Ephemeral River Basins

Sharing temporary waters in southern Africa

An earth science review of the Orange-Fish River Basin, Namibia

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May 2008

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Roger Swart has worked as a regional geologist in Namibia since 1982 – firstly for the Geological Survey of Namibia and then NAMCOR, the National Petroleum Corporation. The nature of his jobs in these posts meant that he worked widely in Namibia and that he has worked with numerous other geologists – local and international. Since 2007 he has worked as an independent consultant. His speciality is the study of sedimentary rocks which underlie much of the Fish River Basin. Recently he has become interested in the erosional and geomorphological history of Namibia. A non-technical book on the landforms of Namibia, which he has co-authored with illustrator, Christine Marais, will soon be published.

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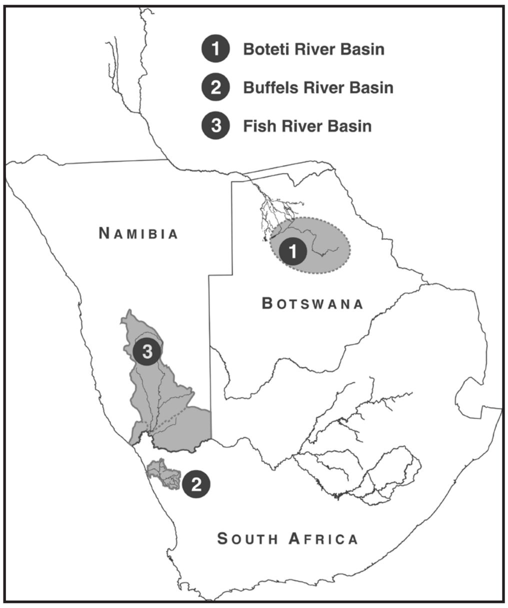
Ephemeral River Basins in Southern Africa Project

Ephemeral River Basins (ERB) in Southern Africa is a project that promotes the sustainable, equitable and improved utilisation of water and other natural resources in ephemeral river basins in southern Africa through the process of integrated resource management (IWRM). Although IWRM is accepted – internationally and regionally – as the approach promoting sustainable management of water resources and the river basin is considered the ideal unit over which to apply it, the basin management approach has not been widely tested and implemented in ephemeral river basins in southern Africa.



The ERB in Southern Africa Project, however, explores the potential and options for basin management in three ephemeral river basins in southern Africa – the Boteti, an outflow of the Okavango Delta, in Botswana, the Buffels, a westward-flowing ephemeral river in the Northern Cape, in South Africa and the Fish River Basin, a tributary of the Orange River, in Namibia.

Despite being ephemeral, all three river basins are essential water resources in their areas. The three basins have different biophysical and socio-economic characteristics and are managed under different legislative, policy and institutional arrangements. Together, they thus provide good examples to explore the potential and options for basin management in ephemeral rivers and on which to base a comparative analysis for wider application.

The purpose of the project is met by five main activities:

- Sensitising managers and users of natural resources to the concepts of IWRM and basin management
- Assessing the potential for the application of integrated basin management
- Establishing appropriate forums for promoting IWRM in the three basins
- Documenting the biophysical and socio-economic status of the three basins
- Documenting best practices, lessons learnt and case studies as a comparative analysis for wider application.

This is one of many reports emanating from the ERB in Southern Africa Project. For more information on the project, visit our website at http://www.drfn.org.na/erb/index.html

The project is funded by the Norwegian Ministry of Foreign Affairs and co-ordinated by the Desert Research Foundation of Namibia (DRFN). Work in the Boteti River Basin is being led by the Harry Oppenheimer Okavango Research Centre (HOORC), in the Buffels by the Surplus People Project (SPP) and in the Fish by DRFN.

Acronyms and Abbreviations

^{0} C	degree centigrade
amsl	above mean sea level
DRFN	Desert Research Foundation of Namibia
ERB	Ephemeral River Basins Project in Southern Africa
ERB-Botswana	Ephemeral River Basins Project in Botswana
ERB-Namibia	Ephemeral River Basins Project in Namibia
ERB-South Africa	Ephemeral River Basins Project in South Africa
GDP	gross domestic product
HOORC	Harry Oppenheimer Okavango Research Centre
km	kilometre(s)
km^2	square kilometre(s)
m^3	cubic metre(s)
mamsl	metres above mean sea level
NMC	Namaqua Metamorphic Complex
ppm	part(s) per million
SPP	Surplus People Project
t	metric tonne(s)

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Orange-Fish River Basin, Namibia

1. Introduction

The Orange-Fish River Basin covers an extensive area of southern Namibia, draining nearly 120,000 km^2 (Figures 1 and 2: page 20). The Basin includes rocks formed during all the major rock-forming periods known in Namibia. Consequently, the variety of rock types, fossils and mineral deposits that can be found in the Basin is enormous. Similarly, the landforms of the Basin reflect the wide variety of lithologies found, as well as the long geomorphological history of the area. The Fish River Canyon has been proposed as a World Heritage Site, largely on its geomorphological merits. Other sites, such as Brukkaros and certain fossil localities may also, in the future, be considered for World Heritage status because of their unique geological origins, excellent exposures, associated fossils and modern flora and fauna. The Orange River[1] mouth is also a Ramsar Site, the first such transboundary site in Africa. Geology has not only influenced the location of mineral and groundwater resources in the Basin but also the archaeological record, in that it has determined the location of caves and springs used by the earliest known inhabitants of Namibia (Apollo XI cave site). Understanding the geology of the Basin is therefore important in its resource management. The characteristics of each geological unit are summarised in Annex 1 (page 17).

2. Geological History

The entire Orange-Fish River Basin is located on the western margin of the Kalahari Craton (Figure 3: page 21), a stable granitic-gneissic shield that forms the nucleus of the southern African sub-continent. Over large areas of the Basin, the Craton is covered by a thin veneer of sedimentary and volcanic rocks deposited after formation of the Craton. Although southern Namibia is generally regarded as tectonically stable, several active faults are present.

2.1 Orange River Group (Figure 4: page 21)

The highly deformed and metamorphosed amphibolites, metasediments and associated intrusive rocks that make up the oldest rocks in southern Namibia (2,000-1,700 million years old) are known as the Orange River Group. The evidence of the geological origins of these rocks has largely been obliterated by the intense pressures and temperatures that they have been subjected to. Intermittent outcrops of these rocks are scattered between the Hom River and Rosh Pinah (Miller 1992). The slightly younger Vioolsdrif Intrusive Suite, which intrudes the Orange River Group, is magmatic in origin and is also highly deformed. These two groups are localised remnants that survived later phases of tectonic activity and were originally much more extensive. Reconstructions of the palaeogeography of the time are highly tenuous.

2.2 Elim Formation and Rehoboth Sequence (Figures 5a and 5b: page 22)

Isolated outcrops of sedimentary and volcanic rocks belonging to the Elim Formation and Rehoboth Sequence (1,670-1,420 million years old) occur on the west and north-west margins of the Basin and in adjacent areas. These rocks are intruded by basic dykes and are important from a mineral potential aspect, particularly copper, lead and gold.

[1] The Orange River is the southern border of Namibia with South Africa

2.3 Namaqua Metamorphic Complex (NMC) (Figure 6: page 23)

The highly deformed Namaqua Metamorphic Complex (NMC), which covers an extensive part of southern Namibia, and the volcano-sedimentary Sinclair Sequence of central Namibia were formed between 1,800 and 1,000 million years ago. They host much of the mineral potential of the area. At the time of formation, these were on the edges of an early super-continent known as Ur (McCarthy and Rubidge 2005; Figure 7: page 23). The NMC represents extensive reworking of older crustal material of which little remains now. Major shear zones, or large fault zones, such as the Tantalite Valley shear may be over 500 km long and were the loci for the emplacement of mafic intrusions and pegamatites. These shears have a dextral sense of movement, i.e. blocks on opposing sides of the fault appear to have moved to the right in relation to the other (Figure 8 a-c: page 24).

2.4 Sinclair Group (Figure 9: page 25)

The slightly younger Sinclair Group (1,400-1,200 million years old) formed during rifting of the early craton and is characterised by four cycles of immature rift fill sediments and bi-modal volcanism, i.e. eruption of mafic and felsic volcanic rocks. Rocks of this group, also known as the Rehoboth Magmatic Arc (Watters 1974), form an arcuate rim around the north-west margin of the Kalahari Craton. The Sinclair Group is not as deformed as the NMC and extensive outcrops of precursor sequences are preserved. Consequently, its geological history is better understood.

2.5 Gannakouriep Dyke Swarm (Figure 10: page 25)

Younger mafic dykes, known as the Gannakouriep Dyke Swarm intrude the Namaqua Complex and Sinclair Groups. The dyke swarm is believed to be 717±11 million years old and is one of the largest dyke swarms on Earth (Reid et al. 1991). All the dykes in the swarm trend north-east to north and may represent a failed rift system. Although they are relatively insignificant in extent forming thin, linear features, the dykes have an important effect on the flow of the Orange River, forming barriers downstream of which rapids are often located. They also exert an influence on diamond deposition.

2.6 Pan-African Orogeny

The following stage of crustal evolution in southern Africa was the Pan-African orogeny from 800 to 500 million years before present. The orogeny is sub-divided into three parts, the Kaoko Belt in the north-west of Namibia well beyond the Orange-Fish River Basin, the Damara Belt in central Namibia and the coast parallel Gariep Belt in south-west Namibia (Miller 1983). The Damara and Gariep mobile belts lie largely outside of the Orange-Fish River Basin (Figure 3: page 21) but had a profound effect on the physiographic development of the Basin and were also the source for much of the sediment in the Nama Basin, which today underlies much of the Fish River Basin.

2.7 Nama Basin (Figure 11: page 26)

The Nama Basin developed as a broad, gentle foreland basin in response to these orogenies which were developing to the north and west. The Nama Group, which was deposited in the Nama Basin, has been sub-divided into three formations – a basal Kuibis Subgroup, middle Schwarzrand Subgroup and an upper Fish River Subgroup. Two sub-basins are also recognised, the northern Zaris Basin separated from the southern Witputs Basin by the Osis Ridge. In the deepest parts of the sub-basins thicknesses are around 2–3 km thinning to less than a kilometre towards the Osis Ridge (Grotzinger 2000; Figure 12: page 26).

The deeply dissected margins and canyon lands within the Nama Group allow detailed mapping of ancient sedimentary environments and the relationships between them. The Nama Group consists generally of carbonate shelf sediments interbedded with shallow marine siliciclastic sediments (Kuibis and Schwarzrand Subgroups), overlain by largely fluvial red sandstones and shales with minor shallow marine units (Fish River Subgroup). Volcanic ash beds have been recently discovered at many different levels of the basin and have played an important role in determining precise age dates for the succession. The Nama Group is critical in understanding Earth's history as the time period in which it was deposited, covers the Precambrian-Cambrian boundary and consequently the explosion of life on Earth (Knoll 2003) (covered further under Palaeontology, pages 7-9) (Figure 13: page 27). Carbonate reef facies occur at several levels in the sequence. These comprise stromatolitic and thrombolitic build-ups, which form laterally continuous biostromes or reefs. They develop upwards from isolated patch and pinnacle reefs through to more sheet-like bodies. Excellent outcrops of these have been well described on the farm Driedoornvlakte (Adams et al. 2000) and in the Zebra River gorge (Grotzinger 2000), which is outside of the basin. Other reefs known from southern Namibia however require further examination.

2.8 Karoo Sequence (Figure 14: page 28)

Sedimentary and volcanic rocks of the Carboniferous to Jurassic Karoo Sequence occur in the Aranos basin on the north-eastern edge of the Fish River Basin as well as the Gamchab Basin in the far south (Figure 14a: page 28). The basal unit of the Karoo succession comprises the Dwyka glaciation – a major trans-continental unit, the equivalents of which are found on all five Gondwana continents (Africa, India and Arabia, Australia, South America, Antarctica). Recent dating of ash beds found at Ganigobis give an age of 300 to 302 million years old for the sequence (Bangert et al. 2000). The palaeo-position of Namibia at this time was much closer to the South Pole and southern Namibia would have been at around 60º S at this time. Polished glacial pavements are preserved underneath the sediments. This glaciogenic unit contains shallow marine sandstone and mudstone facies with several fish and invertebrate fossil localities known (discussed further under Palaeontology, pages 7-9).

The glacial beds are, in turn, overlain by sandstones and mudstones of the Permian Ecca Group. The sandstones of this Group are potentially good aquifers. The depositional environment of the Whitehill Formation, a black mudstone that forms part of this group, was probably in a saline lacustrine setting. This has been determined by various techniques including stable isotope studies, associated fossils and geochemistry. Well-preserved fossils of *Mesosaurus*, an early swimming reptile, are well known in the Whitehill Formation.

A significant time gap exists after the deposition of the Ecca Group with no Triassic sediments preserved in southern Namibia, despite the fact that they are very well known further south in South Africa and also from central Namibia. The final phase of Karoo crustal evolution was the eruption of 360 m of basaltic lavas (Figure 14b: page 28) that make up the Kalkrand Formation in the Late Triassic-Early Jurassic around 178 million years ago (Marsh et al. 1997). This is part of the more extensive volcanism that makes up the Drakensberg Mountains in South Africa and is also found in north-eastern Namibia near the town of Grootfontein and the Batoka Gorge on the Zambezi River. Extensive dolerite sills and dyke swarms (Figure 14c: page 28) of this age intrude the Karoo Group rocks, in particular at the level of the Whitehill Formation. The Giants Playground area near Keetmanshoop is all in dolerite sills, a rock type which seems to be preferred by *Aloe dichotoma*, although not exclusively so.

The area north-west of Karasburg appears to have been faulted sometime after the deposition of the Karoo Group rocks giving rise to the Karasburg Mountains (see Geomorphology section).

Other faults occur in the western parts of the Orange-Fish River Basin and trend north-south to north-west – south-east and are generally normal faults, although some strike slip movement has been observed. Some of these faults have remained active and may reflect the edge of a new proto-continent (see Geomorphology, pages 10-12).

2.9 Kimberlites and Brukkaros (Figure 15: page 29)

At least 42 diatremes, pipes and dykes of Kimberlite have been recognised in the Gibeon area and other bodies are scattered throughout the Basin (Kurzlaukis and Lorenz 2000). None of these Kimberlites are diamondiferous. The prominent Brukkaros structure which rises 600 m (Figure 16: page 30) from the surrounding plain also formed at this time. Although the mountain has a volcanic form, it does not contain any volcanic eruptive rocks. The Smithsonian Institution had a solar observatory on the western side of the mountain from 1926 to 1931, the ruins of which can still be seen.

The base of the complex is 7 km in diameter and the internal ring is 3 km across. Formed some 75 million years ago (Reid et al.1990, Kurszlaukis 1994), the mountain has a basal diameter of 10 km and a summit diameter 4.5 km from crest to crest. The structure is complex and is not a true volcano, but rather formed as a result of several different processes. Initial updoming of the plain was accompanied by many small eruptions in the area, mostly radial to the centre of the dome. Later subsidence of the central parts of the dome was as a result of these smaller eruptions drawing material out from underneath the body. The crater that formed in the centre then received sediment from the edges of the dome which consisted of the surrounding rock and some material that had been ejected from the smaller volcanoes (see Figure 17: page 30 for a summary diagram of the history of the crater). Continued subsidence of the crater meant that the material on the edges of the crater has a very steep dip and some material is also found to have slumped down. In the centre of the crater there are lake deposits with plant fossils. The walls of the crater have been highly cemented by the volcanic fluids so the volcano has resisted erosion while the country rock has been eroded away. Other minor intrusions occur in the Basin as well.

2.10 Kalahari Group (Figure 18: page 31)

The Kalahari Group, which covers large portions of the rest of Namibia, does not occur extensively in the Orange-Fish River Basin. These cover deposits only occur as isolated patches, mainly as fluvial terraces of the Orange River. These, although they are insignificant in areal extent, are world class diamond placer deposits. Two ages of terraces have been recognised, only one of which, the so-called Proto-terrace, contains commercial reserves of diamonds. Mining of these terraces has exposed abundant fossils of Early to Mid-Miocene age (Bluck and Ward 2008).

2.11 Gibeon Meteorite Swarm

The Gibeon meteorite swarm is one of the largest known such occurrences on Earth being spread out over an area measuring 120 x 390 km. At least 120 known specimens, totalling around 25 t, have been recovered but there is an extensive network of illegal smuggling of meteorites out of the country. First recorded by James Alexander in 1838, they are coveted by collectors all over the world and specimens are readily available on the international market, even though it is illegal to trade within Namibia in meteorites or to export them. Chemically they are composed of 90% iron, 8% nickel, 0.4% cobalt and 0.04% phosphorus. Major minerals are kamacite and taenite (99%). Widmannstätten texture, a feature found in many meteorites, is well developed and is one of the reasons for their popularity amongst collectors. The age of the fall is not known but is believed to have originated from a single meteorite that entered the Earth's atmosphere at a low trajectory. The source of the original meteorite is believed to be from the meteor belt between Jupiter and Mars. Some 23 meteorites are on display in the Post Street Mall in Windhoek while several more are housed in the Geological Survey Museum at the Ministry of Mines and Energy, Windhoek and other institutions around the world.

3. Mineral Potential

(See Figure 19: page 31 for location of active mines and significant deposits)

3.1 Orange River Group

The Haib, Lorelei and other small copper deposits are known from the Orange River Group. Haib is one of the oldest porphyry copper deposits known. Porphyry copper deposits are typically low grade but high tonnage and are normally mined by open cast techniques. They form in orogenic belts and are associated with magmatic bodies. Known for more than 100 years, Haib averages 0.23% copper over 1,300 t with small quantities of molybdenum, silver and gold. Limited mining has taken place in the past and since the 1970s several exploration programmes have evaluated the deposit. The grade of the deposit is extremely low in international terms but current high commodity prices are making the exploitation of the deposit attractive again. Other important considerations, however, are the cost of electricity, stripping ratio, access to other infrastructure (road, rail, ports) and water supply. The current deficit in electrical supply in southern Africa is not conducive to development of this project.

3.2 Elim Formation

The white quartzites of the Elim Formation host lead, copper and some gold resources. Gold was produced at the Witkrans Gold Workings from 1939 to 1945 (32.2 kg), but more recent exploration has been unsuccessful in delineating additional resources worth mining (Evans 1979).

3.3 Namaqualand Metamorphic Complex

Large, economic massive sulphide deposits are known from the NMC in the North West Province of South Africa and numerous small bodies are mined or have been mined in the past. There is also significant additional potential for further discoveries to be made. Several types of ore bodies are known from this area – rare-metal pegmatites, skarns, uraniferous alaskite and mafic intrusions. The large base metal sulphide (Pb-Zn-Cu) deposits (Gamsberg and Aggenys) in South Africa are found in stratiform deposits and potential exists for further discoveries of this type in Namibia. Rose quartz diggings are well known and are generally exploited by small operators.

The rare pegmatites are well known for tantalite with lesser amount of beryllium and lithium. The Tantalite Valley is the best known location, but another group of outcrops occurs on the farms Sandfontein, Ramansdrift and Norechab in the area.

Scheelite, an ore of tungsten has been produced from skarns, the zone of contact metamorphism between an igneous rock and a limestone country (host) rock.

Uraniferous pegmatites occur in the Warmbad area. Work in the 1980s indicated that these are low grade and low volumes but more extensive exploration is currently underway to confirm or refute this. Recently released drilling results show a maximum grade of 490 ppm, which is very low.

The mafic intrusive complexes can contain platinum group elements as well as nickel-copper mineralization. The Tantalite Valley Complex in particular has nickel and copper, but the value is less than 1% and is therefore not economical to develop but additional deposits may be found. The Tantalite Valley has pegmatites which are capable of yielding up to 1 t ore, grading 300 to 500 ppm Ta_2O_5, a potential economic deposit.

3.4 Sinclair and Related Sequences

Extensive disseminated copper-lead-zinc and gold vein mineralisation has been known from Sinclair rocks since the 1850s and extensive exploration effort has been targeted in the area. However, these were largely unsuccessful. The Sinclair Mine is an example of a vein system and was operated successfully in the first half of the 20th Century but is now defunct. The currently defunct Klein Aub Mine is the only major mine that was activated and was operational for 21 years continuously. This mine is located in typical rift sediments.

3.5 Gariep Group

In the Orange-Fish River Basin the Gariep Group is currently the major source of base metals, particularly for lead and zinc. The Rosh Pinah Mine has been active since 1969 and currently has proven reserves of 6 t at an average grade of 8.68% zinc and 2.25% lead with potential for further reserves. Rosh Pinah produces some 70,000 t of zinc concentrate and approximately 28,000 t of lead annually. The nearby Skorpion deposit that was opened in 2003 has a resource of 24.6 t at an average grade of about 10.6% zinc. Additional exploration is underway in the region for further deposits of a similar type. Currently zinc mining produces 2% of Namibia's GDP and the opening of Skorpion Mine created 600 new jobs, 90% of which are held by Namibians (Mines 2006).

3.6 Nama Group

The sandstones and limestones of the Nama Group are not an attractive target for mineral exploration. A brecciated black marble from the Nama, known as Potoro Leonardo, with a golden yellow matrix, has been quarried for dimension stone. This occurrence is just to the west of the Basin being some 100 km south of Aus but indicates that further potential for deposits of this type may exist. The original mine is now defunct but exploration of the Nama Group may identify similar marble deposits that could be exploited in the future.

3.7 Karoo

Sedimentary rocks of the Karoo succession have little economic potential. Some oil and gas potential exists with the Whitehill Formation being a world-class petroleum source rock but which is unfortunately regionally immature. Minor bitumen veins and oil shows, that have been sourced from the Whitehill Formation, are found, but it is likely that these have been generated by local heating caused by the intrusion of dolerite dykes. A similar phenomenon is well known from the Irati Shale of Brazil, an exact equivalent of the Whitehill Formation. Dolerite dykes are extensively quarried in the region for road metal.

3.8 Miocene Gravels (Kalahari Group)

Although insignificant in extent, the Miocene-aged gravels that are developed as fluvial terraces along the banks of the Orange River are vitally important to Namibia as a major component of the diamond industry which provides 30% of the export revenue for Namibia and accounts for 10% of Namibia's GDP (Mines 2006). The diamonds in the terraces are of a high quality, a feature reflected in the fact that in 2005, 14.5% of the company's revenue came from the river mines but only 7.3% of the total carats produced (Namdeb website).

Two main ages of river terraces have been recognised, only one of which, the so-called Proto-terrace contains commercial reserves of diamonds (Bluck and Ward 2008; Figure 20: page 32). Currently, one mine is active on the river (Daberas) while another (Sendelingsdrift) is undergoing full feasibility review. Other deposits such as Auchas and Lorelei have been mined in the past. Several mines also exist on the south bank of the river.

4. Palaeontology

The fossil record of rocks in the Orange-Fish River Basin is diverse and rich. The record ranges from the first evidence for skeletal life on Earth some 550 million years ago to the abundant fossil record in the Orange River diamond-bearing gravel deposits which are around 18-17 million years old. Many of the fossil localities in Namibia are unique and are the sites from which many species have been described and should be considered for World Heritage Status.

4.1 Nama Group Palaeontology

The Nama Group has outstanding three-dimensional exposures of Ediacaran (a newly named geological time period for the late Proterozoic, 620–542 million years ago; Figure 13: page 27) platform carbonates, palaeo-channels and shallow marine sediments. Canyon exposures throughout the Basin (Figure 21: page 32) allow detailed mapping of different sedimentary environments, their relationships to each other and recognition of the fossil record in the Basin. Exposed ancient carbonate reefs (Figure 22: page 33) that are barely modified from when they originally grew can be studied in three dimensions (Grotzinger et al. 2000). Within these reefs there are stromatolites, built by microbial mats on an ancient sea floor, but also the skeletal remains of early reef-building organisms. In the modern day, reefs generally develop in warm, quiet, tropical environments, but in these reefs there is plenty of evidence for storms of unusual severity. The value of these outcrops is enhanced even more by the presence of volcanic ash beds which allows precise dating of the rocks. The ability to date the ash beds with this accuracy means that they can be used to estimate rates of biological evolution and sediment deposition.

The Ediacaran fauna, after which the time period is named, was first discovered in Namibia by Paul Range in 1908. Today they are known worldwide and cover a time range from about 620-550 million years ago.

The significance of these fossils was, however, not appreciated until work in Australia during the 1940s and 1950s highlighted the age and stratigraphic importance of the fossils. They are the first evidence for macroscopic forms, but the Ediacaran fauna is enigmatic: traditionally they have been regarded as being the precursors of modern taxa and classified as such, however, recently Adolf Seilacher has suggested that they show no affinity with more recent invertebrates and that they were filled with a 'plasmoidal fluid' rather than cellular tissue (Seilacher 1992). He termed them Vendobionta, an extinct kingdom lineage. The claims are hotly debated and it is difficult to find any two scientists who will agree on any issue on their affinities to modern organisms.

In the Nama Group the Ediacaran fossils are found only in the shallow marine beds of a previous time. Some appear to have lived attached to the sea floor while others floated free. The nature of these fossils is, however, still a matter of contention.

Characteristically, Ediacarans are flat with relatively little surface relief. They can be fairly large, up to a metre in length. Their recognition in the field is difficult; best found in low light conditions in the early morning or evening. As they have no hard body parts, their preservation, particularly in rocks of this age, is unusual and can probably be ascribed, at least in part, to the lack of mobile predators and scavengers in the seas of the time (Figure 23: page 33).

Important Ediacaran fossils known from Namibia include *Rangea*, *Pteridinium*, *Swartpuntia*, *Ernietta* and *Cyclomedusa*. Some of these are illustrated in Figure 24 (page 34).

In the 1970s, Gerard Germs discovered additional new fossils in the Nama Group. These were small, shelly fossils which he named *Cloudinae* (Germs 1972a, Germs 1972b). Previously, generations of geologists had been taught that the development of mineralised skeletons was associated with the Cambrian explosion. These are the oldest known shelly organisms on Earth and were a series of funnel-like cones which stacked into each other. More recently in the 1990s, John Grotzinger has found another fossil, *Namacalathus* (the Nama goblet, so named because of its form) with a lightly mineralised frame that could flex in an ocean current or storm (Grotzinger et al. 2000). Careful reconstruction of the fossils has revealed a digital virtual fossil which is eerily life-like (Figure 25: page 35). More recently, other coral-like animals (*Namapoikia*, the Nama crown) have also been found in the Nama rocks and which colonised fractures in the reefs (Wood et al. 2002).

In southern Namibia, ancient canyons were cut into older sequences with ash beds dated 543 million years old; the canyons themselves also have ash beds (539 million years old). This means that the cutting of the canyon straddles the Ediacaran-Cambrian boundary, a key time period of Earth's history (Figure 26: page 36) (Grotzinger pers comm. 2008).

The relative abundance of fossils in these Precambrian rocks solves one of Charles Darwin's dilemmas – *Why are there no fossils before the Cambrian period?* The fossils have been there but needed careful work to find and were not known in his time. The dilemma however is not completely solved yet as debate still rages as to whether these fossils are ancestors of ourselves and other vertebrates or were they a limb on the evolutionary tree that died? With its excellent outcrops and outcrops that cover this important time period, the Nama Group will continue to be a research destination for a long time (Knoll 2003).

4.2 Karoo Palaeontology

Karoo fossils are no less important than the Nama Group fossils. Although the full Karoo succession is not developed in the southern parts of Namibia, there are still important fossils both from an evolutionary aspect and a historical point of view.

The basal unit of the Karoo, the Dwyka Group is of polar glacial origin but is surprisingly rich in fossils. Trace fossils in particular are abundant and are well known on tiles quarried from near Noordoewer. A wide variety of tracks are present on these tiles, including traces of crustaceans and fish (Figure 27: page 37). Near Hardap Dam in the shales of the Dwyka Group, there are abundant fossils of a bivalve, *Eurydesma mytiloides*. The oldest vertebrates in Namibia also come from the Dwyka at Ganigobis, just east of Brukkaros crater. These are palaeoniscoid fish, primitive jawed fish that are preserved in silica-rich phosphatic nodules and which are characteristic of freshwater environments. These nodules may take on the shape of the fish preserved inside (Figure 28: page 38). Three different genera have so far been identified from Namibia, *Namaicthys*, *Watsonicthys* and *Elonichthys* (Evans 1998).

Fragmentary plant material is found in the Dwyka Group in southern Namibia but in the younger Permian Ecca Group one of the best known fossil plants, *Glossopteris*, is found. *Glossopteris* is known from all the Gondwana continents and this in fact was one of the earliest lines of evidence used in support of the concept of plate tectonics. Also found in the Whitehill Formation of the Ecca is a freshwater swimming reptile, *Mesosaurus* (Figure 29: page 39) which also occurs in equivalent units in Brazil. *Mesosaurus* is a historically important fossil that was used as one of the first lines of evidence to prove the theory of plate tectonics. Rare insect fossils have also been recovered from the Whitehill Formation.

4.3 Late Karoo Fossils

In southern Namibia no Triassic sedimentary rocks, and hence, fossils are preserved. The next youngest known fossils are early Jurassic fossils, tentatively identified as conchostrochans (Hiller pers comm. 1990) that are found at Hardap Dam in sediments interbedded with volcanic rocks. These are poorly preserved.

4.4 Brukkaros Plant Fossils

The central part of the Brukkaros structure contains lacustrine sediments deposited at the time of formation of the mountain. Fossil plants have been found in these sedimentary rocks, including conifers, horsetails, ferns and the earliest flowering plant known in Namibia. The angiosperm flower was 12 mm across and had five petals. It appears as if this lineage was archaic and no modern family members are known (Kelber et al. 1993).

4.5 Cenozoic Fossils

In southern Namibia there was another large time gap before the preservation of the next fossil assemblage. These have been discovered in the diamond pits along the Orange River and provide a remarkable record of life in Namibia around 20-17 million years ago in the Miocene period. Many fossils have now been discovered in the Namib Desert too. Along the Orange River several tens of thousands of fossils have now been excavated. The list of animals from the diamond mines is extensive but notable specimens include a variety of early elephants, crocodiles, bear-dogs, giant hyraxes, several deer-like ruminants and fossil pigs. Fossil trees have also been found, probably derived from upstream and deposited in log jams in the river. These include *Terminalia* and yellow-wood species. The Miocene fossil assemblage found along the Orange River is generally interpreted to have developed in a climate moister and more humid than that prevailing today with woodlands dominating the landscape. There is an extensive publication record on these fossils with comprehensive reviews by Pickford and Senut (2000 and 2003).

5. Geomorphology

The geomorphology of the Orange-Fish River Basin largely reflects the nature of the underlying geology which over most of the basin is flat-lying Nama or Karoo rocks. It is only in the far south, where erosion has been sufficient to remove the cover rocks and in the Karasburg Mountains, that the flat-lying monotony of the Namaland plains is interrupted. The Orange-Fish River Basin can be sub-divided into four main geomorphological zones based on general landform, slopes and underlying geology. These zones (Figure 30: page 39) are the (a) Nama-Karoo Plains, (b) Karasburg Mountains, (c) the Gamchab Basin and (d) the Orange River Canyon area. The Orange-Fish River Basin is bordered on its western side by the Great Escarpment and on its eastern side by the Kalahari Sandveld.

5.1 Nama-Karoo Plains

The largely featureless Nama-Karoo plains dominate the landscape with only Brukkaros providing a break from the monotony. The Fish River Canyon and its tributaries incise deeply into the plains exposing the underlying basement rocks, especially in the far south. Although the Nama-Karoo plain sits well within what is regarded as a stable continental plate with little tectonic activity, there is actually abundant evidence for tectonic activity, young enough to affect the drainage patterns of the rivers, form domes and create small valleys.

The Hebron Fault close to Sesriem and which lies just west of the Orange-Fish River Basin is a well-known fault that has been active in the recent past. Several other faults which trend north-west to south-east appear to have disturbed and affected the drainage patterns (Figures 31: page 40 and 32: page 40). A large dome structure is present south-west of Mariental – this dome is 44 km x 34 km in dimension and rises 200 m above the surrounding rocks (Figure 33: page 41). The Hudub River that cuts across the dome must have been in place before the dome was formed – it would have been flowing across the flat plains and as the dome developed the river incised down into the rising structure maintaining its course and level. The dome will be referred to here as the Hudub Dome after the river. The river cuts a 200 m deep gorge through the dome, down to the same level as the surrounding rocks. A smaller dome, the Hatzium Dome (Heath and Toerien 1962), is also present on the north-east side of the Hudub Dome and is known to contain kimberlite dykes, suggesting that a large magmatic body may underlie the dome. The Hudub Dome forms part of a large block measuring 290 km x 75 km at its widest in the north, tapering down to 25 km in the south (Figure 34: page 41). This block appears to have been formed by faulting with more uplift in the west causing deeper incision of the rivers in the west. The upper portions of the Fish River appear to postdate the formation of this block as the river flows north around it before swinging east and then south around it.

Two other smaller domes are located south-west of Maltahöhe (Figure 35: page 42). These were investigated with gravity techniques and are underlain by dense material, suggesting that they are also underlain by igneous intrusions (Wendorf pers. comm., unpublished data).

Other faults that trend north-south in the far north of the Basin (Figure 36: page 42) are the extension of a series of major faults, several of which are responsible for the springs in Windhoek and at Gross Barmen. Overall this appears to be a major fault system traversing Namibia about which we know very little.

The location of the Fish River Canyon, one of the largest (in fact, often called the second largest) river canyons in the world, is also fault controlled. With the main lower canyon having a river length of 68 km, a width of 4 km and 0.5 km deep, the Fish River Canyon rivals many of the other canyons in the world. The much larger Grand Canyon for comparison is 446 km long, up to 29 km wide and 1.6 km deep, but other canyons – such as the canyon of the Blue Nile in Ethiopia which is at least 1.6 km deep – also rival, or may be even bigger than the Fish River Canyon.

The canyon has been carved out by erosion by the Fish River, the closest there is to a perennial river within the borders of Namibia. The flow of the river today is highly ephemeral with rare flash floods punctuating what is normally a relatively small flow. Canyons like this originate by the simultaneous down-cutting and headward erosion of the main river and its tributary streams. The Fish River would have been meandering across what was a relatively flat plain when uplift of the landscape occurred. The timing of this uplift is not exactly known but appears to have been around 65 million years ago at the end of the Cretaceous period. The Fish River then started cutting back towards its head waters and down into the rock below. Softer, weaker rock was cut back undercutting the harder layers which formed cliffs. Without adequate support underneath, these harder layers collapsed, thus widening the canyon. The depth of the canyon was achieved by down-cutting of the river towards the new base level, which in this case was the Orange River. The river level falls from 425 m to 250 m amsl over its course in the canyon itself. The canyon was originally locked into its position by small faults which can be seen from the main viewpoint (Figure 37: page 43). A striking feature of the canyon is also the fact that most of the tributary incision is on the western bank of the river with little tributary incision in the east (Figure 38: page 43). This indicates that when the landscape was lifted it was tilted down to the east and that the widening of the canyon is occurring westwards.

5.2 Karas Mountains

The Little and Great Karas Mountains are block faulted mountains (Figure 39: page 44), that is, they were formed by normal faults sometime after the end of deposition of the Nama Group (500 million years ago) and the start of deposition of the Dwyka Group around 305 million years ago. The highest point (Schroffenstein) in the Great Karas Mountains is 2,202 mamsl. The north-south extent of the mountains is about 90 km and they rise 500 m above the plain in the case of the Klein Karas and over 700 m for the Great Karas. The underlying portions of both the Little and Great Karas Mountains are formed from the Namaqua Metamorphic Complex overlain by the Nama Group. The Kuibis and Schwarzrand Subgroups are rather thin here suggesting that this area was originally on the margins of the basin. Outcrops of the Dwyka Group are also found. Rejuvenation of the faulting occurred some 135 million years ago (Münch 1974).

5.3 Gamchab Basin

This area is dominated by large, broad, gently sloping valleys with drainage directed towards the Orange River (Figure 40: page 44). The bedrock is made up primarily of Karoo Group sediments with some dolerite sills. The area is covered with sparse grass and few trees except in the watercourses.

5.4 Orange River Canyon

Close to the Orange River, deep dissection has occurred (Figures 41: page 45, and 42: page 45). In places, the river has incised a meandering course over 700 m deep into the metamorphic bedrock. The size of the meander loops is larger than those that could be formed by a river with the current discharge level, suggesting that they have been inherited from earlier times when the outfall of the river was higher (Figure 43: page 46). The sedimentary record from offshore Namibia shows evidence for the presence of a major delta system related to the Orange River between 103 and 65 million years ago and it is in this time period that the meander loops must have been developed. The river at this time would have been flowing over flat-lying Karoo and Nama strata and would have been allowed to meander freely on a broad flood plain. The uplift of the western side of the sub-continent that occurred around 60 million years ago and the 'soft' sedimentary rocks that were overlying the area were rapidly removed and the river entrenched itself into the bedrock similarly to the Fish River Canyon. Now that the river has incised deeply into the bedrock it is locked in and major changes in the river channel are nearly impossible (Bluck and Ward 2008).

6. Groundwater

Two main geohydrological zones have been defined in the Orange-Fish River Basin (Christelis and Struckmeier 2001). These are the Fish-Aroab groundwater basin and the Karas Basement basin and are defined on the basis of geology and hydrogeology.

6.1 Fish-Aroab Basin

This area is underlain largely by the Nama Group sediments. Several towns in the basin are supplied from groundwater sources, including Aroab, Kalkrand, Gibeon, Berseba and Bethanie. In the west, the basin is bordered by the Great Escarpment and in the east by the Weissrand Escarpment, east of which are the younger Karoo and Kalahari sediments of the Stampriet Basin.

The flat-lying, largely undeformed Nama Group rocks do not have good primary permeability or porosity but groundwater is rather hosted in joints, faults and solution features in limestones and dolomites. Target areas for drilling boreholes are joints and faults although contacts between limestones and sandstones may also yield water. Limestones of the lower Nama Group produce artesian water from solution cavities in the area west of Maltahöhe.

6.2 Karas Basement Area

The metamorphic rocks of the Karas Basement area make poor aquifers with low porosity and permeability. Warm-water springs are known from the basement with the best known being that at Ai-Ais (66.5º C). Other warm-water springs occur at Warmbad (34º C) and at Tzamab-Gründorn. Exploration for water is focused on faults, especially close to riverbeds where recharge is higher.

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Annexes

Annex 1: Summary of characteristics of geological formations

AGE (millions of years)	NAME	ROCK TYPES	MINERAL POTENTIAL	FOSSILS	GROUNDWATER	COMMENTS
65-0	Kalahari	Fluvial, aeolian sands; conglomerates	High in Miocene conglomerate; diamonds	Internationally important; rodents, mammals, birds	Good in aeolianites	
c. 75	Brukkaros/Kimberlites	Carbonatite sediments; kimberlite	Low (kimberlites NOT diamondiferous)	Within crater facies; plant	Important in fracturing local rocks	
300-250; 180	Karoo	Sedimentary; basalt, dolerite	Low	Fish, reptiles, invertebrates; plant	Good in sandstones	
550-530	Nama	Limestones; sandstones, shales	Low	Internationally important Early shelly fauna	Good in limestones	Dominant unit in basin
800-500	Pan-African/Damara	Metamorphosed sediments; granites	High; Cu, Au, U	none	Low	Largely extra-basinal
c. 717	Gannakouriep	Doleritic	Low	none	Low, locally important	
1,400-1,200	Sinclair	Metamorphosed sediments; volcanics	Moderate-high; Cu	none	Low	
1,800-1,400	Namaqua	Gneisses; granites	High, Cu, U	none	Low; fractures	
1,670-1,420	Elim/Rehoboth	Metamorphic sediments; volcanics	High; Au, Cu	none	Low; fractures	
2,000-1,700	Orange River Group	Granite, gneiss; amphibolite	High; Cu-Pb	none	Low; fractures	

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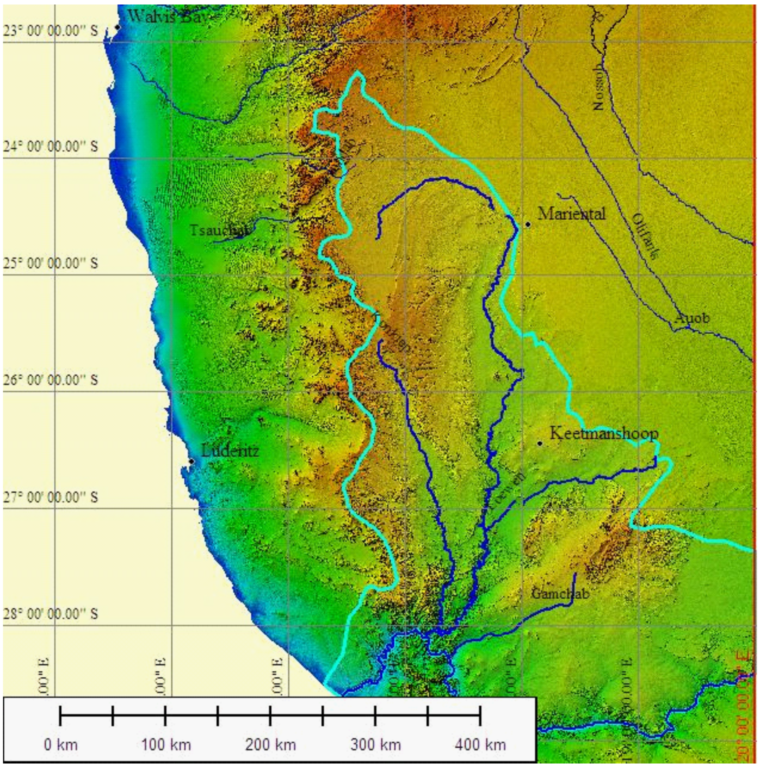


Figure 1: Relief image of the Orange-Fish River Basin showing major rivers and towns

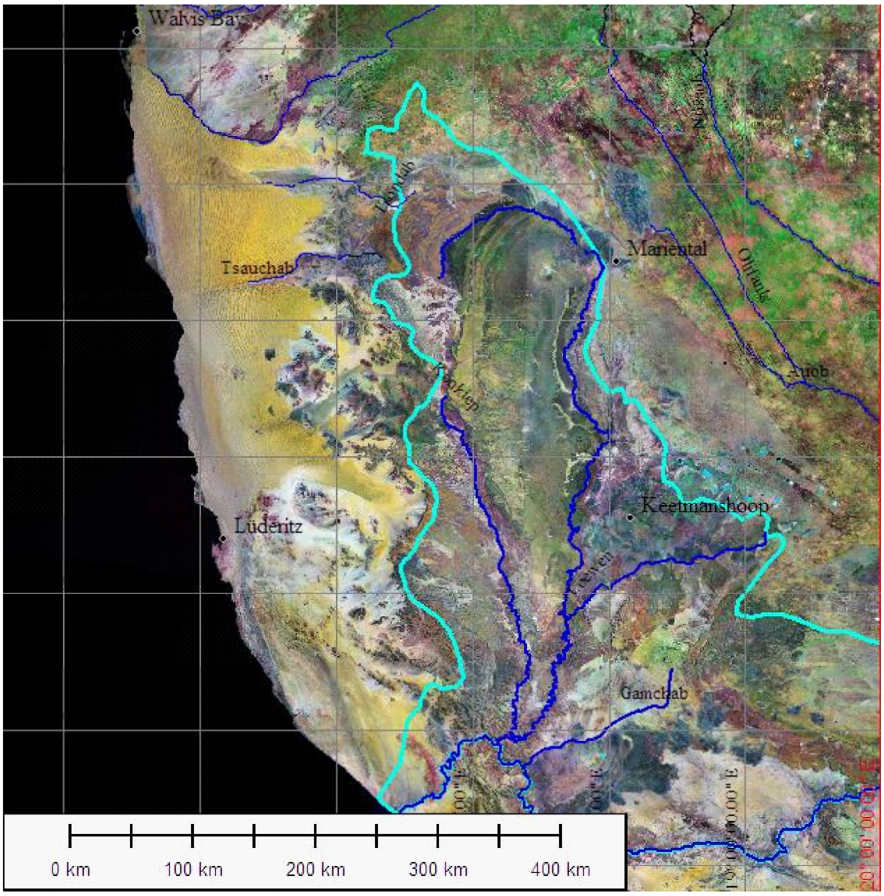


Figure 2: Satellite image of the Orange-Fish River Basin; same area as shown in Figure 1

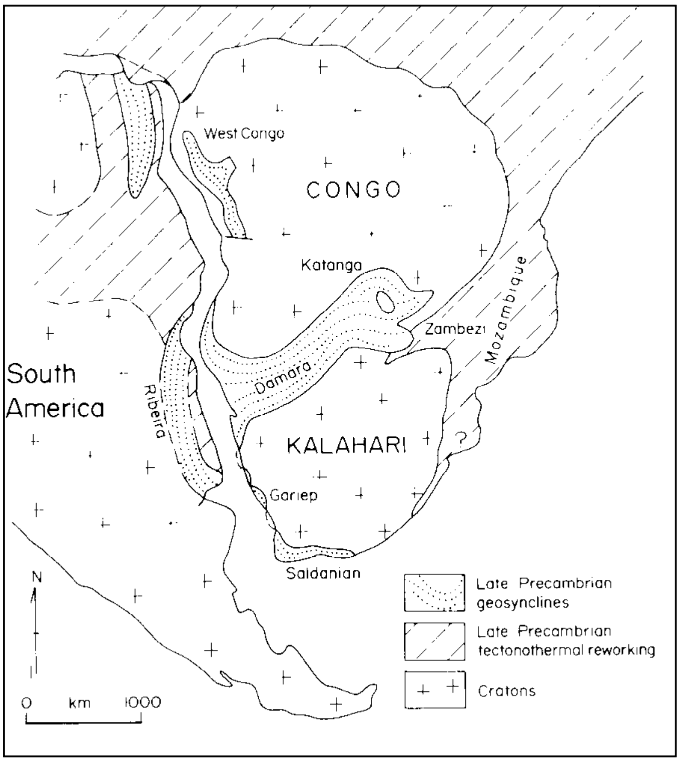


Figure 3: Map of the tectonic framework of southern Africa showing the distribution of major cratons and orogenic belts
Source: Tankard et al.,1982.

Figure 4: Distribution of Orange River Group rocks in southern Namibia

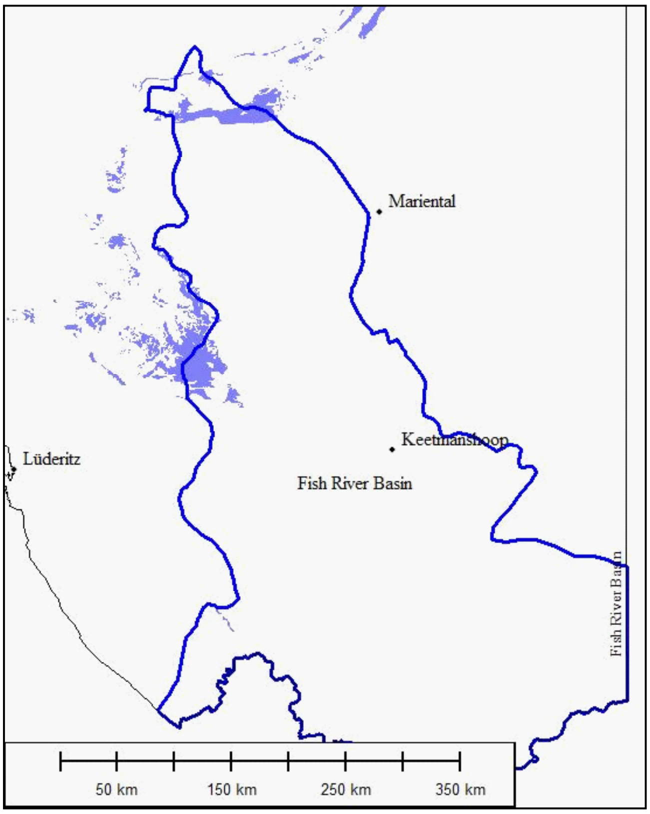


Figure 5a: Distribution of Rehoboth Sequence rocks in southern Namibia

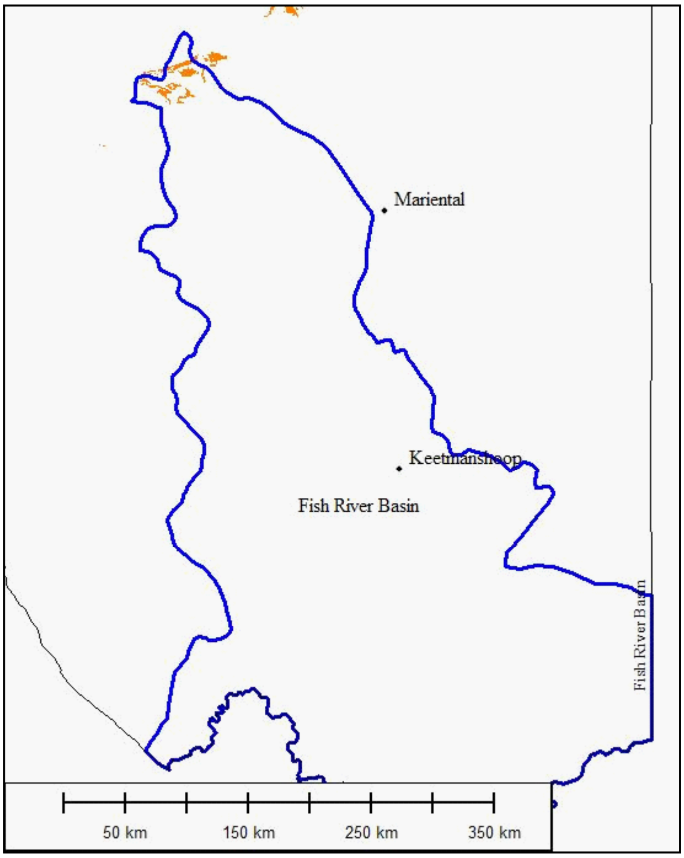


Figure 5b: Distribution of Elim Formation rocks in southern Namibia

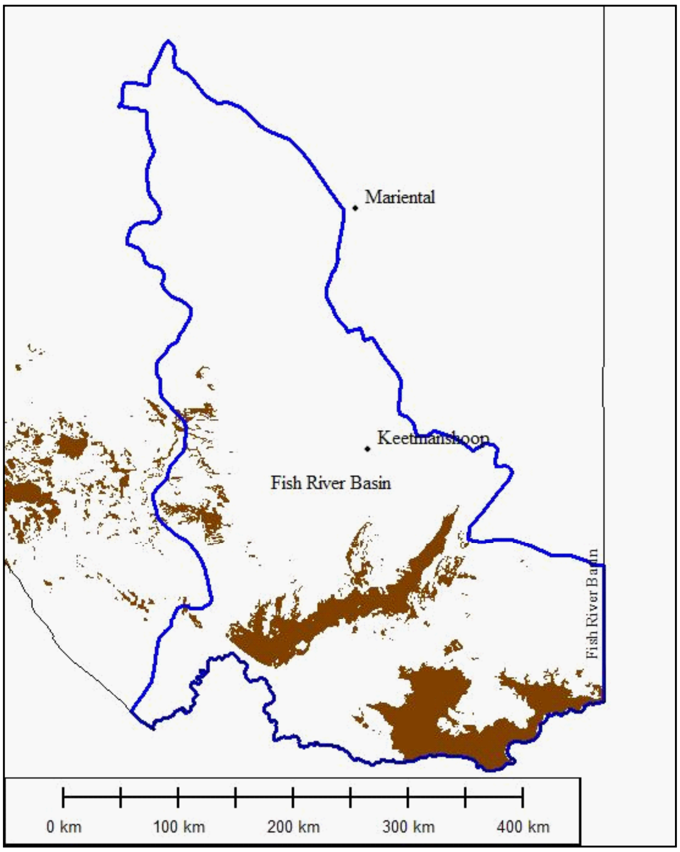


Figure 6: Distribution of Namaqua Metamorphic Complex rocks in southern Namibia

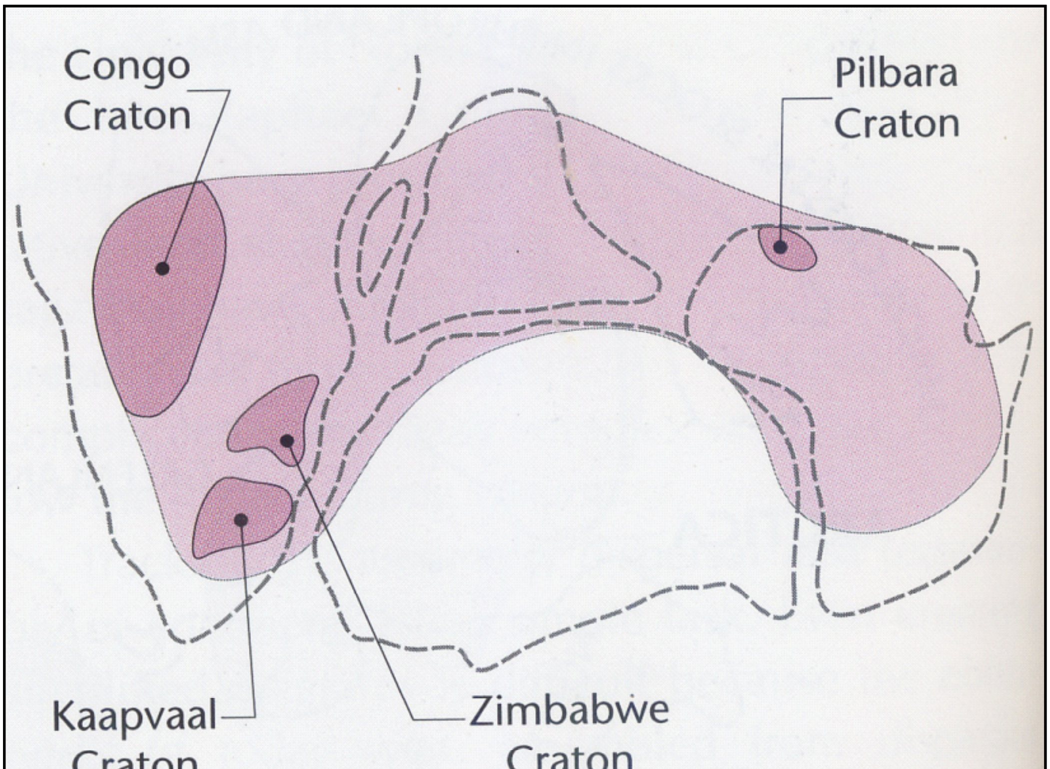


Figure 7: Ur, shown here in shades of purple, is Earth's oldest continent. The Orange-Fish River Basin is situated on the south-west margin of the old continent.

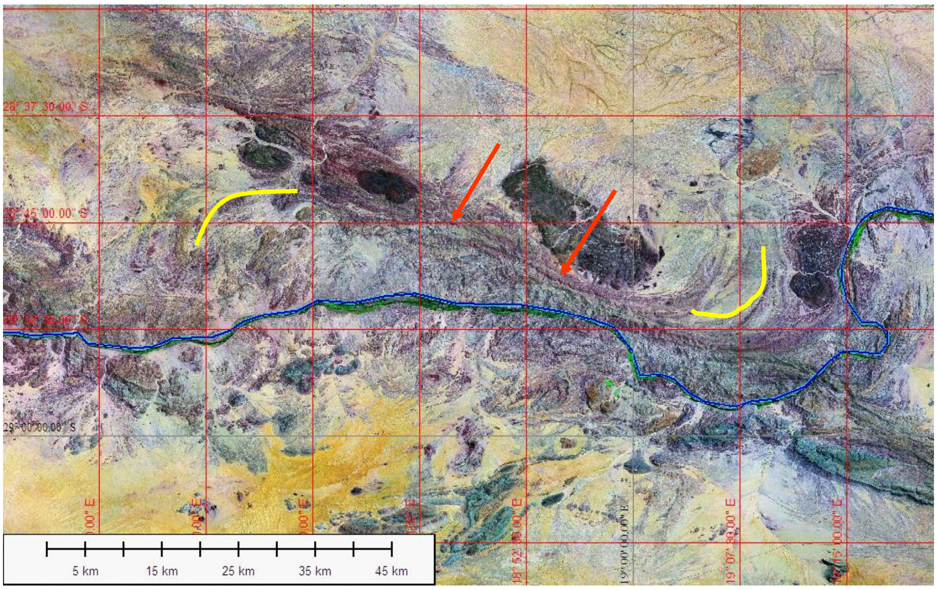


Figure 8a: Satellite image of the Tantalite Shear Zone indicated with red arrows; note the 'dragging' (yellow lines) of lithologies into the fault zone (also see Figure 8c). The Orange River flows east-west across the bottom of the image.

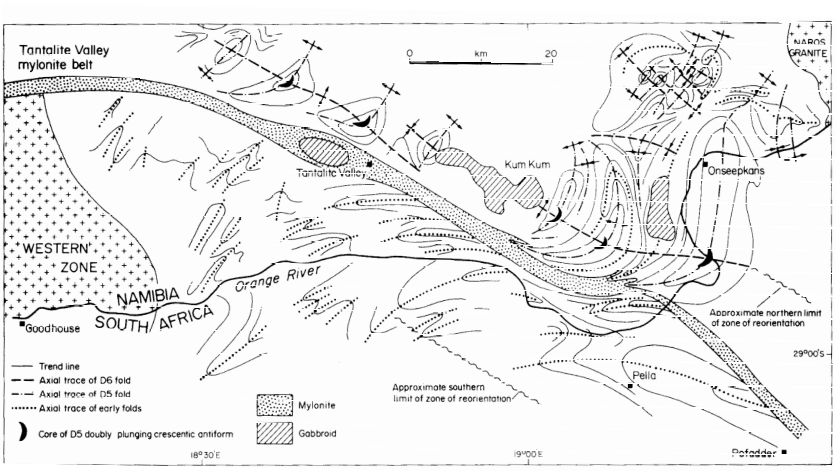


Figure 8b: Structural map of the Tantalite Shear Zone shown in Figure 8a

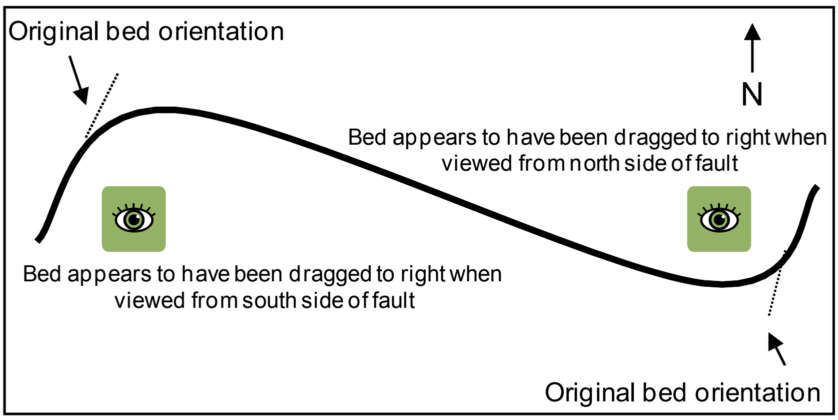


Figure 8c: Diagram illustrating the sense of movement on the Tantalite Valley fault

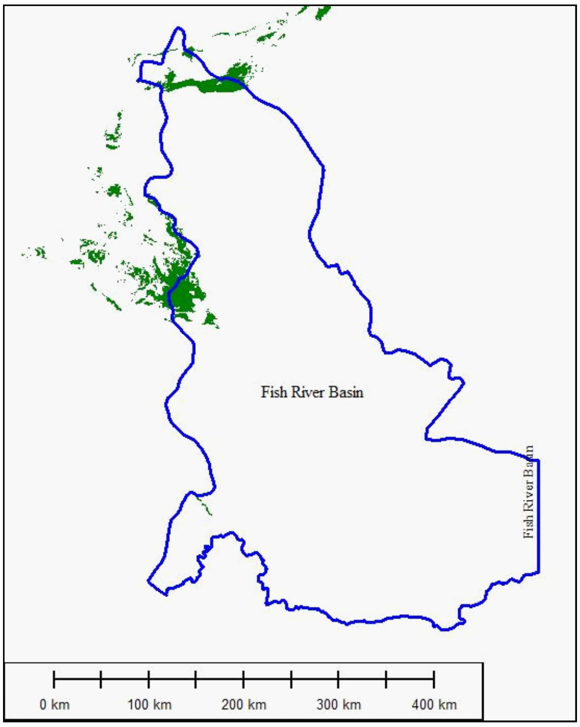


Figure 9: Distribution of Sinclair Group rocks in southern Namibia

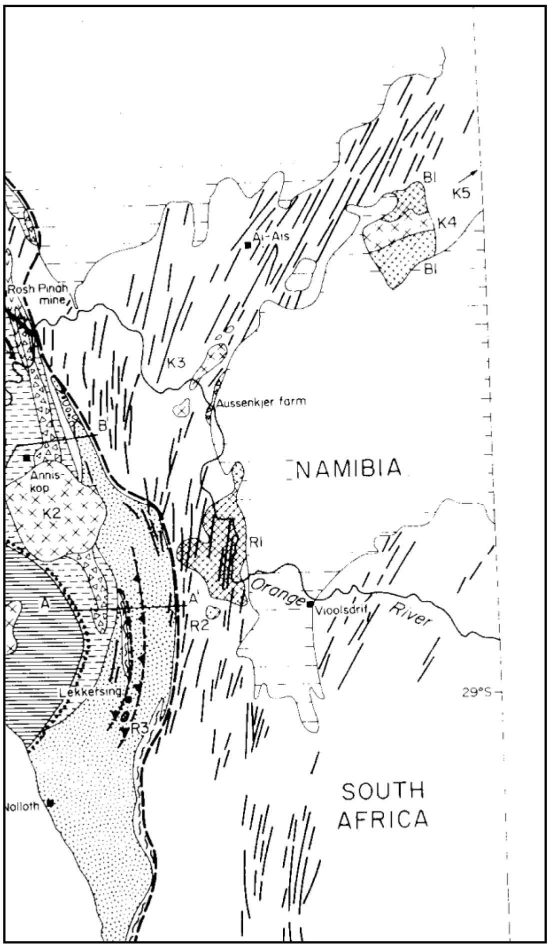


Figure 10: Location and distribution of the Gannakouriep Dyke Swarm (black lines) in South Africa and southern Namibia
Source: Tankard, et al., 1982

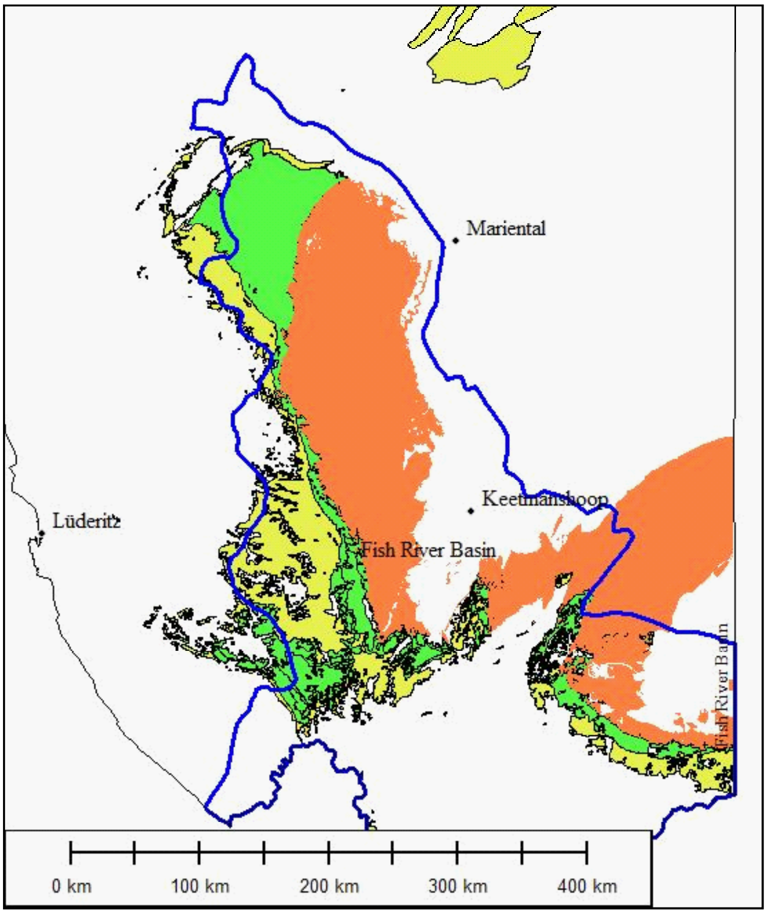


Figure 11: Distribution of Nama Group rocks in southern Namibia

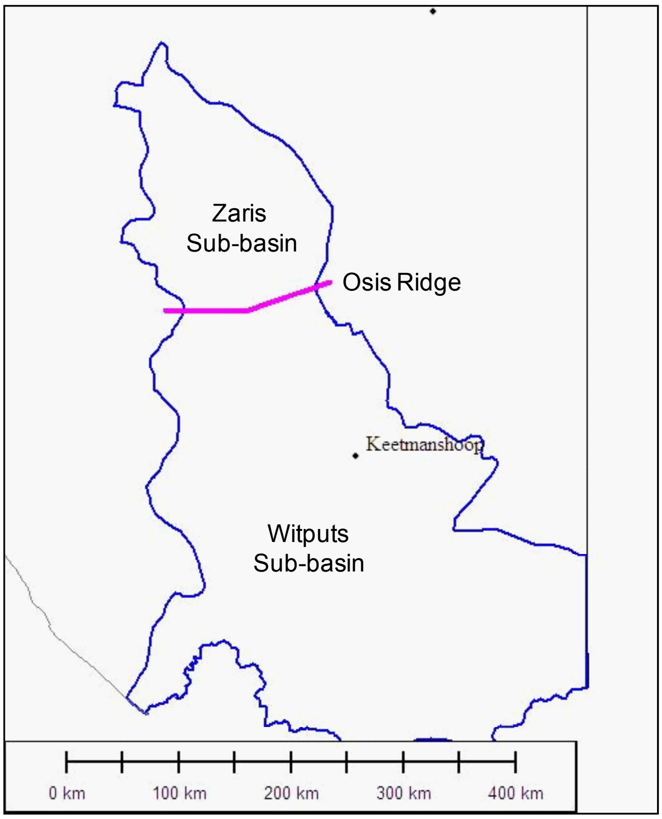


Figure 12: The Zaris and Witputs sub-basins of the Nama Basin are separated by the Osis Ridge

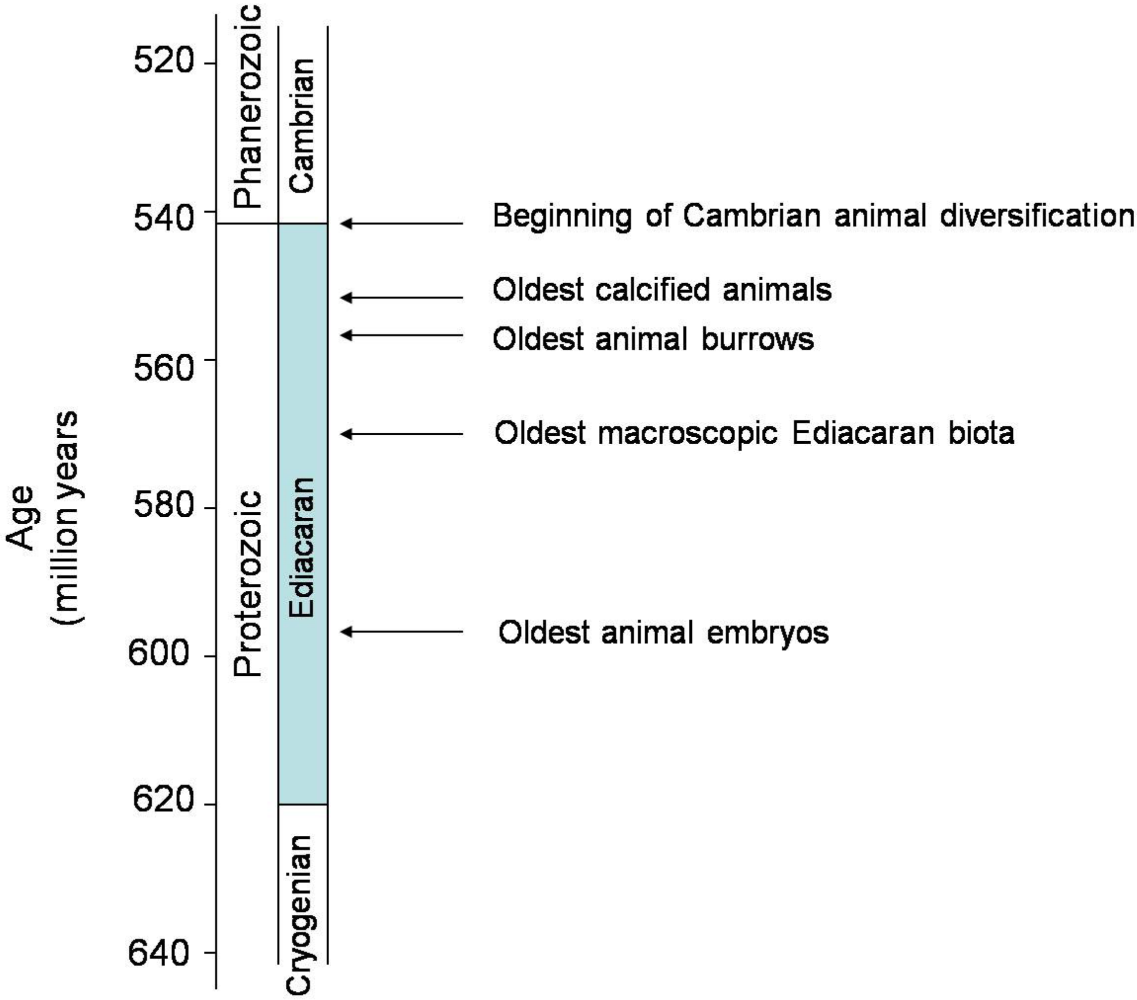


Figure 13: Timetable of major biological events associated with the newly-defined time period, the Ediacaran

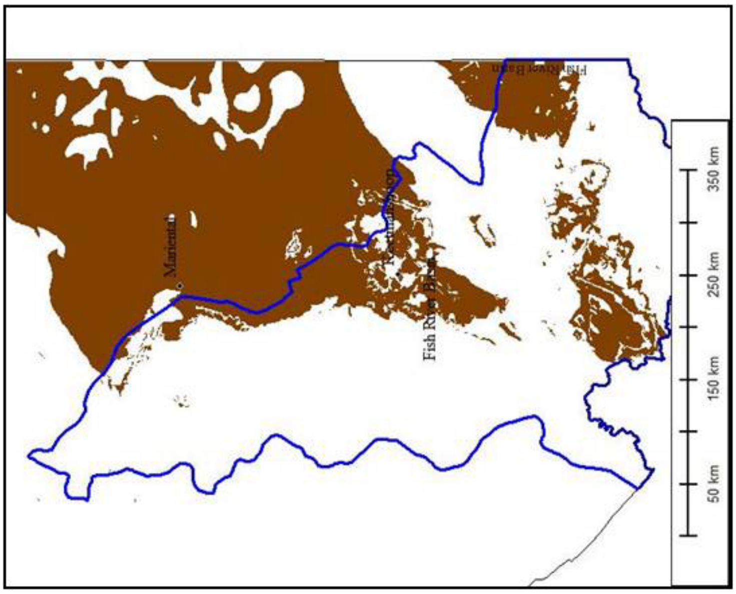


Figure 14a: Distribution of Karoo Group sedimentary rocks in southern Namibia

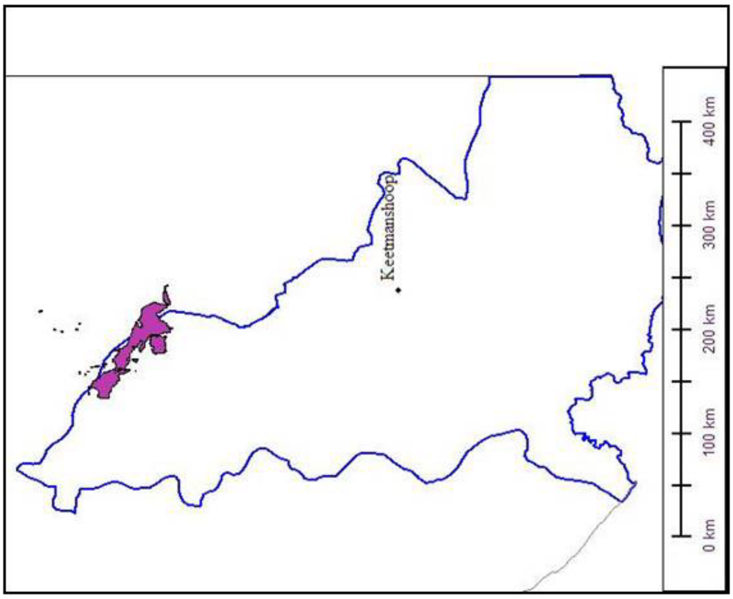


Figure 14b: Distribution of Karoo Group volcanic rocks in southern Namibia

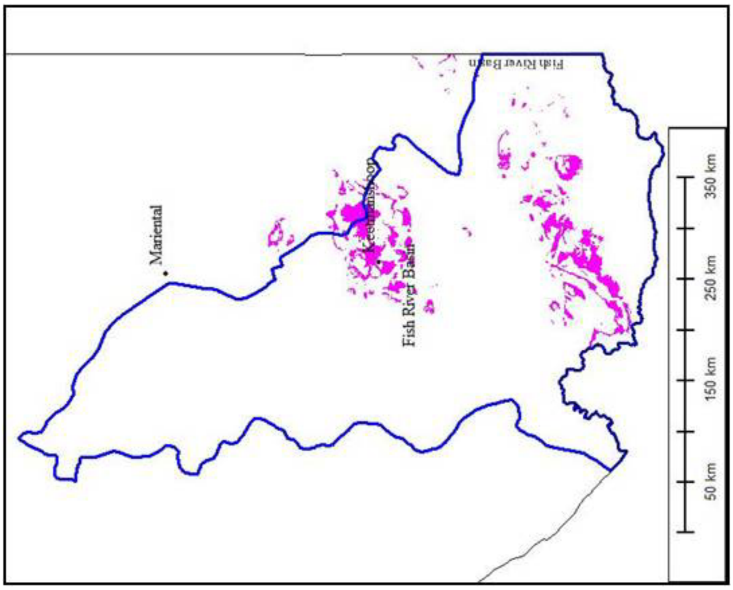


Figure 14c: Distribution of Karoo dolerites in southern Namibia

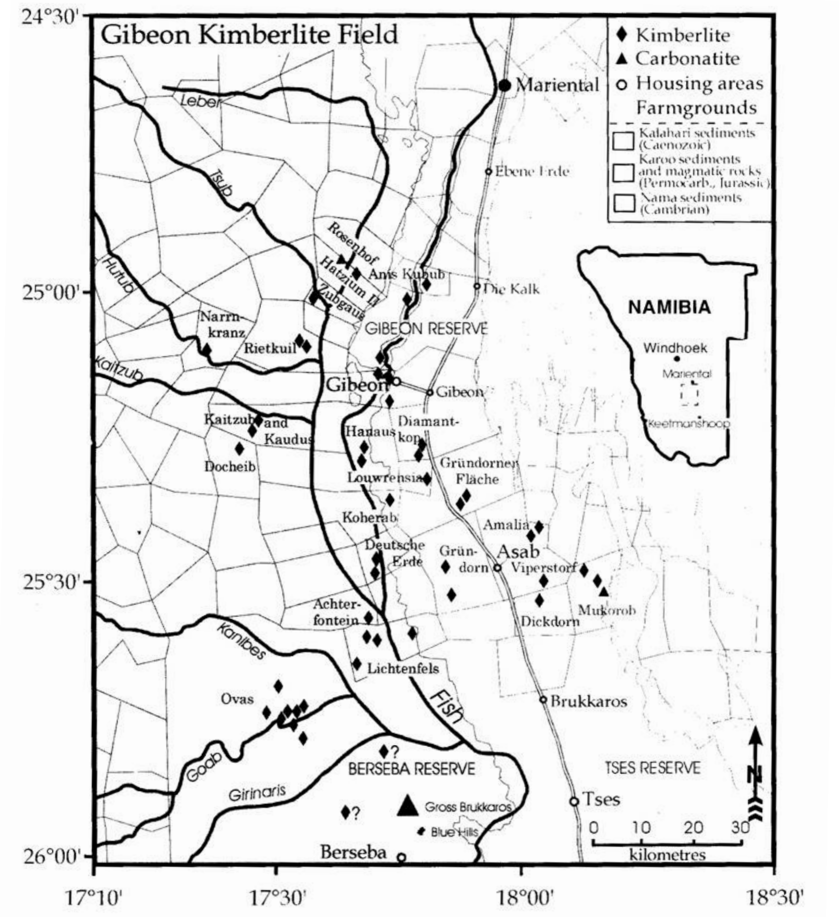


Figure 15: Late Cretaceous kimberlites cluster around Gibeon, north of Brukkaros
Source: Kurszlaukis and Lorenz, 2000

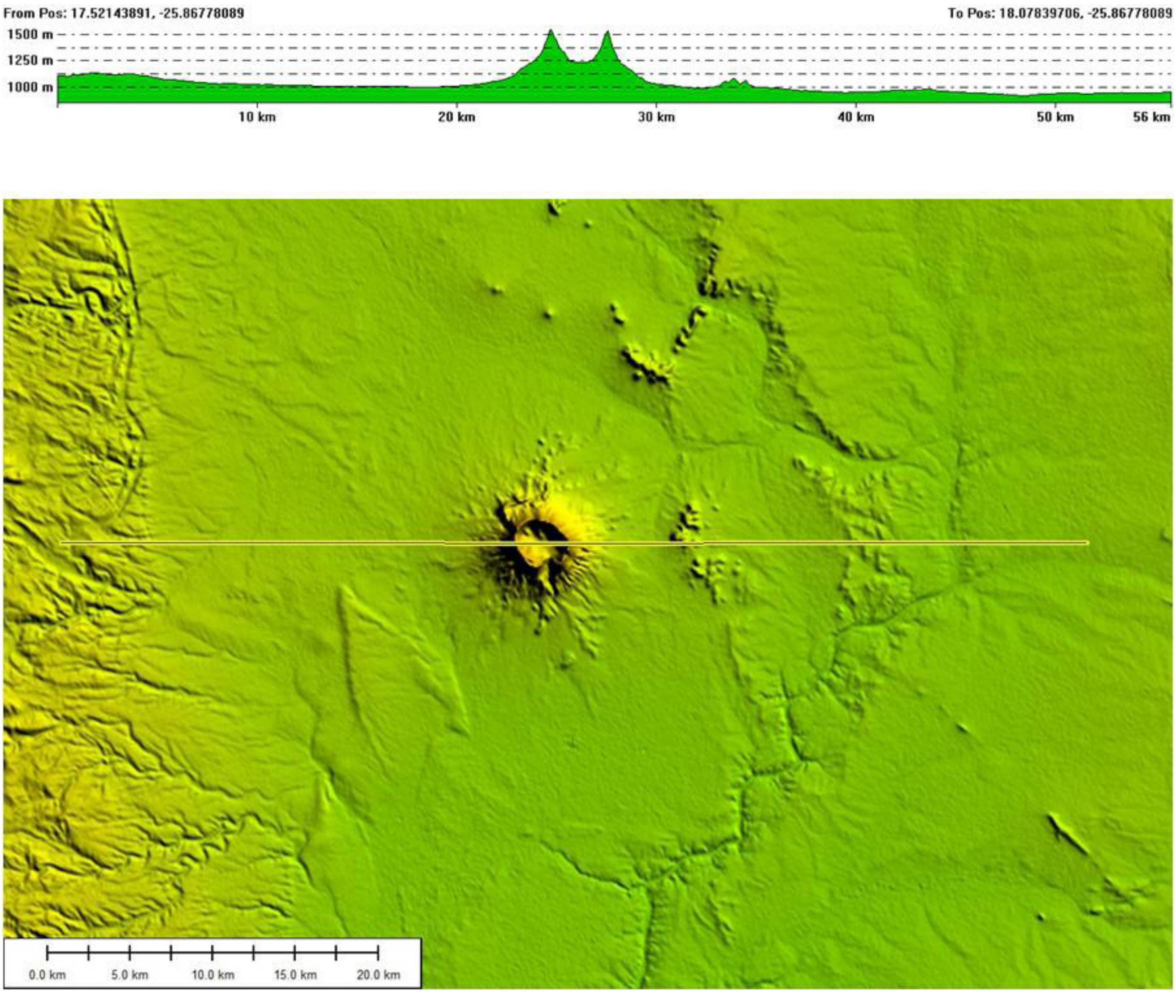


Figure 16: Section through the Brukkaros structure (above) and relief image showing location of section (below)

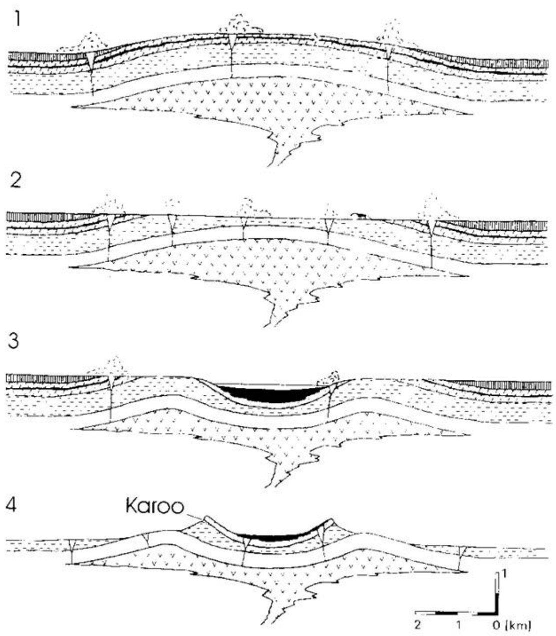


Figure 17: Diagram summarising the geological evolution of Gross Brukkaros
Source: Lorenz et al., 2000

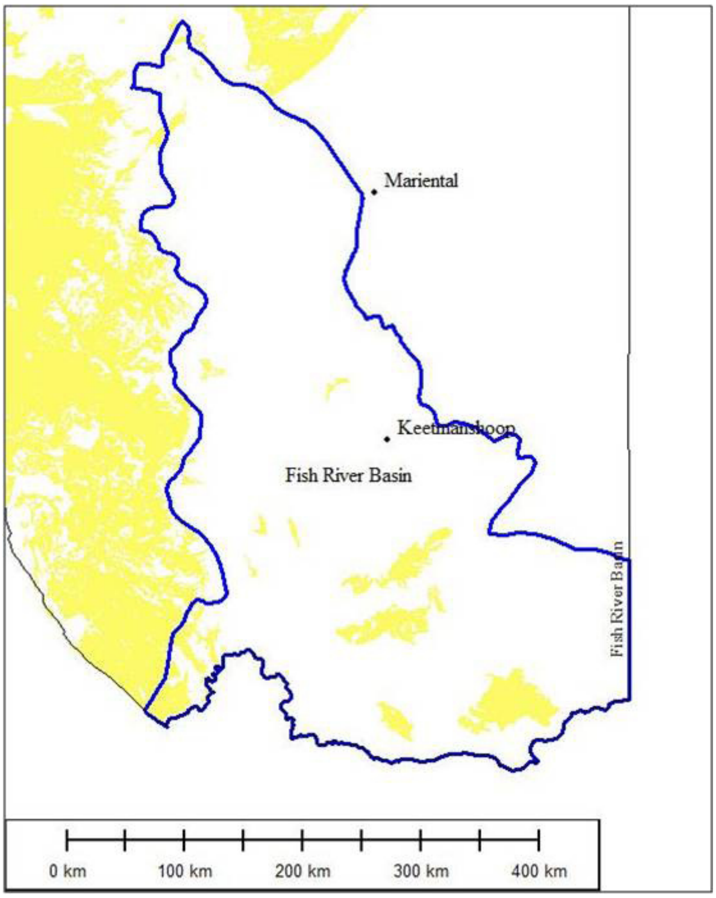


Figure 18: Distribution of Quaternary (Kalahari and Namib) sediments in southern Namibia

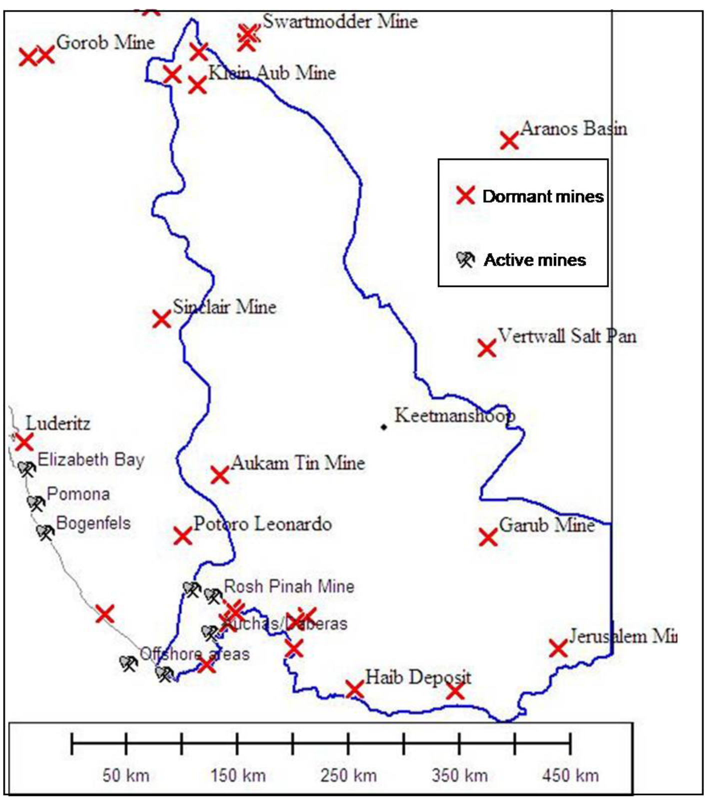


Figure 19: Location of active and dormant mines in southern Namibia

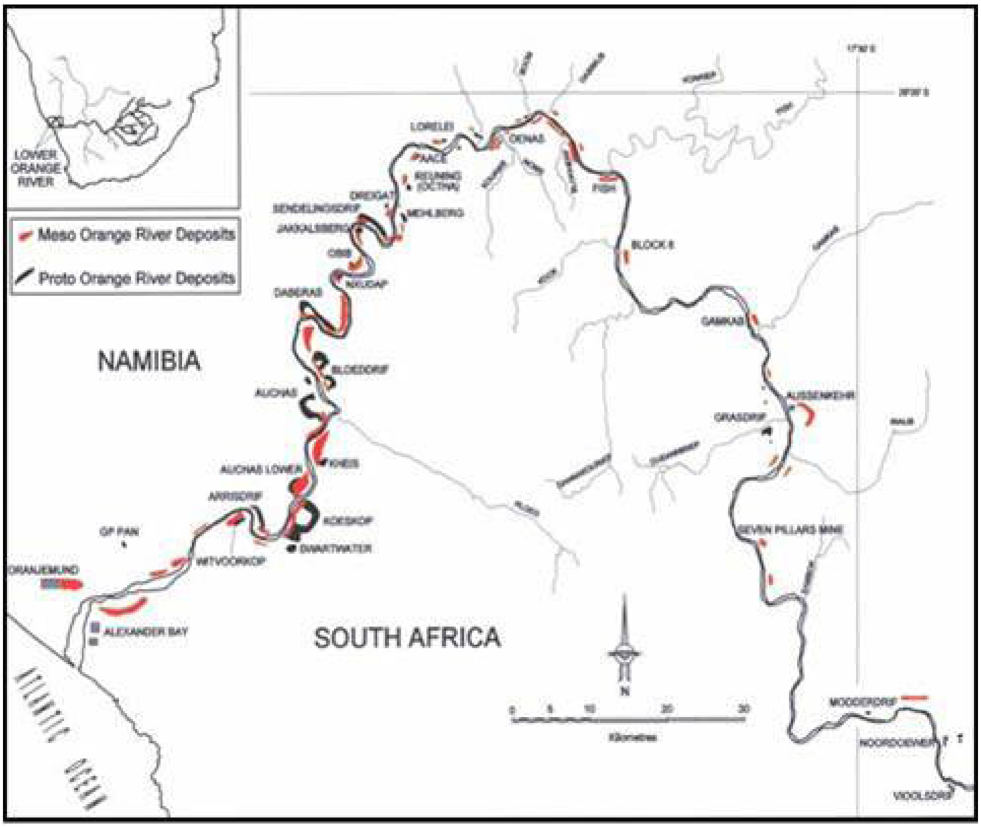


Figure 20: Location of alluvial diamond mines and deposits in terraces of the Proto-Orange

Figure 21: View of tributary canyons to the main Fish River Canyon showing the excellent outcrops

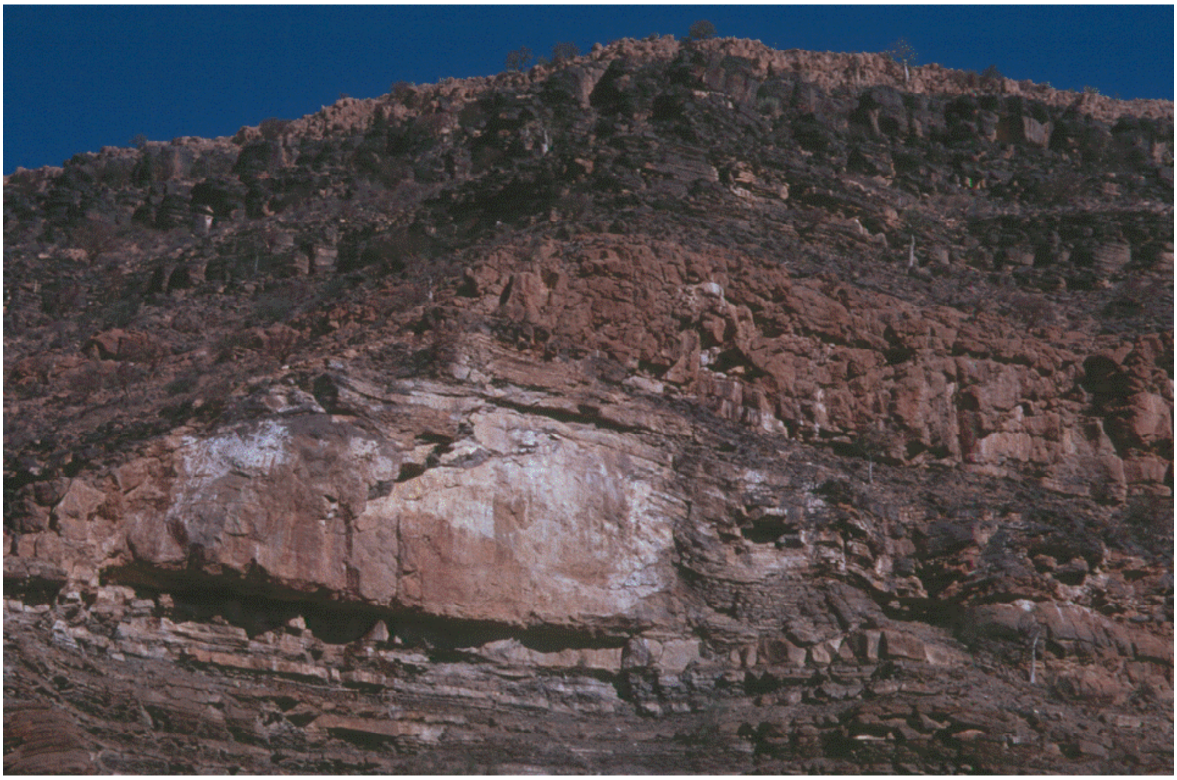


Figure 22: Carbonate reefs are well developed in the Nama Basin. The reef can be recognised as the pale massive unit which interfingers laterally with siliciclastic beds.

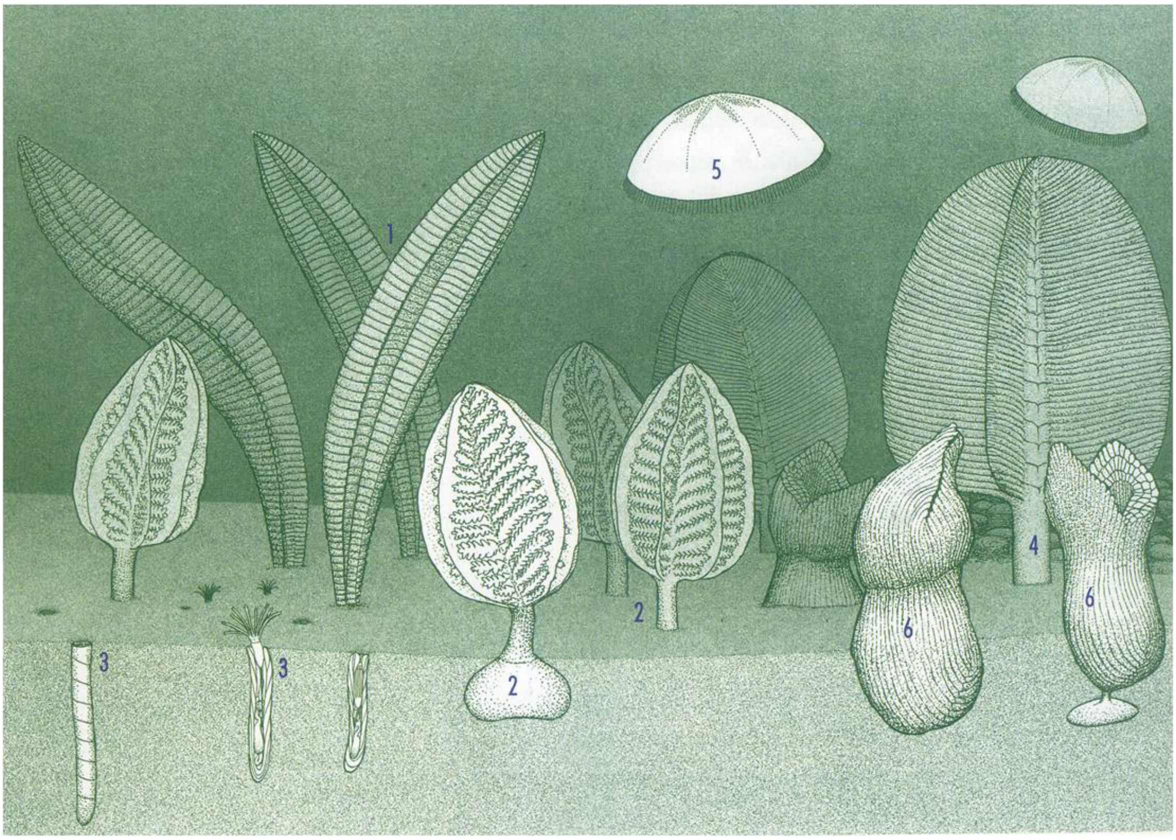
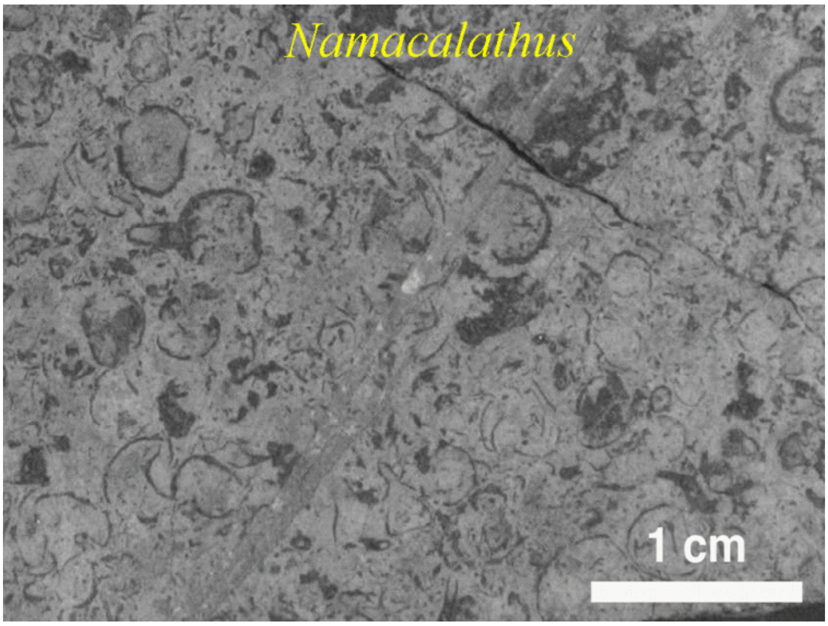


Figure 23: An artist's reconstruction of Ediacaran life in the Nama Sea
1 = Pteridinium; *2* = Rangea; *3* = Cloudina; *4* = Swartpuntia; *5* = Cyclomedusa; *6* = Ernietta.
Source: McRae, 1999

Figure 24: Some ediacaran fossils from southern Namibia

(a)



(b)

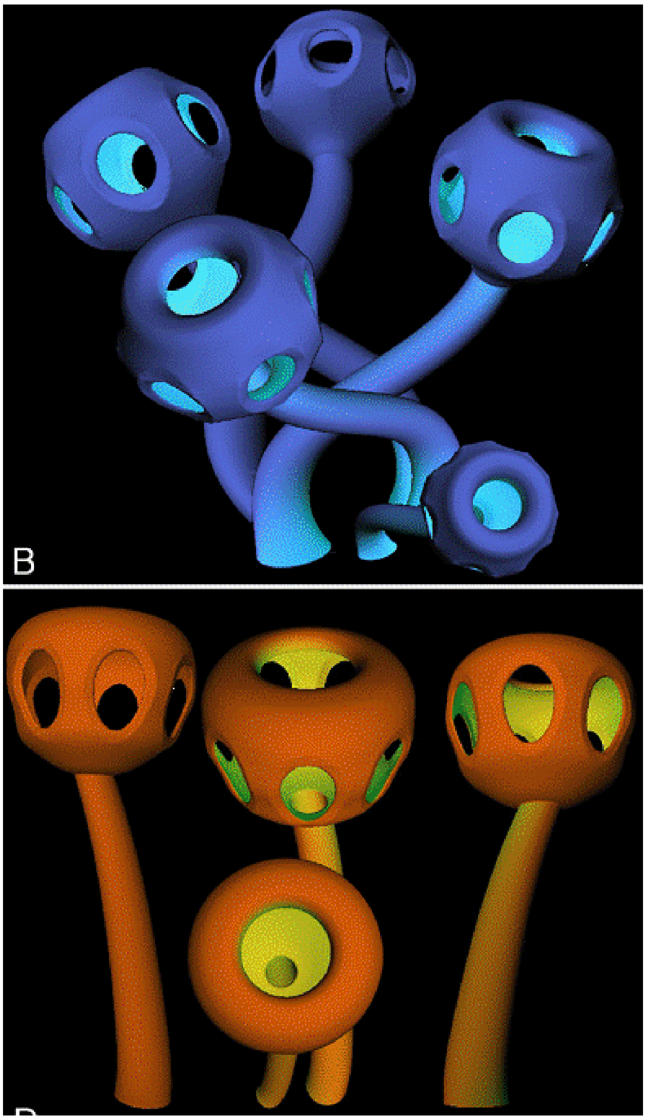


Figure 25: (a) Ouctrop of Namacalathus fossils and (b) digital reconstructions of their original form
Source: Grotzinger, pers.comm

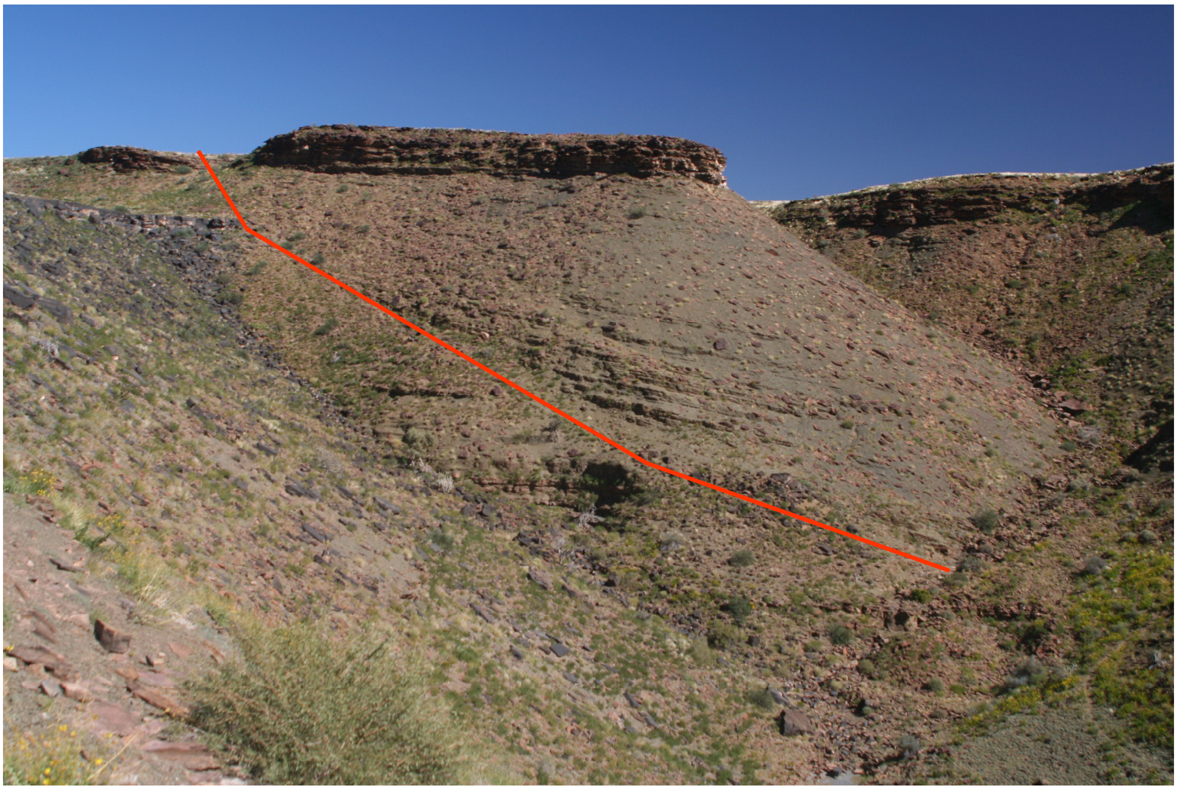


Figure 26: Incised palaeocanyon, marked in red, that immediately post-dates the Precambrian-Cambrian boundary

(a)

(b)

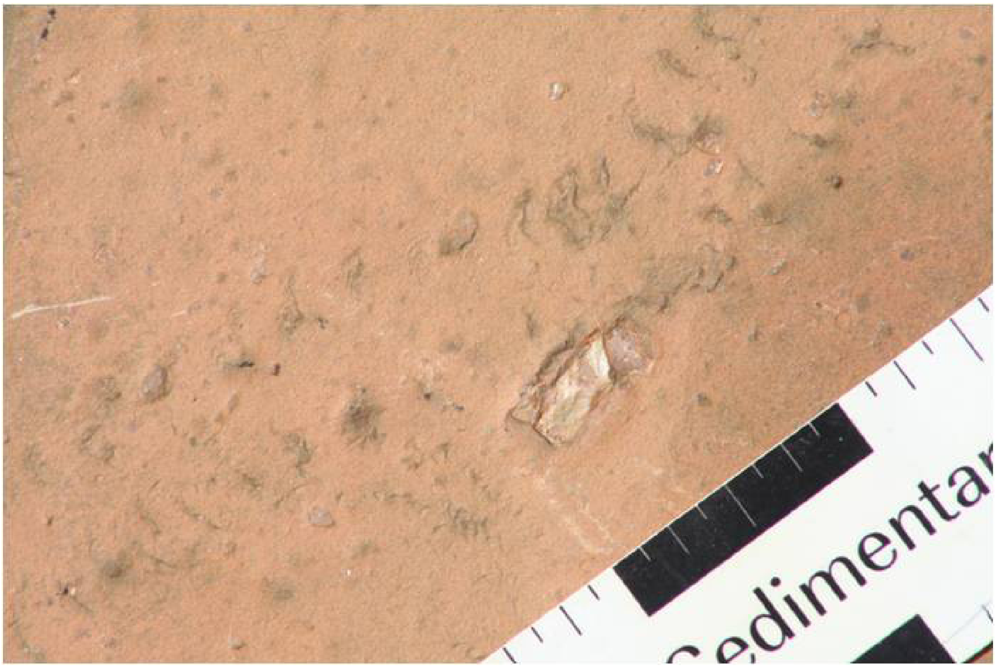


Figure 27: Tracks of molluscs (a) and arthropods (b) in the shales of the Dwyka Group

Figure 28: Opened phosphatic nodules from a cliff outcrop in the Fish River near Ganigobis with fish fossils

Figure 29: Mesosaurus fossil from southern Namibia showing spectacular preservation

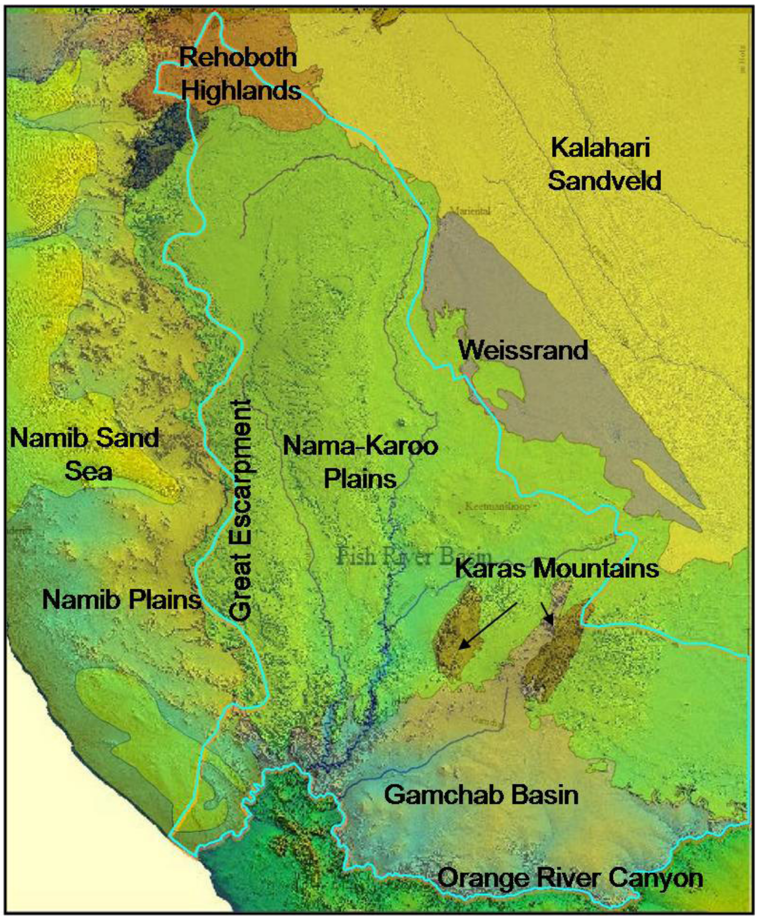


Figure 30: Landform map of southern Namibia superimposed on digital terrain model
Source: Mendelsohn et al. 2003

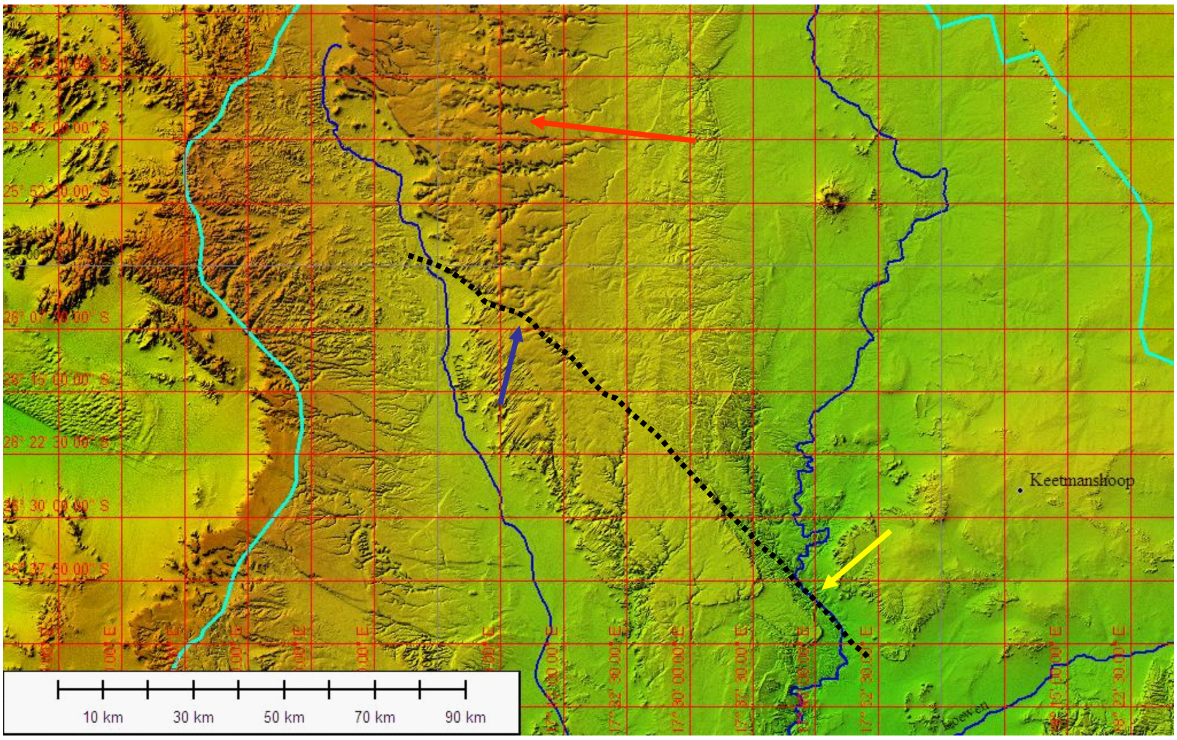


Figure 31: Digital terrain model of part of the Basin showing some major faults with evidence for recent activity; the black dotted line indicates the trace of the fault, the blue arrow where drainage has been disturbed by the fault, the yellow arrow where the Fish River has followed the fault and the red arrow where deeper incision has occurred on the uplifted block.

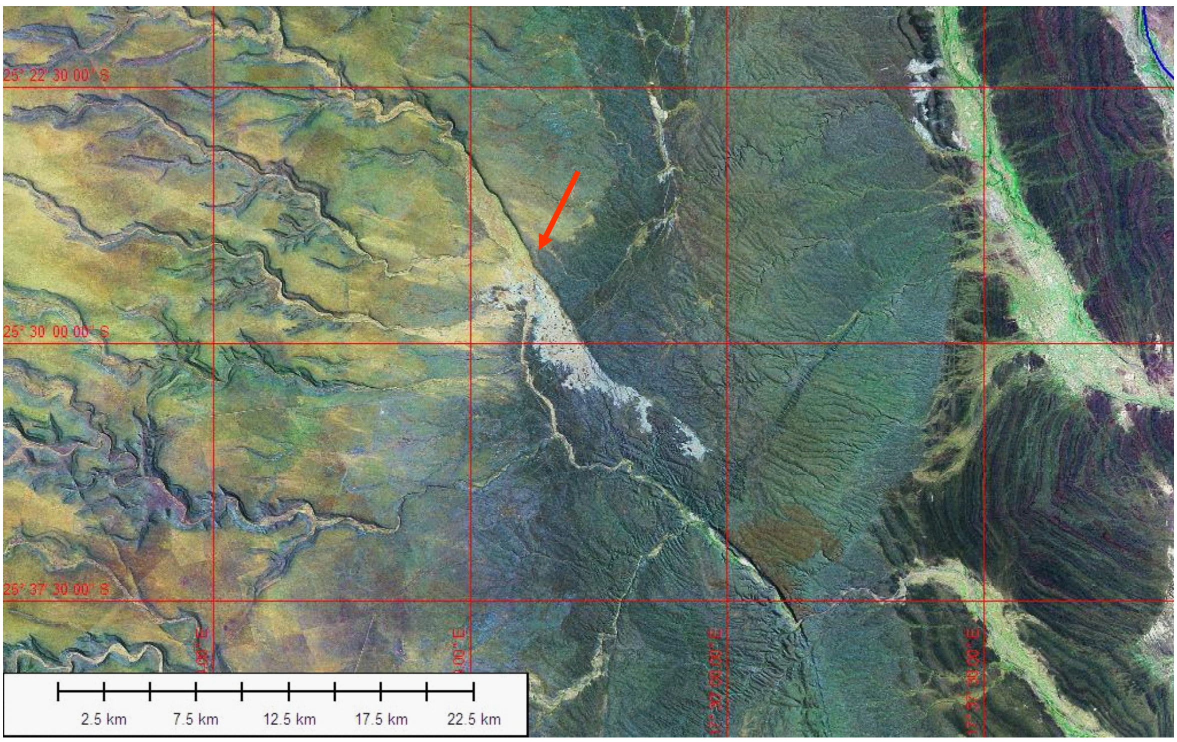


Figure 32: Drainage disruption by fault (indicated by red arrow) and incision on the western edge of the upfaulted block

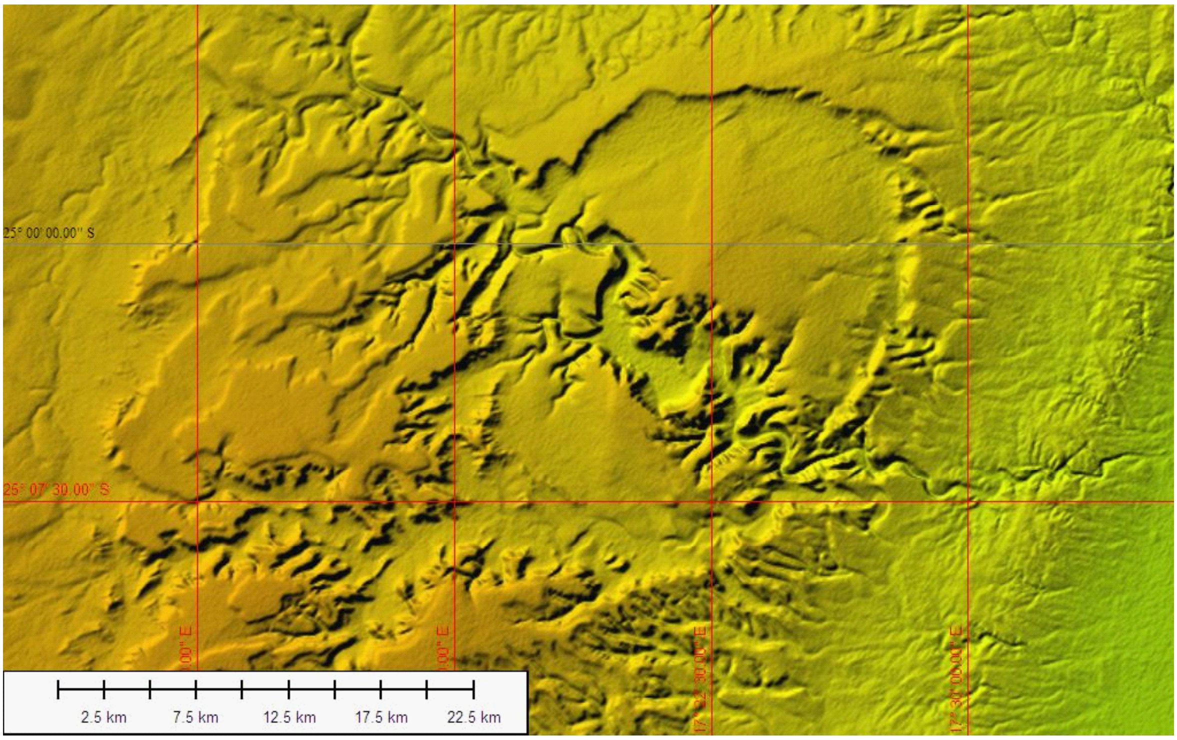


Figure 33: The Hudub Dome showing how the super-imposed river has cut a 200 m deep gorge through it; this indicates that the river must have been flowing across the plain before the dome formed.

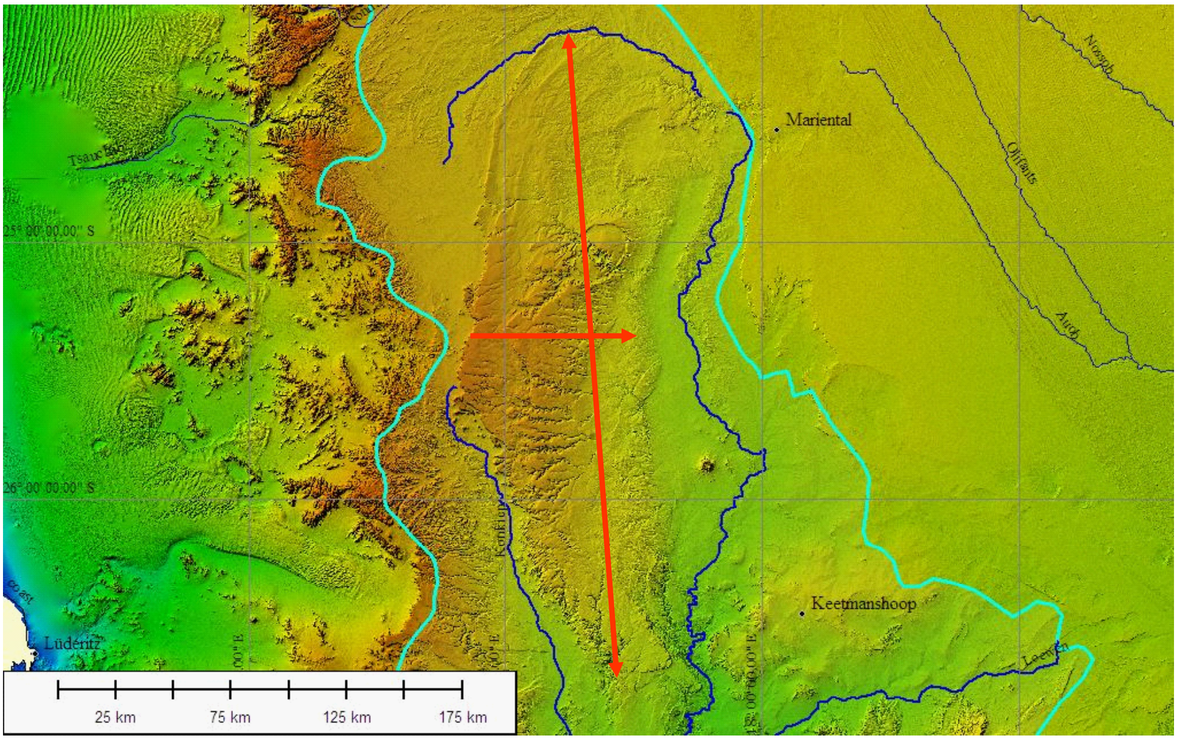


Figure 34: Large uplifted block (indicated by red arrows) in the centre of the Basin; the Fish River flows north around the edges of the block, suggesting that the block formed before the development of this part of the drainage system.

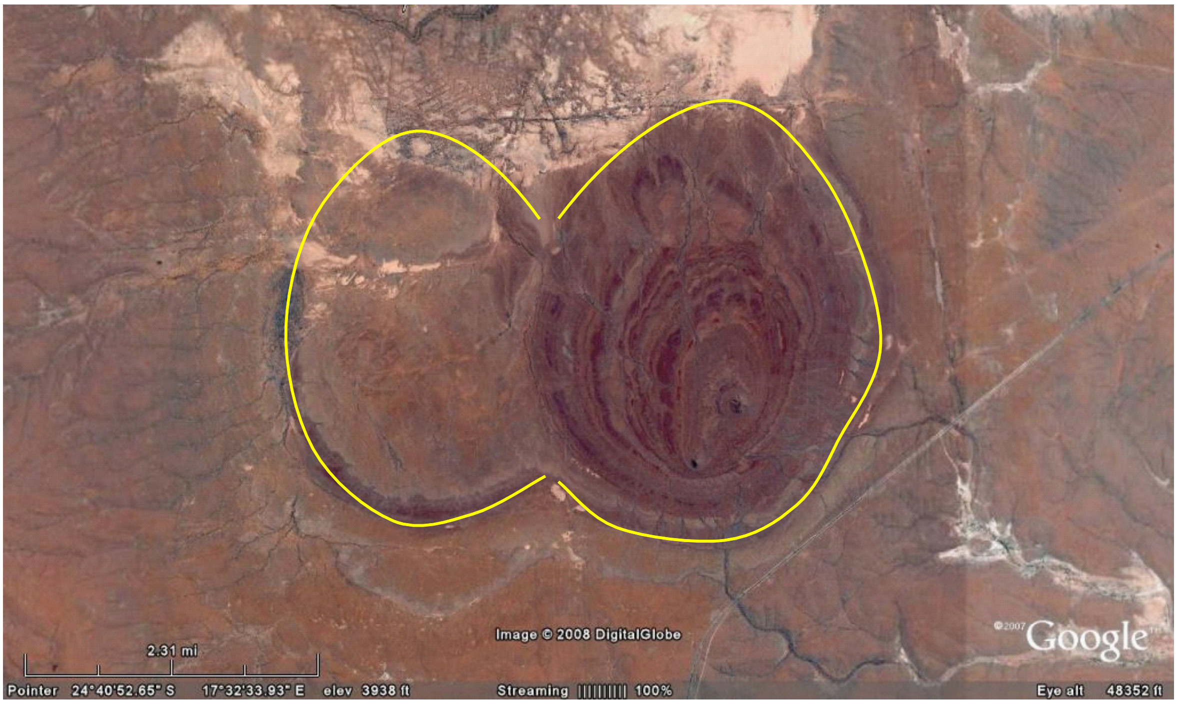


Figure 35: Image from Google Earth of two dome features (indicated in yellow) south-west of Mariental; these domes are underlain by dense rocks, probably igneous intrusives.

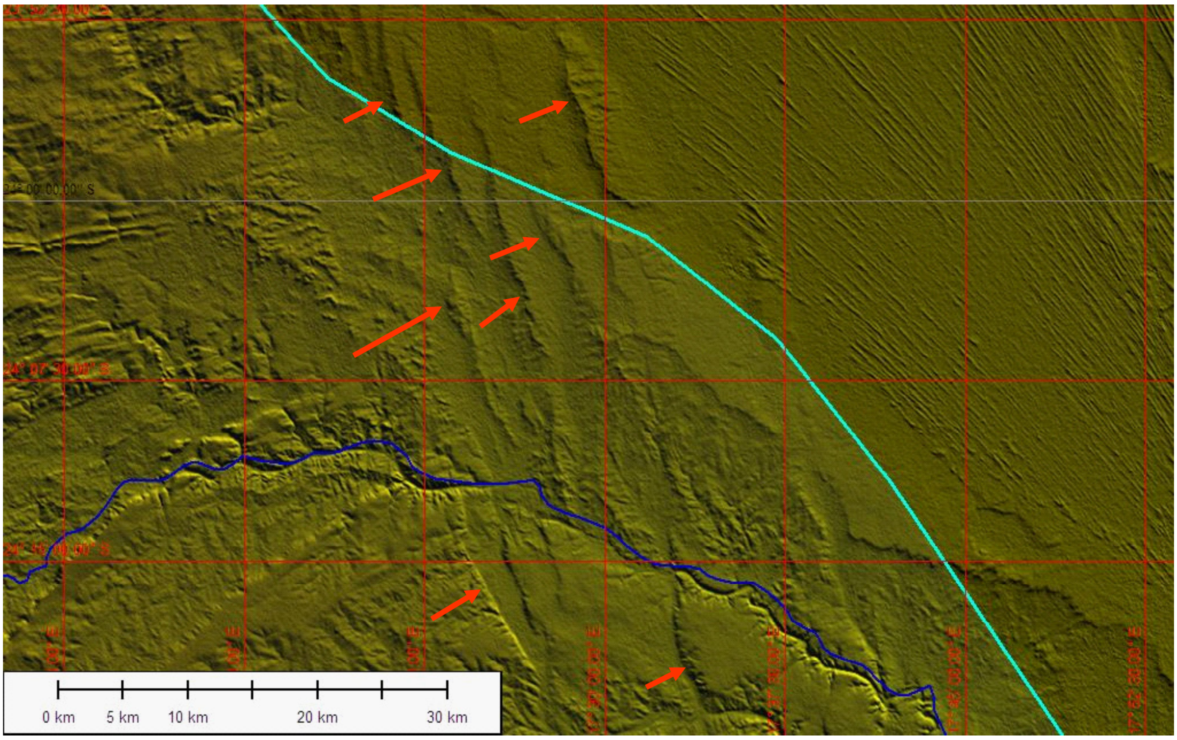


Figure 36: North-west of Mariental, several north-south trending faults form the southern end of a much larger fault system traversing Namibia; the pale blue line is the basin margin, the dark blue the Fish River. The faults are indicated with red arrows.

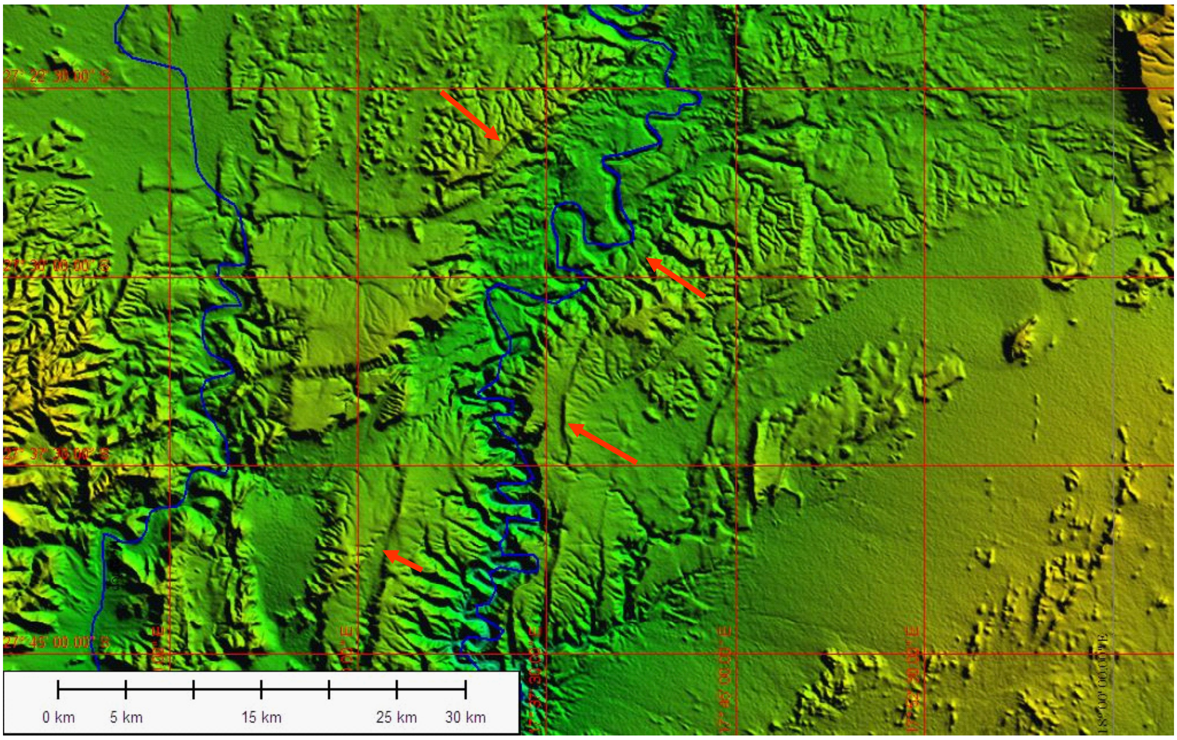


Figure 37: The position of the Fish River Canyon is controlled by several faults, indicated here in red.

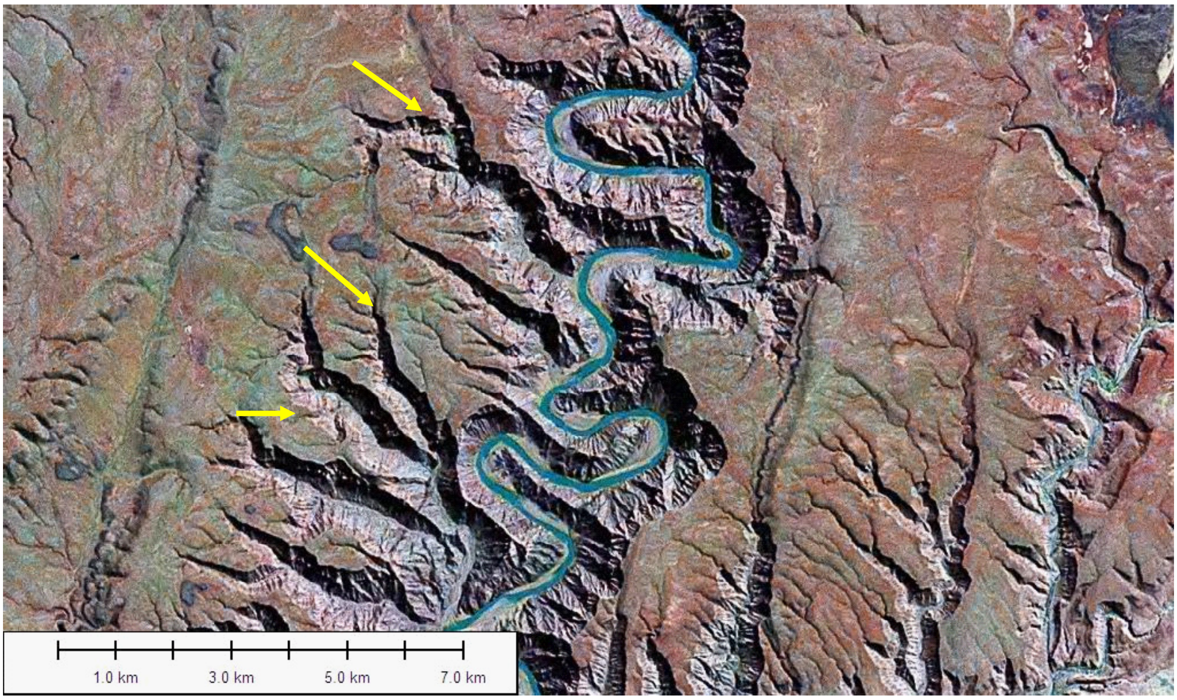


Figure 38: Landsat image of the Fish River Canyon area showing preferred incision (arrowed) on the western side of the canyon

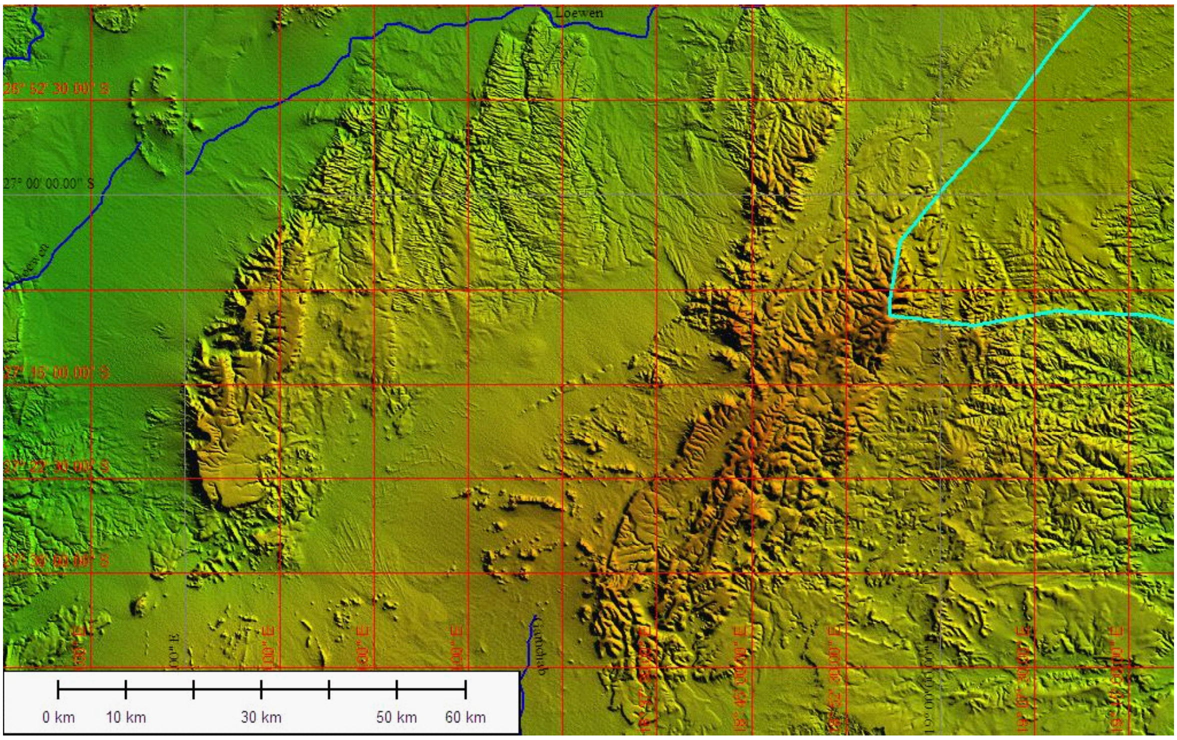


Figure 39: The Groot and Klein Karas Mountains were formed by block faulting. The age of these faults means that they are not as well defined as more modern faults as they have been weathered.

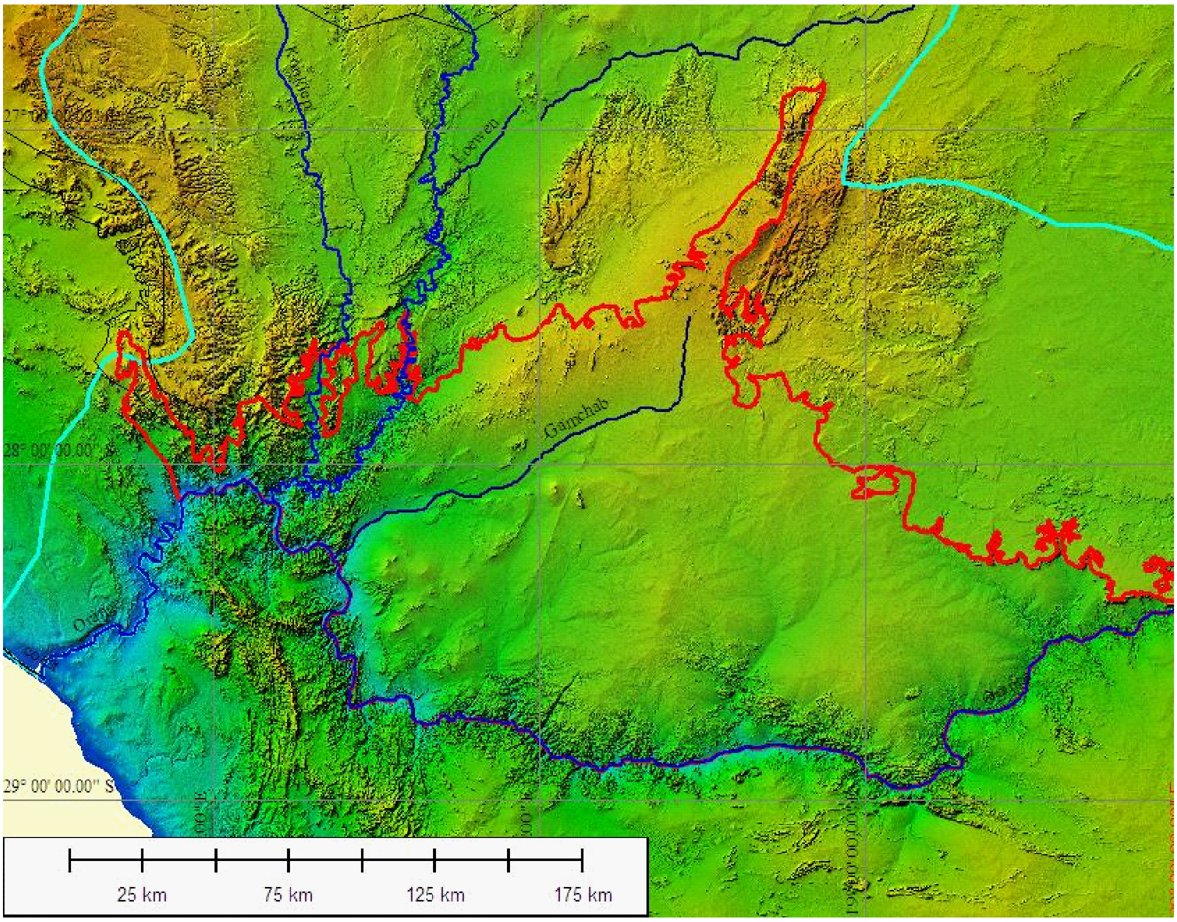


Figure 40: The Gamchab Basin (outlined in red) is characterised by low relief with flat plains with sparse grass cover. All rivers flow south to the Orange River.

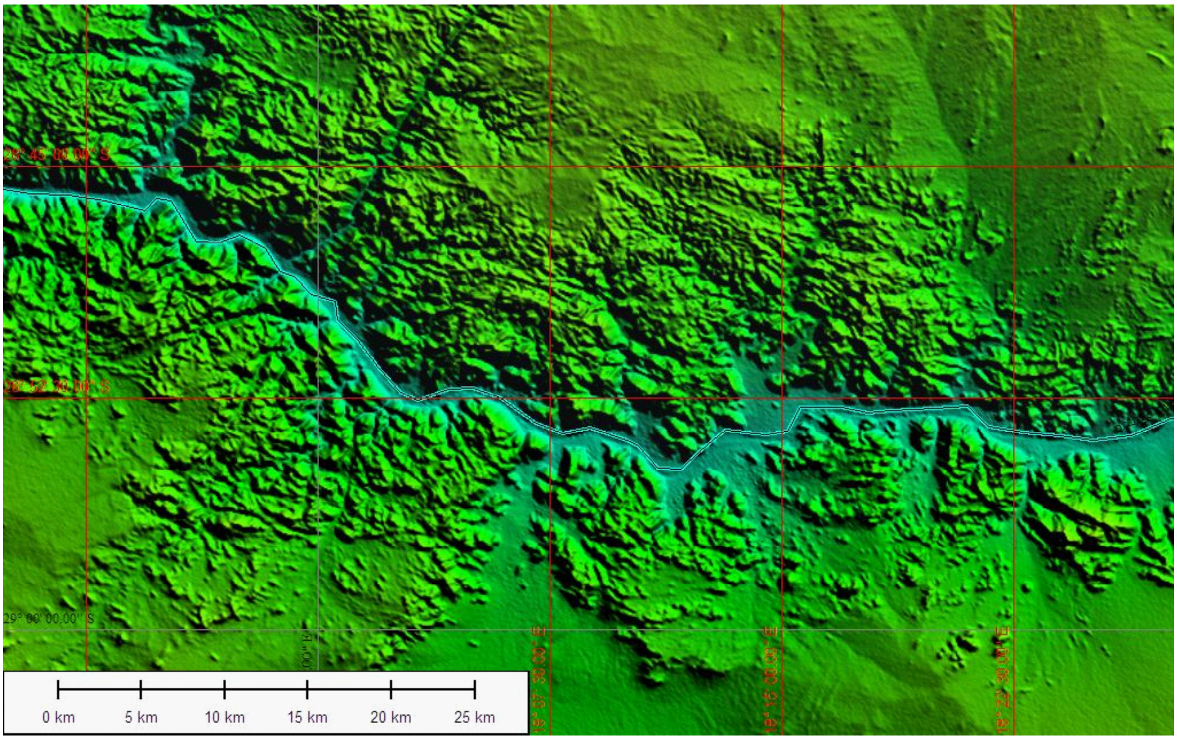


Figure 41: In contrast to the Gamchab Plains, the Orange River Gorge is rugged with deep incision.

Figure 42: The deeply incised Orange River Gorge provides spectacular scenery.

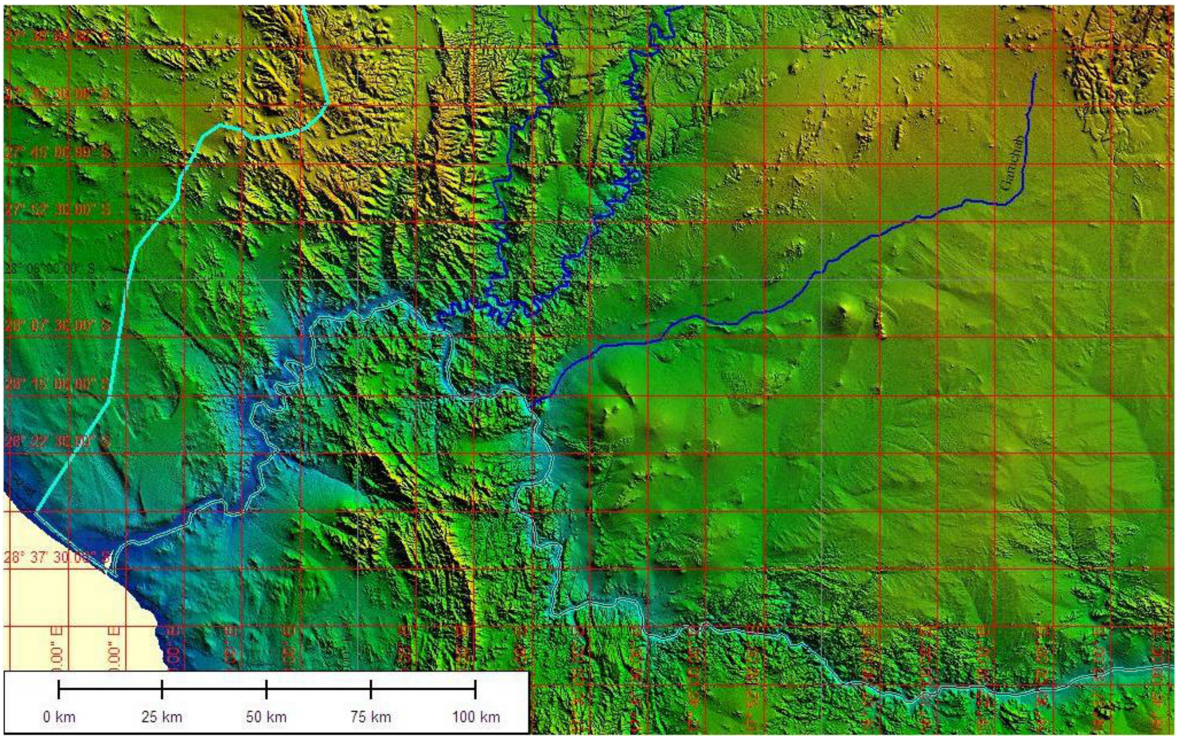


Figure 43: The large meander loop size of the Orange River can be compared here with the much smaller loops of the Fish River, a function of the lower discharge in the Fish River.