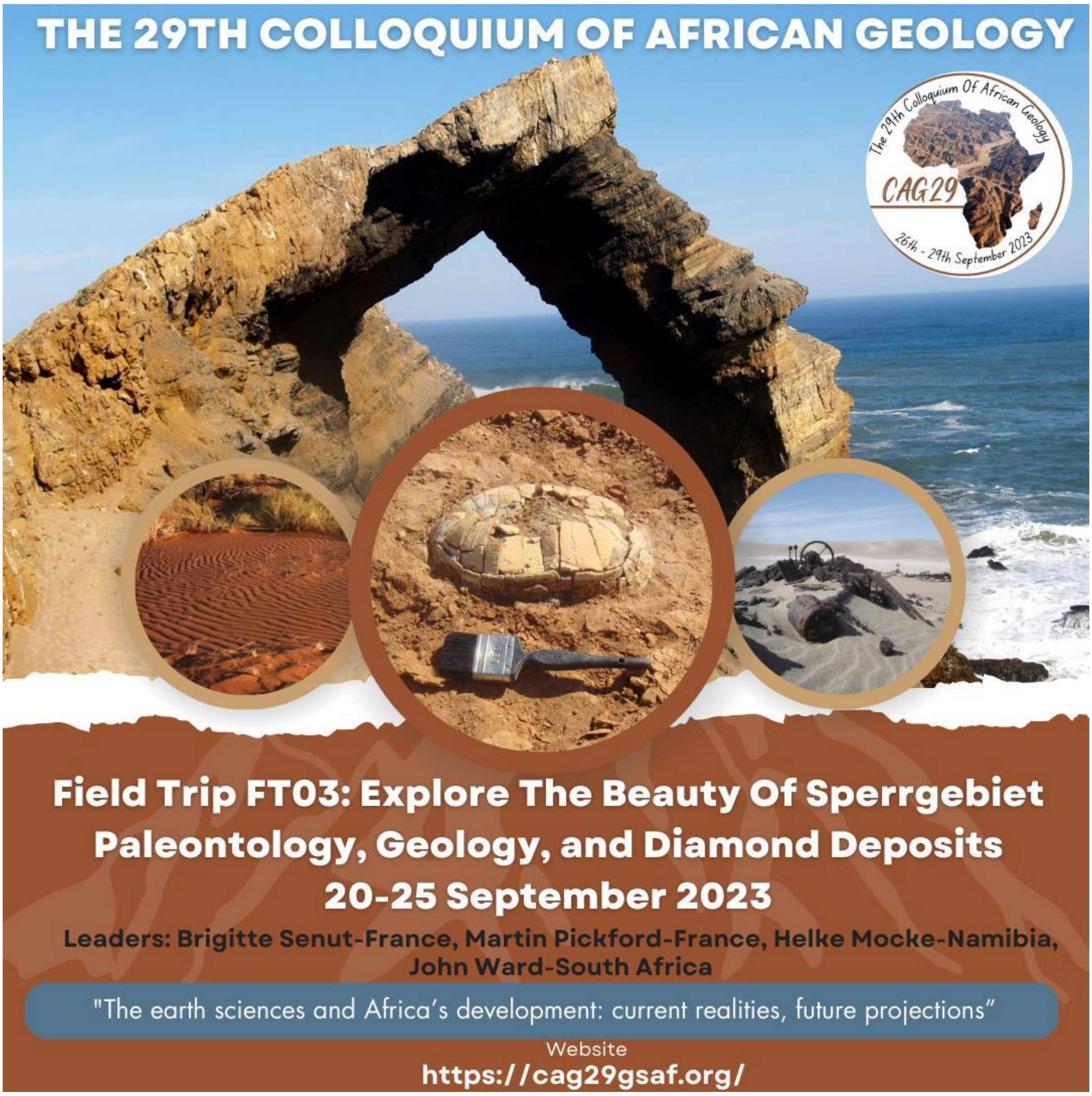
Sperrgbebiet

Excursion Guide



THE 29TH COLLOQUIUM OF AFRICAN GEOLOGY

Field Trip FT03: Explore The Beauty Of Sperrgebiet Paleontology, Geology, and Diamond Deposits

20-25 September 2023

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"The earth sciences and Africa's development: current realities, future projections"

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Sperrgebiet Field Trip

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The Sperrgebiet (Forbidden Zone) of Namibia was declared out-of-bounds by the German Government in 1908 soon after the discovery of diamonds close to Kolmanskop, 10 km inland from Lüderitz. The zone, now known as the Tsau-#Khaeb National Park, extends from the Aus-Lüderitz road in the north to the Orange River in the south (ca 200 km) and from the Atlantic coast in the west to the Great Escarpment in the east (ca 70-100 km).

The Basement rocks of the Sperrgebiet comprise Precambrian gneisses, shales, quartzites, dolomites and various intrusive rocks (syenite batholiths, dolerite dykes). There are few rocks units between the Precambrian and Cainozoic, among which are Karroo age dykes and possibly late Cretaceous silicified surface deposits (Katchen Plateau Silcrete). After the separation of the South American and African continents, there was relatively rapid backwearing of the southwest coast of Africa resulting in the formation of the Great Escarpment. A small occurrence (200 m²) of Late Cretaceous sandy limestone at Wanderfeld IV, near Bogenfels, has yielded ammonites, oysters and gastropods. This occurrence, even though tiny, is relevant to understanding the timing of events and rates of geomorphological processes in the Sperrgebiet, because it reveals that by the Cenomanian, the Langental was already a substantial valley, quite soon after the separation of the African and South American plates.

The superficial deposits of the Sperrgebiet consist of a variety of sedimentary and volcanic rocks, as well as alteration products related to volcanic activity (hydrothermal alterations producing a high diversity of silicified rocks) weathering (alterites) and near-surface processes driven by groundwater flowage (ferricretes, travertines) as well as to processes of near-surface induration of superficial deposits under desert conditions (the Namib calc-crusts linked to fog and dew). Close to the coast there are substantial beach deposits which accumulated when sea-level was higher than it is today, and there are analogous deposits offshore, laid down when sea-level was lower than it is today, notably during the late Oligocene. All the diamonds found in the Sperrgebeit have been obtained from these superficial deposits close to the coast, the onland ores being prevalent in the Salt Namib where the surface deposits are rich in salt and often gypsum, the result of long term transport of tiny droplets of sea spray inland for up to 20 km. In the Inner Namib in contrast, the soils and surface deposits generally lack salt. Finally, the Southern Namib is known for the extremely mobile dune trains that traverse northwards, predominantly in the Trough Namib and to a lesser extent the Innen Namib, where they eventually contribute their sand to the Namib Sand Sea of the Namib-Naukluft Park. Some of these dunes move up to 300 metres per year.

Being near the coast, the superficial deposits of the Sperrgebiet comprise both marine and continental strata, with middle Eocene shallow marine deposits rich in molluscs and shark teeth known at Langental close to the coast, contrasting with richly fossiliferous freshwater palustral limestones of Lutetian (Black Crow) and Bartonian-Priabonian ages (Chalcedon Tafelberg, Silica North and Silica South) in the Trough Namib, which have yielded large quantities of fossil mammals, other vertebrates and invertebrates as well as plants. In the interior (Innen Namib), Lutetian-Bartonian volcanic activity produced the Klinghardt Phonolite field and related peri-volcanic deposits such as Priabonian-Bartonian calc-tufas at Eocliff and Eoridge. The latter are immensely rich palaeontological resources that have already yielded tens of thousands of fossil mammal specimens, most of which represent taxa that were new to science. The faunas from these limestones indicate wooded to savannah-like conditions at the time of accumulation (ca 37 Ma) and interestingly, some of them show biogeographic relationships with South American mammals such as ctenohystricid rodents and sloths.

Growth of the Antarctic Ice Cap to continental dimensions at the beginning of the Oligocene (Rupelian) heralded the Oligocene low sea-stand (Chattian) which persisted until the Aquitanian (basal Miocene). During this epoch deep valleys were incised into the Namib surface (Orange River, Grillental, Fiskus, Langental, Glastal). The main Oligocene deposits encountered in the Sperrgebiet consist of ferricretes (ferruginisation of near-surface deposits) outcrops of which are sporadic but widespread in the region, the best known occurrence being at Buntfeldschuh. The palaeoclimate during this phase of Sperrgebiet development was likely to have been considerably more humid than it is today, as suggested by the widespread occurrence of ferruginised superficial rocks. This period was also one of infrequent but intense storms in the interior, with the result that the inner Namib was the locale for the deposition of impressive sheet conglomerates (hamadas) in the low relief land beneath the hills and mountains in the vicinity of the Great Escarpment and the Klinghardt Volcanic edifices. Some of these conglomerates contain fossilised tree trunks up to 20 metres tall, suggesting that the hinterland was well wooded with forest patches, an interpretation that accords with the widespread ferruginisation that occurred during the same period.

With the massive marine transgression that took place at the beginning of the Miocene (sea-levels up to 145 metres above modern sea levels), sedimentation occurred in diverse palaeovalleys that had been incised into the Namib during the Oligocene low-sea stand (as much as 150 metres below modern sea-levels). The main fluvio-palustral sedimentary bodies are in the Bogenfels area (Langental) and the northern Sperrgebiet (Grillental, Elisabethfeld, Fiskus) while in the Orange River Valley in the south the penecontemporaneous deposits at Auchas and Arrisdrift accumulated in meander loops. These early to middle Miocene fluvial and palustral sediments (21-17 Ma) are rich in fossil vertebrates and fossilised termite hives that indicate that the palaeoclimate was probably savannah-like to steppic, more arid than the preceding Oligocene period but not yet fully desert as it is today.

The South Atlantic anticyclone was established more or less in its present-day form, intensity and position about 17 Ma and this led to aridification of the southwest African coastal region and the onset of a winter rainfall regime in the southern Namib (evidence from gastropods such as *Trigonephrus* which are adapted to this climatic regime and do not survive outside it). Ferruginisation of superficial deposits ceased, the last evidence of this process being representd by outcrops at Grillental, Elisabethfeld and in the Langental, cementing silt and sand which contain Early Miocene mammals. This major palaeoclimatic change resulted in fully desertic conditions becoming established in the Namib, one result of which was the accumulation of aeolianites in diverse localities (Rooilepel, Karingarab) representing the onset of the Namib Desert. This period was also one of extensive aeolian deflation assisted by the burrowing activity of ants, rodents and other animals which constantly brought fine fractions of soil and sediment to the surface, from where it could be blown away by the wind, leading to regional downwasting. In some places downwasting as fast as 1 metre per century has been demonstrated, such as on the ground left bare by diamond mining activity (Langental, Grillental, Elisabethfeld) where the bases of trommel screen heaps from mining during the 1920's are now a metre to a metre and a half above the surrounding silty sediments. In places downwasting slowed down or ceased altogether when thick reg-like sheets of coarse, angular gravel were formed.

The present-day geomorphology of the Namib indicates that aeolian deflation was more active along the coastal strip, from the shoreline up to 20 km inland, which resulted in much greater rates of erosion in this sector than in the Innen Namib 20-50 km from the ocean. Because of its highly dissected morphology, the German geologists called the coastal sector the Flächen Namib (the Trough Namib) and the flatter inland sector the Innen Namib. All the early diamond exploitations were in the Trough Namib, with the richest accumulations occurring in the floors of endorheic depressions such as Idatal and Hexen Kessel. Along the coast, pocket beaches were formed in south-facing embayments in the shoreline, and these often contain significant quantites of diamonds. Diamonds were also trapped in oxbow deposits of the Orange River Valley, such as Auchas and Arrisdrift (often called the Proto-Orange and Meso-Orange terraces) of Early Miocene age.

Climatic fluctuations occurred throughout the Neogene, with periods of slightly more humid conditions (steppe to savannah as shown by fossilised termite hives - *Hodotermes*) interspersed with hyper-arid conditions (as shown by the presence of desert-adapted gastropods (*Trigonephrus*) fossilised in aeolianites and the Namib calc-crusts along with the fossilised hives of the sand termite - *Psammotermes*). In many areas it was also a period of induration of loose soils and regs, which produced the areally extensive Namib I and Namib II calc-crusts. These calc-crusts are not calcretes, but are due to the cementation of superficial deposits by frequent episodes of wetting by fogs and nocturnal condensation of water from the atmosphere (dew) which dissolved calcite in dust, only to precipitate it a few hours or days later when the moisture evaporated. Repeated millions of times, up to three or four metres of calc-crust have accumulated in some areas, even at the tops of hills, down their flanks and in the valleys beneath. Some hills in the Sperrgebiet (Chalcedon Tafelberg, Buntfeldschuh) are up to two metres taller today than they were during the Pliocene, due to the fixing by calc-crust processes, of loose sand blown onto their summits by the wind.

Groundwater levels fluctuated during the Neogene, such that springs that were active in some areas dried up, only to resurge at a later date. Some of these springs deposited impressive quantities of travertine in their vicinity (Klinghardtfelder, Elisabethfeld, Grillental, Kaukausib, Hexen Kessel), with the result that layers of travertine are often interbedded with layers of aeolianite, some of which are fossiliferous indicating that the Pliocene was a relatively humid phase in the Namib with the water table close to the surface in several places. Some travertine layers and associated aeolianites (Hexen Kessel) have yielded Neolithic stone tools and marine mollusc shells, the latter probably representing food gathered along the coast and carried inland for consumption close to the rare sources of fresh water, where the shells of oysters and *Patella* were discarded, along with numerous pieces of ostrich eggshells (eg at Kerbehuk) and tortoises (some of which have been burned). Many of the stone tools were manufactured from the silicified limestone that was silicified by hydrothermal activity related to Klinghardt volcanism some 40 million years ago.

Understanding the geomorphology and geology of the Sperrgebiet helps to explain the present-day distribution of diamonds in the region. The diamonds are widely considered to have been derived ultimately from kimberlites in the interior of South Africa, from where they were transported coastwards by rivers such as the Vaal and Gariep (Orange River) draining the interior of the continent. Among these, the Orange River drainage is considered to have been the most important conveyor belt transporting diamonds from the South African interior towards the Atlantic coast. As the South African Subcontinent underwent post-break-up epeirogenesis (regional uplift), the eastern sector was generally uplifted at a slightly greater rate than the western sector, such that most of the drainage of the subcontinent was directed towards the Atlantic coast, with only minor amounts towards the Indian Ocean. Because of this long-duration, regional-scale geomorphological asymmetry of the subcontinent, most of the diamonds derived from the interior were transported towards the Atlantic rather than to the Indian Ocean side of the continent. Once they arrived at the coast, the diamonds and associated agates, and BIF (Banded Ironstone Formation) clasts were then subjected to marine influences such as long-shore drift, wave-battering, rise and fall of sea-level etc. often coming to rest at so-called trap-sites such as bedrock gullies, pocket beaches, the margins of cones of fluvial deposits near the mouths of rivers and so on.

In the Sperrgebiet, marine beach deposits occur as high as 145 metres above present-day sea-level (Eisenkieselklippenbake, Buntfeldschuh), and all of them have yielded diamonds. It has long been postulated that the input of diamonds into the Sperrgebiet started during the Eocene. As soon as the diamond-bearing deposits were left high-and-dry by decreasing sea-level, the deposits in which they occurred then became subjected to onland geomorphological processes such as fluvial activity, bioturbation, and during the Neogene, to aeolian activity. The latter - helped by the activity of ants, termites, lizards and small mammals which brought underground silt and sand to the surface when they burrowed into the soil - resulted in the deflation of vast areas of the Sperrgebiet by removing immense quantities of clay, silt and sand from the region, but leaving behind the denser diamonds and the agates and BIF which accumulated in deflation lags and depressions. For these reasons a comprehensive understanding of all the geomorphological processes that have shaped the Sperrgebiet is a basic necessity to the diamond-mining community.

The installation of the South Atlantic Anticyclone and the flow of cold water from the vicinity of the Antarctic Ice Cap generally northwards into the Atlantic led to the installation of the Benguela Current and its upwelling cells, which in their turn produced ideal conditions for the production of coastal fogs, for which the coast of the Sperrgebiet is well known. The long-shore drift component of the Benguela Current led to the diamonds that entered the sea at the mouth of the Orange River being swept northwards along the coast, with smaller diamonds being swept along at a greater rate than larger ones, with the result that average diamond size decreases as one traverses northwards from the mouths of the input rivers.

The coastal fogs of the Namib consist of almost pure water, but waves that break along the shore add tiny droplets of salty water that can contain minute quantities of hydrogen sulphide (produced by decaying algae among other things). If these droplets of sea spray are blown inland, they eventually drop to the surface and add their tiny chemical loads to the surface deposits in the form of salt (NaCl) and weak sulphuric acid. The latter reacts with calcite in the soil or dust to produce gypsum crystals (Calcium sulphate) and Carbon dioxide which enters the atmosphere. Repeated hundreds of times per year these processes eventually build up near-surface masses of needle-like gypsum crystals or thin gypsum plates up to 40 cm across and one or two cm thick, depending upon the superficial environments in which they formed.

Like their prehistoric precursors, the German miners left behind evidence of their passage in the region. The former people discarded stone tools (flakes, blades, grinding stones) and food residues (shells of marine molluscs, ostrich eggshells, tortoise carapaces some of which were burnt) close to freshwater springs, as well as rudimentary structures made out of boulders (stone blinds and werfs) especially near hilltops. There are also signs of prehistoric mining activity at certain localities where silicified limestone, from which cutting blades and stone arrow heads could be made, was extracted from outcrops such as the Knapping Site, near Eocliff at the edge of the Klinghardt Mountains.

The German mining community and their workers left behind discarded bottles, broken trommel screens, disused railways, uncountable trommel-screen heaps, many fines dumps, prospecting trenches, roads and buildings, including the ghost towns of Kolmanskop, Pomona and Bogenfels (named for the famous rock arch first mentioned in writing by Portuguese sailors, but well known to local inhabitants who are reputed to have used the site for certain tribal fertility rituals). Many of the prospecting trenches dug by the Germans all along the coastal strip, are still visible. They are one metre wide and run west to east from the coast inland to an altitude of 200 metres and are spaced exactly

200 metres apart. They are continuous across valleys, up the flanks of hills and across the tops of ridges. Many of these trenches can be observed on Google Earth and the precise spacing and orientation of the trenches attest to the accuracy of the surveyors who plotted them on the ground.

Places that will be visited

Baker’s Bay Camp

Buntfeldschuh

Langental, Bogenfels (Rock Arch) and Eisenkieselklippenbake

Idatal and Stauch’s Laager

Pomona Ghost Town

Elisabethfeld and Grillental

Figure 1. One of Namibia's outstanding tourist attractions, Bogenfels Arch is reputed to have been a site of coming-of-age rituals by local inhabitants.

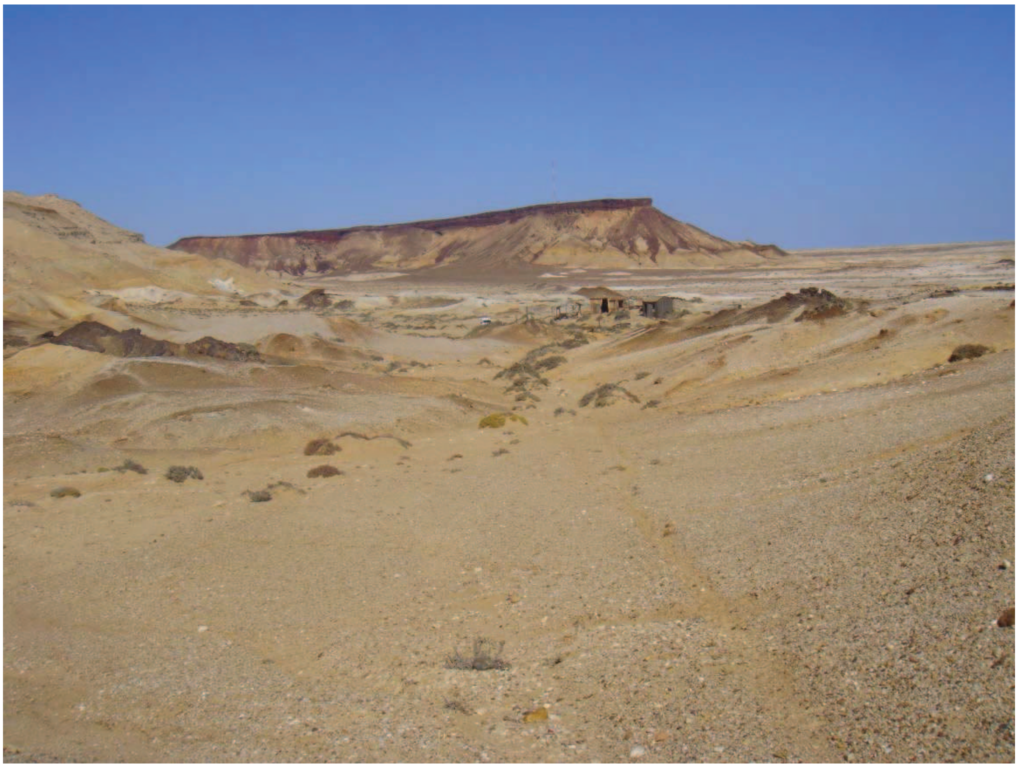

Figure 2. Kakaoberg viewed from the Camel Camp at Buntfeldschuh. Altered Basement (Alterite) at the base of the sequence, is overlain by Eocene marine gravels and silts, then by Oligocene (Rupelian) coastal dune sands that were ferruginised during the Late Oligocene (Chattian) and capped by Plio-Pleistocene Namib Calc-crust (not visible in photo).

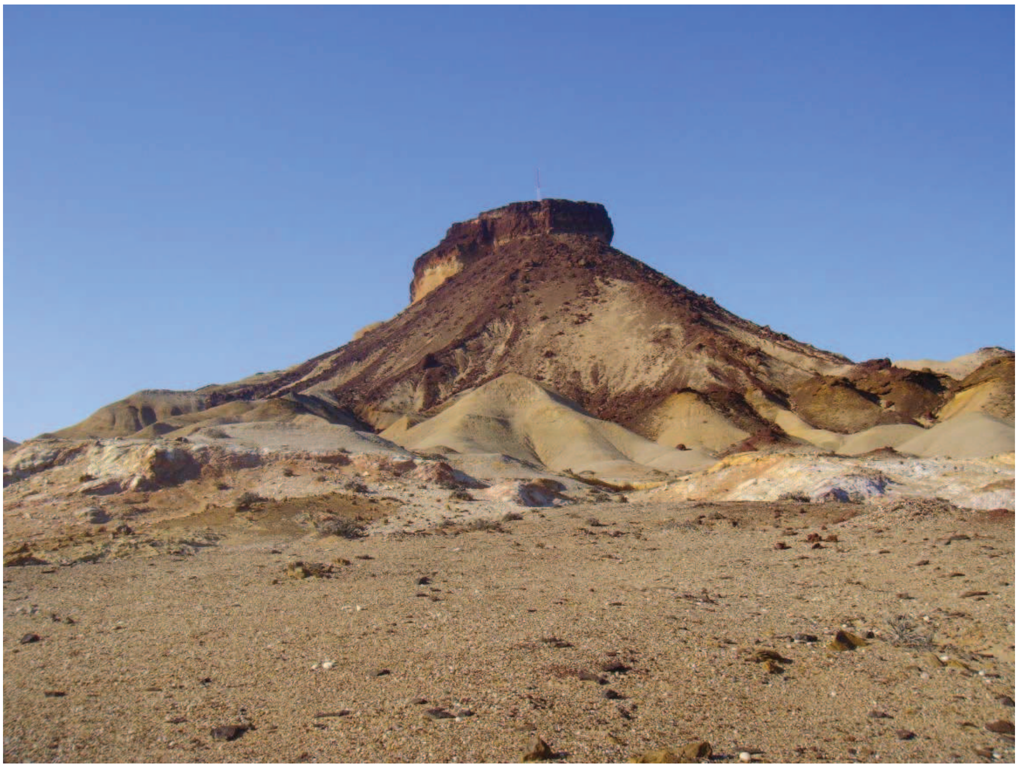

Figure 3. The northern nose of Kakaoberg showing altered Basement rocks at the base, overlain successively by Eocene shallow marine deposits, Oligocene dune sand that was ferruginised during the Chattian and Plio-Pleistocene Namib Calc-crust (not visible in the photo).

Figure 4. Thousands upon thousands of trommel screen heaps in the Langental are witnesses to the scale of diamond mining in the area during the 1920’s.

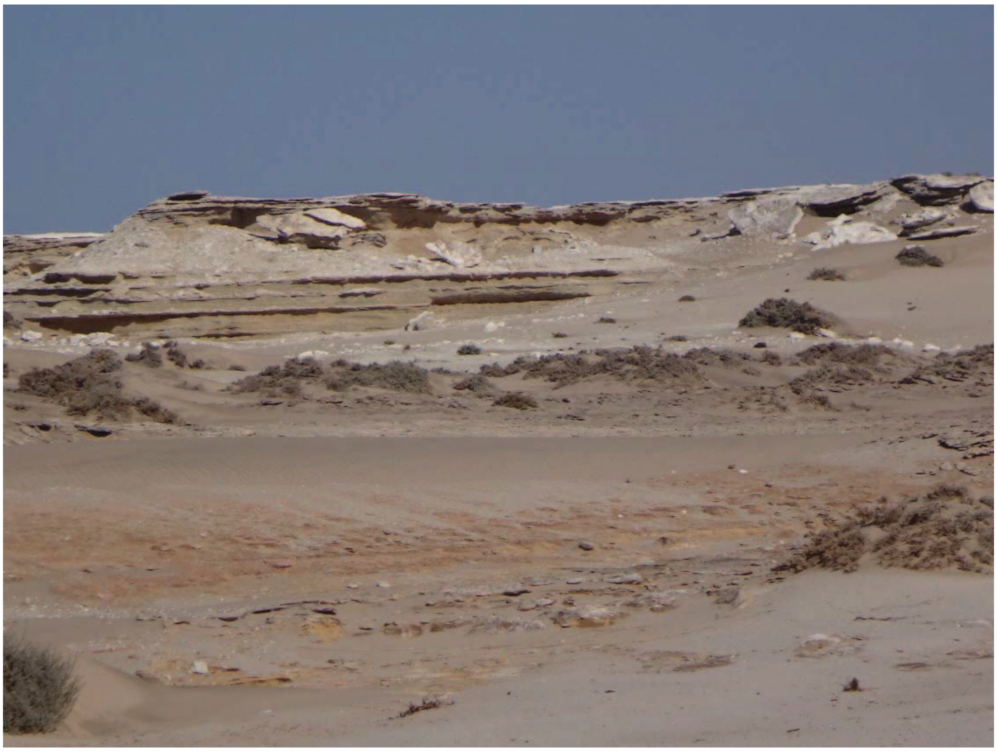

Figure 5. Early Miocene red and green silts at Elisabethfeld, overlain by intercalations of Plio-Pleistocene travertine and aeolianite, and finally by loose sand and granules.

Figure 6. Carapaces of the land tortoise *Namibchersus* are common at Elisabethfeld.

Figure 7. Fossil hypsodont macroscelideans are abundant at Elisabethfeld, attesting to the presence of grass in the region during the Early Miocene.

Figure 8. Fossilised hives of the polycalate termite *Hodotermes* attest to more humid conditions in the Grillental during the Early Miocene than prevail there today.

Figure 9. The Grillental dune train descends the southern shoulders of the valley, then crosses the valley and ascends the northern flanks, eventually to join the Namib Sand Sea north of Lüderitz.

Figure 10. The dunes at Grillental advance rapidly northwards by as much as 300 metres per year.

Figure 11. The Grillental dune train is highly mobile, some dunes moving as much as 300 metres per year.

Figure 12. Metre wide German diamond prospecting trenches in the Sperrgebiet were oriented east-west and spaced at 200 metre intervals all along the coastal strip. They ran uninterrupted across valleys, up slopes, over hill tops and down the other side from the sea shore inland to an altitude of 200 metres.

Figure 13. Remains of the Sperrgebiet railway system at Idatal. The rusting rails evoke an active past that ceased about a century ago.

Figure 14. Bottle dump at Elisabethfeld dating from the period of mining over a century ago.

Figure 15. Wind-powered sand abrasion is a major erosional process in the Northern Sperrgebiet, as revealed by this sand-blasted bottle in the Grillental.

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29th COLLOQUIUM OF AFRICAN GEOLOGY

Sperrgebiet Field Excursion
20 – 25 September 2023

Excursion Leaders:
M. Pickford, J. Ward & R. Swart

OVERVIEW

The journey of Namdeb's sparkling gemstones began some 100 million years ago when dinosaurs roamed the African plains. It started within the great depths of our Earth, where diamonds were transported to the surface by ancient volcanoes, known as kimberlites. Here they remained resident until changes to the earth's surface saw the release of these precious stones into torrent river systems, to be further transported over 1,000 km to the Atlantic Ocean. Only the finest gemstones survived the vigorous energy of these natural waterways before they came to rest in geological formations that are unique in the world. The largest and most complex diamond mega-placer deposits can be found on the south-west coast of Namibia within the Sperrgebiet - "The Forbidden Area".

Since the initial discovery of diamonds in 1908 near Lüderitz, Namibia, this regional composite placer deposit has yielded over 100 million carats of >95% gem quality stones. Most of this diamond production has been recovered from a variety of placer types that range in age from contemporary deposits to those that are some 42 million years old. The Sperrgebiet hosts three major placer types: fluvial (Orange River), marine (spit/barrier beaches, linear beaches, pocket beaches) and aeolian (including deflation; **Figure 1**).

After diamonds were discovered near the town of Kolmanskop (east of Lüderitz), a number of German-controlled companies operated in the northern Sperrgebiet that were later amalgamated by the late Sir Ernst Oppenheimer in 1920 to form Consolidated Diamond Mines of South West Africa (Corbett, 1989). In 1974, this company was incorporated as CDM (Pty) Ltd, a De Beers Consolidated Mines Ltd (DBCM) operation, that subsequently entered into a 50/50 partnership between De Beers Centenary AG and the Government of the Republic of Namibia in 1994, giving rise to the current Namdeb Diamond Corporation (Pty) Limited (Ward, 1998). Namdeb currently holds the mining licences (ML42, 43, 44 and 128C) that span from the onshore some 10 km offshore between Oranjemund in the south and ~40 km north of Bogenfels (**Figure 1**).

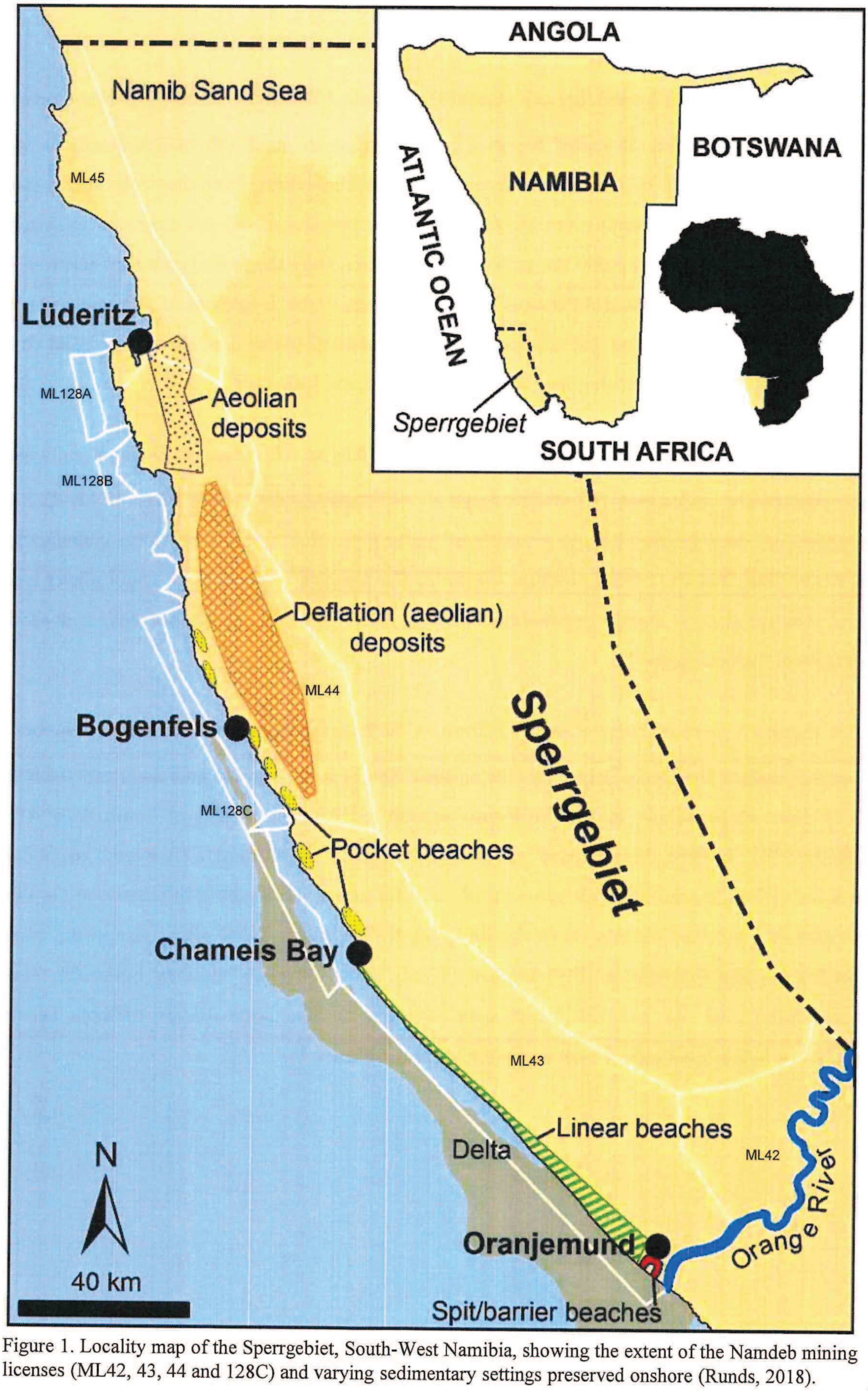
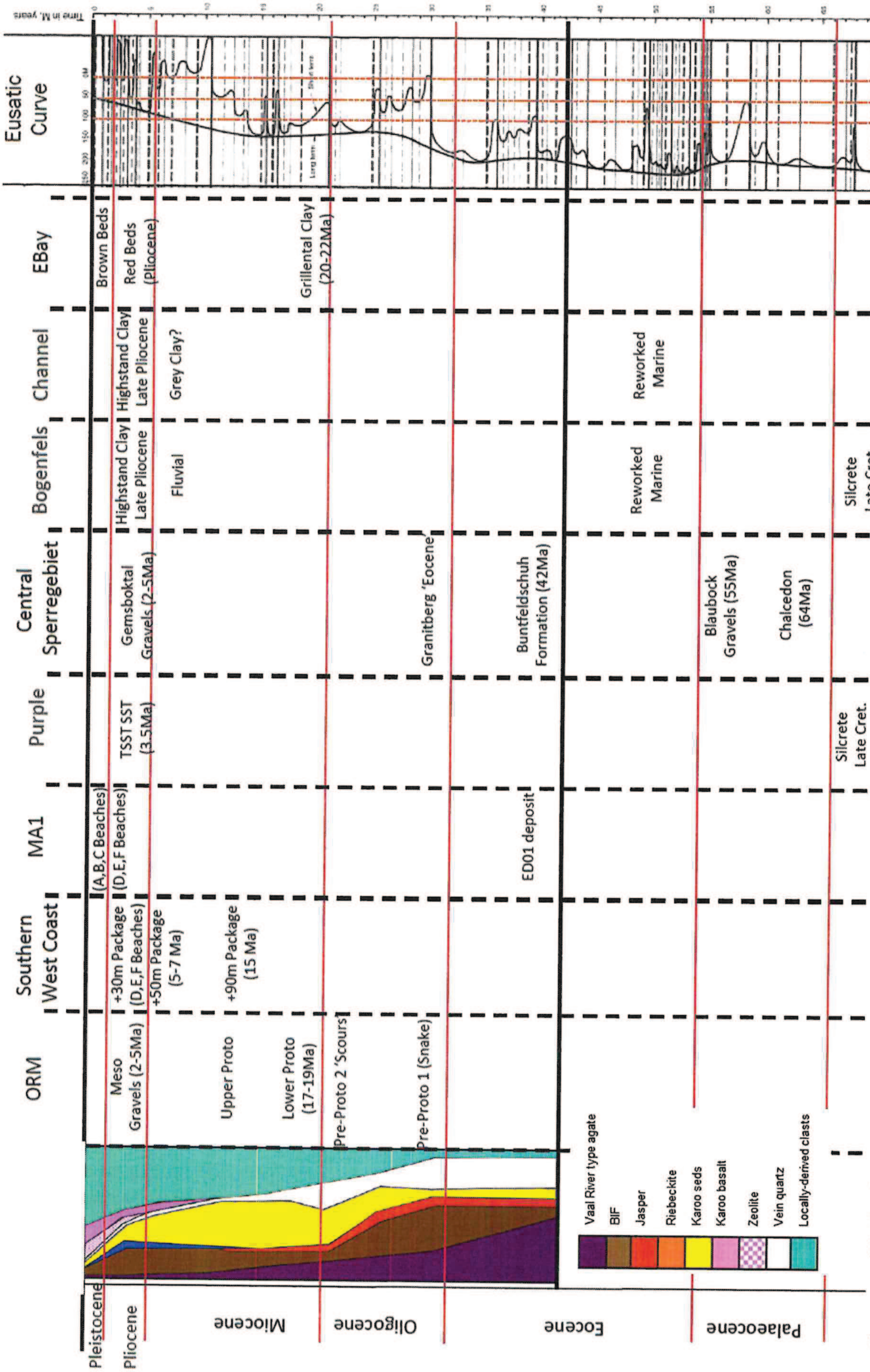
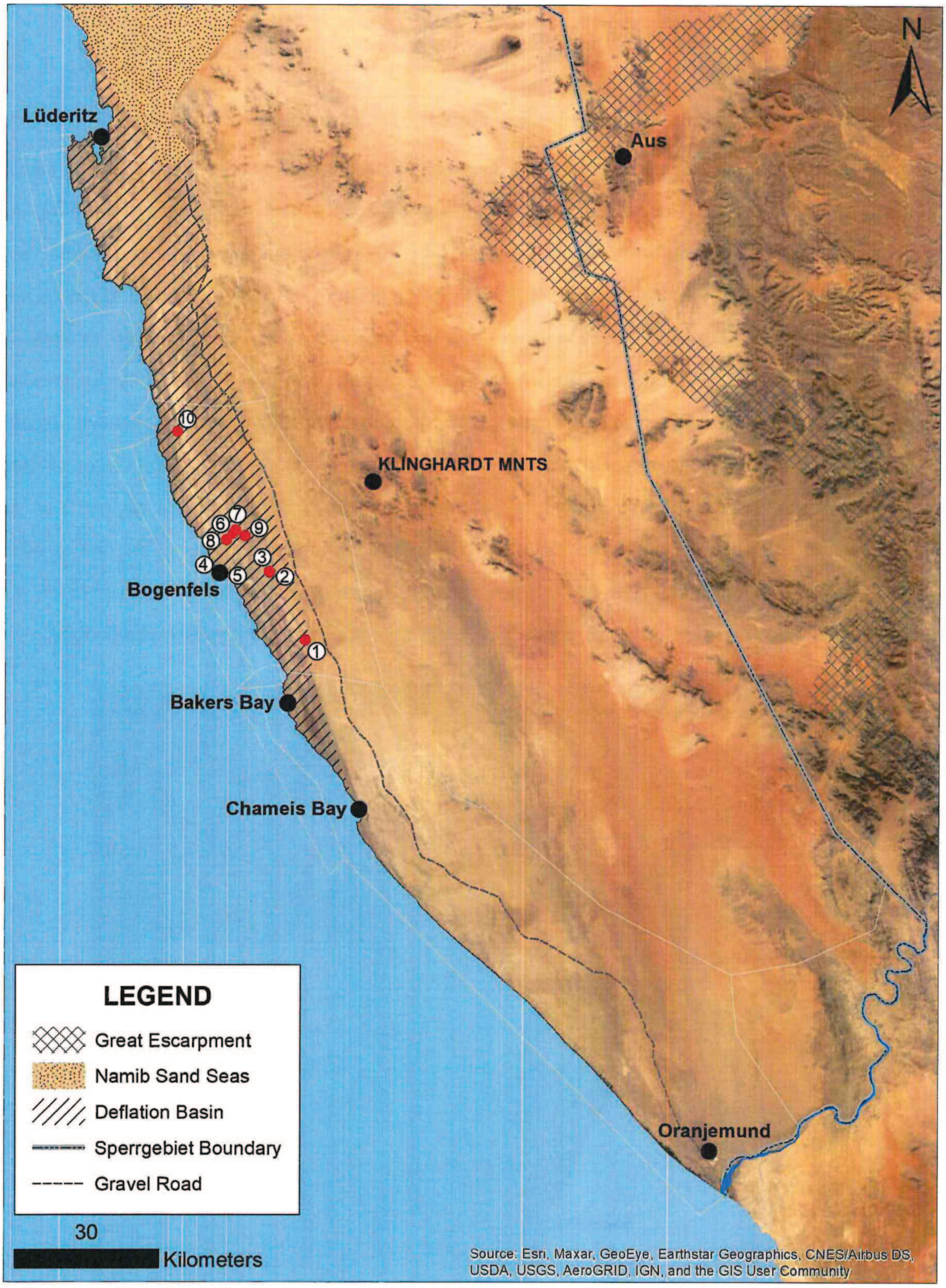


Figure 1. Locality map of the Sperrgebiet, South-West Namibia, showing the extent of the Namdeb mining licenses (ML42, 43, 44 and 128C) and varying sedimentary settings preserved onshore (Runds, 2018).

Time frames (approx.)	Geological units and/or events	Notes
Recent	Modern Orange River virtually barren of diamond; End of diamond "flush" = supply from Cratonic interior to coastal sink)	Source to Sink model for diamond mega-placer formation over ca. 40 Ma of Cainozoic
Holocene	A Beach; Holocene "high" at 1.5 m high stand	Strandlines diamond-bearing; Namib Desert and Dominant Southerly wind regime; Longshore drift; Average diamond size fines northwards away from the Orange River outfall.
	Lowstand marine packages offshore: -5 m etc…	
Pleistocene	C Beach (6-8 m high stand); B beach = Eemian (ca 137,000 years BP = 4 m highstand, 2nd richest onshore marine); maximum onshore marine placer development from Late Pliocene through to Holocene	Deflation Basin and aeolian transport corridors move landward and seaward depending on relative sea level at that time. Pedogenic calcrete duricrust formation
	Lowstand marine packages offshore, e.g. -20 m etc.	Various spring deposits through Pleistocene – Holocene
Late Pliocene	Meso-Orange; low grades but maximum average stone size; diamond "flush" in death throes; 50 marine package and 30 m marine package (= D,E,F beaches) = richest onshore marine deposit	BIF-rich gravels = "heavy tail" eroded out of RSA interior; Obib dunes, Annental Sandstone; Sossus Sand Formation from Late Pliocene onwards under hyper-arid conditions; Pedogenic calcrete duricrust formation
Early – Middle Miocene	Proto-Orange = Arries Drift (Arrisdrif) Gravel Formation; grade dropping, average stone size increasing; diamond "flush" waning. Langental, Grillental Early Miocene "Namib" drainages – fossiliferous, Linear oases across narrow desert strip. Rooilepel Sandstone = aeolian offtake from Lower Orange valley (equivalent of Tsondab Sandstone Formation); 90 m highstand marine package	Linear Oasis across Namib Desert, *Trigonephrus* terrestrial snails indicate winter rainfall already present but Namib Desert in full swing
Late Oligocene – Early Miocene	Pre-Proto Orange; Highest grade but not quite matched by average stone size; peak of the diamond "flush" from the interior; maximum development of offshore marine placers	Oligocene lowstand and possible uplift = incision of Orange River and Lower Fish River courses through Karoo Cover and into Basement rocks
Between 41 and 37 Ma	Buntfeldschuh Formation and Kakaoberg Sandstone Member	ED Eocene Orange River (small average stone size and low grade = start of the diamond "flush" from the interior); Eisenkieselklippenbakke; "Eocene" shoreline; Bogenfels Eocene fossils; Strong South wind influence with northward longshore drift; Onset of Namib Desert aridity
Between 46 Ma and 37 Ma	Thermal Spring deposits related to Klinghardt volcanic activity	Fossiliferous, with ancestral golden mole adapted to aeolian dunes
46 Ma	Klinghardt Phonolite Province	
47-48 Ma	Black Crow Limestone deposits, probably terminal Blaubok Gravels phase	Pan/Playa deposits – pre onset of aridity
Pre-46 Ma; Paleocene	Blaubok Gravels	Alluvial fan & channels with fossilised tree trunks (pre-Namib onset)
End Cretaceous	Kätchen Plateau Formation	Regional Silcrete on deep weathering
?80-60 Ma	Pomona Beds	Alluvial sheetwash
Late Cretaceous	Wanderveld IV	Marine, shallow inshore
Mid – Late Cretaceous	Kudu Offshore = Orange River 1M km^2 catchment, meander belt 10 km wavelength	O.R. Cretaceous Delta & Littoral
130 Ma	Granitberg	Intrusive
600-700 Ma	Gariep	Pan-African Orogenic belt from marine basin



Courtesy of K. Strydom.



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

1. Buntfeldschuh Escarpment/Chocolate Mnt.
2. Gemsboktal Gravels
3. Eisenkieselklippenbake
4. Bogenfels Village
5. Bogenfels Arch
6. Blaubok Gravels
7. B10 Area
8. Wandervel IV & Langental Marine Section
9. Stefan's Kop
10. Pomona

THE SPERRGEBIET

The highest standing relative sea level along the west coast of southern Africa was at ~170 m amsl and occurred during the Eocene. The central Sperrgebiet of Namibia hosts diamondiferous marine deposits which are Late Eocene in age. Remnants of this so-called "Eocene" shoreline are intermittently preserved along the landward (eastern) edge of, and within, a prominent deflation basin between Buntfeldschuh in the south and Graniteberg in the north (130 to 190 km north of the Orange River mouth; **Figure 2**). The Eocene marine deposits reach elevations of up to 160 m amsl (at Eisenkieselklippenbake) and are characterised by an exotic clast assemblage typified by the presence of honey-yellow chalcedony, resinous agates, jasper, epidosites, vein quartz, ironstones, banded ironstone and chrisoprase, most of which are resistate clasts derived from the Kaapval craton (**Figure 2**). This "Eocene" assemblage is evident in pebble gravel bands of the marine deposit that are currently being reworked by ephemeral streams to form sheetwash-type deposits in the N-S trending valleys of the deflation basin. The aeolian grit fraction, in sandsheets directly downwind of, and spatially associated with the sheetwash-type deposits, also contains abundant yellow chalcedony.

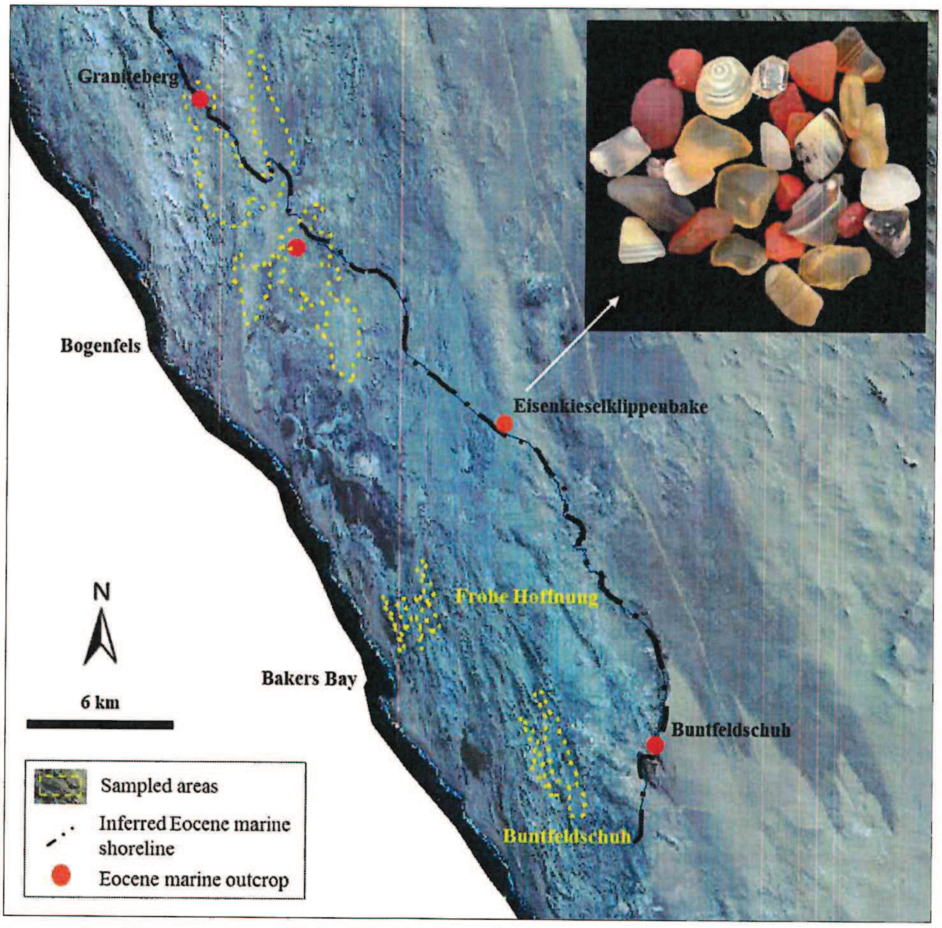


Figure 2. Eocene shoreline remnants. Frohe Hoffnung and Buntfeldschuh are historical German mining areas.

The deflation basin, termed the "Trough Namib" by Kaiser (1926), consists of a 150 km long coastal tract ranging from 0 – 15 km wide between Chameis Bay and Lüderitz, to the south of the main Namib Sand Sea (Rogers *et al.*, 1990). The offshore to onshore supply of fine-grained sediments into the Namib Sand Sea (Sossus Sand Formation; SACS, 1980) has occurred since at least the Middle Cenozoic (Ward, 1998). After accumulating in J-shaped bays along the coast, the sand fractions are blown further inshore by strong onshore winds (**Figure 3**; Bluck *et al.*, 2005, 2007). The area is characterised by a long history of reworking by different geological process. The deflation basin is floored by rocks of the Late Precambrian Gariep Group, together with refoliated older gneissic basement. A long-lasting combination of hyper-arid environment, against a cold sea generating abundant salt-laden mists, strong southerly winds and ephemeral sheetwash flooding weathered, eroded and sculpted the valleys into north-south wind corridors, that presented ideal settings for the concentration of diamonds (Burrell, 2010). The principal original source of the diamonds found in these deflation deposits is believed to have been the shoreline gravels of the "Eocene". These shorelines were broken down and distributed into the valleys. A combination of salt weathering and aeolian action broke down and winnowed out the fine material, leaving resistant lag deposits, principally of siliceous clasts and diamonds.

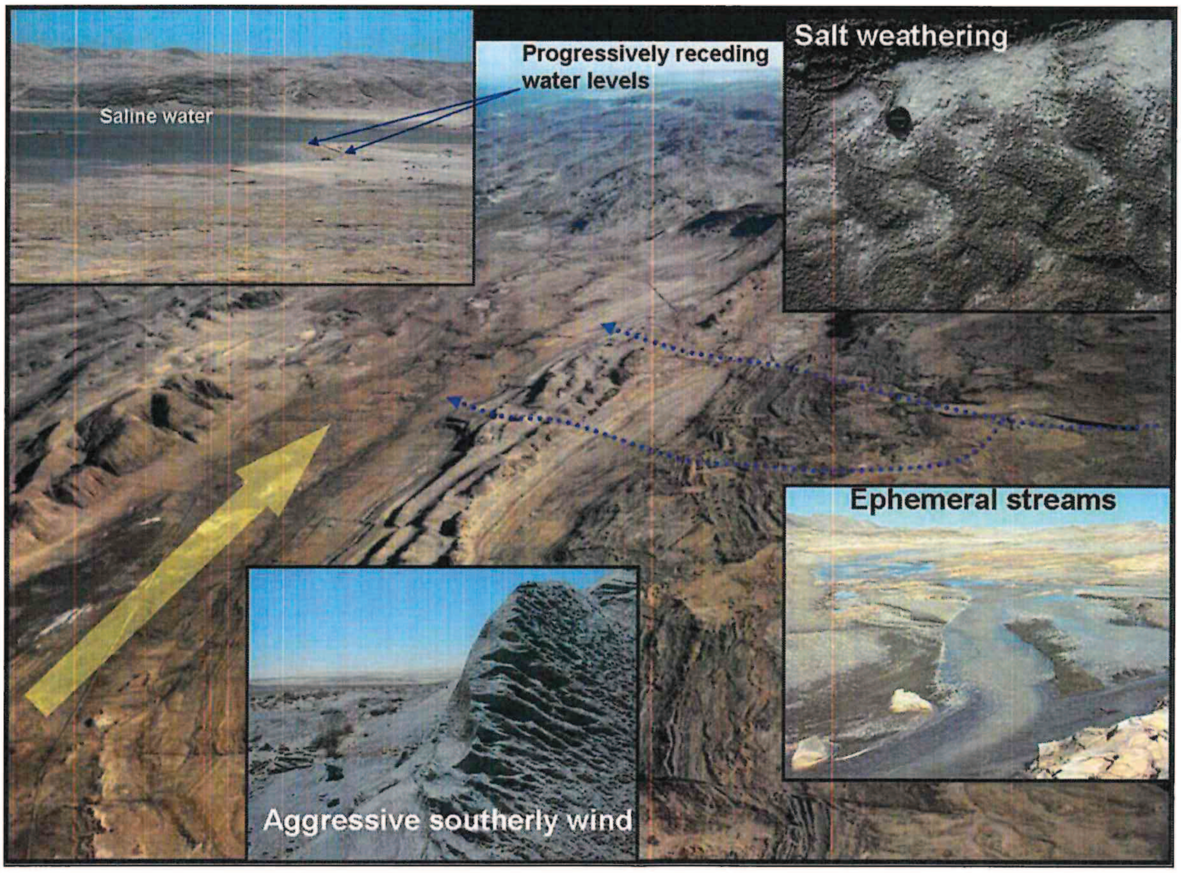


Figure 3. Emplacement processes (Awases, 2008).

BUNTFELDSCHUH ESCARPMENT/CHOCOLATE MNT.

The ~100 m high, several km long, Buntfeldschuh escarpment comprises the Buntfeldschuh Formation made up of a three lithostratigraphic units: 1) a lower unit of marine gravels and green sands (interpreted as shoreface sediments) overlying schists of the Gariep Supergroup basement, 2) middle zone of grey/brown, poorly indurated sandstone (interpreted as beach face sands) with concentrations of heavy minerals and 3) and upper zone of red/brown aeolian sands (interpreted as a coastal dune belt) capped by ferricrete in the southern end (**Figure 4**; Burrell, 2010). The lower marine unit has been tectonically affected by thrusting, capped by the upper, largely tectonically-unaffected regressive marine unit that is capped conformably by aeolianites of the Kakaoberg Sandstone Member (Swart and Ward, 2018). In spite of the marine setting, fossils are rare and this large exposure remains poorly constrained chronologically except for a maximum age of 47 Ma based on *Isurus* shark teeth (Swart and Ward, 2018). However, given the well-defined "exotic" clast assemblage at Buntfeldschuh escarpment that can be mapped past Eisenkiesselklippenbake and into the Langental area where marine fossils indicate a 37 – 41 Ma age. It is considered highly likely that the Buntfeldschuh Formation at the escarpment is also of a similar age (Swart and Ward, 2018).

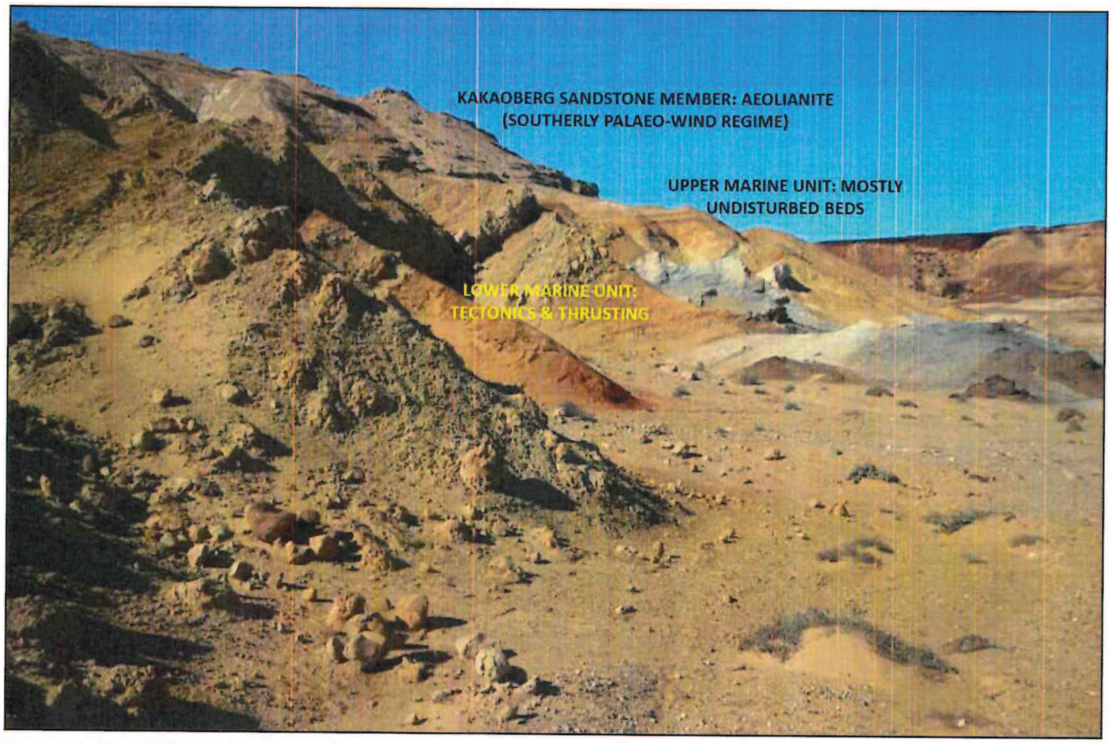


Figure 4. Buntfeldschuh Formation comprises three lithostratigraphic units (Swart and Ward, 2018).

GEMSBOKTAL GRAVELS

In the Northern Sperrgebiet, the presence or absence of phonolite cobbles has been used to distinguish between the Blaubock gravels (which has no phonolite pebbles) and the Gemsboktal gravels, which is rich in phonolite clasts (Pickford, 2015). The Gemsboktal beds (Late Miocene) blanket an enormous area to the east of Bogenfels (**Figure 5**; Stocken, 1978). Rarely exceeding 10 m in thickness, the beds are interpreted as sheetflood accumulations associated with the Gemsbok valley which represents the distal end of the rubble-filled drainages originating in the Klinghardt Mountains (Stocken, 1978). The Gemsboktal beds comprise poorly sorted boulder gravels, characterised by sub-angular and sub-rounded phonolite fragments (Burrell., 2010).

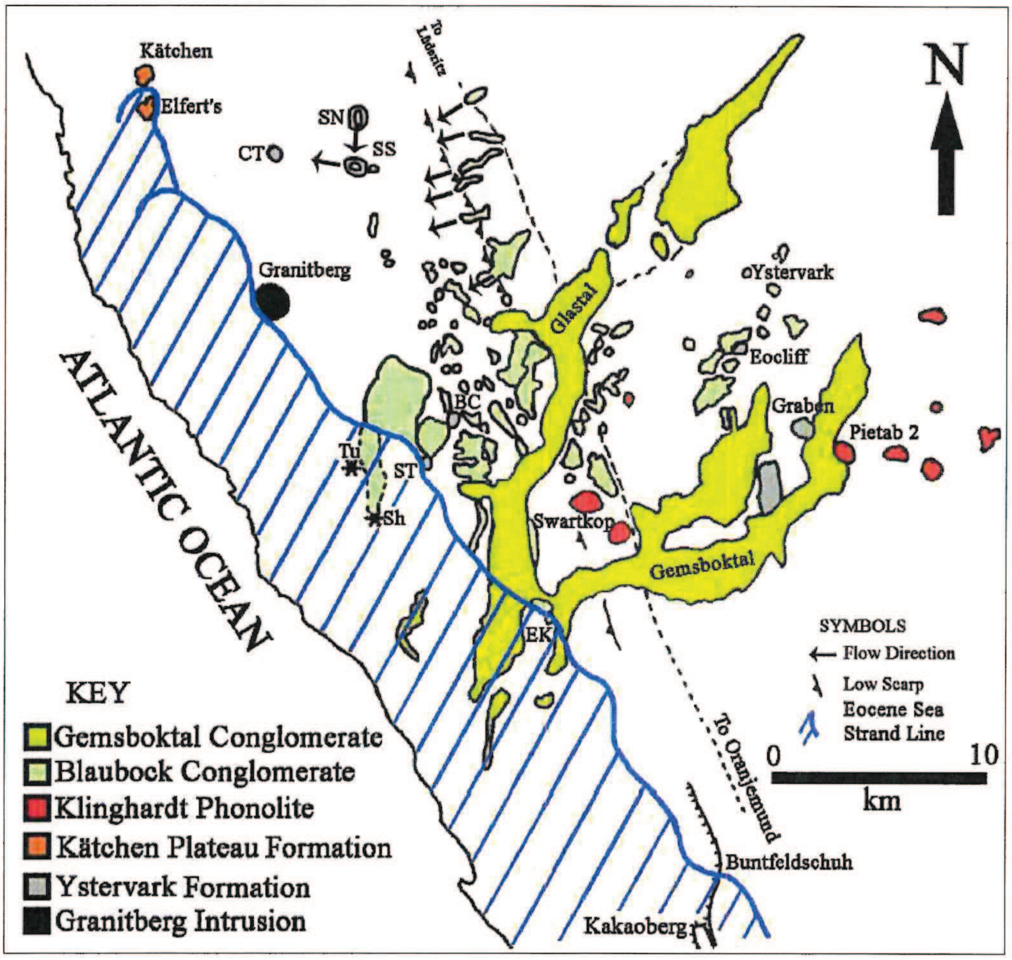


Figure. 5. Distribution of outcrops of the Gemsboktal Conglomerate and Blaubock Conglomerate relative to the "Eocene Sea" highest strand line. (BC = Black Crow, CT = Chalcedon Tafelberg, EK = Eisenkieselklippenbake, Sh = Langental Shark Site, SN = Silica North, SS = Silica South, ST = Steffenkop, Tu = Langental *Turritella* Site; Pickford, 2015).

EISENKIESELKLIPPENBAKE

The principal original source of the diamonds in the north is believed to have been the shoreline gravel of the "Eocene" that were deposited around 42 Ma at topographic levels up to at least 170 m amsl (e.g., Eisenkieselklippenbake; **Figures 2 and 6**). The highest deposits of chalcedonic gravels are found today at the unusually named Eisenkiesselklippenbake.

Figure 6. Eisenkieselklippenbake ~155 m Eocene "shoreline" (Swart and Ward, 2018).

BARCHAN DUNE TRAINS

Flying over the Sperrgebiet gives a magnificent view of this coastal desert where barchan dune trains can be seen marching northwards toward the Namib Sand Sea (**Figure 7**). These dunes are regarded as some of the largest examples of barchan dunes known on Earth and are situated inland from Bogenfels Arch. The dunes vary in height seasonally, from about 25 – 33 m (Rogers *et al.*, 1990). The smaller dunes travel northwards over 100 m per year, whilst the larger ones move 30 m per year.

Figure 7. Barchan dunes of the Namib.

BOGENFELS VILLAGE

The derelict buildings at Bogenfels are a testament to early pioneers in their pursuit to mine diamonds in an inhospitable desert environment. Mining at Bogenfels commenced during 1909 by the Deutsche Diamanten Gesellschaft (DDG), which formed part of nine companies that had rights to prospect and mine in the area since the proclamation of the Sperrgebiet by State Secretary Bernard Dernberg in August, 1908. These activities ceased with the onset of war in 1914 and the German mining activities came to an end with the establishment of Consolidated Diamond Mines of SWA Ltd. (CDM) in 1920. Mining, however, recommenced in 1935 on a much smaller scale and although interrupted by the Great Depression and World War II, the operations continued until 1948.

BOGENFELS ARCH

The most famous landmark of the Bogenfels area, and a Namibian national icon, is the Bogenfels Arch, which gave the village its name. (**Figure 8**) Sculpted by the aggressive coastal conditions, the Bogenfels Arch stands 52 m high and consists of the east-dipping limb of a syncline in the Late Proterozoic Bogenfels Formation. The sloping "roof" and the lowermost horizon of the supporting pillar are formed from resistant silicified dolomite, whereas softer sediments were located within the fold.

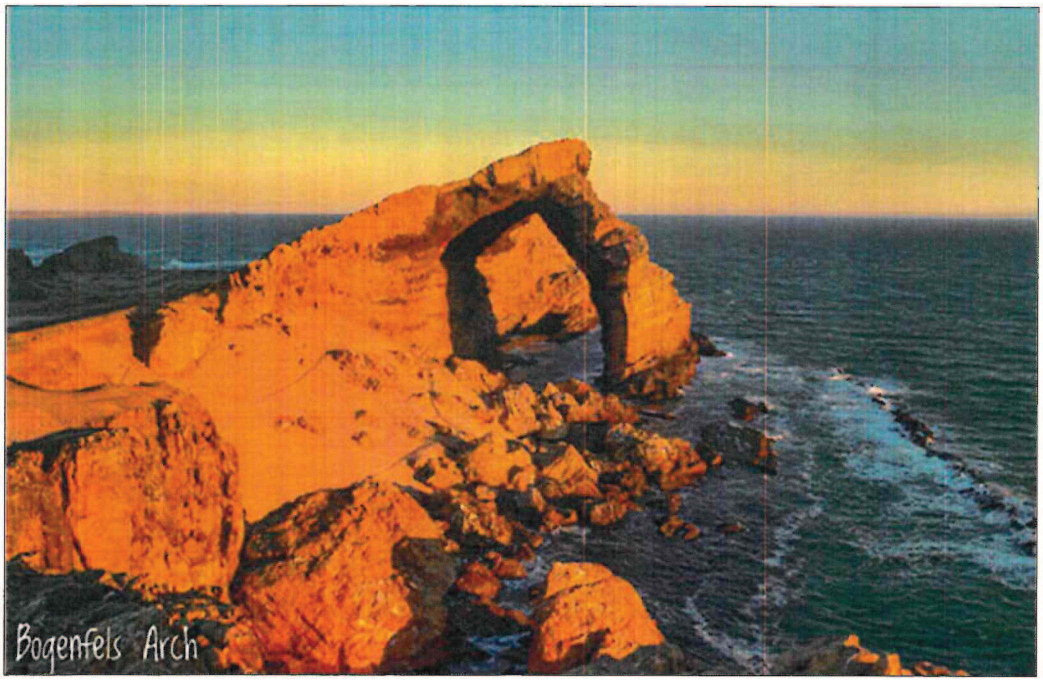


Figure 8. Bogenfels Arch (P. Saravanakumar).

BLAUBOCK GRAVELS

Prior to the marine influx of diamondiferous material during the mid to late Eocene, deposition of Palaeocene Blaubock gravel took place (Burrell, 2010). The quartz and Nama quartzite rich cobble to small boulder gravels of the Blaubock Formation are the oldest known Cenozoic deposits in the Sperrgebiet (Swart and Ward, 2018). These gravels originate in the central parts of the Sperrgebiet, east of the Klinghardt Mountains, but west of the Escarpment. They do not contain phonolite clasts (observed in the Gemsboktal gravels) and are thus pre-46 Ma in age. The Blaubock gravels are coarse-grained alluvial fan type deposits up to ~10 m thick. The presence of large tree trunks (with no roots or branches; up to 10 m long) in the Blaubock gravels point to a better wooded catchment that has not existed in the Namib since then (**Figure 9**; Swart and Ward, 2018). In places isolated remnants of these resistant Blaubock gravels exist, with Eocene Suite exotic pebbles found round the edges of these "island remnants" (**Figure 9**). Fluvial reworking after the emplacement of the Eocene Suite exotics gave rise to fluvial terraces comprising a mixture of Blaubock gravel and Eocene Suite exotic pebbles (Burrell, 2010).

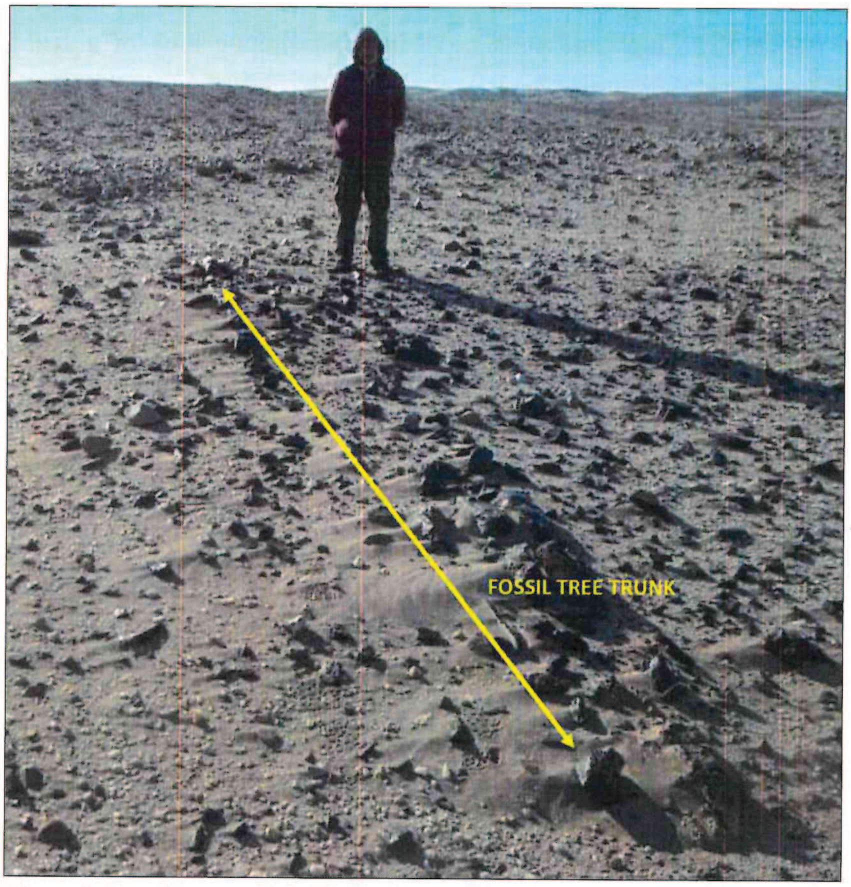


Figure 9. Fossil tree trunk in Blaubok gravel formation (Swart and Ward, 2018).

B10 AREA

Historical mapping of the Eocene "shoreline" northwards from Buntfeldschuh has been undertaken in the past and noteworthy occurrences at ~150 m amsl are observed at Eisenkieselklippenbake and Stefan's Kop, but at lower elevations at B10 (Swart and Ward, 2018).

WANDERFEL IV AND LANGETAL MARINE SECTION

At Wanderveld IV, a fossilferous limestone dating back to the Late Cretaceous is preserved; whereas, at Langental, the Eocene marine sediments (shallow littoral) are well represented (SACS, 1980).

The Cretaceous sediments of Wanderfeld IV consist of limestones and silt of inter-tidal marine origin and are limited to a thin layer in a locally restricted area north-east of the Bogenfels Arch (**Figure 10**). The deposit is important as it is the only known Cretaceous marine deposit on the west coast south of Angola (Schneider & Marais, 2004).

The surface area around the so-called "Oyster Trench" exhibits a "carpet" of exotic clasts typical of the late Eocene input. The trench itself shows the presence of a thick-shelled oyster species (*Ostrea*) from which it may be inferred that during Eocene time sea water were appreciably warmer than those prevailing today. In addition to the *Ostrea*, and numerous *Turritella* casts, nautiloid specimen have also been recovered. The area has been dated 37 – 41 Ma based on marine micro- and macro fossils (Swart and Ward, 2018). From the nature and distribution of the sediments the Eocene marine incursion is interpreted as a relatively rapid transgression which effected very little bedrock planation or coastal modification and was for the most part confined to pre-existing valleys and depressions. Consequent upon such a rapid transgression, the diamond content of the Eocene marine beds is very low, but as a result of long-continued deflation processes, extraordinarily rich valley-floor concentrations of diamonds eventually resulted, invariably associated with recognisable Eocene gravel residua. (Stocken, 1978)

Figure 10. Well-round 2 cm quartz clast in the Cretaceous limestone at Wanderfeld IV (Pickford and Senut, 2016).

STEFAN'S KOP

Irregular silica deposits hosting algal structures, micro-layering and freshwater gastropods, such as *Lymnea* and *Hydrobia*, that are also interpreted as thermal spring deposits include Eisenkieselklippenbakke and Stefan's Kop. The presence of *Hydrobia* freshwater snails in many of these silica rich deposits points to clean, sediment-free waters (**Figure 11**). At both Eisenkieselklippenbakke and Stefan's Kop, clasts from these silica deposits have been incorporated into the nearby ~155 m amsl Eocene "shoreline" gravels (**Figure 12**).

Figure 11. Fossilferous silica thermal spring deposit comprising *hydrobia* freshwater snails (Swart and Ward, 2018).

Figure 12. Blaubock gravels underlying ~155 m amsl Eocene "shoreline" gravels at Stefan's Kop (Swart and Ward, 2018).

POMONA

After the diamond discovery in the Kolmanskop area by Zacharias Lewala was confirmed by August Stauch in 1908, a rush was on to secure ground and start mining (**Figure 13**). The results led to a northward and southward diamond rush away from Kolmanskop. From Kolmanskop southwards, prospecting campaigns explored the valleys (and sometimes the rocky interfluves) with systematic trenching. These 1 m wide "German trenches" were cut across the south-north striking bedrock valleys, the paddock samples being sieved on site using hand driven trommel sieves and the products taken to nearby jig stations for final washing, concentrating and sorting. The diamond records were meticulously plotted on detailed maps of these deflation-formed valleys – scoured out, in places to just below sea level, by a combination of vigorous prevailing southerly winds, ephemeral stream and pan moisture and destructive salt weathering to leave some of the richest diamond placers in the Sperrgebiet – all of 10cm thick that have, at some localities, been mined seven times! In the Marchental, near Stauch's Lager, there are reports of the early (1910 – 1912) exploration parties of August Stauch and Professor Scheibe picking the diamonds by moonlight in a deflation place.

Small mining towns of Pomona and Bogenfels sprung up in this pre-First World War push southwards in search of diamond fields in the increasingly harsh, bedrock based topography of this section of the Sperrgebiet where the "Eocene: shoreline was the principal source of diamonds, the northern limit of the winter rainfall ensured minimal vegetation cover that promoted local fluvial erosion from frontal systems that were mainly coast-restricted, these small ephemeral rivers and terminal pans generating salt weathering and disintegration of the bedrock which was blown away northwards by vicious southerly winds that sorted the generally small diamonds into northward tails away from these mini depocentres (Kaiser, 1926; Corbett, 1989).

Figure 13. Deflation valley mined by Germans and sample site (5 x 5m2) on the deflated calcretized surface bearing small pebble to grit sized exotics. In the far background a barchan trail is running behind a vegetated sandsheet (Sperrgebiet Geological Excursion Booklet, 2007).

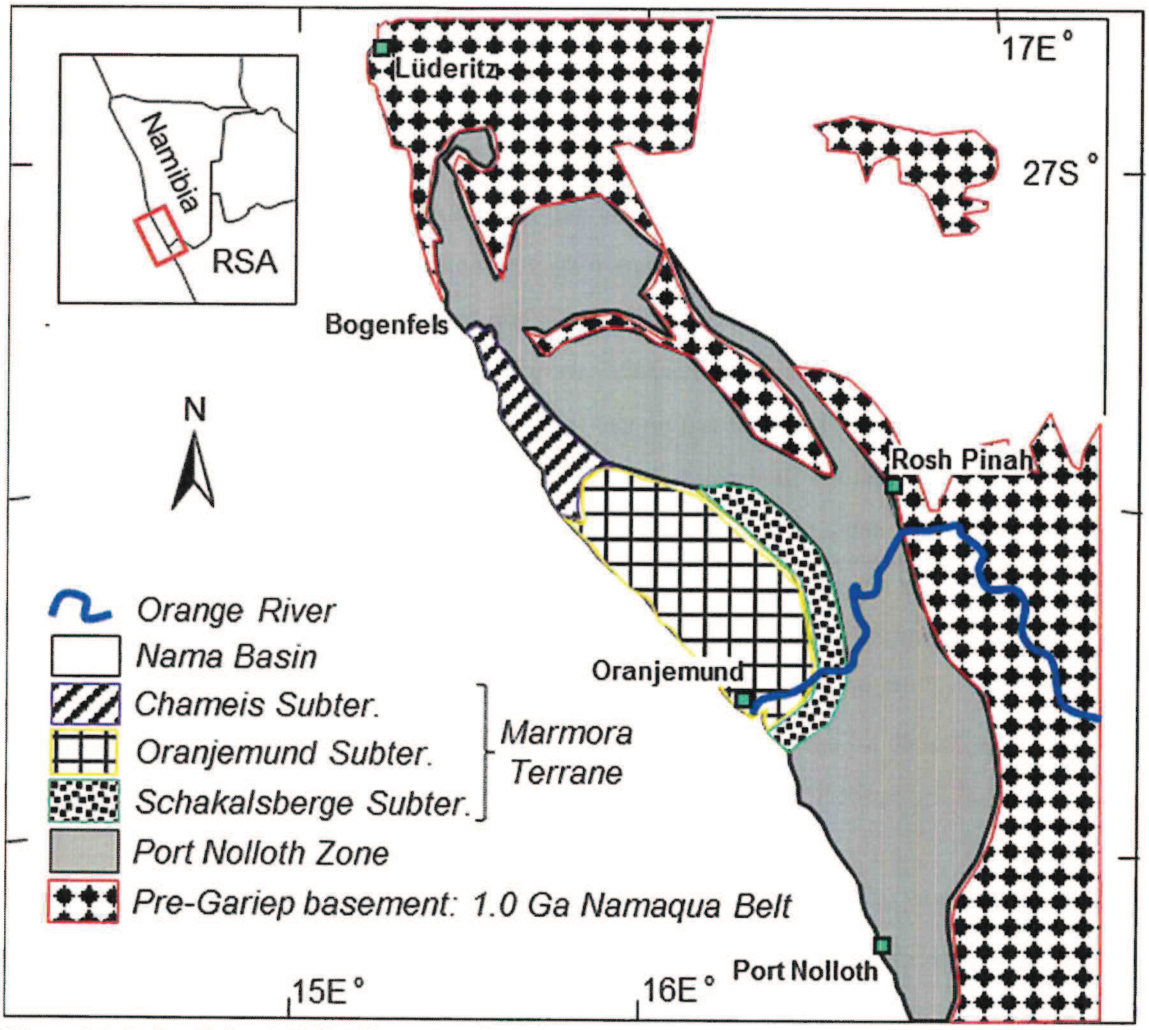


Figure 14. Gariep Belt subdivided into tectonic terranes (Runds, 2018 adapted from Frimmel *et al.*, 1996).

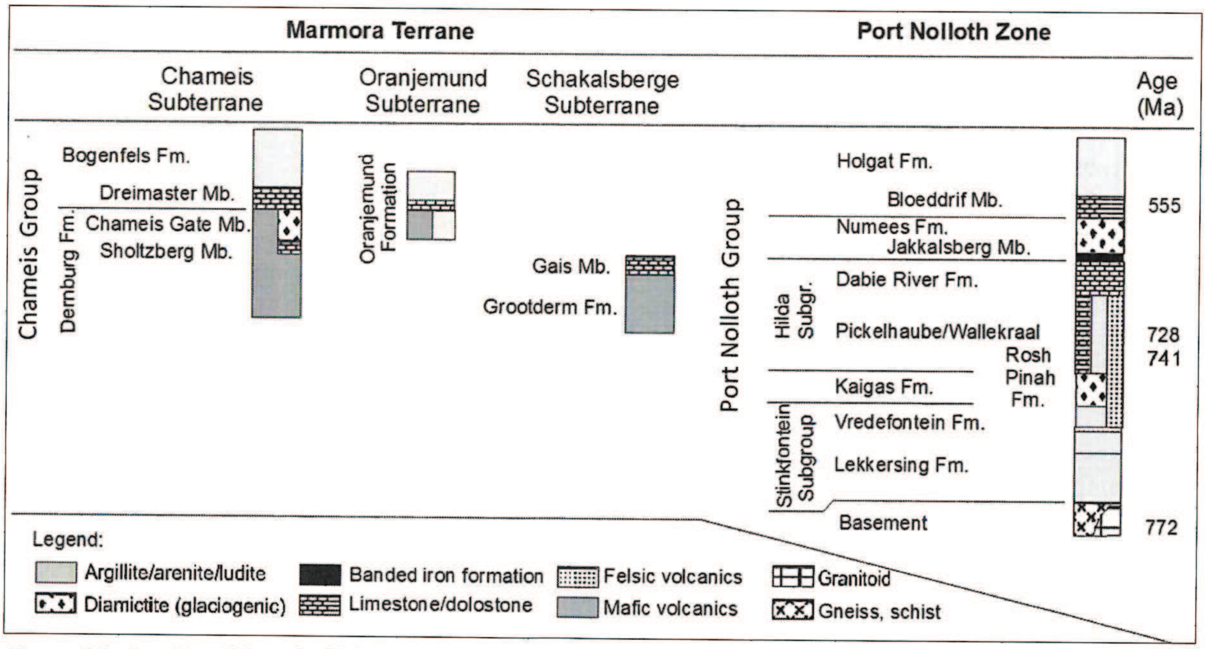


Figure 15. Stratigraphic sub-division of the Gariep Supergroup, with suggested correlations between the Port Nolloth Zone and Maromora Terrane (Frimmel, 2000).

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