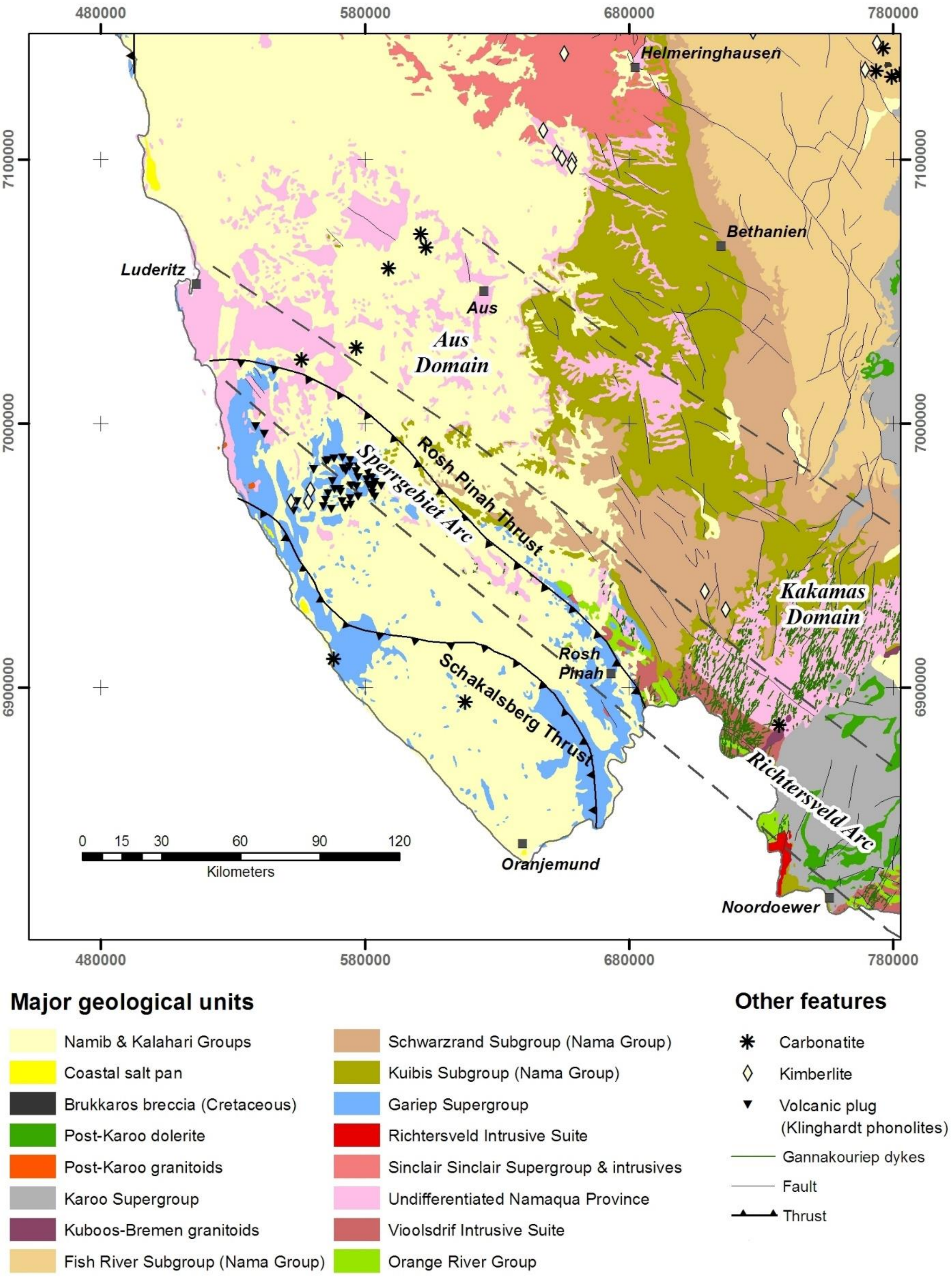

Figure 1. Geological overview of the project area (after 1: 1000 k Geological Map of Namibia, 1980)

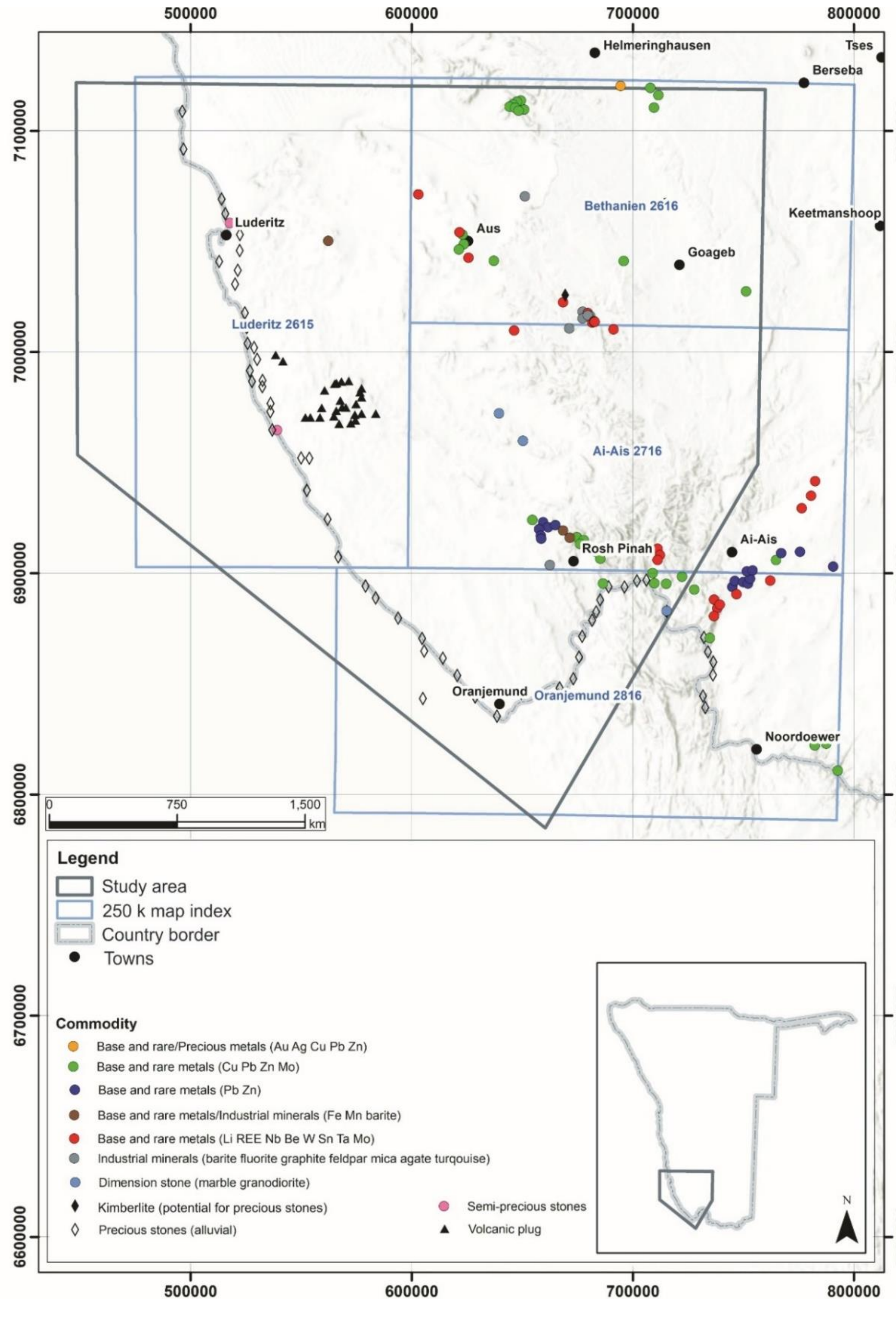

Figure 2. Locality map of the project area showing known mineral occurrences (superimposed on ESRI multi-directional hillshade terrain model)

Mineral potential

Ore deposits related to various plate tectonic settings are summarised by Robb (2020) and Pirajno (2016). Based on tectonic setting, various geological environments encountered in the project area have potential for a range of commodities and mineralisation styles (Fig. 2).

1) Namaqua-Natal Metamorphic Province

In the project area, pre-, syn- and late/post-tectonic rocks relative to the Namaqua Orogeny are present. The Sperrgebiet and Richtersveld Arcs formed in a calc-alkaline island-arc setting along a subduction zone (Macey *et al*., 2017). This setting can be represented by an island arc - inter-arc basin, which has potential for a) island arc-related porphyry copper-(Au, Mo; e. g. Haib, Namibia) and related hydrothermal/epithermal gold (e. g. El Hueso, Chile); b) island arc / incipient rift-related, Kuroko-type (Zn, Cu) volcanogenic massive sulfide (VMS; e. g. Kidd Creek Cu-Zn-Ag, Canada); and c) inactive inter-arc, basin-related podiform Cr (nickel sulfide, Pt) deposits (e. g. Masinloc Chromium, Philippines). Alternatively, it can occupy an island arc – back-arc basin proximal to a continent, which may host a) orogenic gold (e. g. Otjikoto, Namibia); b) podiform chromite and sulfide segregations associated with obducted oceanic spreading centres; c) island arc-related porphyry copper-gold and related hydrothermal precious metal deposits (epithermal gold); d) back-arc basin-related Besshi- (e. g. Otjihase Cu-Zn-Ag-Au, Namibia) and Cyprus-type VMS copper-iron (e. g. Skouriotissa Copper, Cyprus) deposits; and e) granitoid-hosted mineralisation (e. g. Sn, W, Bi, Mo, F) associated with a continental arc (e. g. Red Mountain Molybdenum, Canada).

Although the actual setting of sedimentation remains conjectural, the metasedimentary rocks of the Kakamas Domain indicate provenances from nearby arcs (Sperrgebiet and Richtersveld Arcs; Thomas *et al*., 2016), and are associated with the development of a regional, 'hot orogen'-driven, wide, continental back-arc basin and subsequent high-grade metamorphism and granitic magmatism (Macey *et al*., 2022). Continental back-arc basins are prospective for epithermal gold-silver, Carlin-style gold (e. g. Twin Creeks, USA), and VMS-style Zn-Pb-Cu-Ba.

Prodigious late-stage orogenic pegmatites, which are prospective for tantalum, lithium, tin and fluorite mineralisation, occur throughout the Namaqua Metamorphic Province. Li, Sn and fluorite mineralisation, as well as vein-type graphite (e. g. Aukam Graphite Mine) exposed in trenches and pits near or along hill slopes in the Aukam area, indicate exploration potential of the surrounding flat-lying alluvium-covered terrain, which is stratigraphically positioned below the Nama unconformity and underlain by Namaqua rocks.

2) Sinclair Supergroup

The Sinclair Supergroup (Konkiep Group) was formed in a volcanic-sedimentary arc setting with associated bimodal magmatism on an active continental margin in a subduction zone (Miller, 2008b, and references therein). This Andean-type setting is prospective for porphyry copper-molybdenum and related hydrothermal precious metal deposits (e. g. epithermal gold), as well as for granitoid-hosted tin-tungsten (Llallagua Tin, Bolivia) and polymetallic skarn (e. g. Aberfoyle Tin-Tungsten, Australia).

3) Richtersveld Igneous Suite, Gannakouriep mafic dyke swarm and Gariep Supergroup

The Richtersveld Igneous Suite, the mafic Gannakouriep dykes and the metasedimentary and -volcanic rocks of the Gariep Supergroup are related to successive stages of an extensional plate tectonic regime (Pan-African orogenic cycle). The Richtersveld Suite, a NW-trending line of intrusions, is associated with crustal thinning (intracontinental hotspot activity / incipient rifting) prior to Rodinia break-up; intrusive and supracrustal felsic igneous rocks near the Aurus Mountains and along the margin of the Gariep Belt north-west and north of Rosh Pinah have been correlated with the Richtersveld Suite on the strength of age and petrography (Frimmel, 2008; Thomas *et al*., 2016). The younger Gannakouriep dyke swarm represents syn-sedimentary, rift-related magmatism and heralded continental splitting, while the Gariep Supergroup was deposited in intracontinental rift-related grabens (i. e. failed rift; Frimmel, 2008). The latter is subdivided into the external, continental, parautochthonous Port Nolloth Zone in the east and the largely oceanic, internal Marmora Terrane in the west, separated by the Schakalsberg Thrust (Fig. 1).

Ore deposits associated with an intracontinental hotspot / incipient rift setting (Richtersveld Suite) include a) anorogenic granite-hosted mineralisation (Sn, W, Mo, Cu, Nb, F, etc.; e. g. granites of the Bushveld Complex, South Africa; Robb, 2020); b) pyroxenite / carbonatite - hosted mineralisation (Cu, Fe, Nb, P_2O_5, U, F, Nb, REE, etc.; e. g. Phalaborwa Cu-Fe-P; Robb, 2020); and c) sedimentary exhalative (SEDEX) Pb-Zn-Ba-Ag deposits (e. g. Rosh Pinah Zn-Pb-Ag, Namibia). Intracontinental rift settings provide an environment prospective for VMS mineralisation (e. g. Skorpion Zinc, Namibia) associated with submarine exhalative metal-rich hydrothermal fluid discharge, podiform chromium (NiS, Pt) and banded iron-manganese formation (Kalahari Mn Field, South Africa). Also, failed rifts such as the Gariep, may develop into hydrologically closed intracratonic basins prospective for sediment-hosted stratiform copper (Hitzman *et al*., 2010; e. g. Kamoa Copper, Democratic Republic of Congo).

The Gariep Supergroup was subjected to the Pan-African Orogeny at ca. 530 Ma, which was associated with Andean-type ocean-continent collision and subsequent post-orogenic magmatism (Kuboos-Bremen Igneous Province). Older units locally display Pan-African metamorphic and / or structural overprinting. Mineral deposits formed in this tectonic setting are discussed in chapter 2) above. In addition, continental platforms (accompanying intracontinental rift zones) may be associated with Mississippi Valley-Type (MVT) carbonate-hosted Zn-Pb occurrences (e. g. Berg Aukas Zn-Pb-V, Namibia) attributed to orogenic hydrothermal circulation. Carbonatites of the Kuboos-Bremen Province (e. g. Marinkas Quelle) may be prospective for rare earth elements.

4) Nama Group

The Ediacaran Nama Group, which comprises cratogenic (Kuibis Subgroup), flysch (Schwarzrand Subgroup) and molasse sediments (Fish River Subgroup), was deposited in a foreland basin adjacent to the Damara Orogen to the north and the Gariep Orogen to the west. Most of the strata dip very shallowly (1° or less) towards the east, and were only slightly affected by folding and thrusting along the northern and western basin margins during the final stages of Damara and Gariep orogenesis (Grotzinger and Miller, 2008). In contrast to the older, syntectonic, molasse of the Mulden Group of north-western Namibia, which was deposited adjacent to the Damara and Kaoko Orogens and hosts a variety of base metal deposits (e. g. Tschudi Copper) within carbonaceous arenites, no significant ore bodies are known from the Nama Group to date. This may be ascribed to the absence of mineralising fluid sources and ore forming processes in this southern molasse, or, possibly, to hitherto insufficient exploration. Carbonate rocks of the Nama Group within the project area have been quarried for dimension stones (e. g. Leonardo Potoro, Sandykop and Swartkloofberg marbles; Muyongo *et al*., 2020).

5) Karoo Supergroup

The post-orogenic Karoo Supergroup in the project area consists of the Carboniferous glaciomarine Dwyka Group and the Permian lacustrine-fluviatile Ecca Group, which were deposited in the Karaburg and the Aranos Basin (Fig. 1), the latter being an embayment of the Main Karoo Basin. Correlation with coal-bearing strata in South Africa led to various extensive drilling campaigns since the 1950s, which intersected coal of variable quality at different stratigraphic levels within the Ecca Group (e. g. Miller, 2008c).

6) Cenozoic

The Palaeogene Dicker Willem carbonatite complex, situated some 30 km north-east of Aus, is associated with an intracontinental hotspot/incipient rift setting related to intraplate alkaline magmatism. It lies on a major crustal lineament, which extends from the coast south of Lüderitz in a north-easterly direction and encompasses the intrusives of the Lüderitz Alkaline Province as well as several smaller carbonatites (e. g. Teufelskuppe, Keishöhe) known to be associated with rare earth elements. Similarly, other carbonatite intrusions within the Sperrgebiet (Karingarab, Chameis/Panther) are potentially prospective for REE mineralisation or have already been the target of exploration activities. Further mineralisation styles found in intracontinental rift settings are discussed in paragraph 3) above.

Various partly consolidated to unconsolidated Cenozoic sediments along the Orange River, as well as onshore and offshore along the South Atlantic coast have been exploited for alluvial diamonds and semi-precious stones (agate, turquoise) for more than a century. With onshore diamond deposits almost depleted and only limited mining activities still ongoing along the Orange River, present-day mining and exploration is mainly targeting the nearshore and offshore regions, which requires highly sophisticated and specialised technology.

Implications for exploration

Generally, the most promising tools for successful mineral exploration are geochemical and geophysical surveys, aided by satellite image interpretation of lithology and structure during the reconnaissance stage, to obtain a thorough understanding of the local and regional geology, and the geochemical composition of the area (e. g. Hitzman *et al*., 2012). However, remote sensing applications in the project area have proved largely futile in delineating geological units and structures due to the thick, wind-transported overburden covering much of it. For the same reason, conventional geochemical sampling and geophysical surveys may fail to detect base metal anomalies, thus producing deceptive conclusions with regard to the prospectivity of the area (Meyer and Pedley, 2003). Classic examples of major base metal mineralisation in the Gariep Belt include the Skorpion Zn deposit, concealed by 10 to 20 m of calcrete, silcrete and windblown sand (Jennings *et al*., 2003) and Gergarub Zn-Pb-Ag, a hybrid VMS-SEDEX sulfide deposit (Saayman, 2013), which - buried under 30 to 120 m of alluvial overburden - was only discovered more than 30 years after Rosh Pinah and Skorpion (Schaefer and Terblanche, 2019).

Association of generally tabular to stratiform SEDEX ore bodies and their boundaries with smaller fault-controlled sub-basins near the margins of major depocenters can aid exploration of these types of deposits, as this extensional basin geometry is systematic and predictable (Manning and Emsbo, 2018). Therefore, tools capable of delineating the geometry of depositional basins bounded by basement horsts (e. g. graben structures) are critical for targeting sediment-hosted stratiform copper mineralisation, and may prove successful for VMS/SEDEX systems in the Gariep Belt. In addition, a good understanding of the Cretaceous period of intense weathering that induced deep oxidation of some ore deposits in southern Africa is essential in locating high-grade deposits of supergene origin (Selley *et al*., 2005), such as Skorpion Zinc.

Recommended exploration techniques

- High-resolution airborne magnetic and radiometric surveys to delineate structure and concealed stratigraphic units;
- 3D audio-magneto-telluric (AMT) surveys to identify embayment / graben architecture (e. g. Strangway *et al*., 1973);
- Gravity surveys for mapping out favourable structural basins (Hitzman *et al*., 2012);
- Airborne electromagnetic surveys to detect conductive zones of massive to semi-massive sulfide;
- Systematic RAB/RC scout drilling accompanied by geochemical assaying of the deep overburden to bedrock (successfully employed at Gergarub, as a follow-up in the search for Rosh Pinah-type massive sulfide ore bodies);
- Fluid inclusion studies to identify highly saline, chemically complex, non-orogenic quartz vein-hosted fluid inclusions for the localisation of base metal sulfide prospective areas (Board, 1998);
- Given the strong wind regime and transportation of sand/soil in much of the area, sampling of semi-consolidated material, such as termite mounds for the detection of geochemical anomalies.

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Enhancing Geoscience Awareness through Educational Outreach: Programmes for Namibian Learners and Educators

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Abstract :- This report highlights geoscience outreach efforts by the Geoinformation Division of the Geological Survey of Namibia (GSN), focusing on initiatives to align geoscience topics with current school curricula and inspire learners and educators with the importance of geoscience. In 2024, Regional Geoscience Outreach Programmes in the Kunene and Omusati Regions engaged over 2 500 learners, while Geoscience Teachers' Workshops in the //Karas and Erongo Regions involved 17 educators and 500 learners (teachers). These programmes were based on presenting practical applications of geoscience, with the intention to foster interest in science concepts and provide career guidance in the field of geoscience. Through interactive activities at schools and educator-focused workshops, these initiatives demonstrated means for geoscience to bridge the gap between science and classroom learning, and its practical application.

Keywords :- Geoscience education, Outreach

Introduction

Namibia's abundant natural resources emphasise the vital role of geoscience in societal development. However, awareness of geoscience and its practical applications remains limited among learners as well as educators. This is partly due to the fact that geo (or earth) science is not explicitly included in the Namibian school curriculum or in teacher training programmes - a trend seen in many countries worldwide.

To bridge the gap in geoscience education, integrating geoscience into existing curricula through innovative teaching approaches is essential. This strategy, when applied creatively, has the advantage not only of aligning with current educational curricula, but also of helping learners to connect theoretical concepts to real-world applications. During the last decade, but especially over the last few years, the GSN Geoinformation Division has taken significant steps in this direction by implementing outreach programmes in Windhoek and throughout the country that emphasise geoscience applications, inspire enthusiasm for science in general, and hopefully result in novel ways of interaction between 'geoscience-educated' teachers and their pupils (Mocke and Mhopjeni, 2020; Uushona and Hipangwa, 2024).

Geoscience outreach programmes

Two key initiatives were conducted in 2024, i. e. the Regional Geoscience Outreach Programme and Geoscience Teachers' Workshops. Specifically, these projects targeted learners and educators in the Kunene, Omusati, //Karas, and Erongo Regions, aiming to enhance geoscience literacy and teaching capacity both among students and educators.

Regional Geoscience Outreach Programme

This initiative reached over 2 500 learners from Grades 8 to 12 in sixteen schools across the Kunene and Omusati Regions of north-western Namibia. Learners explored fundamental geoscience topics, such as rock classification, the rock cycle and mineral identification, with special focus on the practical usages of specific rocks and minerals in everyday life (Fig. 1). Included in the agenda were also career guidance sessions intended to generate and expand learners' awareness of job opportunities in geoscience and related fields (Fig. 2).

Figure 1. Josephine (GSN) showing and describing different types of rocks and minerals during the regional geoscience outreach programme at Otjerunda Combined School, Kunene Region

Figure 2. Josephine explaining different geoscience disciplines and career opportunities at John Pandeni Combined School, Omusati Region

Geoscience Teachers' Workshops

Jointly organised by the Geological Survey of Namibia and the GeoBus initiative of the University of St Andrews, Scotland, these workshops aim to equip educators with innovative teaching techniques in the field of geoscience (Fig. 3). Following the success of a similar workshop during the 29th Colloquium of African Geology held in Windhoek in 2023 (Uushona and Hipangwa, 2024), the initiative extended its reach to regional educators, focusing on teachers from //Karas and Erongo. The workshops also included learners and outreach-focused students of the University of Namibia (UNAM) based in Keetmanshoop. Topics covered included plate tectonics, earthquake monitoring, volcanic activity and fluvial processes. Interactive activities, such as modelling earthquake-resistant structures (Fig. 4) and demonstrating geological processes by using easy to come by, inexpensive materials (e. g. cookies, backing flour, effervescent tablets, food colourant, glue) made geoscience concepts accessible and exciting.

Figure 3. Lyn from GeoBus, giving a lecture on seafloor spreading during the geoscience teachers workshop at the University of Namibia (UNAM) Geology Department, Keetmanshoop, //Karas Region

Key Learnings

Regional Geoscience Outreach Programme

The outreach programmes demonstrated the importance of aligning content with school curricula to ensure relevance and engagement. Incorporating relatable, real-world examples of geoscience applications engendered interest and created a positive attitude towards learning. Additionally, discussing regional resources, such as local mineral occurrences and mining operations, instilled a sense of ownership and responsibility among students. Interactive teaching techniques, in tandem with the use of comprehensible, non-academic language, and a conducive learning environment, encouraged active participation. Familiarity with Grades 8 to 11 curricula ensured further that the outreach activities were relevant to students' educational needs, while career guidance sessions provided insights into geoscience pathways.

Figure 4. Teachers from PK Devillers Secondary School (//Karas Region) participating in the interactive session of building an earthquake-resistant structure

Geoscience Teachers' Workshops

The teachers' workshops emphasised the advisability of scheduling sessions during mid-term breaks to ensure teacher availability and minimise conflicts with curriculum delivery. Distribution of educational materials and certificates of completion was designed to enhance the professional development of the participants, serving at the same time as an added incentive for enrolment. Practical exercises promoted critical thinking and improved comprehension, while career guidance discussions highlighted the potential of geoscience as a career field for students.

Recommendations

To heighten the impact of future programmes, the development and distribution of educational kits containing such item as rock samples, minerals and basic testing tools, which could be loaned or donated to schools, is envisaged. Collaboration with institutions like the Namibia University of Science and Technology (NUST) could provide simple laboratory equipment for under-resourced schools lacking the funds to invest in such items. Hands-on, practical sessions in smaller groups would allow deeper engagement with geoscience concepts and students for a more satisfactory learning experience. And lastly, the dissemination of promotional materials, such as pamphlets, would enhance the overall experience, as well as serve as an advertisement for future events, while providing refreshments will help to create a positive, eager learning environment.

The incorporation of short field trips into future workshops would reinforce theoretical concepts with real-world, personal observations. But expanding the programme's reach and scope requires additional financial resources and fostering partnerships with local institutions to develop and distribute teaching aids. By addressing these recommendations and working towards their realisation, GSN geoscience outreach will continue to inspire learners and educators, and bridge the gap between classroom learning and 'real-life', while promoting geoscience as a vital and vibrant discipline at Namibian schools.

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Advancing Geoscience at the Geological Survey of Namibia: Integrating AI, Big Data and Geospatial Technologies

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Abstract :- As available geoscientific data increase both in volume and in quality, and processing technologies evolve constantly, the Geological Survey of Namibia (GSN) needs to integrate innovative solutions to meet global standards and help attracting investment into the country. By implementing Artificial Intelligence (AI), GSN can further mineral exploration, make geological mapping more accurate, and better monitor the environment. Big data analytics can process large amounts of geological data for instance for mineral potential mapping, while advanced geospatial technologies provide real-time information on issues such as environmental and natural hazard monitoring to a variety of stakeholders. Challenges including technical skills required to handle complex data and the need for powerful computers, as well as ethical concerns must be addressed, but by adopting these new technologies GSN can contribute to Namibia's sustainable development.

Keywords :- Geoscience, Geological Survey of Namibia, Artificial intelligence, Big data analytics, Machine learning, Geospatial technology

Introduction

Geoscience plays a crucial role in tackling important global issues such as resource management, climate change and disaster prevention or mitigation (Frodeman, 2013). However, as technology advances and global challenges become more complex, traditional geoscience methods need to adapt by embracing new tools and approaches.

One major shift is the growing use of artificial intelligence and machine learning, which are transforming how scientists study and interpret the earth. These new technologies help create accurate models of complex systems, predict events like earthquakes or floods, and better understand long-term environmental changes (Bergen, 2019). Despite their obvious potential, however, there are challenges, such as data privacy, understanding the processes behind AI, and the need to make these intricate tools accessible and user-friendly (Karpatne *et al*., 2018).

Recent studies highlight the importance of collaboration across different disciplines to facilitate and improve decision-making and scientific research, and ensure a broad base for AI applications developed to meet specific geoscientific needs (Karpatne *et al*., 2018). As global challenges and competition grow, integrating tools like AI, machine learning, and big data analytics, will enable GSN to manage complex geological data, predict resource locations, assess risks like natural hazards, provide more accurate geological data for mineral exploration, land use planning and other fields, as well as to improve environmental monitoring. However, their successful implementation requires careful, long-term planning with respect to IT requirements, human resources and confidentiality issues. In the following, examples are given how GSN can profit from these new technologies.

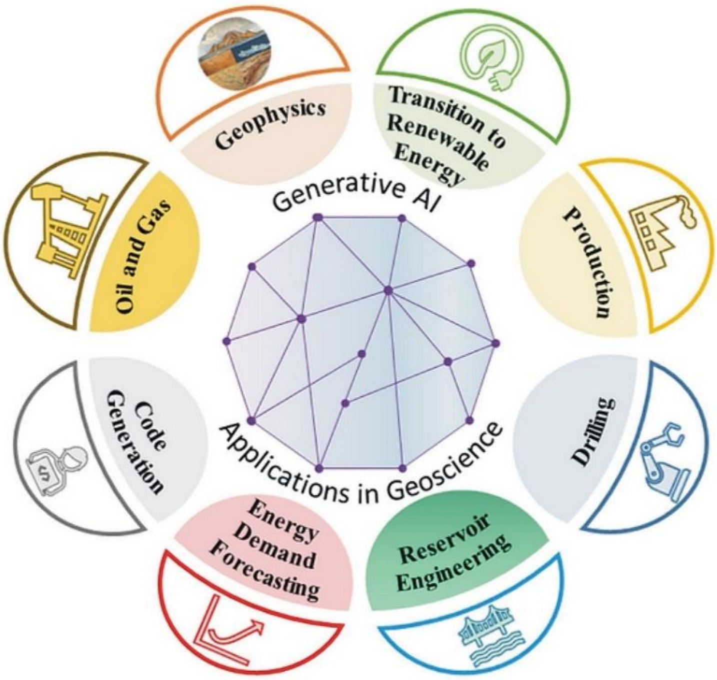
Geoscience Opportunities

Machine Learning and Artificial Intelligence in Geoscience

The Geological Survey of Namibia has been exploring ways to support mineral discovery by providing enhanced data. A current project on mineral prospectivity mapping of the Kunene Region can benefit from the application of AI models to integrate and analyse geophysical and geochemical survey data, drill hole information and satellite imagery to predict potential mineralisation (Köhler *et al*., 2021; Doyoro *et al*., 2025). Deep learning techniques applied to hyperspectral images can detect subtle mineral signatures in remote regions, such as north-western Namibia, thus reducing the need for extensive fieldwork

(Hajaj *et al*., 2024). AI also helps to identify geological features on maps, especially for non-geologists unfamiliar with them. The above examples show that AI is capable of making geological work faster, more accurate and, consequently, more cost-effective.

Historical geological reports, which are stored in the GSN's Earth Data Namibia database, hold a wealth of information invaluable to resource exploration; however, extracting this information can be a lengthy process. Another useful tool - Natural Language Processing (NLP) - analyses geological reports to find relevant information for mineral exploration, assessing environmental impacts or other purposes (Luccioni *et al*., 2020). In addition, geospatial tools are capable of supporting mineral exploration by identifying potential deposit locations based on historical geological data and spectral imaging analysis. Expanding the use of such technologies will enable GSN to improve its services to stakeholders by creating a variety of enhanced map products, such as mineral potential maps.



AI in Geoscience - Source: https://onlinelibrary.wiley.com/doi/10.1111/exsy.13654

Real-Time Insights through Advanced Computing

The integration of cloud-based geospatial platforms, edge computing, and GIS-based analytics is changing the processing and interpretation of geological data (Huang *et al*., 2018). The implementation of real-time monitoring systems using remotely sensed data, such as satellite imagery and drone-based surveys, allows tracking groundwater depletion, land use changes, soil erosion and seismic activity, to name but a few of many potential applications. At GSN, seismic hazard assessment can benefit from AI-driven early warning systems that analyse real-time ground motion in conjunction with historical seismic trends to predict earthquake risks more accurately.

Harnessing Big Data for Predictive Capabilities

As geoscience enters the era of big data, the use of large datasets for predictive modelling is a powerful opportunity. Machine learning techniques, such as deep learning and neural networks, excel at identifying patterns and relationships within such complex datasets (Zhao *et al*., 2024). Apart from mineral potential mapping, these technologies can also be employed to advantage in the prediction of natural hazards and environmental trends (Zhao *et al*., 2024). Last but not least, big data analytics can elevate the role of geoscience in addressing pressing global challenges (e. g. climate change) by integrating and evaluating data from a large variety of sources.

GSN manages and provides extensive geoscientific datasets, including geological, geophysical and geochemical data, drill hole and mineral deposit records, as well as a large variety of remotely sensed imagery. By applying big data analytics to this varied information, economic geologists can identify mineralisation trends, optimise exploration strategies, and improve resource extraction. Indeed, the use of predictive models in mineral exploration has already shown some promise in Namibia's uranium and copper mining sectors, although mineral exploration is by far not the only application for this powerful new tool.

Geoscience Challenges

Data Complexity and Integration

Geological data are inherently complex, consisting of multi-source datasets with varying spatial and temporal resolutions. Integrating historical geological maps with modern digital datasets remains a challenge not only at GSN. To address this, standardised data processing routines that merge old geological records with modern geodatabases have been developed and successfully applied, while AI-driven automated data cleaning methods further enhance the value of the resulting large, diverse datasets.

Ethical and Technological Challenges in AI

While AI-driven tools enhance geological research, they also introduce concerns regarding data privacy, model interpretability and algorithmic bias. AI applications in resource exploration and other fields must be transparent and capable of being reproduced to ensure responsible decision-making (Tucker, 2018). Ethical guidelines, emphasising the need for explainable AI models which provide geologists with clear reasoning behind predictions, are therefore a prerequisite for everyone planning to employ AI applications.

Computational Demands and Infrastructure

Handling large geoscience datasets requires substantial computational power, often exceeding the capabilities of traditional computing infrastructure (Diviacco, 2005). Cloud computing and high-performance computers offer solutions, but they require considerable investment in expertise and resources. This may constitute a major difficulty at present, which could be overcome by collaboration with local and international universities and research institutions. By forming such alliances, GSN could gain access to advanced computing facilities, while building local capacity in AI and data science, and developing a long-term plan to invest in these technologies, which will ensure its remaining at the forefront of geoscience.

Requirements and concerns of AI - Source: https://onlinelibrary.wiley.com/doi/10.1111/exsy.13654

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Namibia Plays Host to the Society of Economic Geologists at SEG 2024

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Keywords :- Geoscience, Conference

After the 29th Colloquium of African Geology (CAG29) in 2023, Namibia was honoured to host the conference of the Society of Economic Geologists (SEG) this year, which took place from 27th to 30th September at the Mercure (formerly Safari) Conference Centre in Windhoek.

This prestigious annual event is one of the main get-togethers for mineral researchers from academia, mining and exploration, government and non-governmental organisations to discuss the results of their work, promote new projects and theories in the field of economic geology, and generally engage with their peers. For some time, it has also been a forum for a variety of supporting sectors, such as information and mining technology, to showcase new techniques, products and services relevant to the search for and research of ore deposits.

Established in December 1920 with a view to create a platform for knowledge exchange between universities and the mineral industry, the Society of Economic Geologists celebrated its 100th anniversary during the COVID pandemic in 2021, with a hybrid conference held in Whistler (Canada) and on a virtual platform. Over the more than hundred years of its existence, it has grown from its modest beginnings of originally 60 members – among them such eminent figures as R. A. F. Penrose, W. Lindgren and J. E. Spurr - to a membership above 6000 in more than 100 countries around the globe. While the annual conference, which usually attracts around 1000 international delegates, from its own ranks as well as non-members, most frequently is held near SEG headquarters in Littleton, Colorado, at intervals it is staged in countries with a long history in mining and ore geology research, such as Chile, Canada, Australia and China to name but a few. Only for the second time – after South Africa 2008 – it now returned to the African continent, thanks to the initiative of past SEG President Chico Azevedo and the SEG Programme Committee. And, indeed, Namibia has been a very fitting choice to commemorate Brian Hoal, Director of the Geological Survey of Namibia in the early years of national Independence from 1992 to 1996 and Executive Director of SEG for 23 years until the announcement of his retirement in May 2022. His post-graduate research on the mid- to late Proterozoic Awasib

Mountain Terrain (southern Namibia) to this day remains the standard work on the geology, geochemistry and geochronology of this remote area on the edge of the Namib, and the news of his passing in March 2023 recalled his usually equable and open-minded personality to all in Namibia who knew him as a colleague and chief.

SEG 2024

This year's conference was organised by the Society of Economic Geologists in associations with the Geoscience Council and the Geological Society of Namibia, the Organising Committee also including representatives from the Geological Survey of Namibia, the University of Namibia, as well as the private sector. Apart from the official SEG platform (www.segweb.org/SEG-2024/), the event was promoted locally via social media, NBC (Namibian Broadcasting Corporation) TV and radio, and the press (e. g. The Namibian). Under the motto "Sustainable Mineral Exploration and Development", a variety of topics from the major mineral provinces of Africa to novel technologies in ore deposit research and the future development of the mineral resource scene in the light of energy transition and other technological advances were discussed in invited and submitted oral presentations and poster sessions.

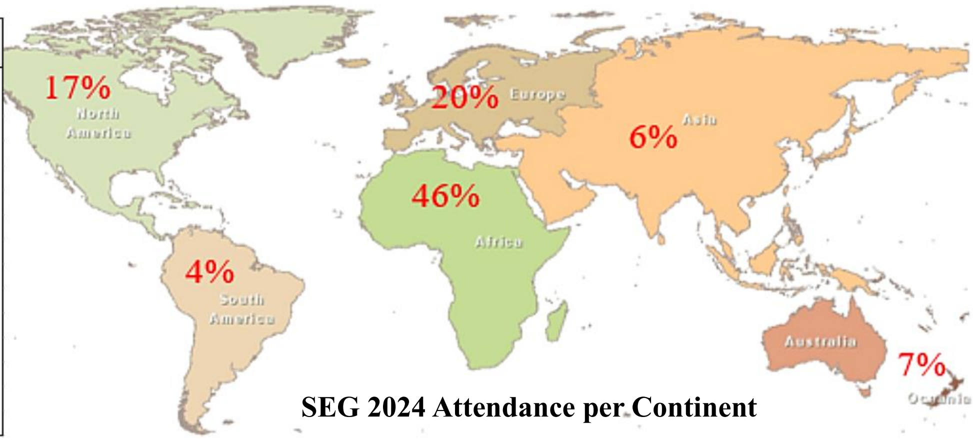
Session Themes

- The Energy Transition: Metals of the Future
- Specialty Metals and Materials
- Innovative Technology Development in Mineral Deposit Science
- Africa's Iconic Ore Deposits
- New Discoveries and Developments
- Resource Development: ESG from Exploration to Remediation
- Gold: Enhanced Discovery & Development
- Vital High-Volume Base Metals

Sponsorship funding by B2 Gold (Patron), BHP and GeologicAI (Premier), Barrick, Equinox Gold and KoBold Metals (Gold), and many others ensured an interesting technical programme substantiated by 23 guest speakers, while the Ministry of Mines and Energy, Namibia (MME), assisted with in-kind contributions. Also, the "Conference Accessibility Programme (CAP), sponsored by Patron Rio Tinto and other companies, as well as many individuals, financially supported 96 geologists from 27 countries. Launched in 2024 to enable local/regional/continental students, early-career professionals, post-doctoral researchers and academics to attend international events, SEG aims to make CAP a permanency to complement its existing Student Presenter Funding programme.

During the four conference days some 850 registered participants from academia, mineral exploration and mining, governmental and parastatal institutions, NGOs, plus supporting industries, such as drilling, analytical, IT and financial services, representing 64 countries, engaged in a close-packed agenda interspersed with refreshing tea-cum-discussion breaks. Beyond the traditional welcome and closing receptions, participants could enjoy the SEG Awards Ceremony, which honoured the outstanding contributions of ten distinguished scientists to the field of economic geology and society, and an Industry Outlook Dinner, featuring a dynamic presentation by the CEO of KoBold Metals, Zambia. Awards were also given to the best student presentations at SEG 2024.

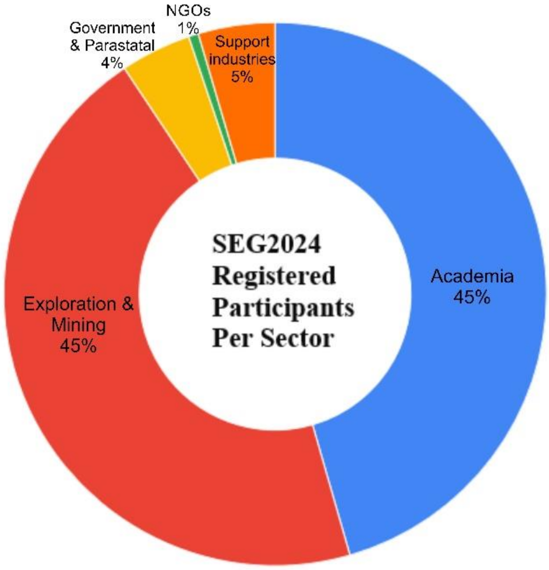
Top 15 countries	Registered participants
Namibia	173
South Africa	92
Canada	83
Australia	60
USA	57
UK	53
Gemany	32
Zambia	22
Ghana	17
Japan	17
DR Congo	14
Ireland	14
Peru	14
Botswana	13
Spain	13



SEG 2024 Attendance per Continent

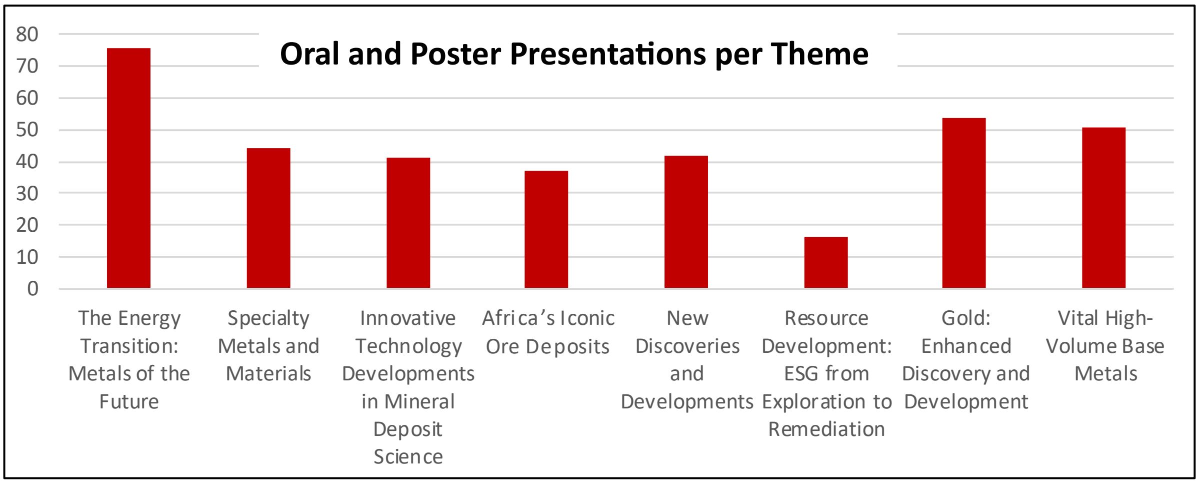
SEG 2024 kicked off with a Cultural Dance Group, which was followed by opening remarks by Senior Mineral Resource Manager of Debmarine Namibia Godfrey Ngaisiue on responsible sustainable exploration and mining, and outgoing SEG President Stephen Piercey, who focused on challenges facing the industry and the future of SEG. Key points of his address included:

- Creation of high-quality publications embracing new media;
- Innovative and inclusive conferences with diverse formats, locations, and global access;
- Learning opportunities for all members at every career stage;
- Establishment of a global community understanding Earth's resources;
- Adaptable governance to ensure the Society's sustainability.

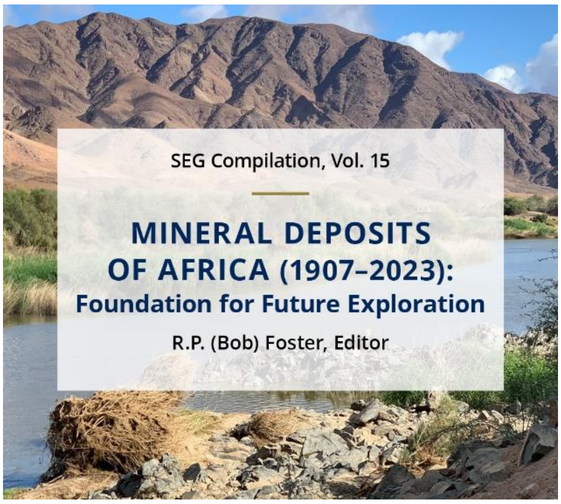


SEG 2024 featured 85 oral presentations in two parallel sessions, plus 275 poster presentations. In addition, the five-member Global Challenges Panel chaired by incoming SEG President Anne Thompson, discussed "Geoscience Capacity Building for the Future" from an African perspective, while three invited plenary speakers addressed the audience on sustainable development opportunities for the mining industry, B2Gold's Legacy in Namibia, and the impact of the Pan-Africa Reporting Code on the future of mining in Africa. Another panel discussion entitled "Conference Reflections and Future Perspectives in Memory of Brian G. Hoal" rounded off SEG 2024, together with a session on "Motivating Future Geoscientists", which featured representatives of the Next Generation Explorers Award (NGEA) Africa Finalist Teams from Cameroon, Namibia, Nigeria, South Africa, Tanzania, and a presentation by the chairperson of the SEG 2025 Organising Committee, which will take place in Brisbane, Australia.

While more than one third of the "regular" presentations dealt with topics of the day, such as energy transition and vital high-volume base metals, "classical" ore geology received a boost from three special sessions (Trifecta 1 – 3) on eminent African themes, i. e. the history of gold mining on the continent, the Central African Copper Belt and the iconic Bushveld Igneous Complex of South Africa, presented by invited authorities. Also, a special SEG publication entitled "Mineral Deposits of Africa (1907 – 2023): Foundation for Future Exploration" (SEG Publication 15) was published in time to celebrate SEG 2024 in Namibia, providing a comprehensive and up-to-date overview of the state of mining and mineral exploration on the continent.



Surrounding the four days of technical sessions, a variety of activities, including pre- and post-conference excursions and workshops took place. Field trips near (Onganja Mine, Windhoek District) and far (Zambian Copperbelt, Great Dyke of Zimbabwe) covered a vast range of commodities and mineralisation systems, such as orogenic gold (Damara Belt), iron-oxide-copper-gold (IOCG, Onganja), REE (northern Namibia), lithium (Zimbabwe), base metals (southern Namibia, Zambia), uranium (central Namibia) and the Namibian diamond mega-placer that - after more than a hundred years of exploitation - still provides a goodly portion of the national GDP. Apart from an interesting and often unique geology, these field excursions, which were guided by international and local geologists such as Murray Hitzman, Alex Kisters, Pete Siegfried, Robert Carr, Judith Kinnaird and Gabi Schneider, also offered some grand scenery across southern Africa like the Bogenfels on Namibia's diamond coast and the stunning Victoria Falls on the border between Zambia and Zimbabwe.



Their popularity is best attested to by the fact that most of the ten excursions, although not cheap, were sold out well before the early registration deadline!

Workshops covered orogenic gold systems, discovery and recovery of critical minerals, the role of fluid inclusions in ore systems and drone technology in mineral exploration, as well as a course on technical writing - a fundamental skill all too often neglected or lacking in geoscience training. A pre-conference SEG and Early Career Day encompassed round table discussions and a 'mentor-mentee' programme. The latter attracted more than 250 participants from diverse sectors of the field, bringing together industry professionals, academic leaders

and students/early career scientists, to foster relationships crucial for professional development. A special field trip to the Matchless Mine near Windhoek was guided by Ben Mapani, geology professor at the Namibian University of Science and Technology.

Last but not least, 27 international exhibitors from mining and exploration, support industries, and professional organisations, among them the Geological Society and the Geoscience Council of Namibia and, of course, the Society of Economic Geologists, took the opportunity to showcase their products and services at an international forum. Special thanks are due to all those locally and abroad, who have helped to make this event, which - with workshops and field trips – spanned two and a half weeks from 19 September to 7 October 2024, a success.

SEG booth at the Exhibitors' Hall

Geological Society of Africa (GSAf) booth

Grateful CAP participants with SEG officials and Organising Committee members

Former Executive Director of MME, Brian Eiseb (left) and Chamber of Mines (Namibia) President, Zebra Kasete (right) attending a lecture session

NGEA Panel discussion wrapping up SEG 2024

B2 Gold and SEG officials at the sponsorship hand-over ceremony

SEG 2024 organising committee chairperson being interviewed by NBC

Swartbooisdrif Sodalite, Kunene Region - Field Trip FT02: REE Deposits of Northern Namibia

Old copper workings – Field Trip FT07: The Iron-Oxide-Copper-Gold (IOCG) Vein System of the Onganja Mine, Windhoek District

Diamonds are forever – Field Trip FT01: A Visit to the Namibian Diamond Mega-Placer, //Karas Region

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Namibia's First Comprehensive Risks Profile of Natural Hazards and Selected Diseases

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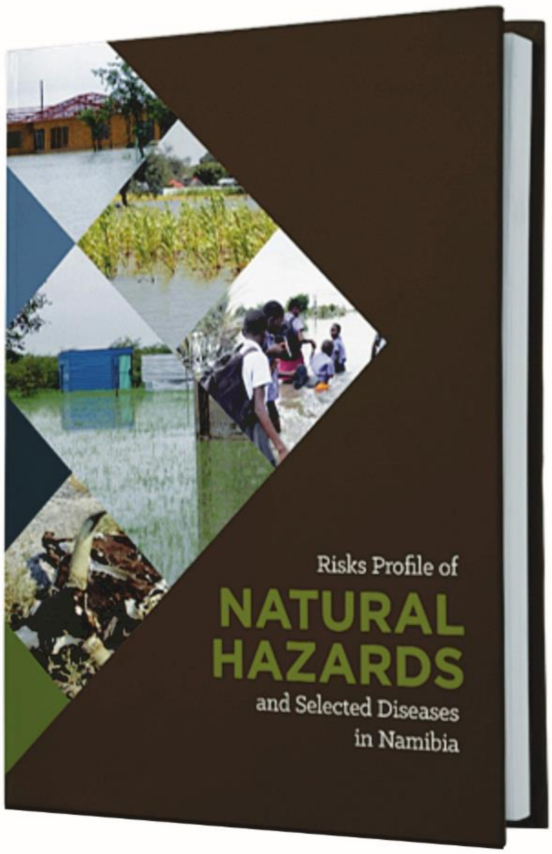
Keywords :- Natural hazards, health risk, disaster management

Natural disasters are increasing rapidly in frequency and intensity globally under the influence of climate change. The usual emergency responses to such events have become costly and unsustainable to responders, such as humanitarian and governmental agencies, and the affected communities and individuals. For example, about 400 natural disasters were recorded worldwide in the Emergency Events Database in 2023, compared to the annual average of 370 disasters between 2003 and 2022 (EMDAT, 2024). In 2023, over 86 000 people lost their lives because of natural disasters, 93.1 million people were affected, and the economic losses amounted to US$ 202.7 billion (EMDAT, 2024). These statistics exclude data from the heatwaves that had record-breaking temperatures; heat-related mortality in 2022 exceeded 61 500 deaths in Europe alone (EMDAT, 2024). Essentially, the global challenges of unprecedented proportions led the United Nations Office for Disaster Risk Reduction (UNDRR) to catalyse in 2015 the first major agreement to reduce, prevent, and respond to disaster risks. This global agreement with a 15-year framework, is termed the Sendai Framework. Its purpose is to provide member states with actionable insights and recommendations to protect developmental gains from the risk of disasters and help build resilient nations (UNDRR, 2015).

Namibia, as a signatory to the Sendai Framework, is threatened by a multitude of natural disasters. These devastating events include the floods of 2008 – 2011 that cost more than N$ one billion in damages and claimed over 100 human lives, as well as the countrywide drought of 2019, exceeding N$ one billion in cost and leading to the loss of 100 000 livestock. In conformity with the Sendai Framework, Namibia subsequently embarked on the journey to profile the risks of and vulnerability to natural disasters and selected diseases within its borders. Risk profiling is a prerequisite for shifting from disaster management, which is unplanned, expensive, and whose costs escalate over time, to risk management. This profiling was spearheaded by the Office of the Prime Minister, with technical capacity provided through collaborative efforts by domestic institutions including the University of Namibia, the Namibia Statistics Agency (NSA), the Ministry of Mines and Energy, and the Ministry of Agriculture, Water and Land Reform. This collaborative domestic effort culminated in a book of 180 pages, entitled *Risks Profile of Natural Hazards and Selected Diseases in Namibia*, covering 14 natural disasters and selected diseases.



Initially, a total of 21 natural disasters and selected diseases were targeted for profiling. However, due to a lack of data, the coverage was limited to drought, flood, wildfire, heatwave, frost, windstorm, lightning, seismic, sea level rise, malaria, COVID-19, HIV/AIDS, diarrhoea, and foot and mouth disease. The study used the indicator-based approach, which takes into account hazard, exposure to hazard, vulnerability to hazard and capacity to adapt (van Western and Greiving, 2017). The analyses exploited Geographic Information Systems (GIS) for enriched spatial output at an unprecedented level of detail, based on enumeration areas representing the smallest geographical units demarcated by NSA for collecting official demographic data for the Population and Housing Census. Compared to only 14 regions or 121 constituencies, the country is parcelled into more than 5000 enumeration areas averaging 16 000 ha, providing a much better data resolution.

From the perception of consulted stakeholders, risk hazards were discerned as devastating (e. g. drought and COVID-19), bittersweet (e. g. flooding), oblivious or normalised (e. g. heatwave, seismic), emerging (e. g. lightning) or managed (e. g. malaria). The perceptions towards drought and COVID-19 were largely fuelled by their widespread occurrence and unpredictability. Despite its destructive impact, flooding on the other hand brings along some benefits, such as a variety and abundance of fish and water.

The impact of heatwaves is superimposed on the arid to semi-arid climate of the country. This makes it evasive to quantify or discern their impact, which therefore is often normalised. Similarly, the low magnitude of earthquakes in the country overshadowed their hidden economic cost through insidious instability of buildings and other infrastructure that may be often and wrongly attributed to poor workmanship. Lightning, which is caused by instability in the atmosphere due to a combination of warm air near the ground and colder air above, is intensifying due to climatic change. Unfortunately, the lack of awareness and limited safety measures, especially in rural communities, make it an emerging hazard, which has been reported more frequently in recent years. The efforts made thus far in the country to contain malaria hide the insecticide resistance of mosquitoes, and its importation from neighbouring countries. The success of malaria management is thus transient, because of the underlying vulnerability as illustrated by the widespread outbreak in 2024.

The unmasking of these risk hazards in the country positions Namibia well to formulate her resilience strategies. The use of enumeration areas made the risk maps scalable for authorities at constituency or regional levels, which facilitates and enhances local planning, accordingly. Regular updating of the risk levels with demographic and auxiliary input data will make the book a living instrument for an effective multi-hazard, early warning system in the country. Therefore, the stage is set for Namibia to embark on a journey of shifting from disaster management to managing risks, which will save lives and diminish the economic losses associated with natural disasters over time.

Acknowledgements

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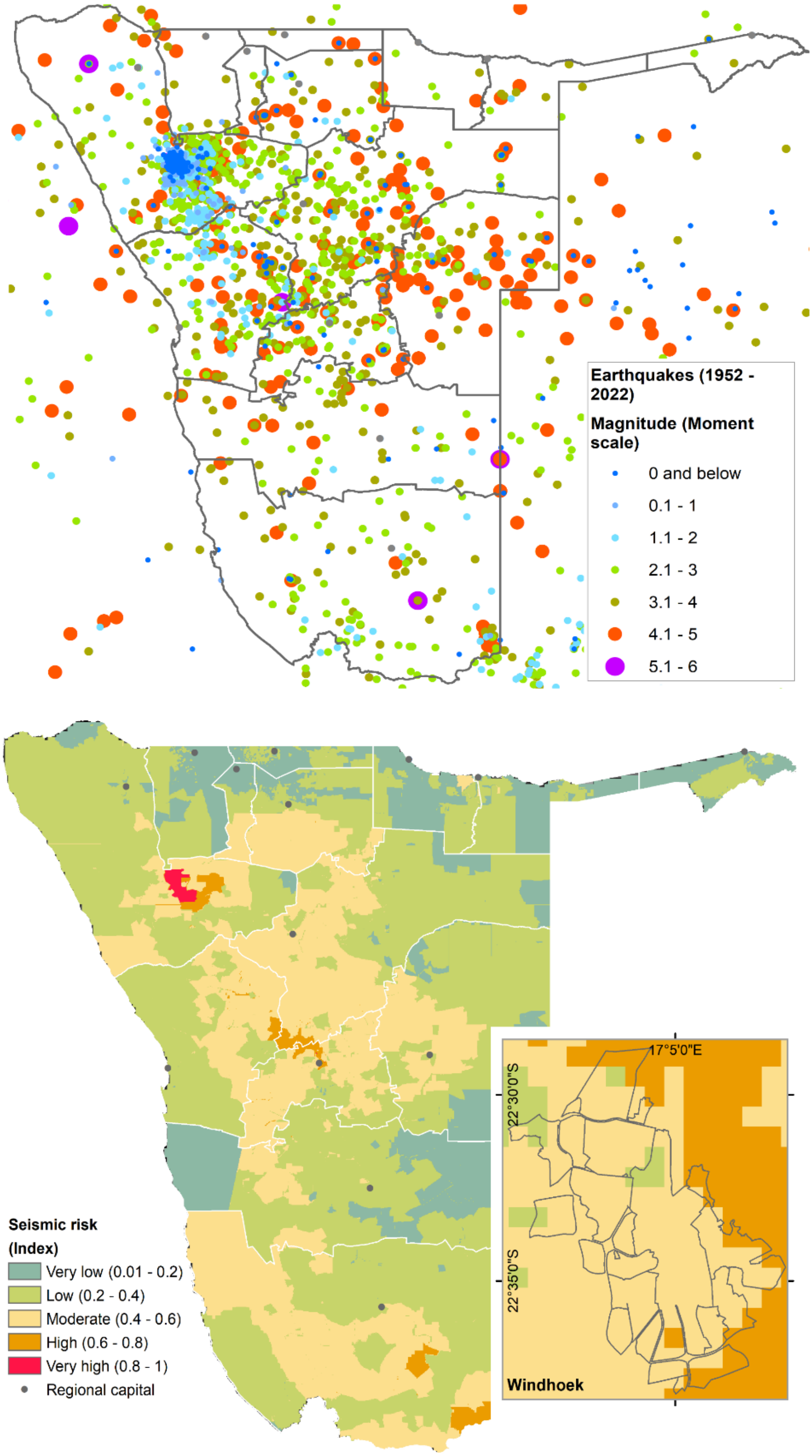

Earthquake occurrence (top) and risk (bottom) in Namibia