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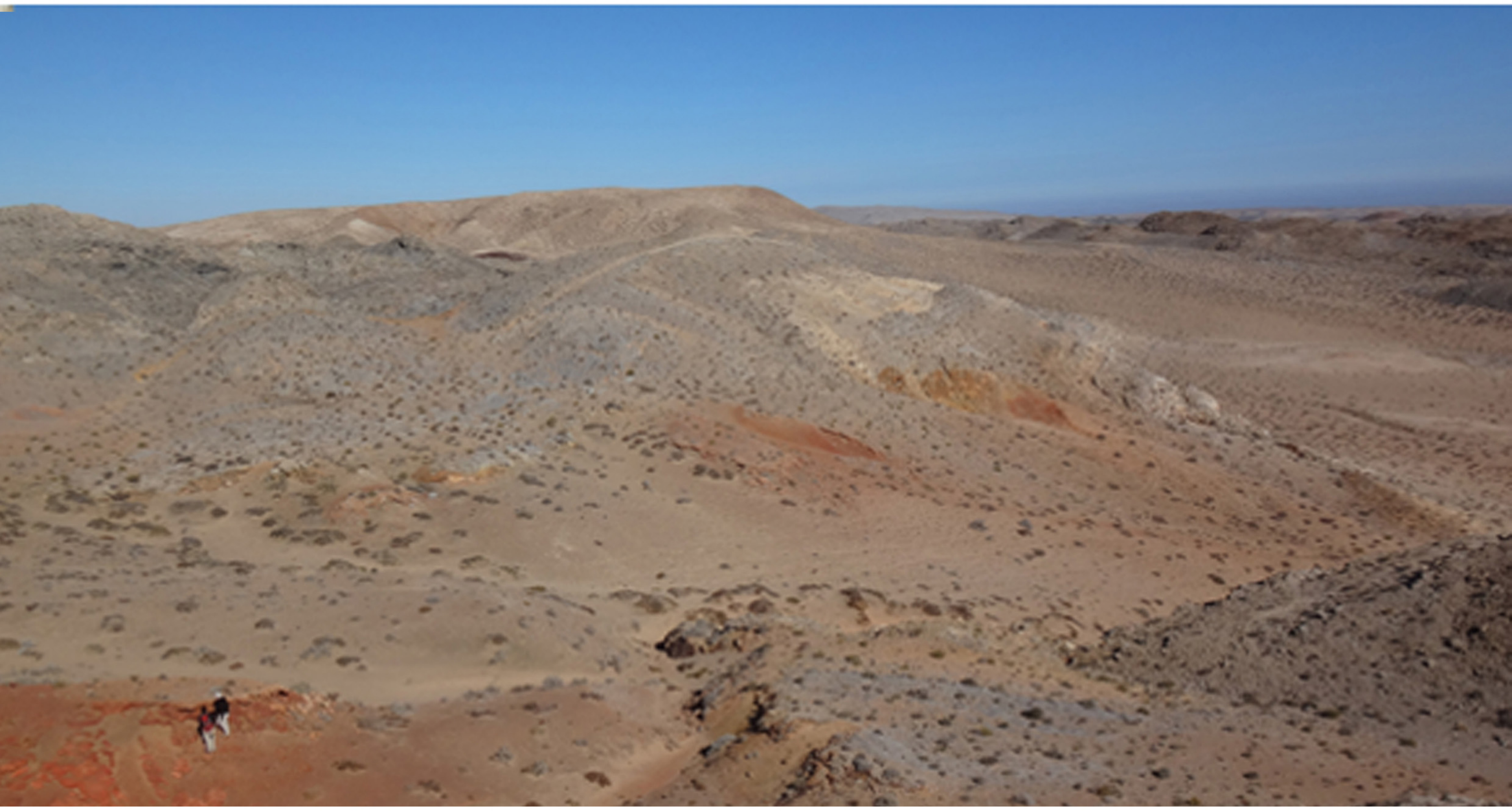

MINISTRY OF MINES AND ENERGY

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Cenozoic Geology of the Northern Sperrgebiet, Namibia, accenting the Palaeogene

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Abstract: The Tertiary and Quaternary deposits of the Northern Sperrgebiet comprise a highly variable suite of rocks encompassing alterites of diverse kinds, silcrete and other palaeosols, palustral marls, fluviatile conglomerates, delta deposits, shallow marine sandstones, marls, grits and conglomerates, volcanic rocks (carbonatites and derivatives of subaerial carbonatite activity such as palustral limestones), phonolite (tuffs, lavas and intrusions), nephelinite lavas, olivine melilitite lavas, aeolianites, tufa domes, onyx fields and salt pans. Many of these rocks have been indurated by calc-crusts or have been ferruginised or silicified. Fossils have been found in many of the sedimentary facies, which have permitted more accurate estimates to be made of the timing of sedimentary events in the region. It is revealed that several previous age estimates of Sperrgebiet rock units are off by an order of magnitude (some deposits such as the Pomona Schichten, previously attributed to the Cretaceous have yielded Lutetian and Bartonian fossil assemblages and even Plio-Pleistocene ones). The aim of this contribution is to provide a revision of the post-Mesozoic stratigraphy of the Northern Sperrgebiet, accenting the Palaeogene period which has been the most misunderstood.

Key Words: Northern Sperrgebiet, Namibia, Palaeogene, Stratigraphy, Biostratigraphy

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Introduction

Nature of the problems concerning Sperrgebiet geology

Understanding of the Cenozoic geology of the Northern Sperrgebiet (Fig. 1) has been hampered by many factors which made its interpretation difficult and, as a consequence, often contentious. From a scientific perspective five main things have complicated its interpretation : 1) the discontinuous and scattered nature of the outcrops which meant that, in many cases, the succession of rock units could not be established on the basis of observable superposition, 2) the relative paucity of fossils meant that the timing of events was difficult to establish even if the sequence of events could sometimes be worked out, 3) the fact that the region lies in the zone where marine and continental geological processes were active in close proximity meant that transgressions and regressions of the sea heavily influenced the local geological record, and thus complicated its interpretation, 4) the large variety of weathering and diagenetic processes that altered the near-surface rocks produced a bewildering variety of end products that often defied common experience, and 5) the intense aeolian activity which has affected the coastal zone since the Early Miocene and possibly even since the Eocene, removing vast quantities of fine sediment, and depositing widespread sand sheets and dunes over much of the area, even on positive relief features.

From a social perspective, the fact that the Sperrgebiet was closed from 1910 (Sperrgebiet means Forbidden Territory) meant that access to outcrops was strictly controlled by mining interests which were especially influenced by considerations of diamond security and economics more than by scientific endeavour, which made it difficult for scientists to examine the ensemble of geological evidence independently. As a result, many of the studies carried out between 1926 and 2000, were done by company geologists, consultants or during brief visits by scientists accompanied by company personnel, few, if any, of whom were able to study the entirety of the Tertiary rocks, and who thereby obtained parochial or partial views of the relationships between the various rock units. Furthermore, most of the reports that were written remained unpublished, which stifled scientific debate, and in the long term led to a substantial archive of circular reasoning and intellectual cul-de-sacs. Additionally, there was little if any check on the correlations proposed by company geologists and visiting scientists who were from time to time escorted to particular spots or outcrops, a procedure which, in the long term, led to the establishment of a rather fanciful array of correlations to erosion surfaces, sea-level curves, global scale palaeoclimatic curves and geomorphological processes, which became "engraved-in-stone" due largely to the lack of scientific debate.

This paper focuses primarily on the scientific aspects of the Cenozoic geology of the Northern Sperrgebiet, but mentions the social aspects when necessary to provide understanding of previous interpretations and hypotheses. Thanks to Namdeb (formerly CDM (Pty) Ltd) relatively unhindered access to the region was accorded to the Namibia Palaeontology Expedition (NPE) which started its surveys in the region in 1992. Members of this expedition have been able to visit many of the key outcrops and some previously unmapped zones, and are thus in a favourable position to explore questions that most prior researchers had been unable to do. Access to unpublished company archives was useful, because, even though the correlations and interpretations expressed in the reports are often contentious or flawed, the field observations, where reported accurately, are of major interest. The greatest advances made by the NPE concern the discovery of many new fossiliferous localities ranging in age from Lutetian to Holocene, which provide constraints on the timing of geological activity in the region, and which throw light on its palaeoenvironment, palaeoecology and palaeo-climatology.

The outcome of this collaboration between industry and academia is a revision of the Cenozoic geology of the Northern Sperrgebiet. However, given the immensity of the area, the thick sand cover over much of the region, and the complexity of its geological history, there remain several knotty problems concerning details of the sequence and timing of geological events, and these are enumerated at the end of the paper in the hope that further work will lead to their unravelling. The main problem areas include the position of the Kätchen Plateau Formation relative to the Ystervark Carbonatite Formation, the processes which led to the deposition and silicification of the Kätchen Plateau Formation and the Sperrgebiet Siliceous Suite, the correlation of the Buntfeldschuh delta deposits, the content and stratigraphic extents of the Blaubock and Gemsboktal Gravel formations, the number of phases of calc-crust genesis, and the timing and nature of ferruginisation events.

The aim of this contribution is to re-interpret the Palaeogene geology and some aspects of the geomorphology of the Northern Sperrgebiet in light of the newly available palaeontological evidence and geological observations.

Background to Study

The coastal strip of southwestern Namibia is best known for the immense quantity of diamonds that it yielded. The presence of these gemstones prompted the German government to declare the area Sperrgebiet (Forbidden Territory) and to organise its proper study via detailed prospecting and geological survey. Over much of the coastal strip East-West prospecting trenches were dug at 200 metre intervals extending from the coast as far inland as the 200 metre contour line, and these were mapped in exceedingly close detail in order to record the distribution of diamonds. Many of these trenches are still visible. The fruits of this programme of scientific research were published by Kaiser & Beetz in 1926. Subsequently, Consolidated Diamond Mines (Pty) Ltd and other De Beers affiliates undertook detailed geological surveys from the coast as far inland as the Klinghardt Mountains, but for a long time the results of this work remained inaccessible to the scientific community because it was stocked in the unpublished archives of the companies (Bennett, 1976; Clarke, 1962; Fowler, 1970; Fowler & Liddle, 1970; Kalbskopf, 1976a, 1976b, 1977; Liddle, 1970a; 1970b, 1970c, 1971; Spriggs, 1988; Stocken, 1978; Sullivan, 1961, 1962; Van Greunen, undated). The most recent synthesis of the geology of the Sperrgebiet is by Miller (2008a, 2008b, 2008d).

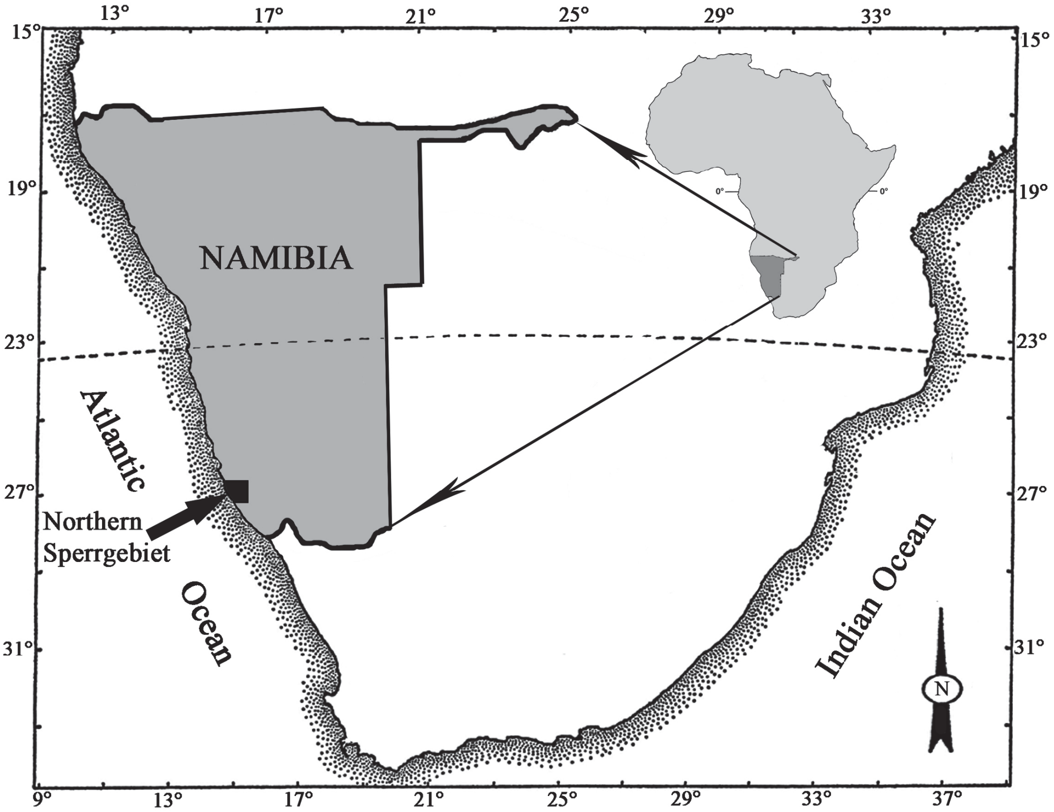

Figure 1. Map depicting the location of the Northern Sperrgebiet, Namibia.

The geological mapping by Kaiser and Beetz (1926) Van Greunen (undated) and Fowler & Liddle (1970) reveal that overlying a highly irregular topography of Basement rocks comprising heavily tectonised Gariep Group sediments of Proterozoic age and Mesozoic intrusions there reposes a thin, discontinuous pellicle of Cenozoic deposits ranging in thickness from a few cm to over 100 metres, above which there is a widespread blanket of loose sand which obscures well over 50% of the land surface. Historically, the combination of poor exposures and disconnected outcrops has introduced a great deal of uncertainty into the interpretation of the sequence of geological events in the region. A further complicating factor is that the Sperrgebiet is at the interface between continental and marine geological processes.

The Northern Sperrgebiet is almost continuously swept by boisterous winds which have removed vast amounts of alterite from the coastal strip, resulting in the deeply dissected landscape called the "Trough Namib" (or "Basin Namib") by Beetz (1926), a zone 10-15 km broad extending along the coast from Chameis to Lüderitz, characterised by elongated depressions and ridges oriented approximately north-south. Further inland, the landscape is generally flatter with broad shallow valleys, hence the name "Plain Namib" or "Innennamib" given to it by Beetz (1926). Outcrops in the Trough Namib are much more accessible than those in the Plain Namib, which are often obscured under a variable thickness of loose sand or Namib Calc-crusts. It is clear from satellite imagery that the inland edge of the Trough Namib has shifted over time, with evidence that it was alternatively several km further inland and further seaward during the past. For example, the Namib Calc-crusts occur widely at the tops of the Tafelberge and on terraces some 15-20 metres lower in what is now the Trough Namib. These calc-crusts occur extensively in the Plain Namib, which probably extended as far west as Pomona during the accumulation of Namib 1 Calc-crust (Fig. 2).

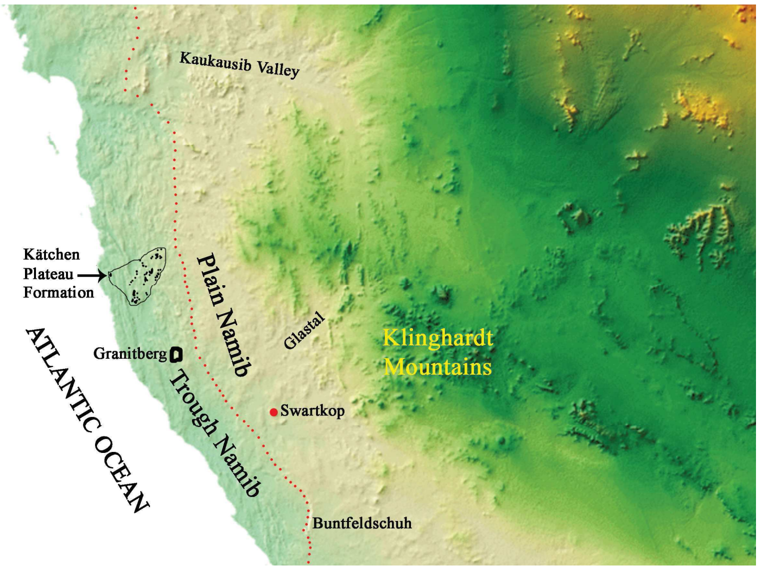

Figure 2. The Northern Sperrgebiet was subdivided by Beetz (1926) into the coastal *Flächennamib* (Trough Namib) and the inland *Innennamib* (Plain Namib). These geomorphological entities are clearly visible in satellite imagery. The Trough Namib corresponds more or less to the zone swept by incessant winds of the South Atlantic Anti-cyclone. Significant parts of the Trough Namib were subjected to marine transgressions during the Eocene and Early Miocene. It is the combination of these factors that renders the interpretation of the geology of the sector so challenging, because marine and aeolian processes removed enormous quantities of sediment and altered Basement rock from the coastal strip, leaving a discontinuous and disjointed Eocene to Pleistocene stratigraphic record. The Plain Namib, in contrast, suffered less erosion, and even underwent calc-crust formation which cemented loose surface deposits and in cases led to vertical accretion in places. Note the distribution of the Kätchen Plateau Formation, restricted to the Trough Namib (only about 20% of the Kätchen Plateau Quartzite is *in situ*, the rest occurs as derived blocks incorporated into ferruginised terrace deposits and/or Namib 1 and Namib 2 Calc-crusts (formerly called Pomonalkalke)).

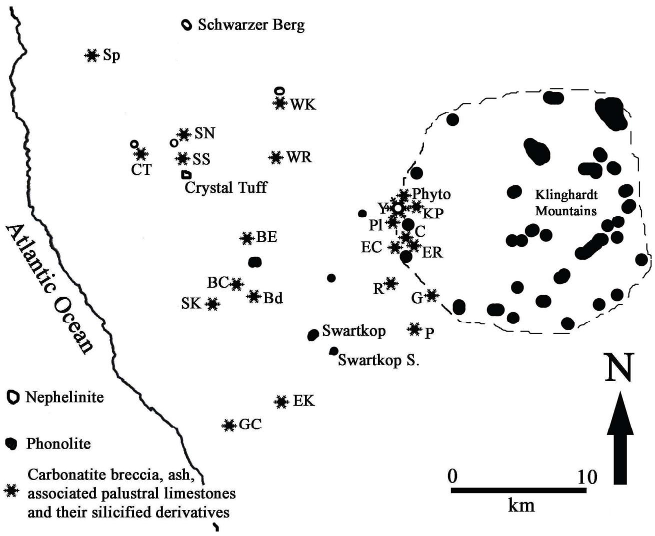

Figure 3. Map showing the position of the volcanogenic deposits of the Northern Sperrgebiet, comprising the Ystervark Carbonatite Formation, the Klinghardt Phonolites and the Schwarzer Berg Nephelinite. BC – Black Crow, Bd – Bedded, BE - Bull's Eye, C – Contact Site, CT – Chalcedon Tafelberg, EC – Eocliff, EK – Eisenkieselklippenbake, ER – Eoridge, G – Graben, GC – Gamachab, KP – Klinghardt's Pan, P – Pietab 2 Freshwater Limestone Depression, Phyto – Phytoherm site, Pl – Plaquette site, R – Reuning's Pan, SK – Steffenkop, SN – Silica North, Sp – RvK Sponge Site, SS – Silica South, WK – Werfkopje, WR – White Ring, Y – Ystervark.

The lack of continuity between outcrops in the Northern Sperrgebiet (Fig. 3) often made it difficult to determine the relative positions of the heterogeneous suite of Cenozoic deposits. As was appreciated by German geologists, fossils were crucial for providing estimates of the timing of events in the region (Böhm & Weissermel, 1913) and each new palaeontological discovery has led to revision of the geological history of the Sperrgebiet. Since 2007, the Namibia Palaeontology Expedition has identified several previously unsuspected fossiliferous deposits of Eocene, Miocene, Pliocene and Pleistocene age which throw a great deal of light on the geological history of the sector lying between the Klinghardt Mountains and the coast. Thus, the geological history of the region is now better understood, but this does not mean that all the stratigraphic relationships and chronological problems have been solved.

Materials and Methods

This revision is based on classic field mapping and fossil prospecting techniques using aerial photographs and satellite imagery for ground control. Google Earth was particularly appreciated and led to the discovery of the Palaeogene sites at Black Crow, Silica North, Silica South, Eoridge and Eocliff. In the field, latitude, longitude and altitude were recorded using GPS instruments set to WGS 84. Similar data was obtained in the laboratory using Google Earth. For the Sperrgebiet, the two approaches yield compatible data sets. It should be noted that altitudes obtained by GPS in particular can be very approximate, but latitude and longitude are usually accurate to within 10 to 15 metres (Annex 1). Altitudes obtained from Google Earth may differ slightly from those established on the basis of ground survey.

Altitudinal profiles of various lithological units were obtained by plotting altitude against shortest distance to the coast. These profiles provide a reasonable idea of some aspects of the geomorphological development of the Northern Sperrgebiet, with remnants of ancient landscapes being preserved beneath various sedimentary units, the profiles of older remnants generally being higher than those of younger ones.

Biochronological information was obtained by comparing palaeofaunas and palaeofloras from the Northern Sperrgebiet with data sets from other parts of the world. Correlation to the marine sequence was already done by Siesser (1977) but further research is needed. Some of the Palaeogene mammals found by the Namibia Palaeontology Expedition (Pickford *et al.* 2008) have been analysed and yield an age estimate of Lutetian for the Black Crow fauna, and Bartonian for those from Silica North, Silica South, Eoridge and Eocliff.

Note on Geological Time Scales

At the time of the work by Kaiser & Beetz (1926) the Eocene was generally considered to span a considerably longer period than it does in modern concepts of the term. Even though the Oligocene was defined by Beyrich in 1854, many authors did not use it until well into the 20th Century. Beetz (1926) barely mentions the term, but does list it in the Table of Formations as Posteocän (or "Oberoligocän bis Untermiocän" according to Stromer, 1926). The Palaeocene was defined by Schimper in 1874, but it too did not feature in many publications until the 20th Century. It wasn't formally accepted in the United States of America until 1939 (Berggren, 1998). Thus, for many scientists, including Kaiser & Beetz (1926) the Miocene was preceded by the Eocene and the Eocene was preceded by the Cretaceous (Pickford, 2008). Thus, the correlations of strata by Kaiser & Beetz (1926) to the Obereocän, Mitteleocän and Prä-mitteleocän should be considered in the light of this extended concept of the epoch. The correspondences are not precise but in today's parlance the Mitteleocän of these authors equates more or less to the Late Eocene: Bartonian (high sea level) while the Priabonian (low sea level) and Rupelian (high sea level) correspond to the Obereocän of Kaiser & Beetz (1926).

Thus, literal reading of Kaiser & Beetz's (1926) geochronology without understanding or taking into account the historical context of the time scale that they employed, results in (mis)correlations which are sometimes widely at variance with what the authors intended. Echoes of these mis-correlations are still encountered in recent literature on Sperrgebiet geology.

The Geological Time Scale utilised in this paper is based on Gradstein *et al.* (2004)

Previous studies and contentious issues

The earliest studies of the geology of the Northern Sperrgebiet were carried out by Merensky (1909), Range (1910), and Lotz (1913) who described aspects of the superficial deposits but did not publish any geological maps. Kaiser & Beetz (1926) in contrast, published six geological maps accompanied by large figures showing topographic profiles and other geomorphological data. They proposed a broad succession of events in the region that, with the exception of the Pomona Schichten, has withstood the test of time and further research, but which has from time to time been modified (often erroneously) by subsequent researchers. Fossils found by Beetz (1926) and others provided biostratigraphic control for some of the strata, notably Eocene marine faunas from Langental *Turritella* Site (Böhm & Weissermel, 1913) and Early Miocene mammals from Elisabethfeld and Langental (Stromer, 1926). These palaeontological discoveries from the marine and continental domains provided useful biostratigraphic anchors on which to moor subjacent strata. It should be noted, however, that the geological maps of Kaiser & Beetz (1926) give the age of the fossiliferous marine deposits at Langental as Miocene - an error flowing from preliminary field estimates of the age of the faunas - that was corrected in the text (Beetz, 1926) once the fauna was determined to have Middle Eocene affinities as understood at the time (Böhm & Weissermel, 1913) which is somewhat older than the present day estimate of Priabonian (Siesser, 1977).

Many researchers have subsequently commented on the geological sequence and timing of events in the Sperrgebiet, but many of the proposed revisions of the sequence and timing of events were poorly supported, or were based on insufficient knowledge of Sperrgebiet geology, or were founded on wide-ranging correlations to geological events in other parts of the world, either at continental scale, such as the African Surface (King, 1949) or marine such as the eustatic record (Stocken, 1978; Dingle *et al.,* 1983; Miller, 2008d). On a number of occasions erroneous data was introduced (Stocken, 1978) such as the altitude of the Eocene agate assemblage at Eisenkiesel-klippenbake (which lies at ca 145 m above sea level (asl) rather than 168 m, the altitude of the summit of the hill) which had deleterious effects on reconstructions of the geomorphological history of the region. Hallam (1964) gave an altitude of 150 metres for the agates at this site, which is close to the mark, but later in the same text he put the altitude at 170 metres and then wrote that the marine beds in the area extended to a height of 200 metres!.

Possibly the most recalcitrant problems encountered by the NPE concern the "silcretes" and "freshwater limestones" of the Sperrgebiet. There has been a great deal of confusion generated concerning the timing of, and processes involved in, the development of "silcrete" in the region and its correlation to silcretes in other parts of Africa, themselves correlated to the African Surface (Stocken, 1978; Partridge & Maud, 1989). As a result, the timing of Sperrgebiet "silcrete" genesis has proven to be contentious (Hallam, 1964; Dingle *et al.,* 1983) as has the nature of the rocks themselves. Subsequent to the work of Kaiser & Beetz (1926) all authors have assumed that the deposits of the Sperrgebiet called "silcretes" formed on land, an assumption implicit in the word. It transpires that by doing so most authors have accepted an extremely broad compositional and geomorphological definition for the "silcretes" of the Sperrgebiet, in effect calling all silica-rich rocks in the area "silcrete". By doing this they included a bewildering variety of rocks silicified at different times, all correlated to the Cretaceous (mid- or late- according to diverse authors such as Liddle, 1971) or Palaeocene. Pether (1986) and Corbett (1989) reported a geochemical duality in the composition of Sperrgebiet "silcretes" indicating diverse origins, but their results remained largely unheeded by subsequent researchers.

Our own examination of the Kätchen Plateau Formation reveals that at Tafelberg Nord it contains abundant vertical burrows with a composite internal structure suggesting an open central part in which the animal lived and moved up and down, surrounded by an agglutinated zone which prevented the walls of the burrow from collapsing inwards. We interpret these traces as “lebenspurren”. These ichnofossils imply that the Kätchen Plateau Formation probably accumulated in a shallow marine setting rather than on land. Silicification occurred once the deposits had been left emergent by a lowering of the sea level.

A major issue with interpretation of the Kätchen Plateau Formation is that about 80% of the quartzite previously attributed to it, is not *in situ*, but occurs as blocks of quartzite incorporated into younger encrustations comprising, in order of accumulation, ferruginised deposits of Oligo-Miocene age, and calc-crusts of Miocene and Plio-Pleistocene age (the Namib 1 and Namib 2 Calc-crusts).

A second contentious issue concerns the interpretation of the supposed “Freshwater Limestones” in the Sperrgebiet. Fossiliferous outcrops at Chalcedon Tafelberg at the inland edge of the Trough Namib were already identified as such by Kaiser & Beetz (1926) who considered that they were pre-Middle Eocene and predated (or formed part of) the Pomona Schichten (their texts and maps have both interpretations). Kalbskopf (1977) and Stocken (1978) in contrast, reported that the Chalcedon Tafelberg occurrence was of Miocene age, on the basis that the limestones overlie a monchiquite lava supposedly aged 15 Ma. However, the “lava” is an intrusion, and is deeply weathered, meaning that the age determination has a high probability of being inaccurate. Liddle (1971) considered that the limestones west of the Klinghardt Mountains in the Plain Namib represented a pre-Late Cretaceous “calcified land surface” that was then silicified. Kalbskopf (1977) reinterpreted the limestones in the Plain Namib as “freshwater limestones” infilling “breccia pipes” and considered that they accumulated contemporaneously with volcanic activity of Oligocene age. These authors also mentioned breccias of carbonatitic affinities which they correlated to the Cretaceous. All these rocks are Eocene.

A third area of widespread mis-understanding of Sperrgebiet geology concerns the processes which cause weathering and diagenesis. Weathering, in the sense of the sum of the processes altering rocks near the land surface resulting in the production of “alterite” from initially solid Basement rocks, which renders such rock friable and easily eroded, needs to be distinguished from near-surface diagenesis which results in cementation, encrustation, induration or alteration of loose surface rocks and superficial parts of the Basement making them more resistant to erosion. In the Sperrgebiet both classes of processes have been active through the Cenozoic, and on occasion, some geologists have failed to distinguish between the two. For example, ferruginous rock masses in the Sperrgebiet have often been pooled together, yet bohnerz was produced by weathering processes related to pedogenesis, implying warm, humid conditions, whereas much of the ferruginised rock in the region resulted from the circulation of groundwater carrying ferrous iron which precipitated near the surface as it was oxidised to ferric iron.

In addition, in the Sperrgebiet, there were two quite distinct pathways by which diagenesis of surface rocks leads to their induration, implicating 1) underground water and 2) atmospheric water. Firstly, hydro-thermal activity related to the Ystervark and Klinghardt volcanism resulted in alkaline water containing dissolved silica circulating outwards from the deep-seated magma chamber beneath the Klinghardt Mountains towards the ancient land surface where it interacted with fresh groundwater in porous rocks near the surface, whereupon silica (and sometimes other minerals such as copper oxides) precipitated, leading to widespread but thin and discontinuous silicification of near-surface rocks of the Northern Sperrgebiet. Secondly, induration of loose clasts at the ancient land surface was achieved by moisture condensing from the air, dissolving carbonate in superficial dust, transporting it downwards a few cm, then evaporating. Repeated many times, this process led to the development of the Namib Calc-crusts which are widespread in the Northern Sperrgebiet. It is stressed that these calc-crusts are not calcretes in the strict sense of the term and they are not “calcified hard-pan soils” (Corbett, 1989). They are the result of many cycles of wetting by condensation and drying by evaporation, the principal source of moisture being fog or rare desert rainfall. These calc-crusts do not respect topography, since they formed in depressions, up sloping ground and at the tops of hills, often “molding” the ancient relief, as for example at

Chalcedon Tafelberg, where the Namib 1 Calc-crust capping the hill drapes down its northern flank into the valley some 30 to 40 metres below the summit. Similar calcareous deposits of Miocene and Plio-Pleistocene age cap the tafelberge at Marien Berg, Langer Tafelberg, Kätchen Plateau, Elfert's Tafelberg and other mesas in the Pomona area (previously included in the Pomona Schichten (Pomonakalke)). In brief, the processes producing calc-crust consolidated loose surficial material wherever it lay given that all the conditions for its genesis were met and repeated often enough over sufficiently extended periods of time.

Recent surveys by the Namibia Palaeontology Expedition, which included field mapping and some petrographic analysis of carbonates, reveals that most of the rocks attributed to the "freshwater limestones" represent airfall carbonatite ash (and their reworked and silicified derivatives) of Lutetian to Bartonian age, overlying bleached dolomite and other alterites, some of which were mistakenly included in the category of "freshwater limestone" (map by Fowler & Liddle, 1970). Partial to complete silicification of these Eocene rocks and the underlying bleached dolomite led to their being correlated to the Cretaceous on the erroneous grounds that all the "silcrete" in the Sperrgebiet was of this age (Liddle, 1971; Kalbskopf, 1977; Miller, 2008d). It is stressed that the Ystervark Carbonatite activity intermittently injected vast amounts of carbonate into the sub-aerial environment over a substantial period, which altered the surficial geochemical environment in many ways, including the soil environment (cf modern Serengeti in Tanzania-Kenya, in which sub-climax vegetation has persisted for more than a million years).

The Namibia Palaeontology Expedition has found fossil plants and animals at a number of localities in partly or completely silicified well-bedded limestones. These discoveries reveal that most of the so-called "silcrete" in the Sperrgebiet is not silcrete in the strict sense of the term, but represents silicification of near-surface rocks including limestone during the Late Bartonian and Early Priabonian as a result of hydrothermal activity related to Ystervark and Klinghardt volcanism, rather than by the usual processes of silcrete genesis. Palaeontological discoveries at several sites indicate that the main period of limestone deposition spans the Lutetian and Bartonian and that silicification was penecontemporaneous with and post-dated it. The palaeofaunas provide secure biostratigraphic anchors by which most of the Palaeogene geological events in the Sperrgebiet can be assessed.

Lithostratigraphic Nomenclature and Biostratigraphy

Early work

Among the early reports dealing with the geology of the Sperrgebiet is the paper by Merensky (1909). He reported that the brownish sands near Kolmanskop were Cretaceous, even though his initial interpretation while still in the field, carried out with Mr Frames, suggested that the deposits were "somewhat recent sea deposits". What occurred is that towards the end of his stay in the Sperrgebiet (which hadn't yet been declared off limits: that happened in 1910) Merensky met some prospectors who had collected fossils from Bogenfels (Merensky did not specify the area in his paper, nor did he visit the site) which he thought were from similar sands and which he interpreted to be Cretaceous (based on his identification of three taxa of molluscs: *Protocardium hillanum*, *Zaria bonei*, *Turritella meadi*). The brownish sands at Kolmanskop are Pleistocene as shown by the presence of eggshells of *Struthio daberasensis* in them (Pickford & Senut, 1999). Thus his first impression as to the age of the sands was much closer to the mark than his published estimate based on fossils from a site almost 100 km away. The sandy deposits are nowadays interpreted as having accumulated as aeolian sands rather than as marine sands (Greenman, 1966; Corbett, 1989). Perhaps Mr Frames realised the contradiction, which is why he left Merensky to publish his revised interpretation on his own.

Range (1910) put the record straight that Merensky's (1909) supposedly Cretaceous fossils were from the Bogenfels area. He correlated the fauna to the Cenomanian.

Although there is room for doubt, it is highly likely that the fossils that Merensky was shown came from the immensely rich Langental *Turritella* Site, and are thus of Priabonian age if Siesser's (1977) correlation is valid. Range (1910) estimated that the

Buntfeldschuh deposits were Cretaceous Danian, and thus younger than the Bogenfels fauna as understood at that time.

In these two publications we detect a somewhat cavalier approach to geological field relationships and biochronology. We also observe an underlying tendency to impose a Cretaceous chronology on the Sperrgebiet on the flimsiest of evidence, a tendency which, in modified forms, has continued to this day. These authors interpreted what they saw (or didn't see) in terms of the geological successions elsewhere in Southern Africa, for Merensky (1909) notably the successions at Uitenhage and Umtamvuna, with the apparent expectation that the Sperrgebiet would be endowed with similar deposits to what he had observed elsewhere in the subcontinent.

As a result of detailed mapping carried out by Kaiser & Beetz (1926) the geological evidence concerning the Northern Sperrgebiet became far better documented, but the theme of a Cretaceous underpinning to the Pre-Eocene deposits was still present, even though in a weakened version, and based on different rocks (alterites instead of marine deposits). It was only with the report of an ammonite at Wanderfeld IV near Bogenfels (a fossiliferous sediment occurrence only a few square metres in extent) that the presence of Cretaceous rocks in the region was finally given some credibility (Haughton, 1930a, 1930b; Cooper, 1974; Klinger, 1977). There is some doubt concerning the occurrence. Is it really *in situ*? Despite their attention to Sperrgebiet palaeontological sites, all of which are marked on the maps that they published, Kaiser & Beetz (1926) did not mention the presence of fossils at Wanderfeld IV, and no fossils occur in the trommel screen heaps surrounding the occurrence nor in the fines dump only 20 metres from it.

Table 1. Translation of the Table of Formations in Beetz (1926)

Table of Formations

	River deposits	Limnic and terrestrial deposits	Marine beds
Pliocene	Small outcrops in the Pomona region	Regional deposition of thick older calc-crust of the Inner Namib (*Trigonephrus*)	Old lagoon and beach deposits (perhaps Diluvial)
Post-Eocene (in part Upper Oligocene to Early Miocene according to E. Stromer)	Younger floodplain: younger fluvial cover with stone and gravel deposits mostly preserved in channels; pebbles with fresh feldspar.	Dune sand at Buntfeldschuh; calcareous sandstone in river channels (*Trigonephrus*); fauna from Elisabethfeld, Bogenfels, Betrieb IV, Freshwater limestone (Gamachab Fauna)	
Upper Eocene and Middle Eocene (according to J. Böhm)			Marine beds, beach facies; fauna from Bogenfels, Buntfeldschuh, sandstone, clay, marl, gravel banks with many agate pebbles
Pre-Middle Eocene, partly combined with eruptive rocks, with the oldest beds as early as Cretaceous	Quartzite Gravels : Older fluvial deposits; gravel outflowing in broad terraces; stone and gravel deposits with decayed feldspar stones, calcareous sandstone, in part silicified	Pomona Beds : arid cover, today existing as Tafelberge and buttes; calcified and silicified; sandstone, quartzite, limestone, localised gravel banks; freshwater limestone, often silicified, with fossils	
	Quartzite Gravel and Pomona Beds, infilling irregularities (sinks, cauldrons and dolines) on an ancient landsurface.		
Perhaps Cretaceous		Weathering crust on an old land surface	

Beetz's (1926) Table of Formations represents a summary of the geological activity in three depositional environments: 1) fluvial, 2) limnic and terrestrial, and 3) marine. It shows an alternation of non-marine and marine activity which gives the false impression that onland geological activity ceased during what he termed the *Eocene High Sea Stand*, and that marine activity ceased during the regressive periods before and afterwards. This is certainly not the case (and probably was not intended), but largely arises from the fact that the focus of the geological maps by Kaiser & Beetz (1926) was the Trough Namib (Flächennamib). Mapping by Van Greunen (undated) and Fowler & Liddle (1970) extended the map coverage into the Plain Namib (Innennamib), but the lithological subdivisions of Beetz (1926) were largely retained by these authors (with some misunderstandings and erroneous translations).

This way of presenting the data meant that the fluvial deposits of the Sperrgebiet were subdivided into two units "*Older Gravel*" and "*Younger Gravel*" separated in time by a hiatus corresponding to the period of deposition of Eocene marine strata. No-one appears to have realised that fluvial activity on land would not cease simply because the sea-level rose, with the result that gravels deposited during the time of high sea-level were conceptually shoe-horned into either the "*Older Gravel*" or the "*Younger Gravel*". These same terms were employed by later geologists such as Van Greunen (undated) but the "*Older Gravels*" eventually got called the *Blaubock Gravel* (Stocken, 1978) and the "*Younger Gravel*" was named the *Gemsboktal Gravel* (Stocken, 1978). Unfortunately, in naming the *Blaubock Gravel* after the Blaubock Beacon, north of Bogenfels, Stocken (1978) selected a type area where the age of the deposits is questionable. Beetz (1926) considered them to be "*Older Gravel*" but Corbett (1989) considered them to be Post-Eocene (in fact Miocene) on account of the fact that the gravels appear to delimit the inland edge of the distribution of agates. He thought it possible that the gravels overlapped the agate deposits, and must therefore be younger than them. Our own interpretation of this area is that the gravels around Blaubock beacon are mostly the same age as the marine deposits at Langental *Turritella* site a few km to the south, but some are somewhat older (reworked in the marine environment and incorporated into beach deposits) and some are younger, unconformably overlying Priabonian marine deposits at Langental Shark Site.

The only Cenozoic sedimentary units formally named by Kaiser & Beetz (1926) were the *Pomona Schichten*, which subsumed the *Pomona Quartzite* and the *Pomonakalke*. The *Pomona Schichten* as employed by Kaiser & Beetz (1926) is a composite unit assembling a large variety of rock types, now known to span the Lutetian, Miocene and Plio-Pleistocene periods. Later authors tended to lump all these rocks together (Van Greunen undated) but over the years the name Pomona became especially attached to the quartzites that cap the tafelberge. The *Pomonakalke* of the Trough Namib turns out to be the same as the *Namib 1* and *Namib 2 Calc-crusts* of the Plain Namib.

The remainder of the sedimentary facies of the northern Sperrgebiet were described by Kaiser & Beetz (1926) but were not named. Instead they were given abbreviations based on the facies observed (Annex 2). Quite a few of these facies were eventually given names by authors who had in cases not seen the rocks they were naming. The outcome was a highly confusing history of nomenclature. For example, the imaginary "silcrete" of the Sperrgebiet (Hallam, 1964) was named the *Chalcedon Tafelberg Silcrete* (SACS, 1980) the type area being an exposure of silicified freshwater limestone rich in palustral fossils of Eocene age. Once this impossibility was understood, the silcrete was renamed the *Pomona Silcrete*, but because Kaiser & Beetz (1926) had already used the name for the *Pomona Beds*, the still imaginary silcrete was renamed the *Kätchen Plateau Formation* (Miller, 2008d) based on strata at the Tafelberge which are not silcretes.

Remapping of the Tafelberge by the Namibia Palaeontology Expedition reveals that the *Pomona Schichten* of Kaiser & Beetz (1926) comprise a highly heterogeneous and heterochronic suite of rock types, only united by their tendency to crop out near the tops of high relief areas in the Trough Namib, to overlie altered Basement rocks and to be heavily indurated. For example, the symbol "bq" assembles quartzite of Palaeogene age and calc-crust (*Namib 1* and *Namib 2 Calc-crusts*) of Mio-Pliocene age (*Trigonephrus* and *Struthio daberasensis* present in the *Namib 2 Calc-crust*). The symbol "bfe" comprises ferruginised lag deposits on terraces some 5-20 metres beneath the summits of the tafelberge, and they incorporate clasts of Kätchen Plateau Quartzite proving that they post-date the Sperrgebiet Silicification Event. The terraces long post-date the neighbouring tafelberge, and the lag deposits covering their surfaces were ferruginised during the Late Oligocene to early-middle Miocene. The definition of the deposits (see legend of Map 4 in the annex) as "*limonite-cemented quartzite at the base of the Pomona Beds*" gives a false impression that they underlie the rest of the *Pomona Beds*. They are lower in altitude, but they do not stratigraphically underlie the quartzites although they do underlie the Namib 1 Calc-crust. A further point to note is that many of the outcrops previously mapped as *in situ* quartzite from which a "Cretaceous" age was inferred for the outcrops, comprise in reality, derived but often closely packed blocks of quartzite embedded in Namib 1 Calc-crust, and are thus reworked into a Miocene deposit. A good example of this is provided by the small hillock close to the abandoned Sonneberg Camp at Kätchen Plateau.

The geological maps published by Kaiser & Beetz (1926) have legends that vary from map to map (Annex 2). The text accompanying the maps presents an overview of the Pre-Neogene rock types. A translation of the part of the table devoted to the Tertiary is provided in Table 1.

Much of the geological map of Van Greunen (undated) covering the *Trough Namib* is basically a clone (with some errors and oversimplifications) of the results of Kaiser & Beetz (1926) with the exception of the parts of the *Plain Namib* which were new. The geological map by Fowler & Liddle (1970) added a great deal of detail about the Klinghardt Mountains, and the zone immediately west of them, thought at the time to encompass various volcanic pipes of parakimberlitic affinities.

Other geologists have added detail to these major mapping enterprises (Greenman, 1966; Corbett, 1989; Pickford & Senut, 1999; Pickford, 2008; Pickford *et al.* 2008) but they did not fundamentally change the results of previous mapping.

Nomenclature of rock units in the Sperrgebiet

The nomenclature of Tertiary rocks in the Northern Sperrgebiet, Namibia, has developed into a complex gordian knot. There are several instances of homonymy, some less problematic issues of synonymy, but most of all, there has been alot of rather loose application of identical place names to diverse rock types. There has been confusion between the genesis and diagenesis of the rocks, especially those that have suffered marked post-depositional changes, with, in certain cases, the products of the diagenetic changes defining the stratigraphic position of the rock unit rather than the nature of the original deposits. For example, the silicified upper part of the *Pomona Schichten* of Kaiser & Beetz (1926) was defined as a separate *Kätchen Plateau Formation* by Miller (2008d) whereas, as originally defined, it is the silicified upper part of the *Pomona Beds*, now known to contain lebenspurren signifying a shallow marine depositional environment. The contact between the quartzite and the underlying beds is gradational in all cases examined, indicating that the less consolidated base is part and parcel of the same stratigraphic units as the heavily silicified upper part, and should not be given a separate formational name.

Previously Defined Rock Units in the Northern Sperrgebiet

The following is a résumé of the names applied to Palaeogene (and some Miocene) rock units in the Northern Sperrgebiet. It is intended to provide an encapsulated history of the nomenclature employed by various authors so that readers can obtain a better understanding of the literature regarding the rocks.

Observant students will notice that there is a great deal of uncertainty about the contents of some of the units, and they will deduce the presence of rampant homonymy and synonymy in the published and unpublished literature. The treatment of the rock units is in alphabetical order, whereas within each named unit, the discussion is mostly by chronological order of publication. Some geomorphological terms are included in order to complete the context of the stratigraphic work.

Arries Drift Gravel Formation

Arries Drift Gravel Formation, also known as *Arrisdrift Formation*, consists of fossiliferous gravels which accumulated in an abandoned loop of the Orange River (Ward & Corbett, 1990). Mammals from the site indicate an age of ca 17.5 Ma (Pickford & Senut, 1999). The deposits are also known informally as the *Proto-Orange Terrace at Arrisdrift* (Pickford & Senut, 1999).

Blaubock Gravel Formation

"*Quartzitschotter*" of Kaiser & Beetz (1926) was named *Blaubock Beds* by Stocken (1978) for the gravel deposits cropping out around the beacon at Blaubock. These deposits were referred to the *Blaubock Gravels* by Corbett (1989) and *Blaubock Gravel Formation* by Miller (2008d) and *Blaubock Gravels (No phonolite clasts)* by Jacob *et al.* (2006). The *Blaubock Gravel*, which lacks phonolite pebbles (in contradiction of the original description by Beetz, 1926) is distinguished from the *Gemsboktal Gravel*, which contains abundant phonolite pebbles (Van Greunen, undated; Jacob *et al.* 2006). This distinction between the two gravels carries no stratigraphic implications, because gravels with and without phonolite cobbles have been deposited somewhere in the Sperrgebiet throughout the Late Palaeogene and Miocene depending upon the availability or absence of phonolite cobbles in the watershed of the drainage systems. Yet it is clear from the literature that the presence or absence of phonolite cobbles has generally been interpreted in stratigraphic terms (Miller, 2008d). See for example Jacob *et al.* (2006) and Pickford *et al.* (2014). This has caused much confusion. Corbett (1989) thought that the *Blaubock Gravel* was Miocene because it overlies agate-bearing Priabonian marine beds in its type area. This is true at the Langental Shark Site. Miller (2008d) in contrast considered that the *Blaubock Gravel* was older than 46 Ma and thus the oldest post-Cretaceous sediment deposit in the Sperrgebiet on the grounds that it underlies the basal agglomerate at Pietab 2. Jacob *et al.* (2006) dated the gravel to 55 Ma. From this it is clear that the *Blaubock Gravel* as previously interpreted, comprises several distinct lithological units deposited at widely varying times. In its type area, Blaubock Beacon, the gravels are Priabonian to Rupelian in age, on the grounds that some are incorporated into the marine deposits of Priabonian age at Langental *Turritella* Site, and others overlie the Priabonian marine deposits at Langental Shark Site, for example.

Black Crow Carbonate

Black Crow Carbonate was introduced by Pickford *et al.* (2008) for the fossiliferous palustral limestones, partly silicified, which crop out in the Black Crow Basin, north-east of Bogenfels. It was previously included by Kaiser & Beetz (1926) in the Pre-Middle Eocene ("bks" – Kalksandsteine mit vereinzelten Geröllen und wechselden Korne: Calcareous sandstone with few pebbles and of varied grain size). It unconformably overlies well-stratified, partly silicified *Black Crow Siliceous Limestone* (silicified *Plaquette Limestone*) which in turn overlies pale green to white quartzite (previously attributed to the *Pomona Quartzite*, but not as heavily silicified as the occurrences at Pomona and of a different colour) which reposes on Precambrian Gariep Group Dolomite. It is unconformably overlain by *Blaubock Gravel* which is cemented by the *Namib 1 Calc-crust* with copper staining and light silicification, in its turn overlain by *Gemsboktal Gravel* and Namib 2 Calc-crust, followed by loose sand.

Bo Alterite

Bo Alterite is defined here as the red weathering debris containing Bohnerz (literally "Bean Ore" - iron oxide pisoliths) and angular chunks of weathered bedrock and associated weathered and altered bedrock of various colours ranging from brown to white, affecting dolomite and other rocks of the Precambrian Gariep Group. The type area is a depression in the scarp 1-2 km north of Chalcedon Tafelberg mapped as "bo" by Kaiser & Beetz (1926). Other outcrops occur beneath Palaeogene limestones at Chalcedon Tafelberg, and widely over the Sperrgebiet as far north as Schwarzer Berg (also spelled Schwarzerberg) where it is overlain by *White House Silcrete*, and as far south as Buntfeldschuh (and beyond).

Buntfeldschuh Formation

The Buntfeldschuh deposits were first described in detail by Beetz (1926) as the *Marine Eocän der Buntfeldschuhsenke*. He explicitly excluded the sandstones above the marine beds calling them *Terrestre Sandstein*. Hallam (1964) referred to the *Buntfeldschuh Beds* and mentions the capping of calcrete and ferricrete (at Kakaoberg). Siesser & Salmon (1979) called the sediments the *Buntfeldschuh Beds*. Dingle *et al.* (1983) included the *Kakaoberg Sandstone* in the *Buntfeldschuh Beds* along with the underlying marine strata. Corbett (1989) recognised two formations, a *Lower Buntfeldschuh Formation* comprising lower and upper marine units and an *Upper Buntfeldschuh Formation* comprising the *Kakaoberg Sandstone Member*. Partridge & Maud (1989) referred to the *Buntfeldschuch* (sic) *Formation*. Ward & Corbett (1990) placed the base of the *Buntfeldschuh Formation* at 54 Ma ranging upwards to ca 43 Ma. Pickford & Senut (1999) positioned the *Buntfeldschuh marine levels* at 43 Ma, with a question mark.

Chalcedon Tafelberg sandy marl

Chalcedon Tafelberg sandy marl was mentioned by Pickford *et al.* (2008) for the red and green marly sandstones that occur under and intercalated with the well-bedded limestones at Chalcedon Tafelberg. The basal layers of sandy marl overlying Gariep Group dolomite, correspond to the *Bo Alterite* which had not been defined at the time of 2008 publication.

Chalcedon Tafelberg siliceous limestone

Chalcedon Tafelberg siliceous lime-stone was an informal term introduced by Pickford *et al.* (2008) to refer to the well-bedded limestone and fossiliferous silicified limestone that crops out at Chalcedon Tafelberg. The basal layers are equivalent to the *Plaquette Limestone* and the upper layers are palustral, freshwater limestones rich in molluscs and aquatic plant remains. It is underlain by *Bo Alterite*, and is unconformably overlain by *Namib 1 Calc-crust* which forms the cap of the hill and drapes down into the valley north of it. There is also a limburgite (or monchiquite) dyke beneath the limestone.

Chalcedon-Tafelberg Silcrete (obsolete)

Chalcedon-Tafelberg Silcrete was named by SACS (1980) for the silcrete capping on the African Surface in the Sperrgebiet. Corbett (1989) referred to the *Chalcedon Tafelberg Silcrete Formation* and concluded that it represents a lateral facies variation of the *Pomona Beds*, and should thus be named the *Pomona Silcrete*. This is an interesting inference suggesting that the lime-stones and quartzites were silicified by the same event, a result supported by the findings of the Namibia Palaeontology Expedition, although the timing of the silicifiction event is considerably different (Cretaceous for Corbett, 1989, Lutetian to Bartonian for the Namibia Palaeontology Expedition).

In contrast, Ward & Corbett (1990) referred to the *Chalcedon-Tafelberg Silcrete Formation* (*Pomona Silcrete*) and positioned it at 65 Ma, while Miller (2008d) pointed out that the *Chalcedon Tafelberg Silcrete* was formed by a different process and at a different time from the silcrete capping the Pomona Tafelberge. He concluded that the name must be abandoned, and that the silcrete near Pomona should be renamed the *Kätchen Plateau Formation*.

Elizabeth Bay Formation (Elisabeth in the German literature)

Elizabeth Bay Formation was named by Greenman (1966). It was modified by later researchers who removed the *Fiskus Sandstone* and the *Onyx Limestone*, and added the Early Miocene marls and nodular limestone at Langental mammal site and the Early Miocene fossiliferous green clays at Grillental and Fiskus.

Eocene Sea Highest Strandline

Eocene Sea Highest Strandline was mapped by Beetz (1926, fig. 6) as the *Höchster Stand der Eocänsee*. It runs generally northwestwards from Buntfeldschuh to Lüderitzfelder and encloses all the deposits containing agates and chalcedony pebbles brought into the area during the "*Eocäne Marine Inundation*" (Kaiser, 1926b). Liddle (1971) extended the strandline a few kilometres northwards to Elfert's Tafelberg. Martin (1973) drew a rather different strandline, with a much more irregular course. Dingle *et al.* (1983) dated the strandline to the late Palaeocene – early Eocene.

Ferricrete (informal)

Ferricrete was employed by Hallam (1964) for the ferruginised *Kakaoberg Aeolianite* at Kakaoberg. It is not a ferricrete in the strict sense of the term.

Freshwater Limestone Depressions

Freshwater Limestone Depressions were mapped by Kalbskopf (1977). These crop out in a north-south belt immediately west of the Klinghardt Mountains. Remapping of the depressions reveals that they are not crater infillings as originally thought, but comprise erosional depressions with an underlying structural component, the depressions coinciding with the positions of small closed synclines a few hundred metres in diameter within an elongated synform structure developed in Precambrian rocks. The carbonates infilling the depressions are comprised of airfall carbonatite tuffs, reworked tuffs, palustral limestones and scoriaceous carbonatite eruptives. Inspection of the maps of Fowler & Liddle (1970) and Kalbskopf (1977) indicates that much of the supposed "*freshwater limestone*" that they mapped consists of bleached dolomite of Precambrian age.

Gabis Felder Conglomerate

Gabis Felder Conglomerate is here defined as the olive green silicified conglomerate exposed east and southeast of Granitberg, in the upper reaches of the Langental. The outcrops in this region were included in the *Pomona Schichten* by Kaiser & Beetz (1926) map symbol "bq". They overlie dolomite and silicified dolomite and are in their turn overlain by *Gemsboktal Gravel* and unconsolidated sand. Van Greunen (undated) mapped these outcrops as *freshwater limestone*. They are likely slightly younger than the Kätchen Plateau Quartzite, but are in any case probably Late Lutetian-Early Bartonian in age.

Gemsboktal Formation

The unit corresponds to the gravels mapped as "bF" *Flussschotter mit unverwitterten Geröllen* of Kaiser & Beetz (1926). *Gemsboktal Beds* were, for Stocken (1978) distinguished from the *Blaubock Gravels* by the presence in them of vast quantities of phonolite pebbles. Ward & Corbett (1990) positioned the *Gemsboktal Gravel* at 16 Ma, close in age to the *Arries Drift Gravel Formation*. However, in the lower reaches of Gemsboktal, the unit is of Late Miocene age, and consists of two layers of gravel (*Lower Gemsboktal Conglomerate* and *Upper Gemsboktal Conglomerate*) separated from each other by an aeolianite, the *Terrassenfeld Aeolianite Member*.

Glastal Grits

Glastal Grits, an informal name applied to white, cross-bedded arkosic grits exposed in the Lower reaches of the Glastal, was incorporated into the *Kalkrücken Sandstone* by Corbett (1989) on the grounds that they are intercalated with beds of the latter unit. Ward & Corbett (1990) referred to the *Glastal Beds* and linked them to the *Grillental Beds*, the *Elizabeth Bay Beds*, and "*Langental*" (in quotation marks). The deposit is Early Miocene in age, having yielded a few mammal fossils similar to those at Langental Mammal Site. Pickford & Senut (1999) referred to the fossiliferous levels as the *Glastal Marls*. Pink calcareous nodules in the unit yield large shells of the land snail *Dorcasia* and a few of *Trigonephrus*. The unit is equivalent in age to the Langental Mammal Site and to the *Strauchpfütz Carbonate*.

Granitberg-Bogenfels Formation

Granitberg-Bogenfels Formation was first described by Beetz (1926) as the *Marine*

Eocän der Granitberg-Bogenfelssenke. *Granitberg-Buntfeldschuh Beds* is a term used by Stocken (1978) for the Eocene marine deposits exposed in the Granitberg area north of Bogenfels, in the Buntfeldschuh Cliffs and at Eisenkieselklippenbake. Corbett (1989) and Partridge & Maud (1989) called the Marine sediments at Langental the *Langental Beds*, while Jacob *et al.* (2006) used the term *Langental (Marine) Beds* in order to differentiate them from the fossiliferous terrestrial sediments of Early Miocene age at Langental.

Grillental Beds

Grillental Beds were named by Greenman (1966) for the fossiliferous green clays in the Grillental and at Elizabethfeld. As originally employed it was the basal subdivision of the *Elizabeth Bay Formation*, the latter being a composite unit comprising strata of widely divergent genesis and times of deposition. Stocken (1978) wrote that the *Grillental Beds* were part of the "*Jungere Revierzeit*" of Beetz (1926) and he extended the name to encompass the Early Miocene marls that yield the Langental Mammal fauna. Stocken (1978) included the basal marls exposed in Chalcedon Tafelberg in the *Grillental Beds* on the basis of an age determination of 15 Ma on a weathered monchiquite sample thought to represent a lava flow underlying the marls. Jacob *et al.* (2006) referred to the *Elizabeth Bay Formation (Grillental Clay Member + Langental (Terrestrial Beds))*. Miller (2008d) discussed the *Elizabeth Bay Formation*, comprised of the *Langental Member* and the *Grillental Clay Member*.

Höchster Stand der Eocänsee

See Eocene Sea Highest Strandline

Innennamib

Innennamib is a term introduced by Kaiser & Beetz (1926) for the relatively undissected country inland from what they termed the *Flächennamib* (*Trough Namib*). It is a synonym of the *Plain Namib* of Stocken (1978).

Kakaoberg Sandstone Member

Kakaoberg Sandstone Member was described and named by Corbett (1989) as a subunit of the *Upper Buntfeldschuh Formation* but being the only subunit of the formation it is automatically a synonym of it. In order to avoid confusion with the deltaic-marine *Lower Buntfeldschuh Formation*, the name *Upper Buntfeldschuh Formation* should be abandoned, and the name *Buntfeldschuh Formation* should be confined to the deposits lying between the *Kakaoberg Sandstone Formation* above and the weathered Basement rocks below (*Bo Alterite*).

Kalkrücken Sandstone

Kalkrücken Sandstone, informally used to denote the basal, red, carbonate-cemented sandstone in the Lower Glastal, was defined by Corbett (1989) as the equivalent of what Beetz (1926) called the *Kalksandsteine in Revierrinnen*, a carbonate cemented red sandstone interbedded with calcified white, cross-bedded feldspathic grits. Fossils from the basal part of the unit, informally called the *Glastal Grits* or *Glastal Marls*, yield Early Miocene faunal elements. It is clear that as described by Corbett (1989) the *Kalkrücken Sandstone* comprises a heterogeneous suite of strata, because it incorporates a deep-red calc-crusted aeolianite which is interbedded between two horizons of *Gemsboktal Gravel*. Ward & Corbett (1990) positioned the *Kalkrücken Sandstone* at ca 25 Ma. Fossils from the base of the unit (*Glastal Grits*) are Early Miocene while those from the reddish aeolianite (here called the *Terrassenfeld Aeolianite*) are Late Miocene (Pickford & Senut, 1999).

Kätchen Plateau Formation

Kätchen Plateau Formation was defined by Miller (2008d) as a dense silcrete capping the *Pomona Beds*. Included in the formation were outcrops at Lüderitz Krater; Swartkopp (sic) and the Schwarzer Berg Area, north and northwards thereof towards Dreizack Berg and NE of the latter. He considered the silicified ferricrete at Kerbehuk to be part of the formation. He was of the opinion that these silicified deposits comprised part of the African Surface despite divergent opinions concerning their genesis - silicified aeolian sands according to Stocken (1978) or silicified erosion lags according to Corbett (1989). Namibia Palaeontology Expedition survey reveals that the silicified sand at Tafelberg Nord contains abundant lebenspurren probably indicating a shallow marine origin for the quartzite which poses questions concerning its age and depositional environment, but most importantly, distancing it genetically and chronologically from the silcretes of the African Surface.

Kaukausib Carbonatite

Kaukausib Carbonatite crops out on the south bank of the Kaukasib Drainage (Miller, 2008b). No details are provided by Miller (2008b) although Verwoerd (1993) discussed the occurrence.

Keishöhe Carbonatite

Keishöhe Carbonatite was summarised by Miller (2008b) following pioneer studies by McDaid (1978) and Verwoerd (1993) as forming low hills 4 km SE of Keishöhe Railway Siding exposing sills of beforsite and ironstone lenses containing alunite cut by narrow dykes of beforsite or microbreccias.

Klinghardt Breccia Pipes

Klinghardt Breccia Pipes were named by Kalbskopf (1977). Because the name Klinghardt has already been used for the *Klinghardt Phonolites*, Pickford *et al.* (2014) included the breccias in *Ystervark Carbonatite Formation*, the type area being Ystervark Hill named for the porcupines that live on it.

Klinghardt Phonolite Formation

Klinghardt Phonolite Formation of Corbett (1989) Ward & Corbett (1990) and Jacob *et al.* (2006) comprises phonolite flows and intrusions in the Klinghardt Mountains, Swartkop and other parts of the Northern Sperrgebiet. Dingle *et al.* (1983) dated the phonolites at 37 +/- 1 myr and 35.7 myr based on the publication of Kröner (1973). Ward & Corbett (1990) positioned them at 38 Ma. Pickford & Senut (1999) positioned the phonolites at 37 Ma. Pickford *et al.* (2014) dated cobbles of phonolite collected at Black Crow and Granitbergfelder 15 to the Lutetian. See Marsh (1987) for petrographic and geochemical analyses.

Langental Beds

Langental Beds were formally named by Siesser & Salmon (1979) following work by Klinger (1977) for the Priabonian Marine strata cropping out at Wanderfeld IV north of Bogenfels. *Langental Beds* was employed by Ward & Corbett (1990) for marine strata. Note that Jacob *et al.* (2006) employed the name *Langental Member* as a geographic sub-unit of the *Elizabeth Bay Formation* comprising fossiliferous Early Miocene terrestrial deposits cropping out north of Bogenfels Ghost Town. In this usage it is a junior homonym of the marine *Langental Beds* of Siesser & Salmon (1979).

Lüderitz Alkaline Province

Lüderitz Alkaline Province Miller (2008a, 2008b) provided a summary of the rocks covered by this term. It includes the *Klinghardt Phonolites* of Cenozoic age as well as Mesozoic intrusives close to the coast, and is thus a composite suite of rocks. The term should be confined to the coastal intrusives of Mesozoic age.

Lüderitz Krater

Lüderitz Krater is a roughly circular, saucer-shaped hill in a broad valley southwest of Chalcedon Tafelberg which has an infilling of probably Late Eocene beach gravels rich in agates (Beetz, 1926). Some of the agates have been incorporated into goethitic-limonitic cobbles which formed during the Late Oligocene to Early Miocene ferruginisation event. Thought to be underlain by *Pomona Quartzite* (Beetz, 1926) or *Kätchen Plateau Formation* (Miller, 2008d) the saucer structure may be somewhat younger than the quartzites which cap the Tafelberge in the Pomona area, possibly correlating to the Gabis Felder Conglomerate. It is not a volcanic crater: despite the name, it has nothing to do with the *Lüderitz Alkaline Volcanic Province*. The north-south axis of the hill has been breached by erosion exposing altered Basement rocks in the floor of the “saucer”, visible beneath a thin veneer of agates, but the margins of the breach are comprised of an abundance of locally derived quartzite blocks which give the impression of continuity with the neighbouring *in situ* quartzite. In his geological map of the northern Sperrgebiet, Van Greunen (undated) misplaced the structure 3 km northwest from its proper location.

Namib 1 Calc-crust

Namib 1 Calc-crust comprises pale cream to grey calcareous duricrusts in the Northern Sperrgebiet cementing varied superficial rock types. The cementation processes affected not only pre-existing deposits but also incorporated loose sand and rubble into the duricrust. In the *Trough Namib*, it occurs at the top of Chalcedon Tafelberg, Elfert's Tafelberg, Marien Berg (where it comprises the pale cream calc-crust (lower limestone) attributed to the *Pomonakalke* by Beetz, 1926) as well as at Langer Tafelberg and widely in the Pomona are. It is evident that there has been modest vertical accretion as loose sand blown onto the duricrust was cemented into it by ongoing encrustation. At Langer Tafelberg and Elfert's Tafelberg, the *Namib 1 Calc-crust* overlies a thin bed of ferruginised granule lag lying atop altered Basement rock, and encloses abundant, large blocks of Kätchen Plateau Quartzite, none of which are *in situ* in their original depositional environment. In other places such as some of the Tafelberge (Liddle, 1971) and in the *Plain Namib* at Eocliff and Eoridge, the *Namib 1 Calc-crust* cementing activity penetrated deeply into fissures in the underlying rocks and infilled them with calc-crust. In cases the crystallisation pressures resulted in displacement of blocks relative to each other. In the sector between Black Crow and Silica North, the *Namib 1 Calc-crust* shows pale green staining (probably copper oxides) and in many outcrops it is slightly silicified, as was already noted by Kaiser & Beetz (1926). There may be two periods of calc-crust activity superimposed on each other. This unit corresponds to the *Older Calcrete* of Van Greunen (undated).

Namib 2 Calc-crust

Namib 2 Calc-crust comprises a pink to deep red or mauve, often nodular, duricrust which cements superficial rocks of the Northern Sperrgebiet. It corresponds to the *Younger Calcete* of Van Greunen (undated). In places such as Granitbergfelder 15, Marien Berg and Langer Tafelberg, the *Namib 2 Calc-crust* is observed to overlie *Namib 1 Calc-crust*. The *Namib 2 Calc-crust* is often fossiliferous, notably containing shells of *Trigonephrus* (in the pink parts of the *Pomonakalke* at Marien Berg as described by Beetz, 1926) and eggshells of *Struthio daberasensis* (at Elfert's Tafelberg) incorporated into the calc-crust at the time that it formed, and not the same age as the clasts that were being encrusted which are considerably older. Stromer (1926, fig. 17) recorded the presence of land snails at Elfert's Tafelberg, which are likely from the *Namib 2 Calc-crust*.

Namib Group

Namib Group was discussed at length by Miller (2008d). He included in this term all the superficial deposits overlying Pre-Cretaceous rocks in the Sperrgebiet and further north. As such, the term is extremely broad, encompassing marine and terrestrial sediments, alterites, volcanic rocks, calc-crusts, silcretes, silicified limestones and ferruginised deposits. Indeed, for the Pomona area it corresponds largely to the *Pomona Schichten* of Kaiser & Beetz (1926).

Older Calcrete

Older Calcrete was employed by Van Greunen (undated) for what is now termed the *Namib 1 Calc-crust*. Kaiser & Beetz (1926) termed this unit the "*Alte Oberflächenkalkedecke der Innennamib*" (symbols "bK", "bkq", "bkQ", "bK/Ph") which means the Old Calcareous Cover of the Inner (or Plain) Namib. Subsequent authors (Van Greunen, undated; Corbett, 1989) changed the phrase "Kalkdecke" to "calcrete" which is misleading because the deposit was not formed by the usual processes of calcrete genesis and it was not the meaning intended by the original authors. The *Older Calcrete* is a synonym of the lower bed of the *Pomonakalke* of Kaiser & Beetz (1926) which is an extension of the *Namib 1 Calc-crust* into the *Trough Namib* where it crops out at almost all the tafelberge.

Phytoherm Limestone

Phytoherm Limestone is named for the deposits comprising the prominent ridge of phytoherms, partly silicified, which crop out along Phytoherm Ridge, north of Eocliff. It is underlain by *Plaquette Limestone*.

Plain Namib

Plain Namib a « translation » of *Innennamib* of Kaiser & Beetz (1926) first used by Stocken (1978) for the relatively undissected country on which the main road from Chameis to Rotkop is constructed. It is comprised of relatively low relief surfaces of pre-Lutetian, Lutetian and Oligocene age with infillings of Miocene sediments in valleys eroded during the Oligocene. Part of this pediplain was already in place by the Lutetian, and it has undergone some down wasting since then, modified mainly during the Oligocene, during which the landscape was lowered by some 30-50 metres, leaving remnants of the Lutetian pediplain in the east perched above the bulk of the *Plain Namib* between the Klinghardt Mountains and the *Trough Namib*.

Plaquette Limestone

Plaquette Limestone comprises the basal, well-bedded, finely laminated carbonate facies of the *Ystervark Carbonatite Formation*. It crops out widely but sporadically in the zone immediately west of the Klinghardt Mountains, but is also well-represented at Chalcedon Tafelberg. In the Werfkopje outcrop, there are hailstone lapilli with characteristic thermal shock fabric, indicating deposition as volcanic ash. Here the limestone layers overlie weathered granite, and are overlain by two lava flows of olivine melilitite, then by *Namib 1 Calc-crust* and dune sands.

Pomonakalke

Pomonakalke is a term coined by Beetz (1926) for calcareous deposits associated with quartzite at Marien Berg. In fact, the calcareous deposits capping the hill are the *Namib 1* and *Namib 2 Calc-crusts*, cementing blocks of quartzite. The *Namib 2 Calc-crust* at the two Marien Berg Plateaux contains abundant shells of *Trigonephrus*. In two places the quartzite is *in situ* about 4-5 metres beneath the top of the hill, but elsewhere the quartzite is not *in situ*. At the north end of the western hill, a mass of quartzite and underlying rock some 100 metres long has slumped and rotated to form a small cuesta dipping southeastwards, covered by *Namib 1 Calc-crust*. This slumped mass could only have moved after sufficient relief had developed immediately to the west, in order to permit gravity to work on it. The ensemble is affected by calc-crust deposition.

Pomona Schichten

First mentioned by Lotz (1913) as the *Pomonatafelbergschichten*, a term which he restricted to the silicified beds capping the prominent flat-topped hills in the vicinity of Pomona mining village. The name was shortened to *Pomona Schichten* (*Pomona Beds*) by Kaiser (1926a, 1926b) who defined the unit as the ensemble of sediments capping and underlying the tafelberge in the Pomona area and overlying Basement rocks. As originally employed, the *Pomona Schichten* comprises a widely heterogeneous and heterochronic suite of rocks, united only by their supposed deposition prior to the Middle Eocene High Sea Stand, their generally indurated nature and their occurrence near the tops of high relief topography. Remapping by the Namibia Palaeontology Expedition reveals that the symbol "bq", which was used in the geological maps by Kaiser & Beetz (1926) for the *Pomona Schichten*, includes rocks of highly divergent ages, ranging from Palaeogene (quartzites), to Oligo-Miocene (ferruginised lag deposits on terraces, *Namib 1 Calc-crust*) to Plio-Pleistocene (*Namib 2 Calc-crust* with *Trigonephrus*).

The maps of Kaiser & Beetz (1926) show the distribution of what they termed *Pomona Schichten* under the symbol "bq" with outcrops scattered on all six of their maps from Buntfeldschuh in the south to Grillental in the north.

Reuning (1931) described some silicified sands near the mouth of the Olifant's River, South Africa, as "absolutely similar to the *Pomona Quartzite*". However, the said quartzites are of Miocene age, underlain and overlain by marine deposits containing fossil molluscs, and have nothing to do with the quartzites at Pomona, other than the fact that both are silicified sand. Hallam (1964) refers to the *Pomona beds of surface quartzites* and the *Pomona Beds and Silcrete* (correlating both to the End Cretaceous Cycle). He was probably the first geologist to interpret the *Pomona Quartzite* as silcrete. Barbieri (1968) mapped the Swartkop area, and identified several stratigraphic units overlying Precambrian Basement rocks. At the base he recognised 10 m of *Pomona Beds* (2 m conglomerate, 8 m marl) which he equated to the Cretaceous, overlain by 0.8 m of "ferricrete" and "silcrete", which he thought were end Cretaceous in age. Then came 34 m of "tuff" followed by 3 m of "hornfels and chalcedony", and 50 m phonolite all of which he put into the Oligocene. Liddle (1970) referred to the *Pomona Beds* and the *Pomona Quartzites*. Liddle (1971) complained that because there was varying terminology for the rocks referred to as *Pomona Series* by Kaiser & Beetz (1926) he would use the term *Pomona Sequence* in which he assembled a heterogeneous suite of rocks including ferruginised horizons. He included the *Pomona Quartzite* (i.e. in the narrow sense of the term referring to the silicified sediments exposed at the tops of the tafelberge) in the *Pomona Sequence* (i.e. in the wide sense comprising all Pre-Middle Eocene deposits occurring all over the Northern Sperrgebiet) but he excluded several of the outcrops mapped by Kaiser & Beetz (1926) as "bq". He accepted the conglomerates in the Gabis Felder as part of the *Pomona Beds* and he included the "*chalcedonic limestones deposited in basins in the Late Cretaceous land surface*" (here attributed to the Eocene *Ystervark Formation*). Partly because of the rather obvious heterogeneity of the rock units included in the *Pomona Schichten* (or *Series* or *Sequence*). Stocken (1978) subdivided the original content of the *Pomona Schichten* of Kaiser (1926a, 1926b) into a lower *Pomona Formation* comprising local sediments filling hollows in the Precambrian Basement in the Pomona Area, and an upper, silicified Tafelberge part which Miller (2008d) named the *Kätchen Plateau Formation*. Dingle *et al.* (1983) used the term *Pomona Beds* in the sense first employed by Kaiser & Beetz (1926). This is because they included all the rocks mapped as "bq" by Kaiser & Beetz (1926) including the *Gabis Felder Conglomerate* which is slightly younger than the *Kätchen Plateau Formation* and the *Pomonakalke* which is Miocene to Pleistocene in age. Phillips *et al.* (2000) correlated the *Pomona Beds* to the Eocene.

Reuning's Pan Carbonate

Reuning's Pan Carbonate comprises fossiliferous palustral limestone exposed as large boulders in the floor of Reuning's Pan. Beetz (1926) referred to this occurrence as "*Floating Reef*" because it is not *in situ*. The dimensions and distribution of the boulders and their angular surfaces indicate that they represent the upper parts of a mass of limestone that was once exposed at the surface but which has subsequently been almost completely buried by recent pan deposits.

Rooilepel Sandstone

Rooilepel Sandstone, was defined by Corbett (1989) as the aeolianites exposed in the flank of Rooilepel, a vast deflation basin inland from Oranjemund, and north of the Orange River. The name means Red Ladle in Afrikaans, on account of the colouration and shape of the depression. Ward & Corbett (1990) positioned the *Rooilepel Sandstone* at 22.5 Ma. The deposits range in age from Early Miocene at the base to Pleistocene at the top (Pickford & Senut, 1999). Pickford & Senut (1999) subdivided the succession into three parts, *Lower Rooilepel Aeolianite* at the base, *Middle Rooilepel Aeolianite and Silt* in the middle and *Upper Rooilepel Aeolianite* at the top. Miller (2008d) refers to the *Rooilepel Sandstone Formation*.

Schwarzer Berg Monchiquite

Schwarzer Berg Monchiquite was used by Corbett (1989) for the nephelinitic rocks at Schwarzer Berg. Kröner (1973) published an age of 35 Ma for the *Schwarzer Berg Nephelinite*. Spriggs (1988) published an age range of 29-31 for the nephelinite. The occurrence was called the *Schwarzeberg* (sic) *Nephelinite* by Phillips *et al.* 2000.

Scoria Limestone

Scoria Limestone is an extrusive facies of the *Ystervark Carbonatite Formation*. It crops out at Scoria Hillock, Eoknoll, Eocliff and Graben where it overlies *Plaquette Limestone*.

Silcrete of the Kätchen Plateau Formation

Silcrete of the Kätchen Plateau Formation was mentioned by Miller (2008c). The deposit is not a silcrete: at Tafelberg Nord it contains lebenspurren, and is possibly of shallow marine origin.

Silica North Carbonate

Silica North Carbonate is a term introduced by Pickford *et al.* (2008) for the well-bedded, highly fossiliferous, partly silicified palustral limestones infilling the Silica North Depression. It overlies Pre-Cambrian Gariep Group dolomite, and is unconformably overlain by *Blaubock Gravel* (*sensu lato*) cemented by Cu-stained *Namib 1 Calc-crust*.

Silica South Carbonate

Silica South Carbonate was defined by Pickford *et al.* (2008) for the well-bedded, richly fossiliferous, partly silicified palustral limestones infilling the Silica South Depression. It infills a depression in the Precambrian Gariep Group dolomite, and is unconformably overlain by *Blaubock Gravel* (*sensu lato*) which has been cemented by Cu-stained *Namib 1 Calc-crust*.

Sperrgebiet Siliceous Suite

Sperrgebiet Siliceous Suite comprises a huge variety of silicified superficial rocks widely exposed in the Northern Sperrgebiet. It corresponds largely to *Verkieselungmassen* of Kaiser & Beetz (1926) and includes silicified freshwater limestone, silicified dolomite, silicified sandstone, silicified facies of the *Ystervark Carbonatite Formation* (*Phytoherm Limestone*, *Scoria Limestone*, *Palustral Limestone*). It is not to be confused with the *White House Silcrete* or any other silcrete for that matter.

Steffenkop Siliceous Deposits

Steffenkop Siliceous Deposits was introduced by Pickford *et al.* (2008) for the silicified fossiliferous palustral limestones in the Steffenkop area, north-east of Bogenfels. It was previously attributed to the Pre-Middle Eocene calcareous sandstone (bks) of Kaiser & Beetz (1926). It overlies weathered (marly) Basement and is unconformably overlain by *Blaubock Gravel* which has been cemented by the *Namib 1 Calc-crust*, and just to the south of Steffenkop there is a concentration of cobbles of reworked silicified limestone probably representing a beach gravel, possibly of Eocene age.

Strauchpfütz Carbonate

Strauchpfütz Carbonate was defined by Corbett (1989) as a sediment unit comprised of interbedded clay and carbonate horizons closely associated with the *Kalkrücken Sandstone*. The name applies to exposures of carbonate at Strauchpfütz and near Eisenkieselklippenbake attributed to unsilicified *Süsswasserkalke* by Beetz (1926) which is Early Miocene, but not to the other occurrences of carbonates given the same name by Beetz (1926), some of which are Eocene. Corbett (1989) shows the *Strauchpfütz Carbonate* overlying the *Kalkrücken Sandstone*, but in fact it is part of the basal facies of the unit as defined by him, being the lateral equivalent of the *Glastal Grits* and the Langental mammal-bearing marls and nodular carbonate, i.e. a narrow correlate of the *Elizabeth Bay Formation* of other authors (Greenman, 1966; Miller, 2008d). In the cliffs west of Strauchpfütz, the base of the *Lower Gemsboktal Gravel* contains derived blocks of *Strauchpfütz Carbonate*. Pickford & Senut (1999) thought that the *Strauchpfütz Carbonate* could be Plio-Pleistocene, but it is much older, Early Miocene (Pickford *et al.* 2008).

Swartkop Fluvial Sediments

Swartkop Fluvial Sediments were considered by Pickford & Senut (1999) to have been silicified after being buried by a phonolite flow. They positioned the beds at ca 37 Ma. These rocks were previously included in the *Pomona Beds* by Kaiser & Beetz (1926). Barbieri (1968) interpreted these deposits as *Pomona Beds*, but they overlie chalcedony which was silicified during the Sperrgebiet Silicification Event.

Swartkop Phonolite

Swartkop (also spelled *Swartkopp*) *Phonolite* was a term coined by Kröner (1973) who published an age of 38 Ma for the lava.

Tafelberg Quartzites

Tafelberg Quartzites was used by Stocken (1978) to differentiate the upper part of the former *Pomona Beds* of Kaiser & Beetz (1926) which he believed represented "silicified superficial deposits overlying the end-Cretaceous erosion surface which bevels the *Pomona Beds*". Miller (2008d) renamed the deposits the *Kätchen Plateau Formation*. The discovery of lebenspurren in the *Tafelberg Quartzites* at Tafelberg Nord alters the interpretations by these authors because the quartzites are not remnants of superficial deposits overlying an erosional surface or bevel, but are sandy shallow marine sedimentary deposits endowed with an infauna, overlying weathered Basement rocks.

Terrassenfeld Aeolianite Member

The term *Terrassenfeld Aeolianite Member* corresponds to the aeolianite mapped by Kaiser & Beetz (1926) as "bs_1" *Sandstein, ein Ruhezeit in der Jüngeren Erosionstättigkeit andeutend* (Sandstone, implying a pause in the younger erosion activity). Pickford & Senut (1999) called these deposits the *Kalkrücken Aeolianites*, but the word *Kalkrücken* had already been applied by Corbett (1989) to all the deposits overlying the Basement in the eastern flank of the lower reaches of the Glastal, comprising the *Glastal Grits* at the base and the overlying *Gemsboktal Gravels* at the top. The name *Terrassenfeld Aeolianite Member* is proposed for the reddened Aeolianite sands intercalated between two layers of *Gemsboktal Gravel* (Pickford *et al.* 2008). It should be noted that the fossil land snails found in the *Namib 2 Calc-crust* developed on top of the aeolianite (Beetz, 1926; Corbett, 1989; Pickford & Senut, 1999) were incorporated into the calc-crust at the time of its encrustation and not at the time of deposition of the aeolianite. They are thus Plio-Pleistocene rather than Late Miocene.

Terrestre Sandstein

Terrestre Sandstein was described at the Buntfeldschuh Cliffs by Beetz (1926). It comprises dark green aeolian sands which overlie deltaic deposits of the *Buntfeldschuh Formation*, and is capped by the *Namib 1 Calc-crust*. The *Terrestre Sandstein* is equivalent to the *Kakaoberg Sandstone* of Corbett (1989). At Kakaoberg, the upper part of the aeolianite has been heavily ferruginised producing a dark brown mass up to 20 metres thick. The ferruginisation occurred prior to the deposition of the *Namib 1 Calc-crust*, as shown by the presence of outliers of this unit lying on top of the ferruginised aeolianite, and incorporating chunks of ferruginised aeolianite in its base.

Teufelskuppe Carbonatite

Teufelskuppe Carbonatite was summarised by Miller (2008b) as a roughly circular intrusion about 1 km in diameter exposed in a hill showing inwardly dipping cone sheets of carbonatitic affinities (McDaid, 1978; Verwoerd, 1993).

Trough Namib

Trough Namib is a translation of "*Flächennamib*" of Kaiser & Beetz (1926) for the deeply dissected zone between the coast and the *Plain Namib*. Until the Lutetian, there was minor relief in the region until deposition of the silicified quartzite which cap the tafelberge. By the Early Miocene, in contrast, much of the relief that characterises the Trough Namib was present, as shown by the distribution of ferruginised lags and alterite in the sides and floors of many of the valleys such as Idatal and Hexen Kessel, and many others in the Pomona area. Much of the relief was probably produced during the Oligocene which was a period of low sea-level, and which saw the downcutting of the Grillental, Glastal, and Gemsboktal among other major valleys that drain not only the *Trough Namib*, but also the *Plain Namib*.

Turritella *Beds*

The term "Turritella *Beds*" was employed by Haughton (1930a, 1930b) for the fossiliferous marine deposits cropping out a few hundred metres north of the *Wanderfeld IV Beds*. They were later called the *Langental Beds* by Siesser & Salmon (1979).

Wanderfeld IV Beds

Wanderfeld IV Beds were defined and named by Klinger (1977) but fossils from the occurrence were first mentioned by Haughton (1930a). Cooper (1974) and Dingle *et al.* (1983) correlated the fossils to the Cenomanian, whereas McLachlan & McMillan (1979) correlated the deposits to the Santonian (ie ca 85 Ma). The fossiliferous sediments were briefly mentioned by Pickford & Senut (1999) and by Miller (2008d) who summarised previous thoughts about them. The occurrence was examined closely in 2015 and none of it seems to be *in situ*. The bulk of the sediment occurs in a single dump in which two types of rock are intermingled, a dense limestone rich in oysters and a sandy marl containing plate-like ammonites and bivalves with concentric ridges on the outer surface of the shell.

White House Silcrete

White House Silcrete is newly named for silcrete overlying altered Basement rocks exposed south of White House in order to distinguish it from the suite of other siliceous rocks which occur in the region which are not silcretes, even though all have, at one time or another, been named as such. The latter are referred to as the *Sperrgebiet Siliceous Suite*. The *White House Silcrete* also crops out north of the Cattle Post and South of Schwarzer Berg, where it overlies *Bo Alterite*.

Younger Calcrete

Younger Calcrete was introduced by Van Greunen (undated) for carbonate encrusted deposits in the Northern Sperrgebiet that were cemented during a later phase of induration than the so-called *Older Calcrete*. It corresponds in part to the *Junge Kalkkrusten* of Kaiser & Beetz (1926) (symbols "egk" and "egk_1") which is the same unit as the upper of the two layers of *Pomonakalke* defined by Kaiser & Beetz (1926) at Marien Berg, which represents an extension of the *Namib 2 Calc-crust* into the *Trough Namib* where it crops out widely at almost all the tafelberge in the region. Even though it shows nodular patches, it is not strictly speaking a calcrete. We here label the unit the *Namib 2 Calc-crust*, as it often overlies the pale cream coloured to light brown *Namib 1 Calc-crust*. It yields abundant fossil *Trigonephrus*, as well as rare eggshells of *Struthio daberasensis*, and is thus Plio-Pleistocene in age. It occurs widely in the Plain Namib, but is also present in many places in the Trough Namib such as Marien Berg, Langer Tafelberg, Elfert's Tafelberg and Pomona Tafelberg.

Ystervark Carbonatite Formation

Ystervark Carbonatite Formation comprises the carbonatitic products of the Ystervark centre, comprising *Plaquette Limestone*, *Scoria Limestone*, *Ystervark Breccia*, and palustral limestones derived from these volcanic products, such the *Black Crow Carbonate*, *Silica North Carbonate*, *Silica South Carbonate*, *Reuning's Pan Carbonate*, carbonate and silicified carbonate at Eisenkieselklippenbake and *Chalcedon Tafelberg Limestones*.

Results of the Namibia Palaeontology Expedition

Post-Basement Geology of the Northern Sperrgebiet

Southwestern Namibia has undergone, and is still undergoing, a long term weathering and erosional phase which started at the commencement of Atlantic Rifting during the Mesozoic. The lithology of the bedrock played an important role in determining rates of erosion, with schists and granite generally weathering more rapidly than quartzites and dolomites. Near the coast, this predominantly erosional regime was influenced by intermittent volcanic, eustatic, climatic and subterranean, near-surface, processes. Notably, eustatic sea-level changes altered erosional base levels and volcanic activity blanketed the eroding surface in pyroclastics and more restricted lava flows, while related hydrothermal activity caused widespread silicification of superfical rocks, augmenting their resistance to erosion. Localised uplift of Basement rocks related to the intrusion of volcanic rocks into near-surface parts of the region led to increased high-energy erosion during the Oligocene. The latter process was augmented by major sea-level regression during the Oligocene.

In addition, rates of erosion in the Sperrgebiet have varied through time due to palaeoclimatic change. During the Neogene, fog-driven diagenesis led to the development of calc-crusts, which caused induration of large patches of loose surface deposits ranging in grain-size from sand to conglomerate and breccia rubble, with calcification occurring in many settings including depressions, sloping surfaces and at the tops of hills. In places, such as the summits of Chalcedon Tafelberg and Marien Berg, there was even some vertical accretion of calc-crust, as wind blown sand was cemented onto pre-existing outcrops of calc-crust onto which it fell. In regions where calc-crust did not form, or where it was subsequently decalcified or eroded away, aeolian deflation has often been extremely important, for example at Idatal and Hexen Kessel.

Probably the most important interruption affecting the overall Cainozoic erosional regime in the Northern Sperrgebiet, was caused by the eruption of widespread, even though relatively thin, deposits of aeolian carbonatitic ash from a centre immediately west of the Klinghardt Phonolite Cluster. These ashes, known as Plaquette Limestone, issued from the Ystervark Centre and possibly from other as yet unrecognised centres, intermittently blanketed large swaths of the region in at least three layers of finely bedded limestone ash each of which is up 2 metres thick in outcrops extending at least 25 km from the centre. Three carbonatite ash levels have been mapped at Chalcedon Tafelberg, 22.5 km northwest of Ystervark which resulted in the accumulation of three well-bedded limestone horizons totalling 5-6 metres in thickness, intercalated with marls derived locally from deeply weathered Basement rocks (schist, dolomite and quartzite). During volcanically quiescent periods, erosion continued, removing ash from high-relief parts of the landscape, and depositing limestone and Basement-derived ‘marl’ into small depressions at a number of localities. This interplay of aeolian deposition and subaerial erosion and transportation resulted in the intercalation of aeolian volcanic limestones, sedimentary marls and palustral limestones, now preserved in relatively small outcrops which represent the former sites of depressions in the country rock. The palustral limestones often contain abundant fossils of Lutetian and Bartonian age.

Plaquette Limestones (finely bedded aeolian carbonatitic ash, sometimes containing hailstone lapilli, and often showing slump structures where it fell onto sloping ground and slumped under its own weight) and their silicified derivatives have been mapped at a large number of localities west of the Klinghardt Mountains. The limestones are preserved in former topographic lows, and the local bases of the deposits vary considerably in altitude. There is a remarkable correspondance between the altitude of the base of the deposits and the distance from the present coastline, the lowest outcrops being closest to the coast, and the highest farthest from the coast. The latter observation rules out the possibility of the existence of a former extensive lake in the region (as proposed by some authors, on the basis of the so-called “Freshwater Limestones” of Kalbskopf, 1977) but accords well with their deposition by aeolian pathways from an active carbonatite volcano. An analogous situation is provided by the still active carbonatite volcano at Ol Doinyo Lengai, in the Serengeti, Northern Tanzania, which is surrounded for a considerable distance by thinly bedded limestones similar to those exposed in the Sperrgebiet, with comparable facies (sun-cracked plaquettes, rain drop marks, local slumping on steeper slopes where the ash blanketed the countryside like snow).

Carbonatite ash that accumulated in topographic lows arrested the weathering and erosion of the depressions, plugging them with an impervious layer of limestone, thereby producing saucer-shaped pans. When filled with water, these pans acted as small ponds or marshes, in which abundant plants and animals thrived, and in which marls and palustral limestones accumulated. The marls were derived from locally exposed weathered Basement rocks, whereas the palustral limestone was brought into the depressions both as clastic particles in surface water and as dissolved $CaCO_3$ in surface waters and groundwater, and concentrated by evapo-transpiration and evaporation.

Towards the end of the volcanic life of the Ystervark vent, an explosive breccia event occurred that intruded the superstructure of the volcano (cross-cutting Plaquette Limestones, Scoria Limestones and Phytoherm Limestone facies) and distributed carbonatite breccia as far as 15 km away. At Black Crow, a 21 cm thick carbonatite agglomerate bed containing several Basement-derived inclusions, is interlarded with highly fossiliferous palustral limestones of Lutetian age.

Erosion removed part or all of the superficial limestone from much of the area, re-exposing the Basement rocks along ridges and hilltops. Widespread hydrothermal activity then occurred, which had two aspects. The first was the eruption of lime-charged water at surface seeps which resulted in the gradual build-up of a travertine dome at Eocliff and the accumulation of carbonates (onyx and palustral limestone) in a nearby shallow depression at Eoridge, which lie on an eroded surface of dolomite at Eoridge and a thin remnant of Plaquette Limestone and Scoria Limestone at Eocliff. Both these occurrences are richly fossiliferous and yield faunas of Bartonian age.

Secondly, penecontemporaneously with, and immediately after the deposition of the Eocliff Limestones, there was widespread silicification of superficial rocks over a vast area extending radially well over 30 km from the Ystervark centre.

Silicification in the Sperrgebiet affected a huge variety of superficial rock types, giving rise to a bewildering array of siliceous rocks. Limestones tended to be altered to chalcedony, dolomite was transformed into grey to brown siliceous, honey-coloured to dark brown rock, often preserving bedding or veins in the dolomite, quartzite was transformed in harder, denser, versions of quartzite, conglomerates were silicified (brown and olive-green varieties of slightly different ages), and marls were transformed into fine-grained micro-crystalline silica. Scoria Limestone that was partly to completely silicified occurs as sponge-like masses full of holes and cavities, whilst phytoherms were selectively silicified to produce cell-like masses arranged in curved layers like large cellular onion skins. In the fossiliferous Black Crow and Eocliff limestones, root traces have been selectively silicified producing silica-lined pedotubules, and algal mats have been silicified, faithfully reproducing the original shapes and textures of the mats. At RvK sponge site (Rauff, 1926) finely bedded silicified limestone overlying altered and partly silicified dolomite and quartzite of the Gariep Group, yielded abundant freshwater sponge spicules. At Silica North and Silica South, gastropod shells and plant stems have been silicified, in many instances leaving the surrounding limestone unaffected, whereas at Chalcedon Tafelberg, the gastropod-bearing limestones were completely silicified over much of their thickness, whilst subjacent beds of compact Plaquette Limestone and marls were left unaltered.

It has been noted that all the occurrences of silicified rock in the Northern Sperrgebiet were formed near the surface (see for example, Bennett, 1976, concerning silicification at Chalcedon Tafelberg). This suggests that alkaline groundwater carrying silica emanating from relatively deep-seated sources, was rising towards the ancient land surface whereupon it mingled with freshwater in the uppermost levels of the ground (1 to 2 metres for the most part) resulting in precipitation of silica. The more porous layers of rock, such as fossils in limestone or soils overlying solid Gariep Group dolomites, were preferentially silicified, whereas more compact rocks such as porcellanous Plaquette Limestone remained largely unaffected by the process. Reworked marls in depressions, for one reason or another (possibly because they were beneath the zone of fresh groundwater), generally tended to escape silicification but in some places they were intensely silicified to produce a fine-grained rock which has been extensively mined by ancient humans for the manufacture of stone tools.

The silicified rocks of the Northern Sperrgebiet occur at various altitudes, indicating that there was considerable relief at the time of silicification. High altitude siliceous deposits occur at Ystervark and Phytoherm in the east (375 m asl), intermediate deposits are exposed at Silica North (226 m asl), Silica South (224 m asl), Chalcedon Tafelberg (214.5 m asl), Black Crow (191 m asl), Steffenkop (148 m asl) and Eisenkieselklippenbake which tops out at 168 m asl, and the lowest outcrops are nearest the present day coastline. Silicified dolomite occurs east of Elfert's Tafelberg in an outcrop that grades laterally into silicified Kätchen Plateau sandstone and conglomerate, suggesting that both were silicified by the same event. The silicified base of the Lüderitz Krater 4 km southwest of Chalcedon Tafelberg is at an altitude of 77 m asl whereas the silicified dolomite at Gamachab lies at an altitude of 46 m asl.

The Eocliff and Eoridge limestones accumulated on an erosional surface whose altitude was 370 to 380 m asl. Viewed from the summit of Swartkop, Eocliff, which is 10 km to the northeast, is seen to lie atop a widespread almost planar surface, above which poke the bulk of Klinghardt Phonolite outcrops. Also perched above this widespread surface there are high remnants of Basement rocks both to the North and to the South, and beneath it there are the broad valleys of Glastal (filled with Oligocene conglomerate) and Gemsboktal (filled with Late Miocene conglomerate).

When the Ystervark Volcano ceased activity, the long-term erosional regime, which had been active in the coastal part of the Sperrgebiet since the end of the Mesozoic, re-established its dominant role in local geomorphological processes and removed most of the surface outcrops of carbonatite, leaving only small remnants in former depressions in the country rock, now upstanding for the most part as positive relief features due to the post-depositional silicification that they underwent which rendered them more resistant than the surrounding rocks. As such, these small, widely-scattered limestone deposits (and their chalcedonic derivatives) yield precious evidence concerning the geomorphological evolution of the Sperrgebiet during the Palaeogene.

The Cenozoic geological succession of the Northern Sperrgebiet comprises the following units (Table 2).

Table 2. Geological succession in the Northern Sperrgebiet, Namibia, based on the results of the Namibia Palaeontology Expedition.

Sequence	Age	Geological activity	Palaeontology
14	Holocene (10 Ka)	Mobile sands, loose deflation lags, salt pans, gypsum and halite in superficial unconsolidated deposits. Namib 2 Calc-crust deposition continues	*Trigonephrus*, *Struthio camelus*
13	Pliocene-Pleistocene (5.3 Ma – 10 Ka)	Namib 2 Calc-crust deposition starts. Onyx deposition in near-coast settings (E-feld, Gamachab, Hexen Kessel, West of Buntfeldschuh). Kaukausib calc-tufa dome. Elfert's Tafelberg Aeolianite, Fiskus Aeolianite, Cutting back of Buntfeldschuh Cliff continues.	*Patella* (at Hexen Kessel) *Vermetus* (at Hexen Kessel) *Trigonephrus* (many places) *Struthio daberasensis* (many places) *Notochoerus capensis* (Kaukausib) *Pedetes* (Kaukausib)
12	Messinian (7.3 – 5.3 Ma)	Namib 1 Calc-crust continues cementing superficial deposits in the Plain Namib and the Trough Namib.	*Trigonephrus*, Chelonia
11	Tortonian (11.6 – 7.3)	Namib 1 Calc-crust continues cementing superficial deposits in the Plain Namib and the Trough Namib. Deposition of the Lower Gemsboktal Conglomerate and sandstone, the Terrassenfeld Aeolianite and the Upper Gemsboktal Conglomerate and sandstone.	Chelonia, *Diamantornis laini* (at Kalkrücken)
10	Langhian-Serravallian (16 – 11.6 Ma)	Namib 1 Calc-crust starts cementing superficial deposits in the Plain Namib and the Trough Namib. Weathering and erosion. Continued widespread ferruginisation of porous near-surface sediments and rocks (Langental, Grillental, Buntfeldschuh, Langer Tafelberg, Elfert's Tafelberg, Kätchen Plateau area).	None
9	Aquitanian-Burdigalian (23 – 16 Ma)	Backfilling of valleys eroded during the Chattian (Elisabethfeld, Grillental, Langental, Glastal and Strauchpfütz). Induration and copper staining of Blaubock Conglomerate (pale grey to white, partly silicified, partly calcareous). Continued	Terrestrial and freshwater Gastropods, ostracods, amphibians, reptiles, birds, mammals, *Tsondabornis minor*

		ferruginisation of near-surface deposits in patches	
8	Chattian (28.1 – 23 Ma)	Incision of river valleys draining into the Atlantic (Kaukausib, Grillental, Fiskus, Langental, Glastal, Gemsboktal). Continuing deposition of Blaubock Conglomerate. Deposition of Kakaoberg Aeolian Sandstone. Onset of ferruginisation of near-surface deposits.	
7	Rupelian (33.9 – 28.1 Ma)	High Sea Level. Continued deposition of Buntfeldschuh Delta deposits. Continuing deposition of Blaubock Conglomerate.	Logs and chunks of silicified wood originating from the underlying marls, are secondarily associated with the overlying Blaubock Conglomerate.
6	Priabonian (38 – 33.9 Ma)	Deposition of Langental *Turritella* Beds, Shark Site Beds and associated marine sediments. Eruption of phonolites and nephelinites. Onset of Buntfeldschuh delta deposition. Weathering producing marls and marly soils. Large trees growing in the area. Commencement of deposition of Blaubock Conglomerate.	**Marine** : Nannoplancton (NP 19 – NP 20) corals, cirripeds, marine gastropods, bivalves, nautiloids, fish, sharks **Terrestrial** : Trees
5	Late Bartonian (39 - 38 Ma)	Widespread silicification event resulting in Brown Silicified Sand and Rubble (Tafelberge), and Silicification of Gabis Felder Conglomerate, silicification of dolomite surfaces and thin soils overlying dolomite, partial silicification of Ystervark Carbonatite and related limestones. Eruption of Schwarzer Berg Nephelinite and some Klinghardt Phonolite.	None
4	Late Lutetian to Bartonian (45 – 39 Ma)	Deposition of the Ystervark Carbonatite Formation (Plaquette Limestone, Scoria Limestone, Black Crow Limestone, Ystervark Breccia, Chalcedon Tafelberg suite, Eocliff Limestone) and intercalated marls derived from Basement alterite. Onset of emplacement of phonolites. Conglomerate deposition at Gabis Felder.	**Bartonian** : Plants, freshwater gastropods, reptiles, birds, mammals **Lutetian** : Sponges, plants, terrestrial and freshwater gastropods, reptiles, birds, mammals
3	Middle to Late Lutetian (47-39 Ma)	Deposition of the Kätchen Plateau Formation near Pomona (= upper quartzitic part of the Pomona Beds of Kaiser & Beetz, 1926) and pale quartzite at Black Crow.	Lebenspurren
2	Early Lutetian (47.8 – 47 Ma)	Local reworking of Basement alterite followed by deposition of pale green to white sandstone at Granitbergfelder 15 and Black Crow (lowest part of the Pomona Beds of Kaiser & Beetz, 1926).	
1	Ypresian (56 - 48 Ma)	Deep weathering of the Basement complex (dolomite, gneiss, quartzite, granite, syenite) producing a wide variety of largely ferric alterites attributed to the Bo Alterites (marl, sandstone, alterite breccia, bohnerz). Formation of “Rondelles”.	No body fossils, but Rondelles could represent depressions in dolomite caused by tree root activity.
2	Mesozoic to basal Ypresian (<75 – 56 Ma)	Weathering and erosion of the Basement complex rocks. Break-up of Africa – South America. (4-5 cubic metres of Cretaceous Limestone preserved at Wanderfeld IV?).	Ammonite, *Exogyra* (age uncertain)

		Silcrete developed on alterite at White House Cattle Post and south of Schwarzer Berg (= African Surface?).	
1	Proterozoic and Mesozoic	Deposition of Basement rocks of the Gariep Group, intrusives of the Lüderitz Alkaline Complex, quartz veins, folding, faulting, erosion.	None

Late Mesozoic Succession of the Northern Sperrgebiet

Wanderfeld IV Beds

Mesozoic rocks are rare in the Northern Sperrgebiet. A small occurrence of marine shelly limestone and coquina sandy marl at Wanderfeld IV has been discussed on numerous occasions (Haughton, 1930a, 1930b; Cooper, 1974; Klinger, 1977; Miller, 2008d) but no consensus about its age and meaning has emerged. Miller (2008d) summarised the situation by pointing out that estimates of the age of the fossils range from Cenomanian (ie ca 100 Ma) (Klinger, 1977) to Santonian (ie ca 85 Ma) (McLachlan & McMillan, 1979). The importance of this occurrence (if the sediments are really *in situ*) is that it indicates that this part of the Langental had already been incised by the Early to Middle Cretaceous.

Elsewhere in the region there was deep but differential weathering of Basement rocks right up to the Early Lutetian. Over the long term, dense Quartzite and Dolomite bedrock has proved to be more resistant to weathering than granite, schist and gneiss. The latter three rock types show deep weathering to Alterite which is easily removed by aeolian activity or flowing water, resulting in long, relatively flat-bottomed valleys flanked by more resistant quartzite and dolomite ridges.

White House Silcrete and Alterite

Inland in the Sperrgebiet, in what Beetz (1926) called the Innennamib (the Plain Namib, as opposed to the Trough Namib close to the coast), erosion has not been as active as it has been in the coastal strip, there are outcrops of silcrete overlying alterite. Exposures can be studied alongside the main road a few km south of White House, north of the Cattle Post and south of Schwarzer Berg. In all three places silcrete is underlain by a deep alterite profile and is overlain by calc-crust, loose sand and gravel lags. We call this deposit the White House Silcrete, which overlies the Bo Alterite.

The White House Silcrete (Fig. 4), which is likely to have formed during the Late Cretaceous or Early Palaeocene, should not be confused with a suite of rocks which were silicified during the late Bartonian, here called the Sperrgebiet Siliceous Suite (also known in the literature as the Pomona Schichten (partim), Chalcedon Tafelberg Silcrete and Kätchen Plateau Silcrete). Despite the vast difference in age and lithology between these two types of silica-rich rocks, almost all researchers have considered them to be part of a single widespread “silcrete” and have usually correlated them to the African Surface of King (1949) (Stocken, 1978; Partridge & Maud, 1989; Miller, 2008d). A great deal of confusion has flowed from this conflation of heterogeneous rock types of diverse ages (Miller, 2008d). Jacob *et al.* (2006) for example, correlated the Chalcedon Tafelberg Formation and other silcrete cappings to the lower Palaeocene (ca 64 Ma) although at Chalcedon Tafelberg and Eisenkieselklippen-bake, they contain Lutetian to Bartonian fossils.

Geomorphological study reveals that the White House Silcrete occurs at significantly higher altitudes than the Bartonian Sperrgebiet Siliceous Suite. Both suites of rock slope towards the coast, making direct comparison of spot heights uninform-ative, but when calculated in relation to the shortest distance to the coast a clear pattern emerges, with the White House Silcrete lying 20-50 metres higher than the Sperrgebiet Siliceous Suite, depending on local variations in the altitude of outcrops of the White House Silcrete and the Sperrgebiet Siliceous Suite.

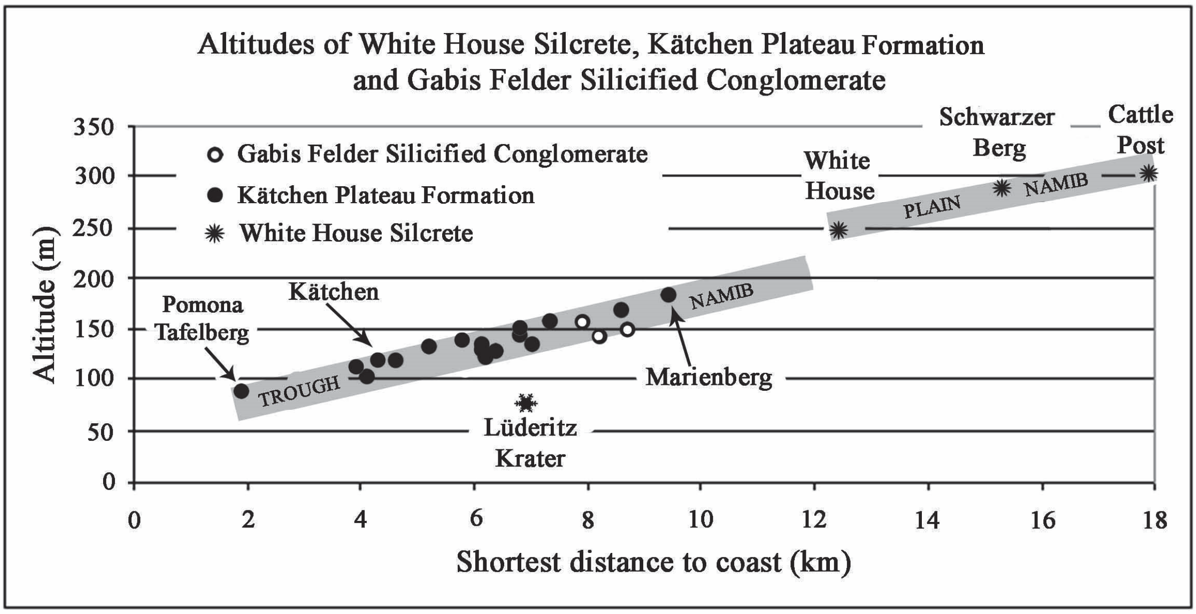

Figure 4. Altitude profiles of the White House Silcrete, the Kätchen Plateau Formation and the Gabis Felder Silicified Conglomerate reveal that they all slope gently coastwards. The White House Silcrete is the highest and therefore the oldest of these rock units, and the Gabis Felder Conglomerate is the youngest. The silicified base of Lüderitz Krater was previously classified with the Kätchen Plateau Formation, but its position relative to these profiles is anomalous and suggests a younger age. Some of the lower "outcrops" of Kätchen Plateau Formation comprise accumulations of reworked blocks lying on erosional terraces some 15-20 metres beneath their original depositional horizon. Most of these terraces correspond in age to the Gabis Felder depositional episode, but it is evident from the geomorphology of the region east of Langer Berg and northwest of Marien Berg, that there are several terraces, each of which carry a load of reworked quartzite blocks, some of them packed densely together.

Palaeogene rocks of the Northern Sperrgebiet

Bo Alterite

As a result of deep deflation and erosion in the coastal strip, much of the alterite generated during the Cretaceous and Cenozoic has been removed, but a few outcrops are preserved at and near Chalcedon Tafelberg ("bo" in Kaiser & Beetz, 1926, hence the name of the unit) (Fig. 5-8). Here it comprises bright red silt-sand and angular breccia containing broken nodules and blocks of iron oxides, round pellets of bohnerz (bean ore : small nodules of pedogenic iron oxide) and angular chunks of altered Basement rocks, suggesting weathering under a relatively warm, humid palaeoclimate and little if any post-formational transportation. Although there is no direct evidence concerning the age of these red deposits, they are overlain by Plaquette Limestones of the Ystervark Formation and must thus be older than the Lutetian. The deposit is probably younger than the White House Silcrete. We postulate an Early Eocene (Ypresian) age corresponding to the Early Eocene Climatic Optimum (Zachos *et al.* 2001).

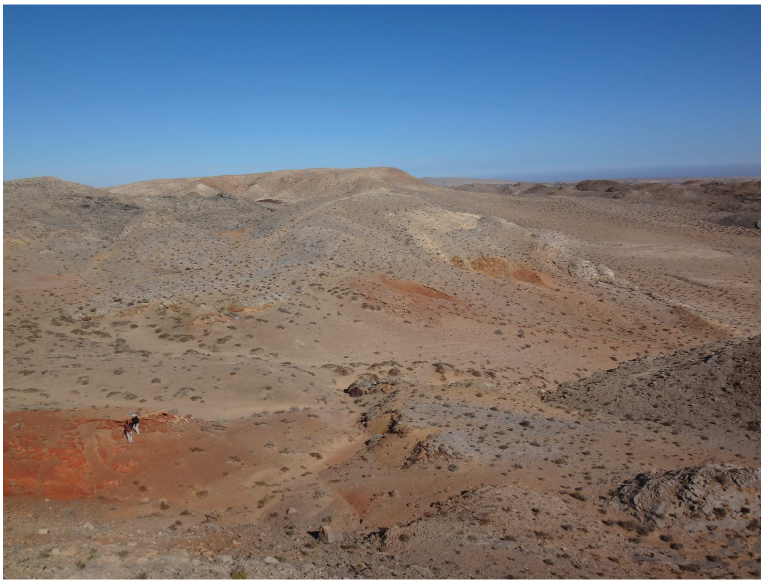

Figure 5. Bo Alterite infilling a depression in Gariep Group Dolomite 1 km north of Chalcedon Tafelberg, the flat-topped hill on the horizon. Similar red bohnerz-bearing deposits occur at the base of the Chalcedon Tafelberg succession.

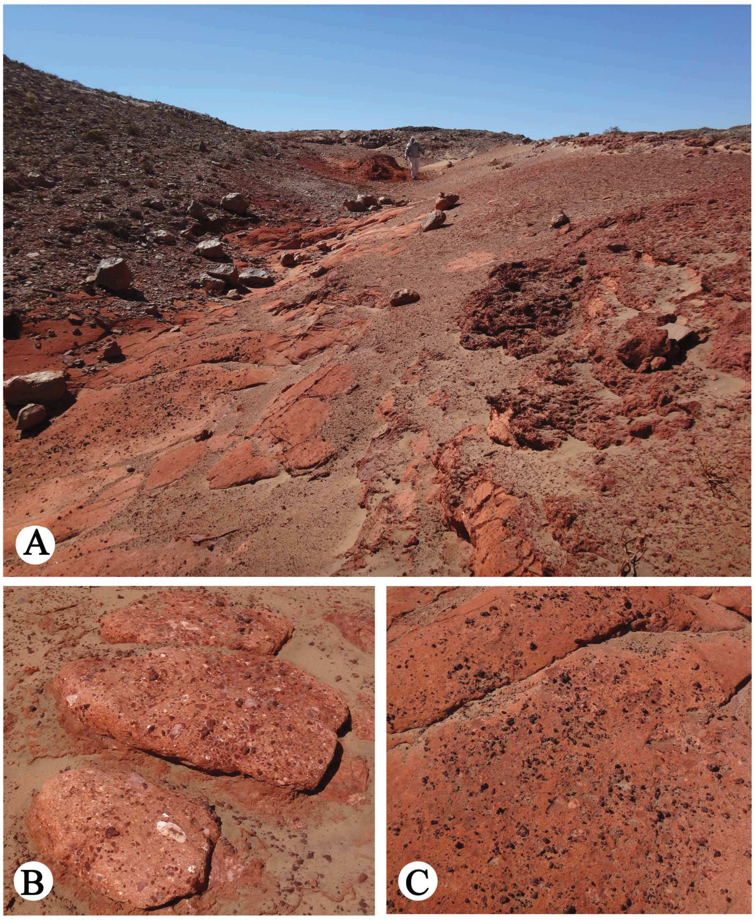

Figure 6. Bo Alterite exposure 1 km north of Chalcedon Tafelberg. A) General view of outcrop, B) close-up view of sandy breccia facies with angular to sub-rounded clasts of alterite (clasts up to 5 cm diameter), C) bohnerz and alterite clasts in sandy facies.

Figure 7. Chalcedon Tafelberg, north flank, Plaquette Limestone of the Ystervark Formation (white horizons above the figure) overlying red marly Bo Alterite infilling a depression in Gariep Dolomite.

Figure 8. Plaquette Limestone of the Ystervark Carbonatite Formation overlying marly sand of the Bo Alterite at Chalcedon Tafelberg attesting to a radical shift in depositional environment from alteration of Basement rocks yielding marls to the accumulation of well-bedded carbonates.

Rondelles

An area of “rondelles” east of Pomona was surveyed in order to determine their mode of origin. Kaiser & Beetz (1926) mapped dozens of rounded features (“R” in their geological maps) which they thought were “dolines”. Many of them are lined with silicified rock (“RvK” verkieselungmassen). The ones examined by the NPE comprise shallow roughly circular saucer-like depressions in dolomite country rock (Fig. 9). They are about 10 to 20 metres in diameter and are scattered over the area, sometimes almost touching, but mostly separated from each other. It can be stated that these features are not dolines in the strict sense of the term (i.e. due to karst processes) but are more likely to be due to penetration of root systems of trees into the dolomite beneath the ancient soil profile. As such the distribution pattern of rondelles probably reflects the tree cover at the time of their formation. Silicification of the superficial rocks of the Sperrgebiet occurred preferentially in the porous zone between compact bedrock beneath and the bohnerz-bearing soil cover above, producing a siliceous lining over the extent of the rondelles. The rondelles must have formed earlier than the Sperrgebiet Silicification Event (late Bartonian). Their position atop the plateau and the fact that they contain bohnerz indicates that they are likely to be contemporaneous with the Bo Alterite which is thought be Ypresian in age.

Figure 9. Area of Rondelles on a weakly incised plateau of dolomite east of Pomona and north of Chalcedon Tafelberg. The dark, roughly circular, saucer-shaped features, which range in diameter from 10 to 20 metres, are lined with brown siliceous rock and fragments of bohnerz. They are interpreted to mark the former positions of trees growing in thin soil, the shallow depressions being due to the activity of roots penetrating into the underlying dolomite. The presence of bohnerz suggests a warm humid palaeoclimate. This cluster contains over 20 examples. Similar features are widespread but scattered in the region, indicating that many have been eroded away in the more dissected country, as for example on the right hand side of the image.

Pomona Beds

Quartzite at Granitbergfelder 15

Indurated sand and gravel lags south and southeast of Pomona, at Granitbergfelder 15 and Black Crow, are overlain at the last site by limestones containing a Lutetian fauna (Pickford *et al.* 2008). At Granitbergfelder 15, there is a prominent outcrop of pale greenish quartzite which overlies alterite, and is covered by Blaubock Conglomerate and copper stained Namib 1 Calc-Crust which is in its turn overlain by Namib 2 Calc-crust (Fig. 10). The quartzite was mapped by Kaiser & Beetz (1926) as part of the Pomona Schichten (“bq”).

At 190 metres above sea-level, the quartzite at Granitbergfelder 15, and the outcrops at Black Crow, could represent a depositional episode coeval with the Kätchen Plateau Formation as the altitudes and distance from the coast are close to those of the deposits at Marien Berg (185 m asl).

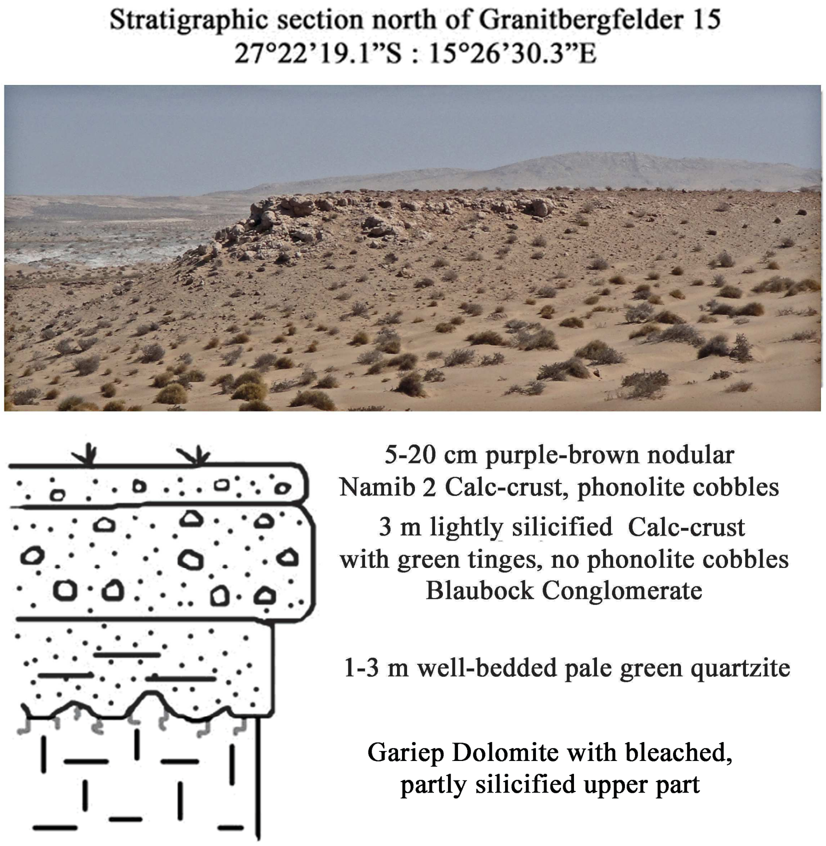

Figure 10. Stratigraphic section in hamada north of Granitbergfelder 15, Sperrgebiet, Namibia. View westwards towards Granitberg (in the background).

Du Toit (1954; also mentioned in Miller, 2008d) identified a fossil snail shell from the Pomona Beds as *Dorcasia antiqua*. The only *Dorcasia* specimens that the Namibia Palaeontology Expedition found in outcrops previously attributed to the Pomona Schichten are from Black Crow, where they are quite common. It is less likely to have come from the area west of Alte Lüderitzfelder Station, where Beetz (in Wenz, 1926) found a snail in marly sandstone. This site is the outcrop labelled "bs" at 27°18'14.2"S : 15°20'13.5"E where many loose blocks of silicified limestone resembling the occurrence at Steffenkop, (Lutetian) litter the ground. The deposit containing the derived blocks of silicified limestone is probably Late Eocene, similar in age to the infilling of the Lüderitz Krater nearby.

Kätchen Plateau Formation

The tafelberge that are such prominent geomorphological features of the region around Pomona usually comprise silicified sandy to pebbly deposits attributed to the Kätchen Plateau Formation (Fig. 11). The outcrops are entirely confined to what Beetz (1926) called the "Flächennamib" (Trough Namib) but it is evident from the distribution of outcrops that the deep incision that today characterises the Trough Namib, did not exist as such at the time of deposition. At Elfert's Tafelberg, local relief was of the order of 20 metres at the time of deposition. In the larger tafelberge such as Elfert's Tafelberg and Kätchen Plateau, the silicified deposits have concave upper and lower surfaces which indicates that they blanketed an irregular topography of low ridges and shallow valleys up to 20 metres below the higher flanks but not nearly as deep as the present-day ones flanking them.

Overall, the tops of the tafelberge decrease in altitude from ca 185 m asl inland at Marien Berg towards the coast, the lowest remnant being Pomona Tafelberg at 91 m asl (Fig. 12). Erosion has left the tafelberge as positive relief features isolated from each other, comprising classic examples of inverted relief – what were shallow (pre-Eocene?) depressions infilled with rubble and sand are today tall ridges and mesas standing high above the neighbouring low ground. Following erosion, many of the outcrops were drowned during the Eocene sea high stand (i.e Bartonian or Rupelian in today's parlance) or stood as islands in the sea.

Kaiser & Beetz (1926) classified these rocks and spatially associated layers of carbonate in the Pomona Schichten, and they generally overlie altered Basement quartzite and dolomite, some of which has been locally reworked but which remained poorly consolidated or unconsolidated at the base.

Liddle (1971) reported the presence of "calcrete" beneath the silicified cap of Kätchen Tafelberg, but the outcrop is an example of Namib 2 Calc-crust containing fossil eggshells. In this context, the Marien Berg outcrop is interesting because it was described by Beetz (1926, fig. 4) as showing three beds overlying weathered Basement. The lowest bed is sandy marl grading to marly sand with rubble and pebbles. This layer is reportedly overlain by calcareous beds (Pomonakalke) which is overlain by *Zuerste verkalkte und dann verkieselt: Schichten* (Pomona Quartzite). However, our examination of Marien Berg, reveals that the quartzite underlies the "Pomonakalke" which has cemented locally derived blocks of quartzite. There are two beds of Pomonakalke, a lower one which is cream coloured and azoic, corresponding to the Namib 1 Calc-crust of Miocene age, the upper one is pink to mauve and nodular and contains shells of the land snail *Trigonephrus*, typically found in the Namib 2 Calc-crust of Plio-Pleistocene age. Thus from the outset, the Pomona Schichten comprised a highly heterochronic suite of strata presented by its namers in the wrong stratigraphic order (Fig. 13-17).

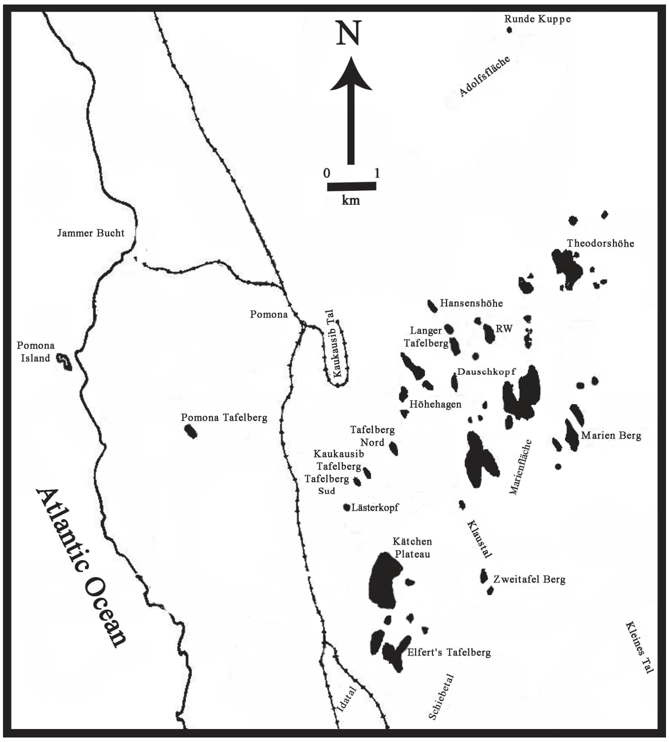

Figure 11. Distribution of Kätchen Plateau Formation and concentrated masses of derived and recemented Kätchen Plateau Quartzite, forming tafelberge in the Pomona Area, Sperrgebiet, Namibia. RW – Rheinpfalz Warte. There are three layers of derived quartzite blocks, cemented by 1) the ferruginistaion event of Oligo-Miocene age, 2) the Namib 1 Calc-crust (Miocene) and 3) the Namib 2 Calc-crust (Plio-Pleistocene). All were hitherto included in the Pomona Schichten.

Miller (2008d) referred the unsilicified sediments beneath the Tafelberge to the Pomona Beds, and the silicified cap rocks to the Kätchen Plateau Silcrete Formation and he correlated both units to the Cretaceous. At all outcrops examined, the contact between the lower less-indurated part of the profile grades upwards into the highly silicified upper part. There is thus only one stratigraphic entity which has undergone differential diagenesis, for which the name Pomona Beds has priority. The Kätchen Plateau "Silcrete" Formation is not a silcrete in the strict sense of the term, and it is considerably younger than the White House Silcrete. The Kätchen Plateau Formation is here considered to be Lutetian and is thought to have been partly silicified by the widespread Sperrgebiet Silicification Event which occurred during the Bartonian-Priabonian. This accords with the viewpoint of Corbett (1989) who considered that the Pomona Quartzite and silicified limestone at Chalcedon Tafelberge were lateral facies variants (although he thought both were Cretaceous). Liddle (1971) indicated that this event led to the silicification not only of the Tafelberge summits but also of the underlying Gariep Dolomites at Elfert's Tafelberg and Langer Tafelberg, as well as the freshwater limestones at Chalcedon Tafelberg which he considered to represent contemporary deposits but different facies. However, Liddle (1971) correlated the silicification event to the Cretaceous. These and other authors assumed that the deposits formed on land, as implied by the word "silcrete" used to describe them.

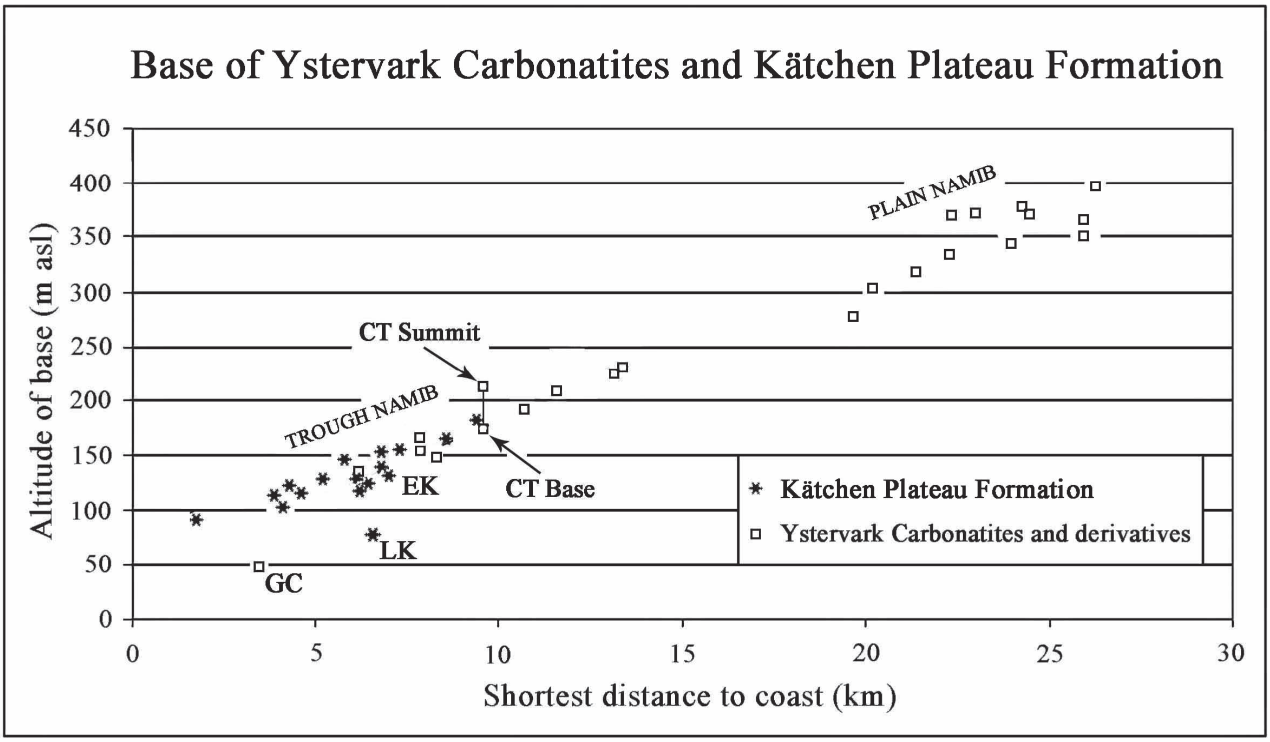

Figure 12. Altitudinal relationship between the Ystervark Carbonatite Formation and the Kätchen Plateau Formation. The Kätchen Plateau deposit lies slightly beneath the highest deposits of the Ystervark Formation at Chalcedon Tafelberg (CT) and Eisenkieselklippenbake (EK) suggesting that they are somewhat younger. Note the anomalously low positions of Gamachab (GC) and Lüderitz Krater (LK).

Figure 13. Tafelberge in the Pomona area viewed from the east near Rheinpfalz Warte, show a uniform gentle slope towards the coast. The brown silicified sands and rubble capping the tafelberge (upper part of the Pomona Schichten of Kaiser & Beetz, 1926, more recently classified as Kätchen Plateau Formation by Miller, 2008d) are usually 1 – 2 metres thick and are underlain by less consolidated quartzitic alterite or locally reworked alterite (lower beds of the Pomona Schichten of Kaiser & Beetz, 1926) with less altered Gariep Group bedrock at the base of the hills.

Figure 14. Kaukausib Tafelberg viewed from Tafelberg Nord with old mine workings in the valley between the two hills. Lästerkopf is in the distance to the left (southwest) of Kaukausib Tafelberg.

Figure 15. Elfert's Tafelberg, immediately east of Stauch's Laager, Sperrgebiet. Note the silicified deposits forming the skyline apparently draping downwards into ancient relief incised into Gariep bedrock. The thickness of the silicified sand and rubble is ca 1.5 metres (view eastwards). The sloping outcrops were ferruginised during the Oligo-Miocene and the quartzite trapped in the ferruginous matrix is not strictly speaking *in situ* in its original position but has been "let down" locally and then incorporated into the ferruginised deposit. Similar ferruginised quartzite-rich deposits occur widely in the areas surrounding Elfert's Tafelberg and Kätchen Plateau and all were previously incorporated in the Pomona Schichten.

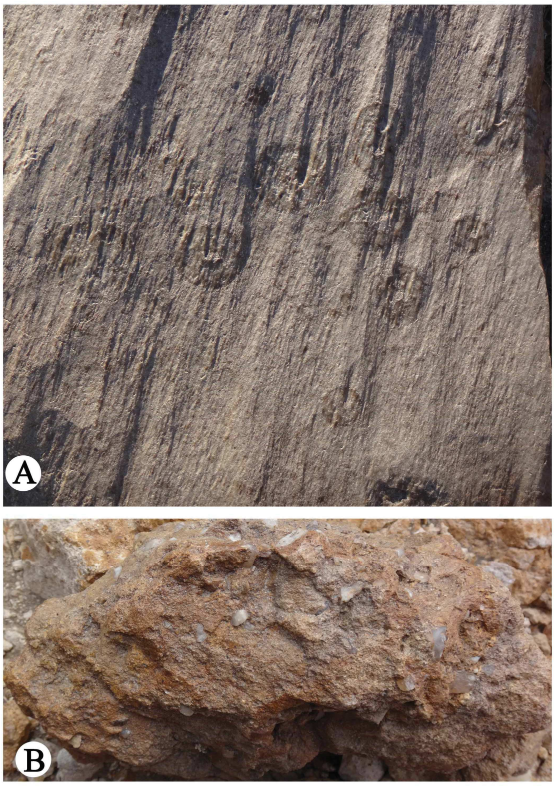

Figure 16. A) Circular (cylindrical) structures up to 5 cm diameter in Kätchen Plateau Formation atop Tafelberg Nord. Note the composite nature of the structures, with a central roughened part surrounded by a smoother circular ring. They resemble burrows of soft-bodied organisms which agglutinate the walls of the burrows to stabilise them. These ichnofossils indicate that the deposits are not strictly speaking silcrete, as widely thought, but are silicified sediments, probably of shallow marine origin. B) Detail of the basal part of Kätchen Plateau Formation showing the brown silicified sandy gravel containing subangular to rounded quartz pebbles.

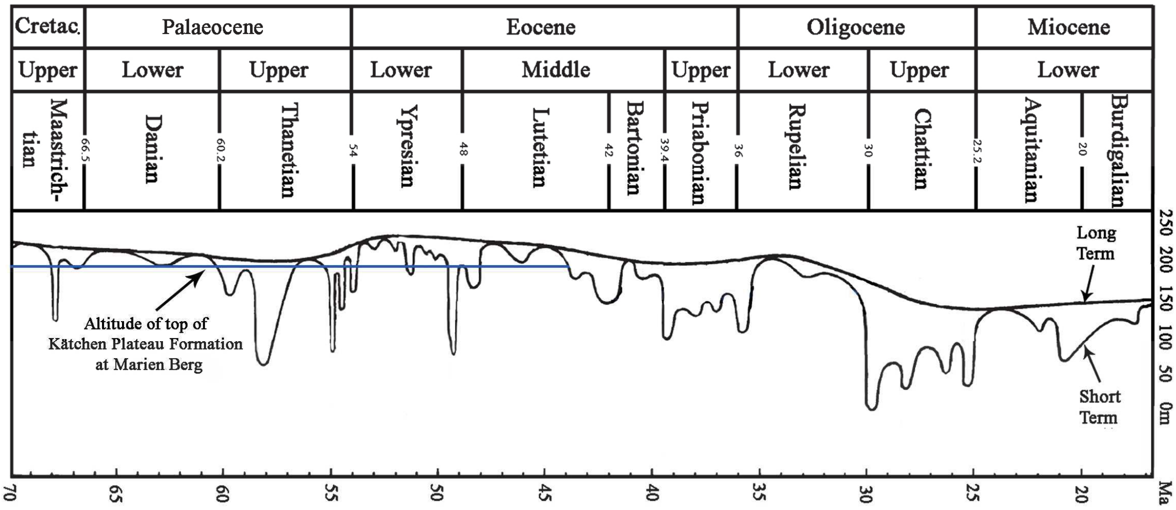

Figure 17. The highest outcrop of Kätchen Plateau Formation at Marien Berg (185 m) plotted onto the Eustatic Curve of Miller (2009). The presence of lebenspurren in the formation at Tafelberg Nord suggest a marine depositional environment, which is quite possible considering that during the Palaeocene and most of the Eocene, sea level was more than 185 m above modern sea level. Correlation to the Ypresian or Lutetian is considered to be most likely, although in the absence of identifiable zone fossils these estimates must remain conjectural.

Gabis Felder Conglomerate

A coarse- to fine-grained fluviatile conglomerate that was confined to valley bottoms was also silicified during the Sperrgebiet Silicification Event. Here called the Gabis Felder Silicified Conglomerate, its outcrops are 10-15 metres lower than the Pomona Tafelberge, which indicates that it is likely to be younger than the brown silicified deposits of the Kätchen Plateau Formation (Fig. 18-19). *In situ* occurrences of this olive coloured conglomerate occur in the upper reaches of the Langental east of Granitberg in the area called Gabis Felder (small outcrops mapped as "bq" by Kaiser & Beetz, 1926, and erroneously identified as "freshwater limestone" by Van Greunen, undated map) where it overlies silicified dolomite and alterite. Derived blocks of this highly distinctive rock are abundant in the Blaubock Conglomerate, especially at Eisenkieselklippenbake, indicating a south-southeast flow direction of the river which transported them.

Figure 18. Gabis Felder Olive Silicified Conglomerate containing abundant angular to rounded quartz pebbles (27°20'20.3''S : 15°24'33.9''E).

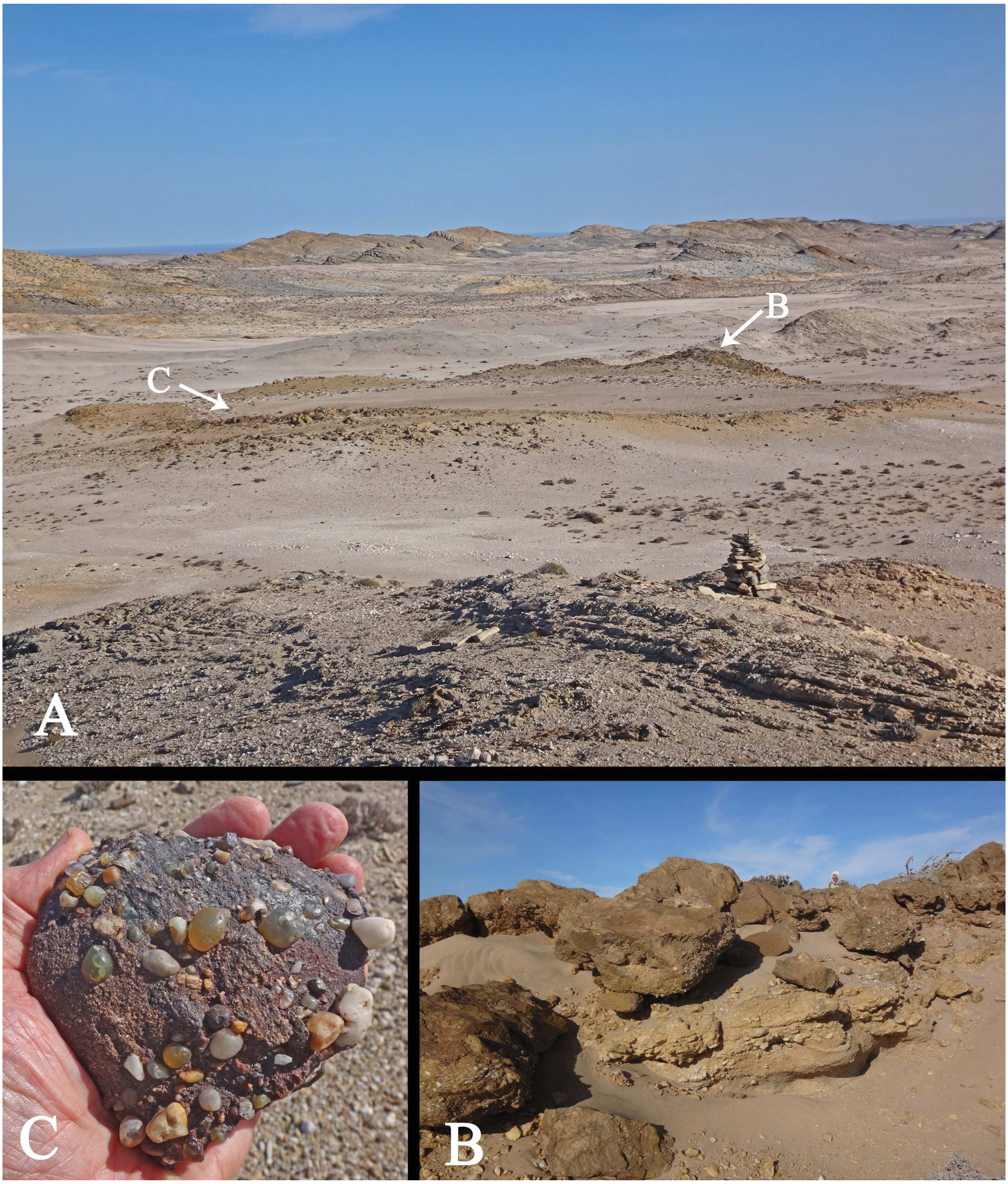

Figure 19. Lüderitz Krater (A) brown silicified conglomerate and sand overlying unconsolidated sandy conglomerate, in its turn (B) overlain by agate-bearing marine deposits, some of which have been ferruginised (C).

Ystervark Carbonatite Formation

Lying unconformably on the Bo Alterite at Chalcedon Tafelberg and weathered profiles of similar age elsewhere (Black Crow, Werfkopje, Klinghardt's Pan (which is not a volcanic pipe as previously thought (Liddle, 1971; Kalbskopf, 1977) but an erosional depression), Graben, Pietab 2 Freshwater Limestone Depression, Eocliff, Eisenkiesel-klippenbake) is a suite of carbonate rocks (sometimes silicified) here called the Ystervark Formation. This carbonatite occurrence joins others already known to exist in the region, including Dicker Willem (49 Ma) north of the Aus-Lüderitz road (Ried *et al.,* 1990), Kieshöhe (McDaid, 1978), Teufelskuppe (McDaid, 1978), Panther (near Chameis) (Verwoerd, 1993) and Karingarab (Ried *et al.*, 1990; Verwoerd, 1993) all in the Sperrgebiet.

The earliest unit of the Ystervark Formation (Fig. 20, 21) comprises well-bedded, fine-grained laminated carbonates, sometimes with hailstone lapilli, often slumped and occasionally with plant remains, the layers sometimes showing "sun-cracks". Hitherto confused with freshwater limestones following the work of Liddle (1971) and Kalbskopf (1977) and considered by these authors to be Cretaceous (Miller, 2008d) these rocks are now interpreted to have originated as airfall tuffs of carbonatitic affinities. Called the Plaquette Limestone, they occur widely but sporadically over the Northern Sperrgebiet, where they are preserved in former depressions in the Lutetian landscape, now mostly visible as upstanding roughly circular outcrops because the deposits are more resistant to erosion than the alterite that they covered (Fig. 22, 23). Resistance to erosion was enhanced by partial to total silicification of these rocks in many places. At RvK Sponge Site in the Trough Namib, well-bedded silicified marl and limestone containing freshwater sponge spicules (Rauff, 1926) accumulated in a depression that had been eroded into schistose and quartzitic bedrock.

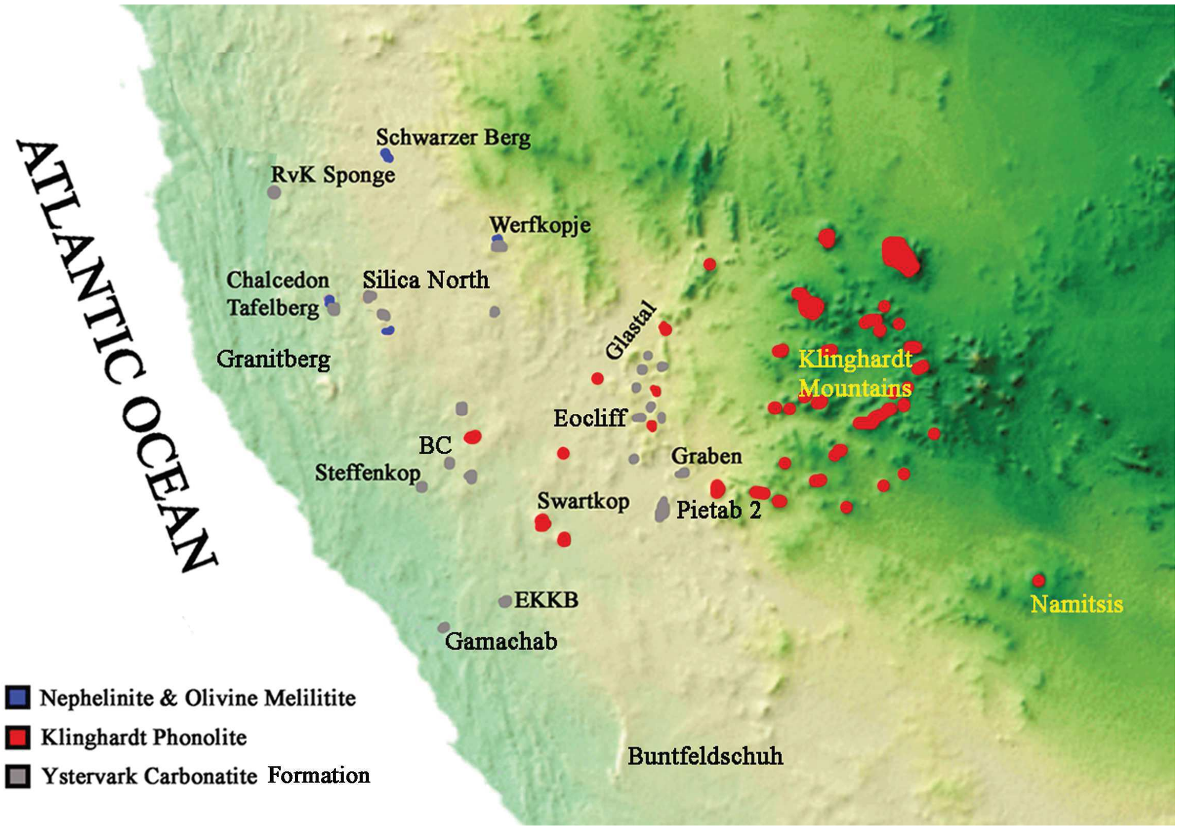

Figure 20. Distribution of the Ystervark Carbonatite Formation, Klinghardt Phonolite, Schwarzer Berg Nephelinite and Werfkopje Olivine Melilitite in the Northern Sperrgebiet. Note that the Ystervark Formation is represented in the Trough Namib by few outcrops, most of the deposits having been removed by erosion leaving witness sections at Gamachab, Eisenkieselklippenbake, Steffenkop and RvK Sponge Site. The unit is better represented in the Plain Namib, but in any case most of it was removed by erosion, not only during the Eocene, but throughout the Oligocene and Neogene. BC – Black Crow, EKKB – Eisenkieselklippenbake.

The outcrops of Ystervark rocks will be described in two sections, the first devoted to the sites close to the volcanic centre in the "Plain Namib" (Beetz, 1926) just west of the Klinghardt Mountains (Fig. 24-49), and the second to the "Trough Namib" closer to the coast (Fig. 50-61), and thus on average finer-grained than most of the deposits in the Plain Namib. In cases where the base of the Ystervark deposits can be studied, it is clear that some of the depressions contained water at the time that the first carbonatite ashes fell to the ground (RvK Sponge Site, Steffenkop, Eisenkieselklippenbake) whereas others were dry (Chalcedon Tafelberg, Black Crow, Graben, Klinghardt's Pan, Gamachab). Ground water levels fluctuated during the Lutetian and Bartonian as shown by the deposits at Chalcedon Tafelberg, where the early carbonate ashes fell into a dry depression floored by Bo Alterite, but which later filled with water in which vibrant plant and animal communities lived. This indicates that the early limestone levels probably sealed the floors of the depressions rendering them impervious, but it also implies that the water table probably rose after the onset of limestone deposition. A difference of at least 25 metres in the altitude of the water table is probable.

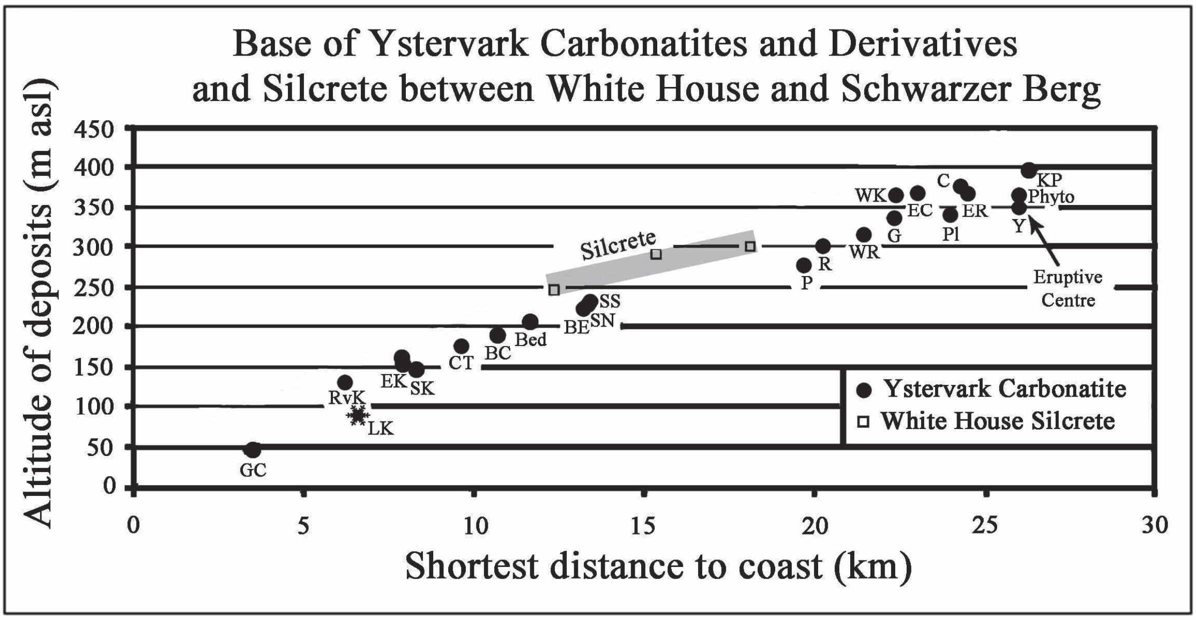

Figure 21. Altitude profile of the Ystervark Carbonatite Formation reveals that it slopes gently and quite uniformly towards the coast from its eruptive centre near the Klinghardt Mountains, and is 40-50 metres lower than the White House Silcrete, in terms of its altitude and distance from the coast. Outcrops lower than 150 metres (Gamachab, Steffenkop and Eisenkieselklippenbake) were subjected to erosion during the Eocene high sea stand. BC – Black Crow, Bed – Bedded, BE – Bull's Eye, C – Contact Site, CT – Chalcedon Tafelberg, EC – Eocliff, EK – Eisenkieselklippenbake, ER – Eoridge, G – Graben, GC – Gamachab, KP – Klinghardt's Pan, LK – Lüderitz Krater, P – Pietab 2 Freshwater Limestone Depression, Phyto – Phytoherm Site, Pl – Plaquette Site, R – Reuning's Pan, RvK – RvK Sponge Site, SK – Steffenkop, SN – Silica North, SS – Silica South, WK – Werfkopje, WR – White Ring, Y – Ystervark.

Ystervark Formation in the Plain Namib

The northwest rim of Klinghardt's Pan (which it should be recalled, is not a breccia pipe as intimated by its previous name Klinghardt Breccia Pipe (Kalbskopf, 1977)) exposes a thickness of half a metre of well-bedded, fine-grained Plaquette Limestone dipping steeply southwards towards the trough of the basin. At this outcrop the base of the Plaquette Limestone is intermingled with sand grains and small clasts of altered schist which formed the surface of the ground at the time that the carbonatite ash was deposited. Towards the centre of the depression, drilling carried out by Kalbskopf (1977) encountered Scoria Carbonatite and Plaquette Limestone beneath a surface lag of sand, marl and locally derived alterite clasts.

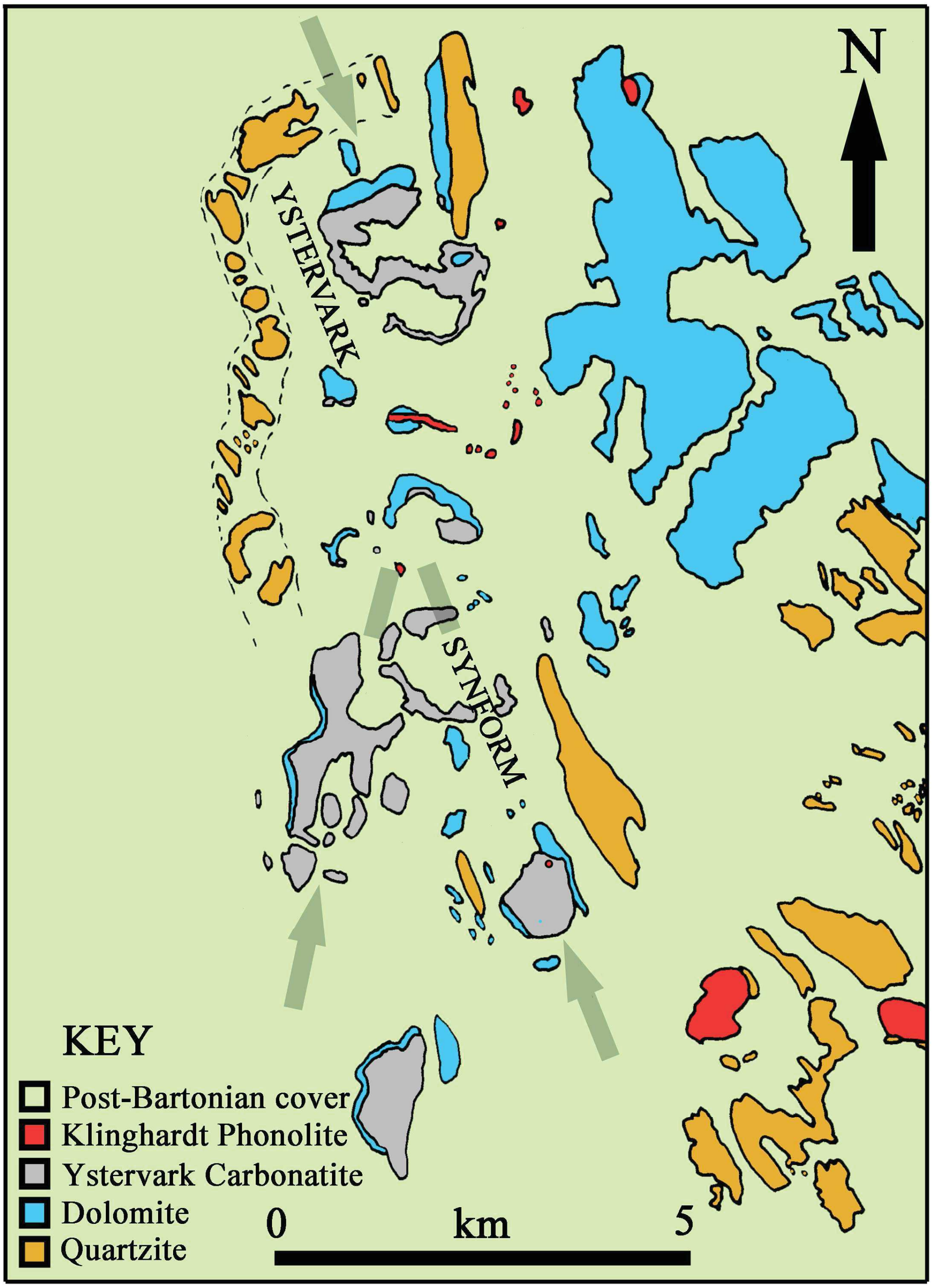

Figure 22. In its type area, the Ystervark Carbonatite deposits occupy saucer-shaped erosional features within the north-south oriented Ystervark Synform (pale arrows). The limbs of the synform comprise upstanding ridges of Quartzite and its axis is Dolomite which exhibits small-scale subsidiary synclinal and anticlinal structures along its outcrop. Erosion of the dolomites during the Ypresian produced a series of saucer-shaped depressions floored by bleached dolomite or, in the case of Klinghardt's Pan, altered schist. The countryside was blanketed in carbonatite ash during the Lutetian and Bartonian, but all that remains of this widespread unit are the parts that infilled the depressions or were heavily silicified and therefore rendered resistant to erosion.

Figure 23. View northwards along the axis of the Ystervark Synform from the Knapping Site showing Klinghardt's Pan in the middle distance and the dark oval hills beyond which are large outcrops of Ystervark Formation rocks, in places intensely silicified. Phytoherm Ridge is to the right and Klinghardt's Depression slightly beyond and to the left. The flanking limbs of the synform comprise upstanding ridges of quartzite shown by yellow arrows.

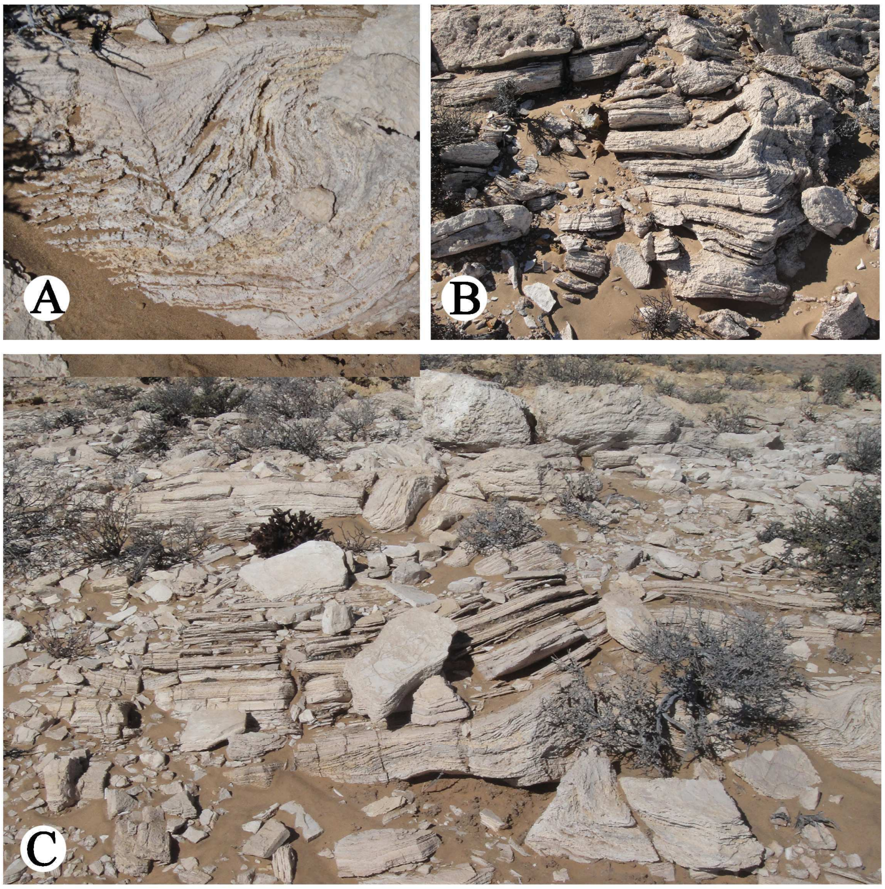

Figure 24. Plaquette Limestone Member of the Ystervark Carbonatite Formation in the vicinity of Klinghardt's Pan and Eocliff. A-B, soft-sediment slumps are common is areas where the ash fell onto sloping ground. C) well-bedded, finely laminated Plaquette Limestone near Ystervark Breccia Hill.

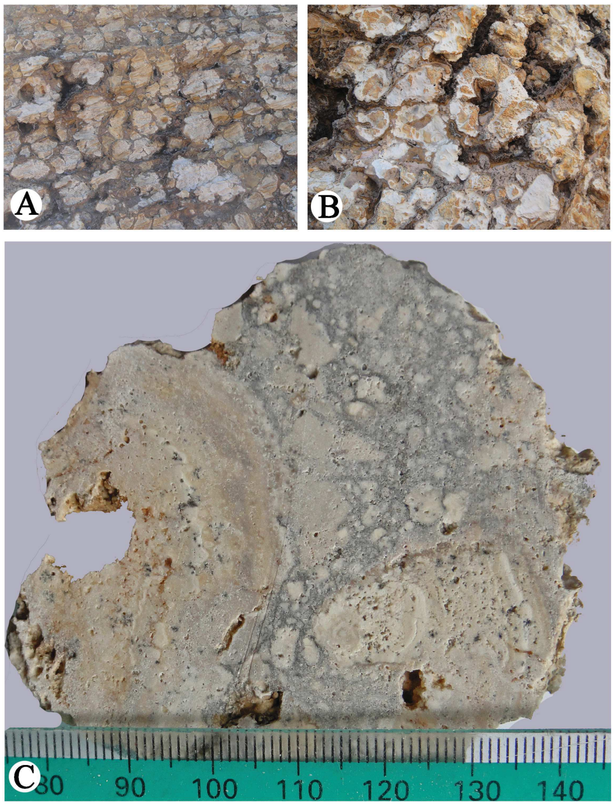

Figure 25. Ystervark Breccia and Scoria Limestone. A-B, coarse limestone breccia (clasts up to 10 cm diameter) supported by fine-grained red carbonatite matrix exposed on the southern flank of Ystervark Hill, C, is a cut section through Scoria Limestone from Scoria Hillock.

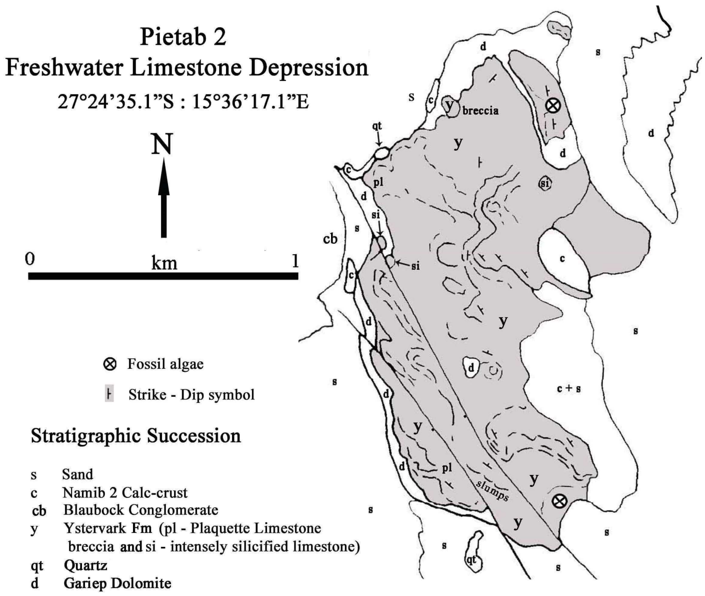

Figure 26. Geological sketch map of the Pietab 2 "Freshwater Limestone" Depression. The limestone in this outcrop comprises Plaquette Limestone and Scoria Limestone erupted by the Ystervark Carbonatite Centre, and silicified derivatives of these rocks. The only fossils from this outcrop consist of algae.

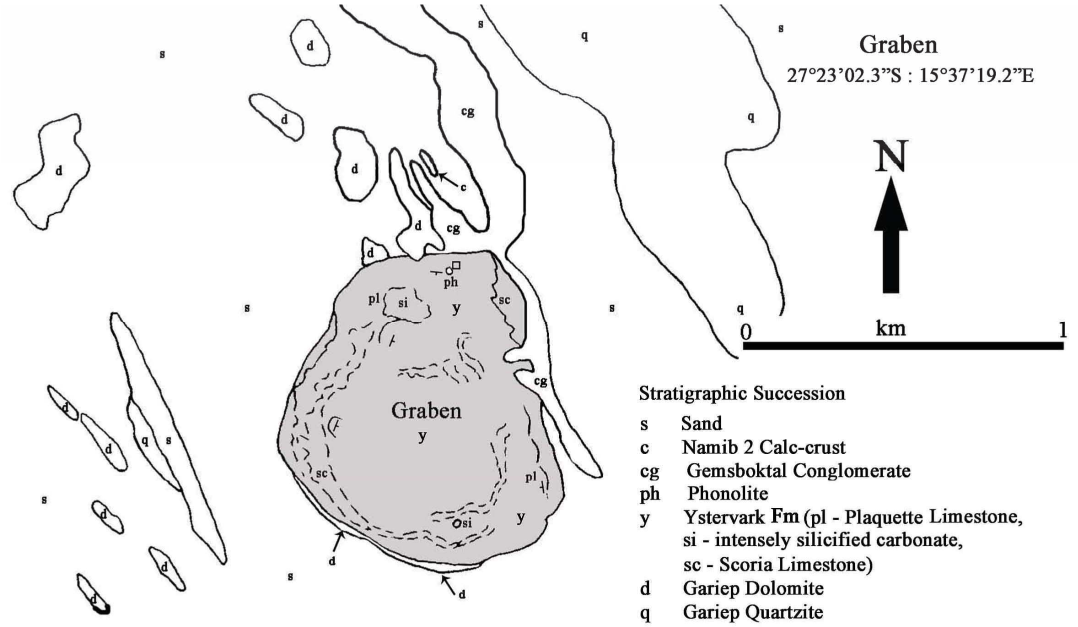

Figure 27. Graben consists of Plaquette Limestone, Scoria Limestone and Carbonatite Agglomerate with brecciated Plaquette Limestone. Note the small phonolite outcrop in the north-east corner of the area, beside which is a pit excavated by German geologists.

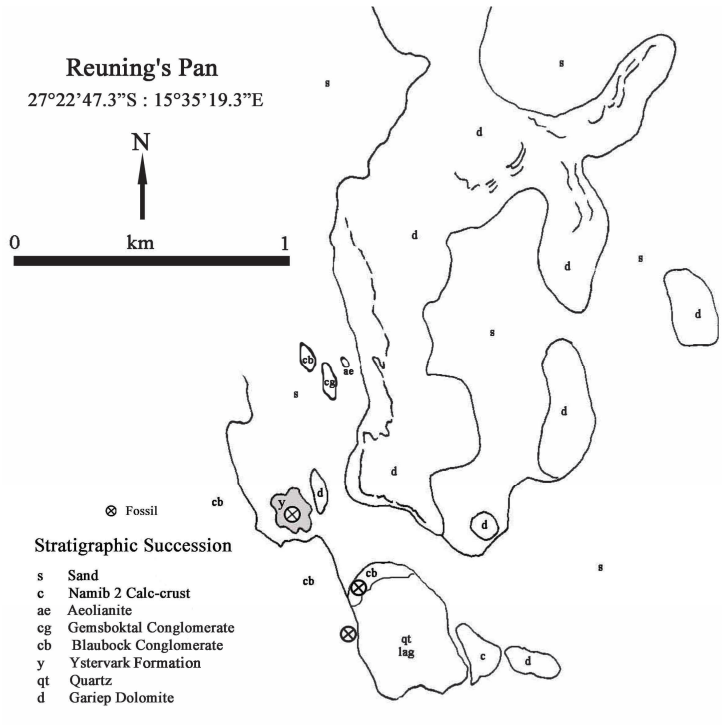

Figure 28. Reuning's Pan area preserves a small outcrop of the Ystervark Formation comprising palustral limestone containing freshwater gastropods. The overlying Blaubock Conglomerate has yielded fragments of reworked fossil wood, and the Namib 2 Calc-crust contains abundant shells of *Trigonephrus*.

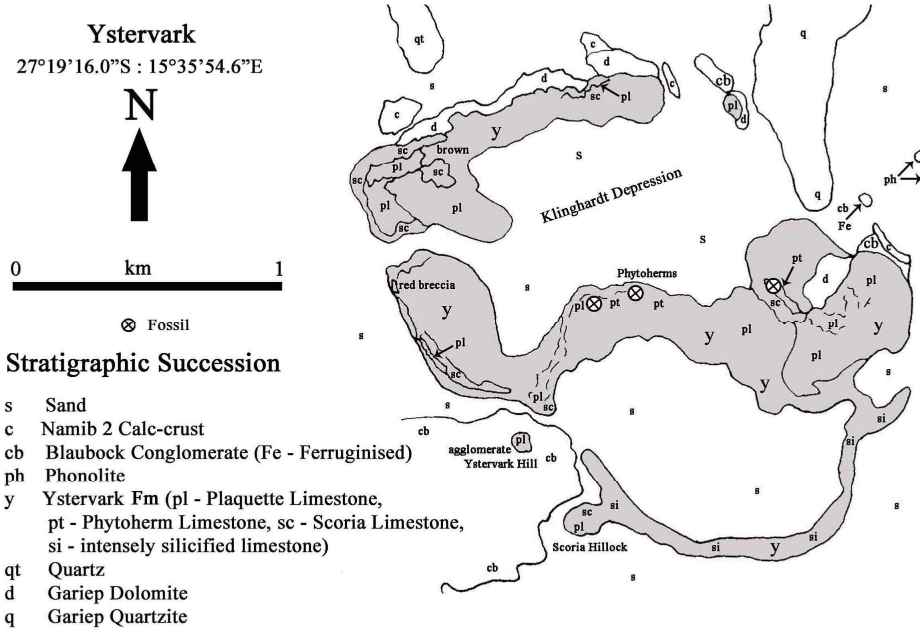

Figure 29. Type area of the Ystervark Carbonatite Formation which locally comprises Plaquette Limestone, Scoria Limestone, Phytoherm Limestone and Carbonatite Agglomerate, much of which has been silicified.

Overlying the Plaquette Limestone are two divergent types of carbonate rocks, one sedimentary, the other volcanic. The 1-2 metre thickness of well-bedded carbonatite ash that fell on the countryside molding its topography like snow, was eroded from higher ground and was then transported as clasts and in solution towards depressions which had been rendered impervious by their infilling of Plaquette Limestone. These reworked limestones are sometimes accompanied by marls derived from nearby outcrops of alterite exposed by the removal of their thin cover of carbonatite ash. The palustral limestones that resulted from this activity are often richly fossiliferous, containing algae in the form of algal mats, aquaphile plants, plant root systems (pedotubules), freshwater and terrestrial gastropods, amphibians, turtles, birds and mammals. Palustral sedimentation was interrupted by sporadic eruptions from the Ystervark Centre, with additional layers of Plaquette Limestone being deposited widely over the Northern Sperrgebiet (Chalcedon Tafelberg has three well-bedded carbonatite limestone layers, each 1-3 metres thick separated from each other by locally derived clastic marls). Nearer the eruptive centre, around Eocliff and Klinghardt's Pan, coarser grained carbonatites were deposited (Scoria Limestone) but during particularly violent eruptions breccia was ejected as far away as 15 km (Black Crow). The latter occurrence proves the Lutetian age of the eruptions, because the breccia occurs sandwiched between two horizons of fossiliferous palustral limestones containing mammals of this age.

Towards the end of the active life of the Ystervark Centre, a coarse carbonatite breccia pierced through the superficial rocks in the area north of Klinghardt's Pan, forming a nearly vertical breccia-filled pipe with lateral sill-like offshoots, accompanied by much brecciation of the Plaquette Limestone, and displacement of blocks of the same rocks at various angles (Fig. 30-33). Kalbskopf (1977) described the breccia at Ystervark Hill, correctly identifying it as a carbonatite, but he misinterpreted the cross-cutting relationships. He wrote that the Plaquette Limestone was a lacustrine cap infilling a former crater floored by Carbonatite Breccia, whereas the field relations reveal without a doubt, that the breccia cuts through the Plaquette Limestones, and is therefore younger than them, rather than older.

Figure 30. Ystervark Carbonatite Breccia intruding Plaquette Limestone at Ystervark Hill, Sperrgebiet, Namibia. Note the vertical contact between the breccia to the right and the disturbed, brecciated Plaquette Limestone to the left.

Figure 31. Ystervark Carbonatite Breccia intruding Plaquette Limestone at Ystervark Hill.

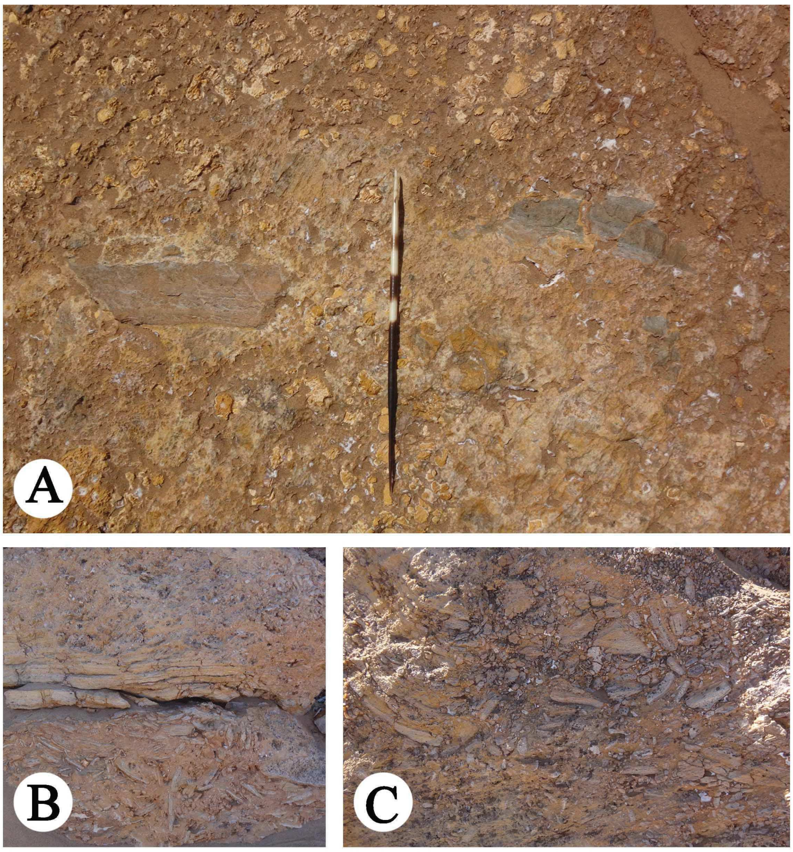

Figure 32. Various facies exposed in Ystervark Hill, Sperrgebiet, Namibia. A) Ystervark breccia exposed at the top of the hill, containing angular chunks of Gariep Group rocks floating in a carbonatite breccia (porcupine quill for scale). B) Brecciated Plaquette Limestone beneath a sill-like offshoot of the Ystervark Breccia Pipe. C) Intermingled pieces of brecciated Plaquette Limestone and Ystervark Carbonatite Breccia exposed on the southern side of the hill.

Figure 33. The summit of Ystervark Hill showing breccia in the foreground which has intruded Plaquette Limestone and thrust it upwards and outwards at various angles.

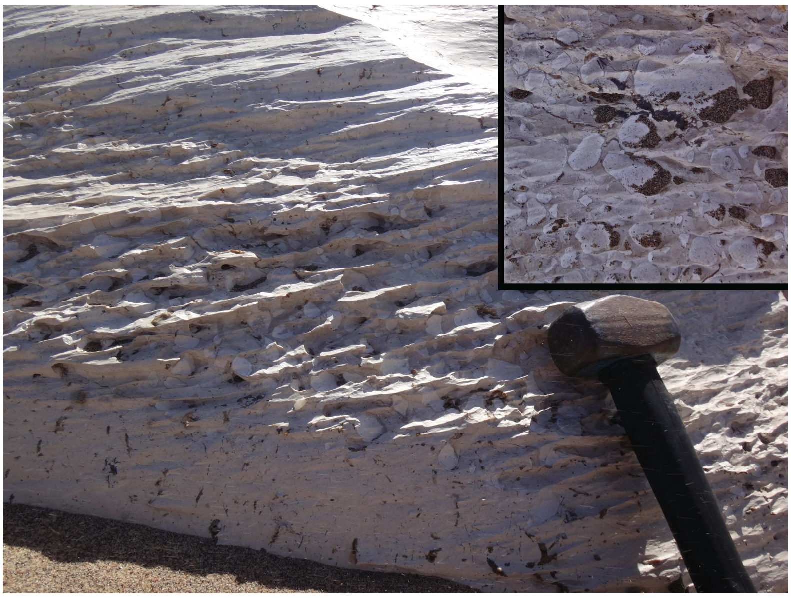

Figure 34. Ystervark Carbonatite Breccia was sometimes blasted considerable distances as shown by this 21 cm thick layer of angular breccia intercalated in fine-grained palustral limestone at Black Crow, 15 km from the eruptive centre. The limestones above and below the breccia horizon are fossiliferous (Lutetian). Note the plant pedotubules in the palustral limestone beneath and above the breccia layer. Inset – detail of breccia enhanced to show irregular outlines of clasts (the dark material is loose sand infilling shallow depressions in the breccia, generally corresponding to breccia clasts, which are slightly more prone to erosion than the supporting carbonatite ash matrix).

Intercalated between Plaquette Limestone layers and Scoria Limestone is a horizon of Phytoherm Limestone up to 2 metres thick, widely distributed in the hills north of Klinghardt's Pan (Fig. 35-37). The phytoherms grew around lime-charged springs (possibly hot springs) that were active all along the ridge a few km north of Klinghardt's Pan.

Figure 35. Exposure of Phytoherms (brown deposits to the right of the image) intercalated with Plaquette Limestone (white well-bedded deposits) dipping to the south.

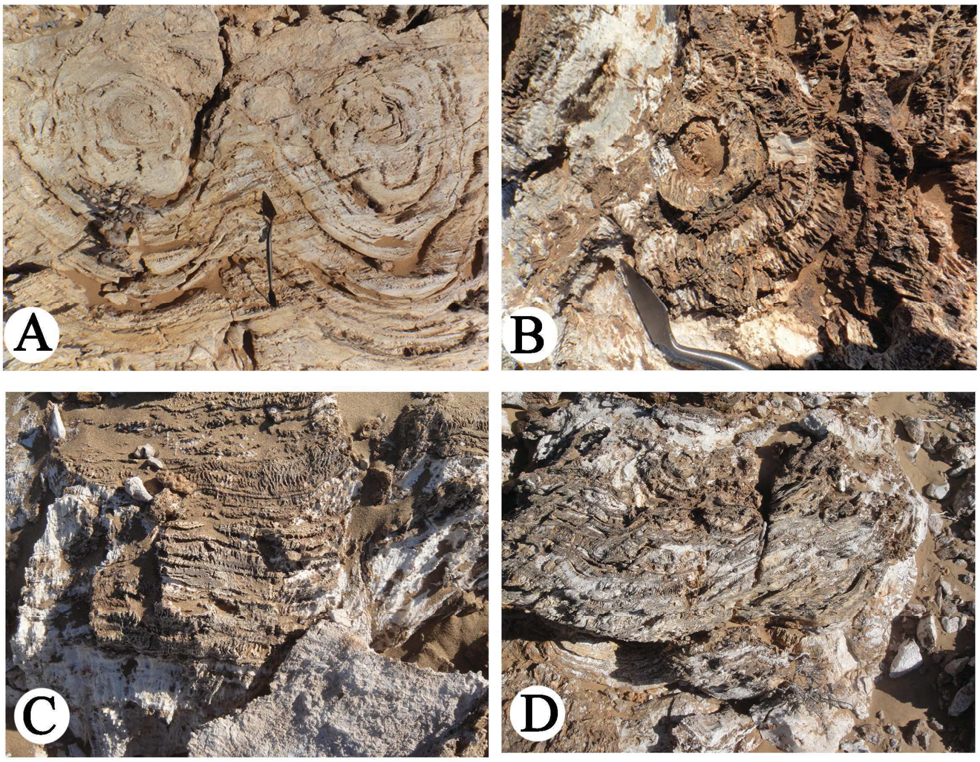

Figure 36. Phytoherms abound along the ridge north of Klinghardt's Pan. A-D are *in situ* phytoherms showing the characteristic onion-skin layering and the cell-like structures in each layer. The tool in A is 185 mm long.

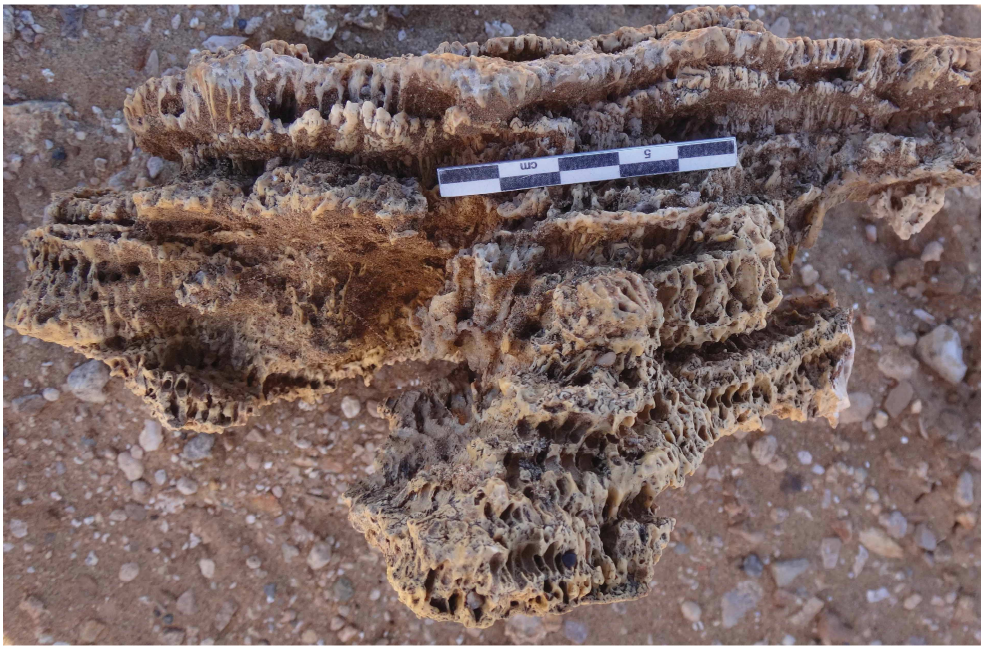

Figure 37. Silicified phytoherm showing details of sub-parallel layers of elongated cell-like structures, probably secreted by mosses (scale: 5 cm).

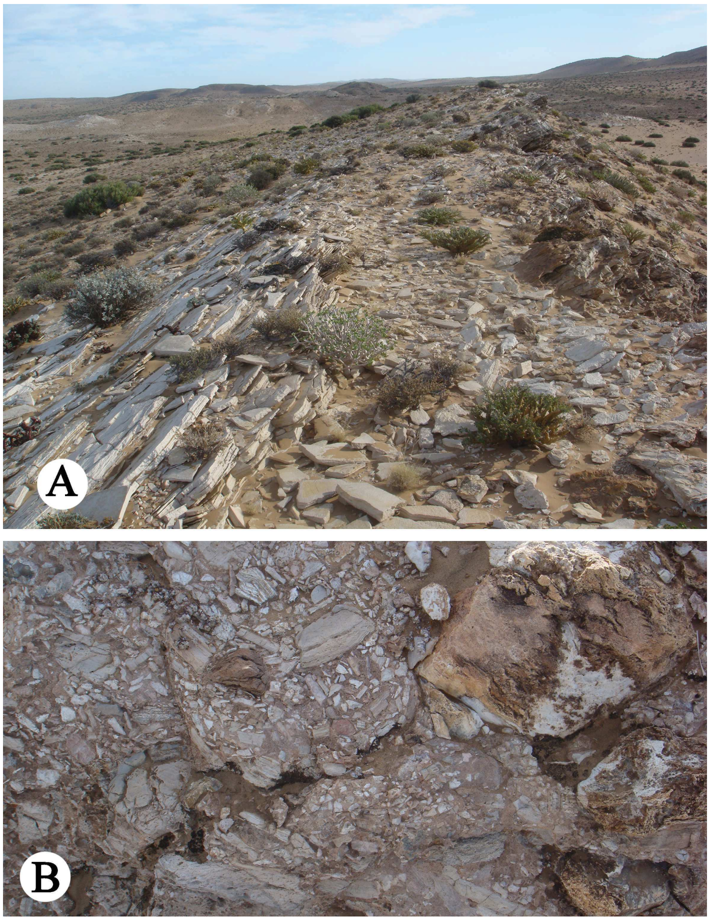

Figure 38. Ystervark Carbonatite deposits at Graben. A) Steeply dipping Plaquette Limestones, B) brecciated Plaquette Limestone and carbonatite matrix. Note that some of the limestone was silicified (brown chunks of partly silicified limestone) prior to brecciation.

Figure 39. Laminated carbonatite ash infilling a depression eroded into marly alterite at White Ring, Sperrgebiet, Namibia. Similar deposits infill several other depressions in the region, including Klinghardt's Pan, Reuning's Pan, Graben and Chalcedon Tafelberg. The deposits are attributed to the Plaquette Limestone of the Ystervark Carbonatite Formation.

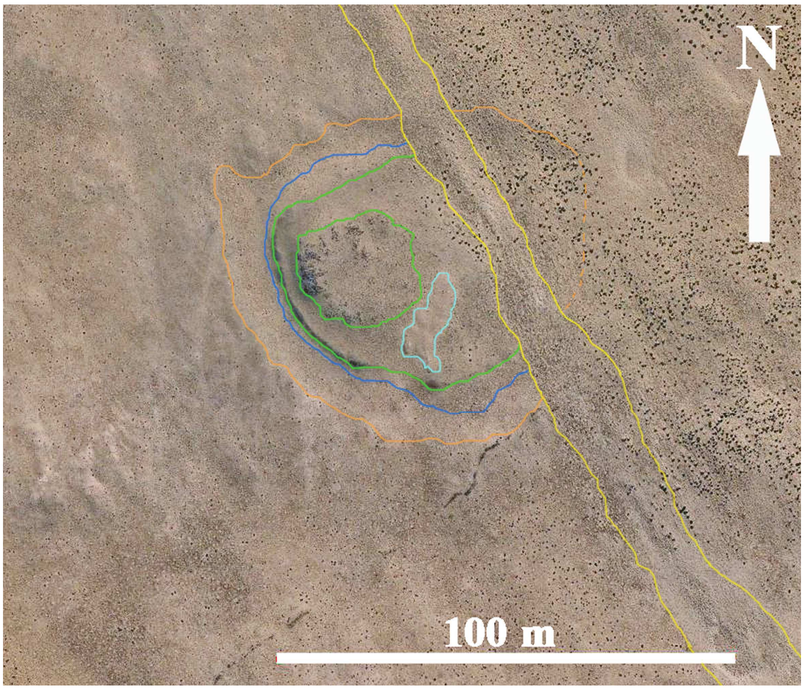

Figure 40. The Werfkopje outcrop is so named because of the presence of Bushman werfs on its summit. The saucer-shaped depression is formed in weathered granite exposed in the margins of the surrounding "moat" (orange line). The base of the thin, well-bedded limestone succession (dark blue line) overlies weathered granite, and is itself overlain by Olivine Melilitite lava (green lines). There is an outcrop of "Older" Namib 1 Calc-crust (pale blue outline) and a longitudinal dune (yellow lines).

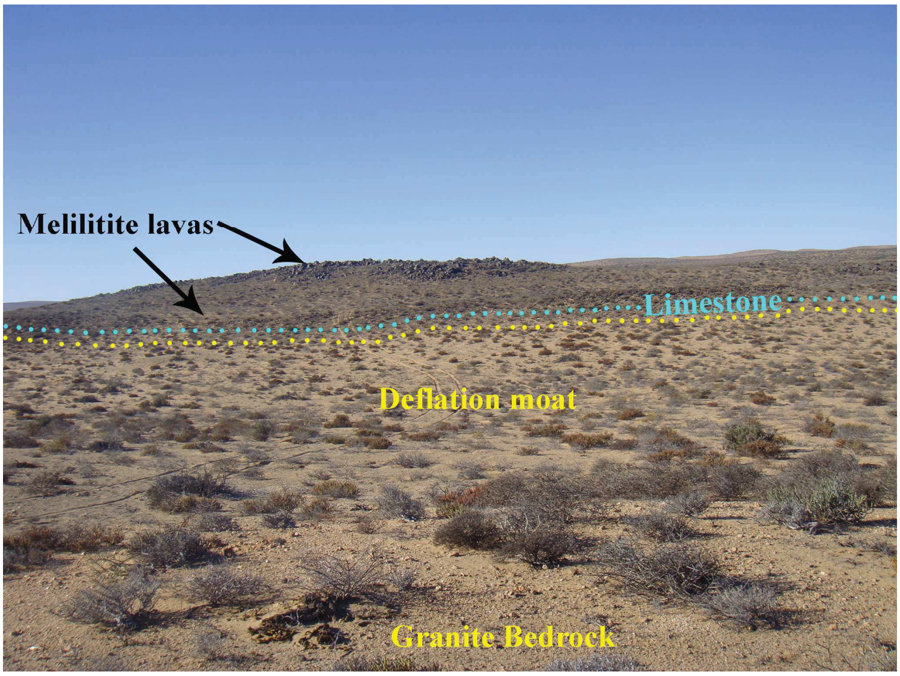

Figure 41. View of Werfkopje from the west, showing the deflation moat with the well-bedded limestone (pale blue line) overlying weathered granite (yellow line) with melilitite lavas forming the summit of the hill.

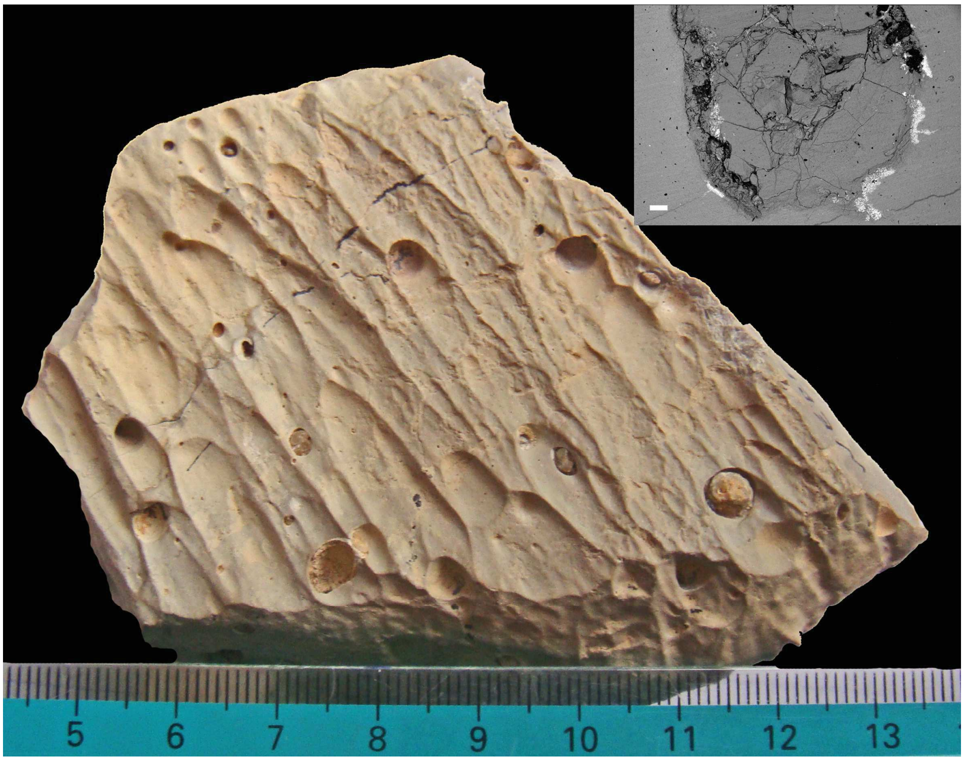

Figure 42. Werfkopje, Sperrgebiet, Namibia. Wind faceted carbonatitic tuff of the Ystervark Formation containing hailstone lapilli. Inset shows a polished section through a lapillus to illustrate the thermal shock fabric characteristic of hailstone lapilli (white scale bar : 200 microns).

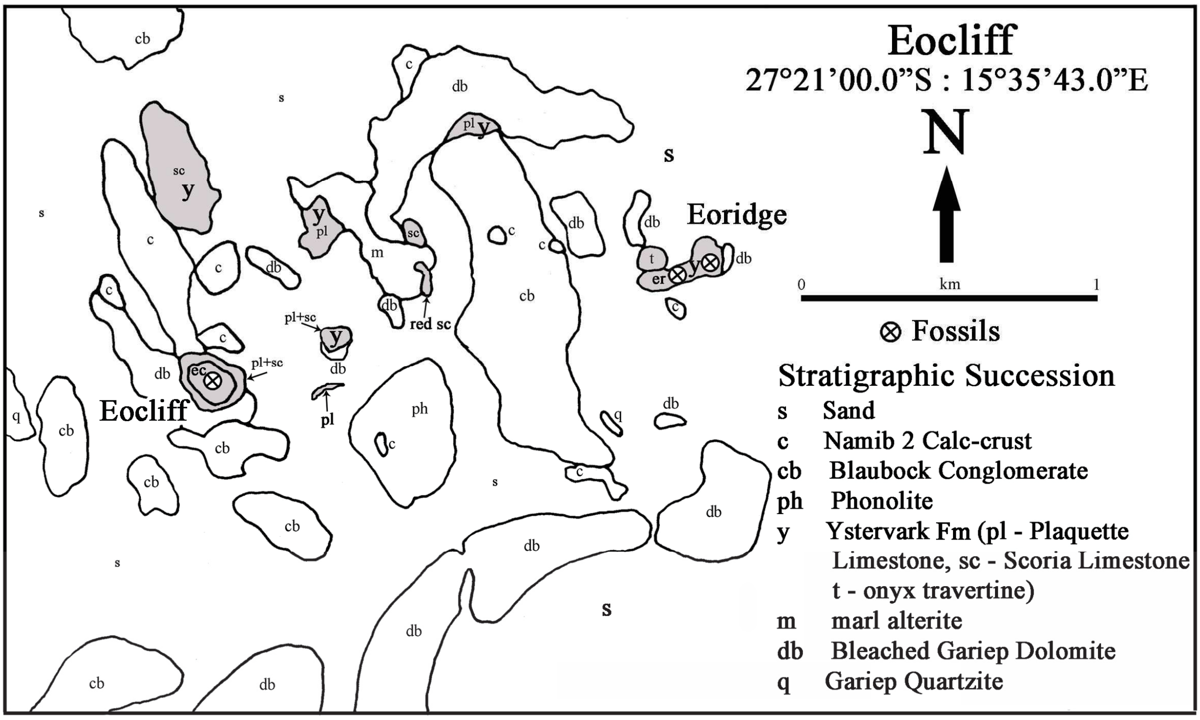

Figure 43. Sketch map of the geology of the Eocliff-Eoridge area highlighting the distribution of the Ystervark Formation carbonates (grey). The Eocliff and Eoridge outcrops are the youngest representatives of the Formation, and are by far the richest in fossils. Note that the Blaubock Conglomerate lies unconformably on the Ystervark Formation.

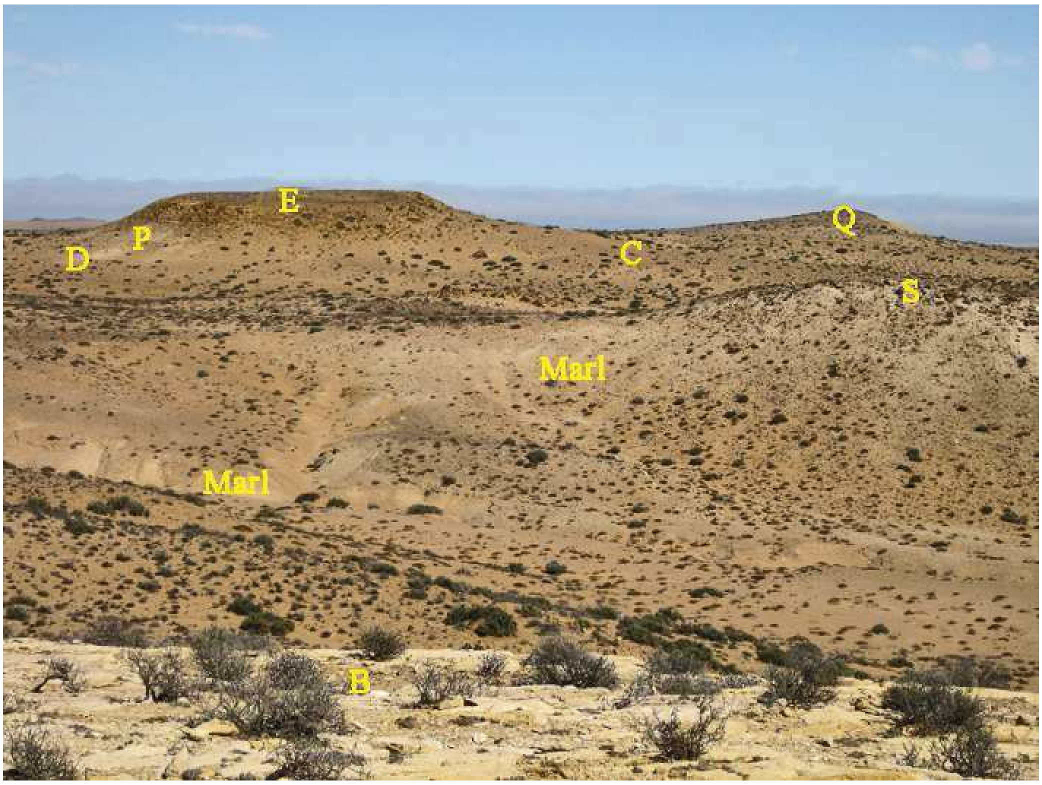

Figure 44. View of the east flank of Eocliff with main rock units identified. B – bleached dolomite, C – Namib 2 Calc-crust, D – dolomite, E – Eocliff Limestone P – Plaquette Limestone overlain by Scoria Limestone, Q – Quartzite, S – silicified limestone.

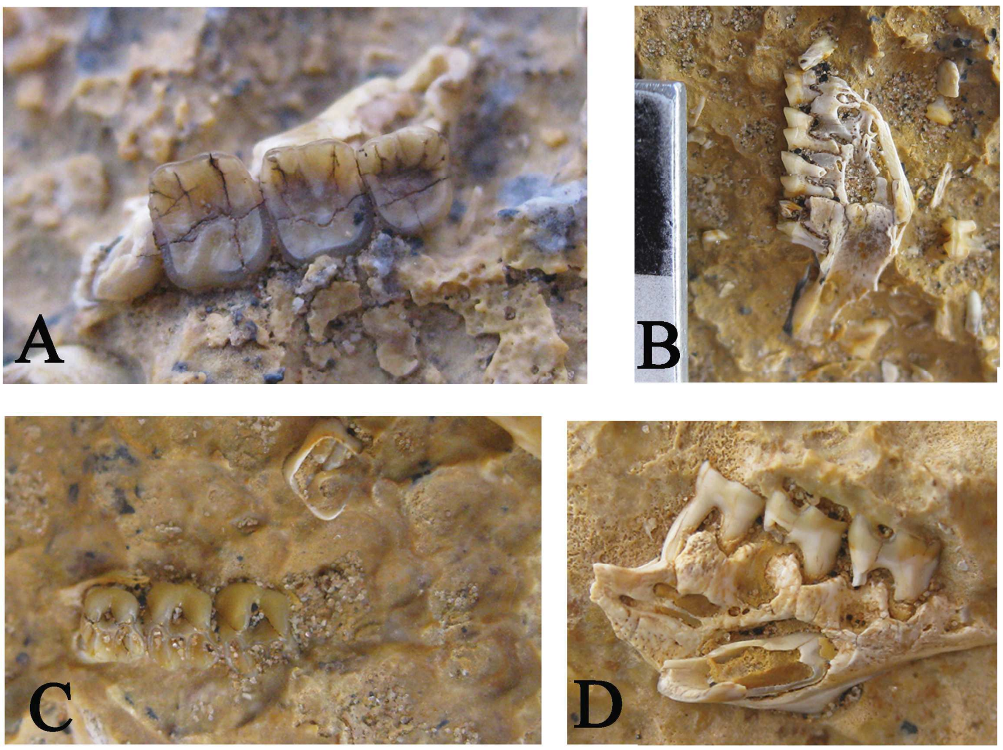

Figure 45. Mammalian microfauna from Eocliff, Sperrgebiet, Namibia, indicate a pre-Priabonian correlation for the deposits. A-D) *in situ* occurrences of rodents.

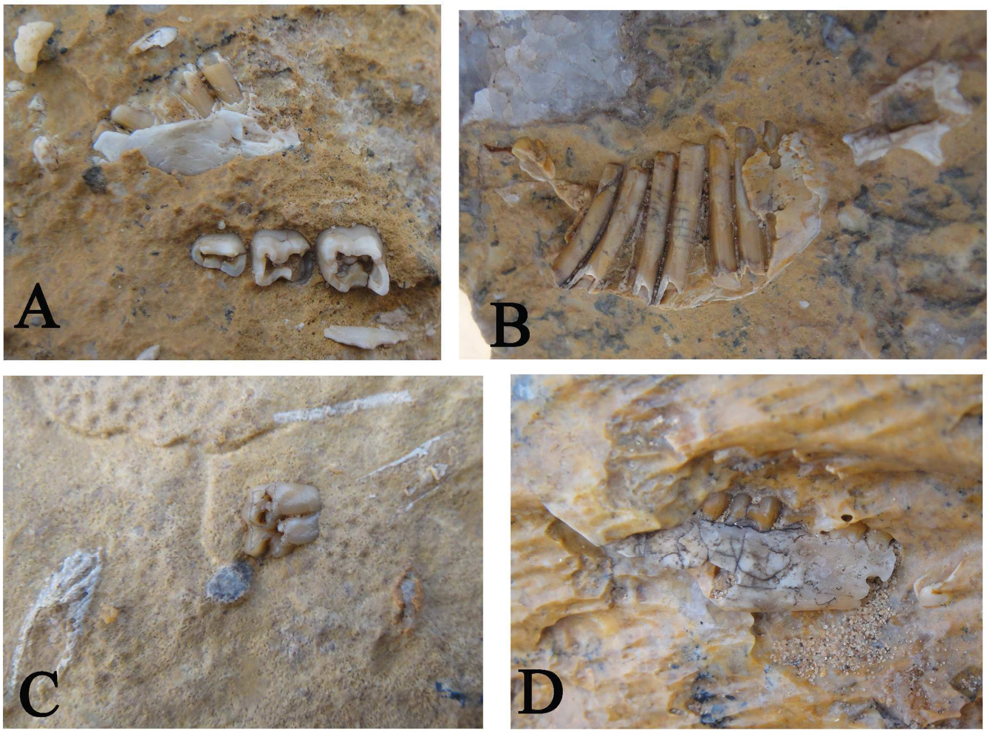

Figure 46. Macroscelididae in the Eocliff Limestone comprise hypsodont forms related to *Myohyrax* (A-C) and brachyodont forms (D). The hypsodont form attests to the likely presence of grass in the area at the time of deposition.

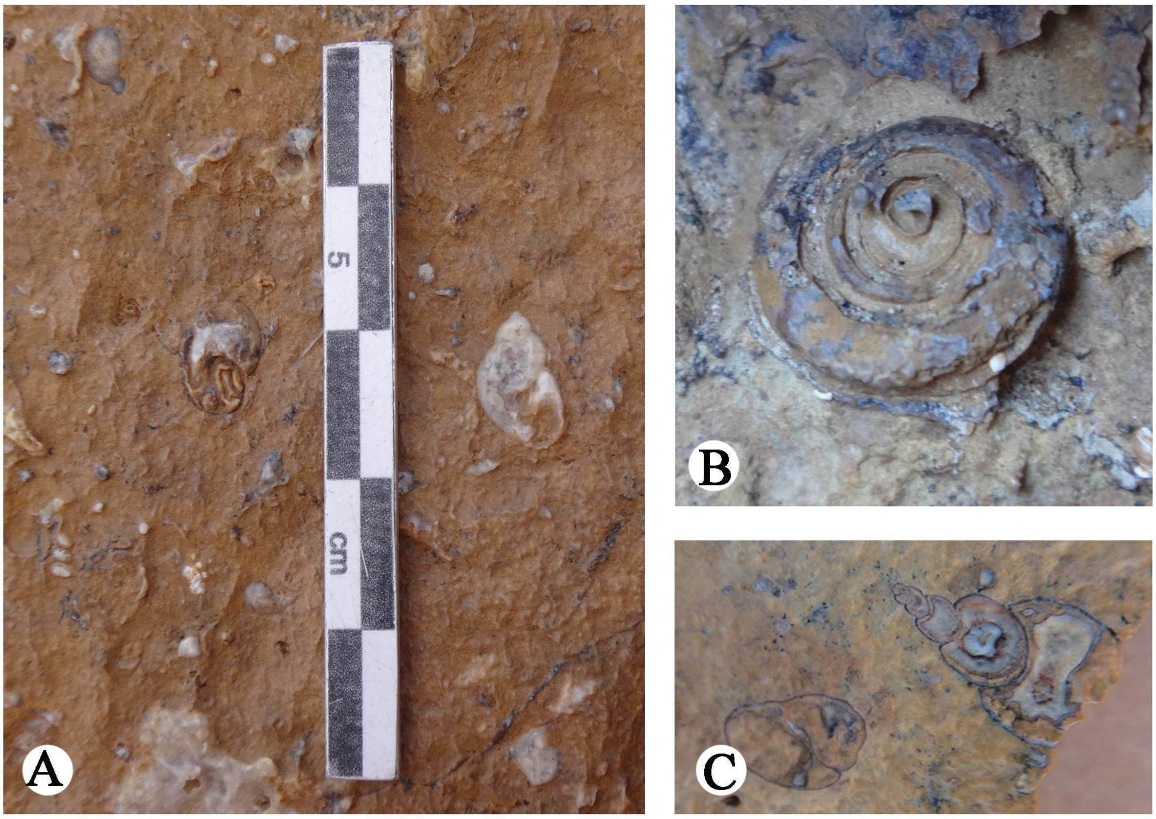

Figure 47. Fossiliferous limestone at Eoridge contains abundant freshwater gastropods. A+C) *Lymnaea*, B) large planorbid ca 12 mm in diameter.

Ystervark Formation in the Trough Namib

The dying phase of activity of the Ystervark centre was accompanied by two phenomena, both related to hydrothermal activity. Alternatively the hydrothermal fluids could be related to deep seated magmatic activity accompanying emplacement of the Klinghardt Phonolites which occurred during this period (Marsh, 1987). The first was the localised seepage of lime-charged water at the surface, a process that gradually built up a 15 metre thickness of yellow-brown highly fossiliferous limestone which, at Eocliff, reposes unconformably on an eroded surface of Scoria Limestone and Plaquette Limestone and at Eoridge where it sits directly on bleached Proterozoic dolomite (Fig. 43-47). The Eocliff Limestone fauna is probably Bartonian. The second process was much more widespread and probably lasted longer as it led to silicification of near-surface rocks over a vast area north, west and south of the Klinghardt Mountains, and it affects the Eocliff and Eoridge Limestones. Silicification began during the lifetime of the Ystervark Centre, as shown by the fact that at Graben, 7.2 km south of Ystervark Hill, chunks of partly silicified limestone occur as angular blocks in the Ystervark Agglomerate.

Figure 48. The RvK Sponge site east of Pomona, Sperrgebiet. Rauff (1926) described freshwater sponge spicules from laminated silicified limestone exposed in the bottom of the depression.

Figure 49. Pit and spoil heap in the bottom of the RvK Sponge Site Depression excavated by Kaiser (1926a) which yielded the laminated silicified limestone rich in freshwater sponge spicules described by Rauff (1926). Note the brown silicified palaeosol and silicified slightly ferruginised dolomite.

During the phase of hydrothermal activity, superficial rocks as far away as 50 km from the Klinghardt Mountains were partly or pervasively silicified to produce an awesome variety of siliceous rocks depending on the host rock that was silicified. These silicified rocks are attributed to the Sperrgebiet Siliceous Suite and should not be confused with the White House Silcrete (Fig. 48-49).

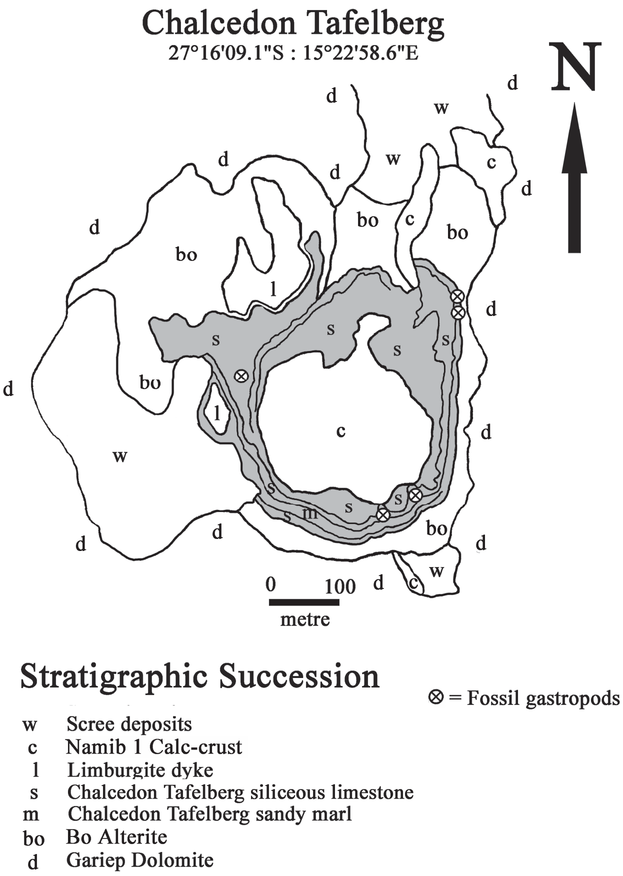

Figure 50. Geological sketch map of Chalcedon Tafelberg.

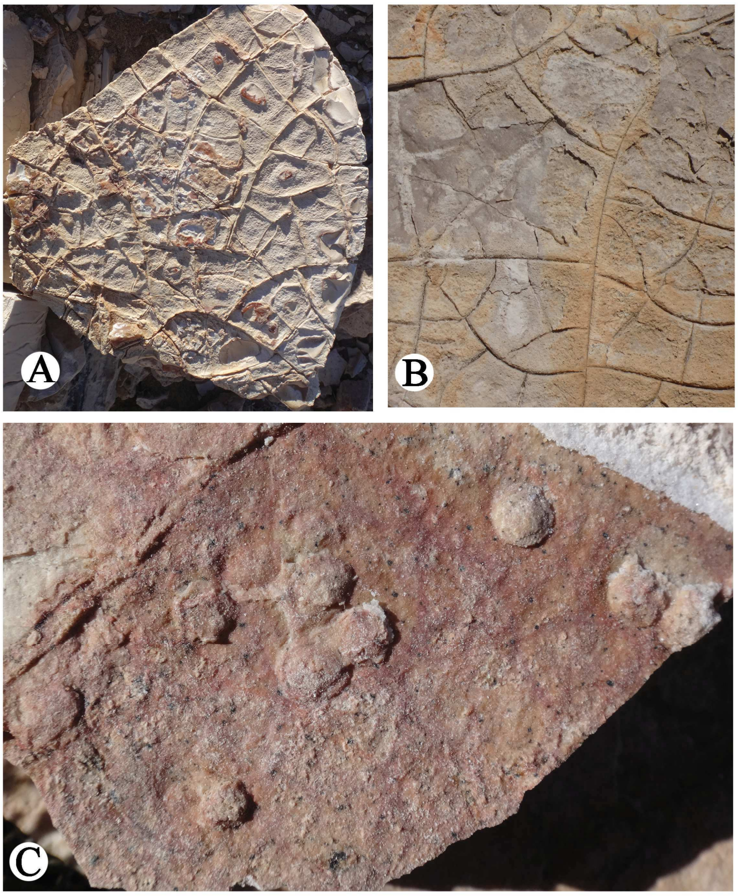

Figure 51. Sedimentary structures in Silicified Plaquette Limestone at Chalcedon Tafelberg. A-B - polygonal patterns resembling sun-cracks, C - pea-sized objects interpreted to be hailstone lapilli similar to those at Werfkopje.

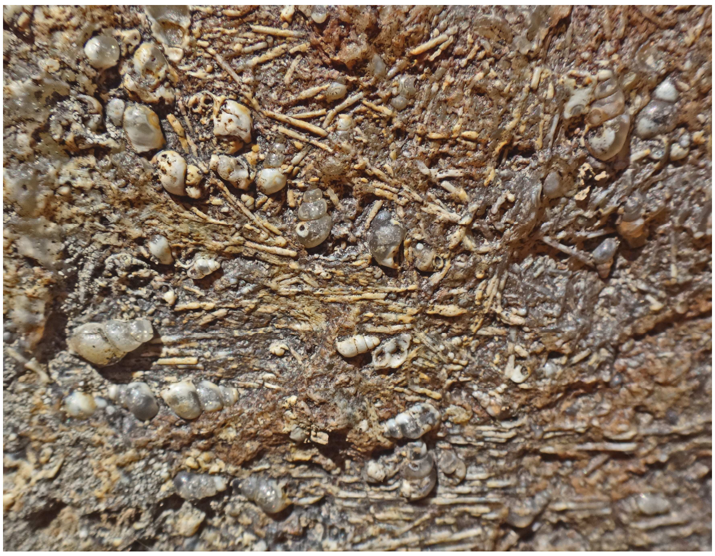

Figure 52. Well-bedded fossiliferous silicified palustral limestone at Chalcedon Tafelberg containing abundant hydrobiid gastropods and aquaphile plant remains.

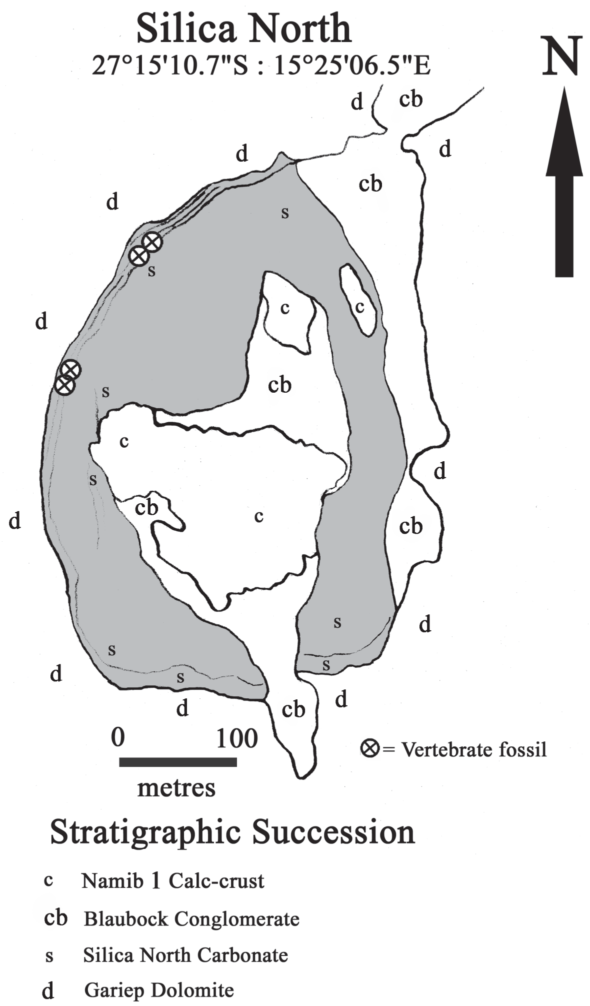

Figure 53. Geological sketch map of Silica North.

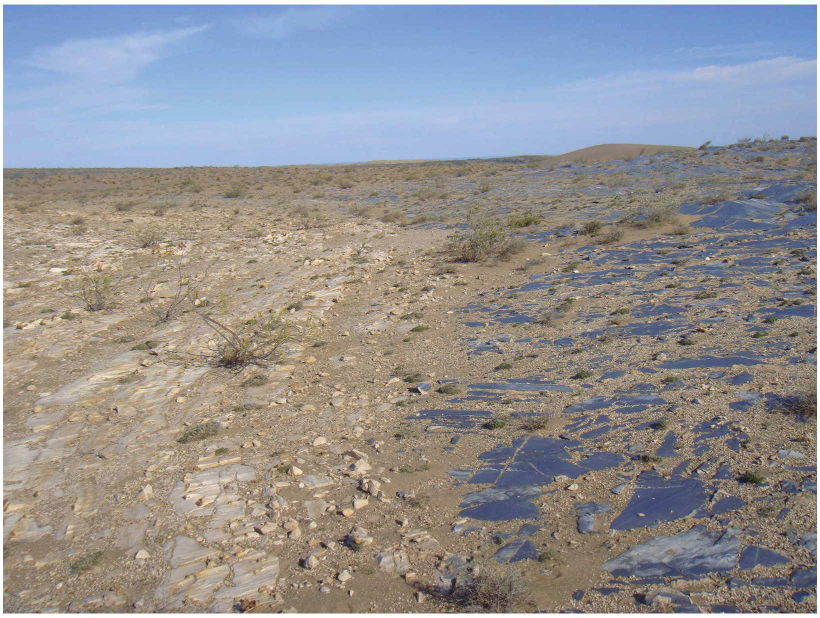

Figure 54. The Northern flank of Silica North showing well-bedded, finely laminated fossiliferous Ystervark Plaquette Limestone to the left of the image overlying relatively fresh blue-grey dolomite of the Gariep Group to the right of the image.

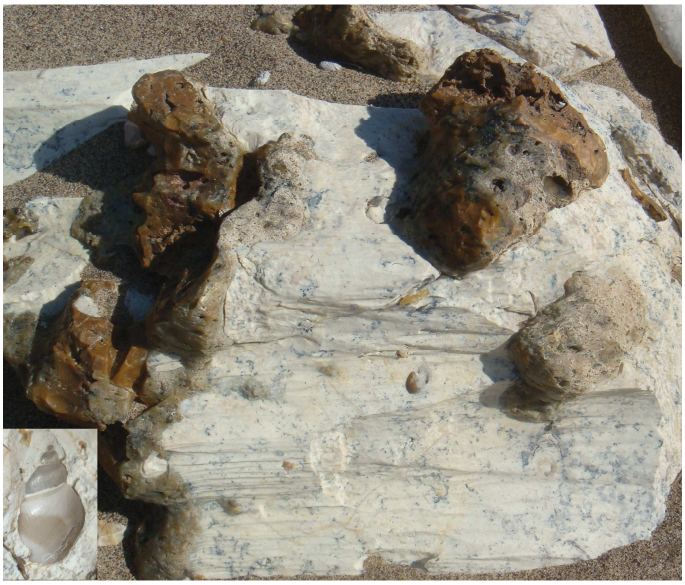

Figure 55. Nodular silicification of fossiliferous palustral limestone at Silica North. Note the gastropods in the limestone between the nodules. Inset: silicified *Lymnaea* shell ca 1 cm tall.

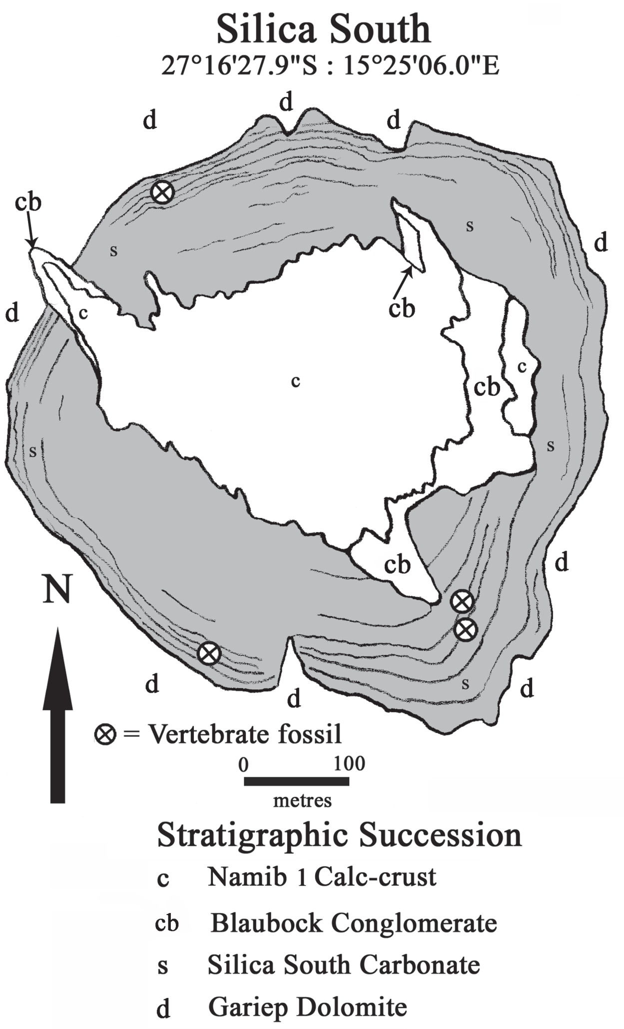

Figure 56. Geological sketch map of Silica South.

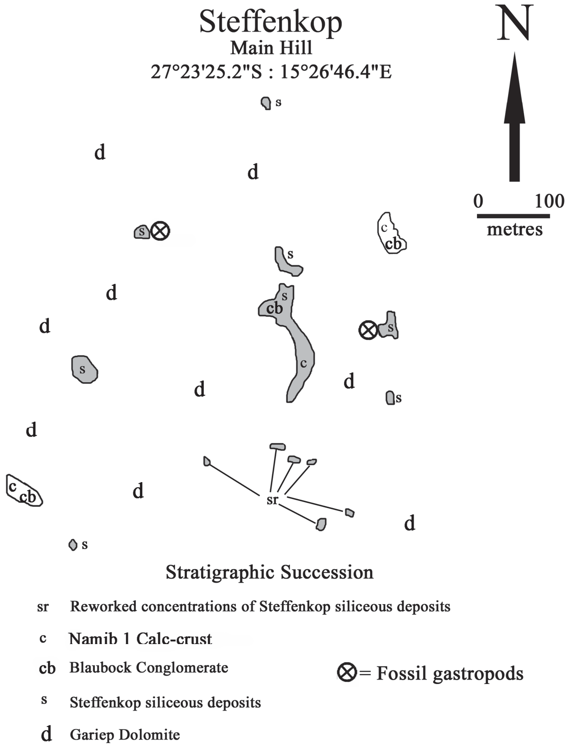

Figure 57. Geological sketch map of Steffenkop, representing the basalmost parts of a former infilling of a depression by Ystervark Carbonatite ash and palustral limestone, subsequently completely silicified.

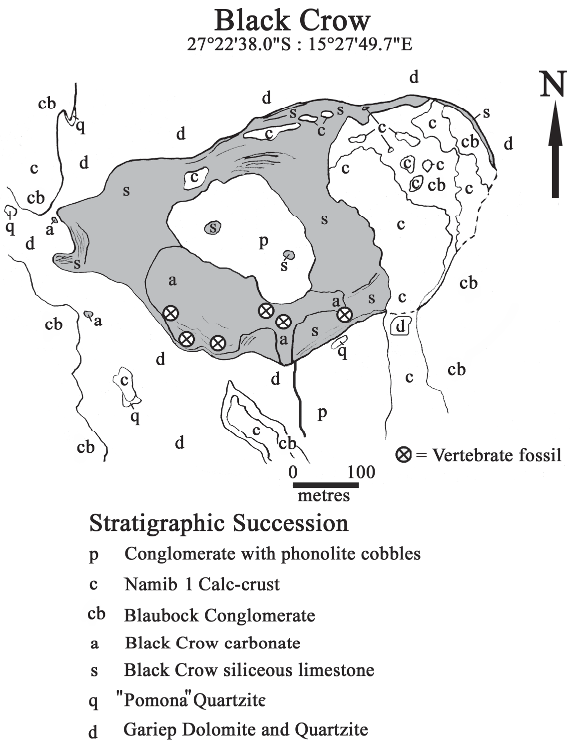

Figure 58. Geological sketch map of the Black Crow area. Note the presence of four small outcrops of "Pomona" Quartzite at the base of the Palaeogene succession.

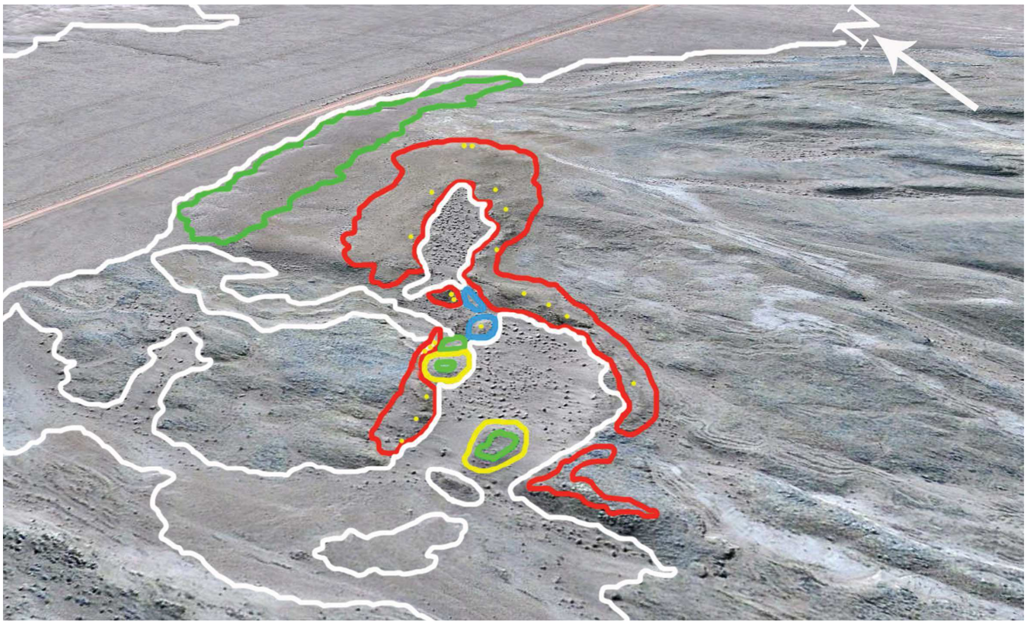

Figure 59. Oblique view northeastwards of Eisenkieselklippenbake Palaeovalley showing the local geological succession. Red outlines fossil-rich silicified Ystervark Formation Limestone overlying Proterozoic dolomites, blue is unsilicified fossiliferous palustral limestone of the Ystervark Formation, yellow is Priabonian agate-rich marine sediment overlain by green, Blaubock Conglomerate, and white is loose sand. Yellow dots are fossiliferous spots within the Ystervark Formation deposits.

Figure 60. Eisenkieselklippenbake palaeovalley at the inland edge of the Trough Namib, shows fossiliferous silicified limestone (the brown deposits between the blue and yellow dotted lines) overlying an incised surface of dolomite (to the right of the image, north flank of palaeovalley) and the cliff in the middle distance, in turn overlain by agate-bearing marine gravels (between the yellow and green dotted lines) which are overlain by coarse Blaubock Conglomerate (between the green and white lines), which are locally overlain by wind-blown sand (above the white lines). Viewed westwards from near the summit of the hill.

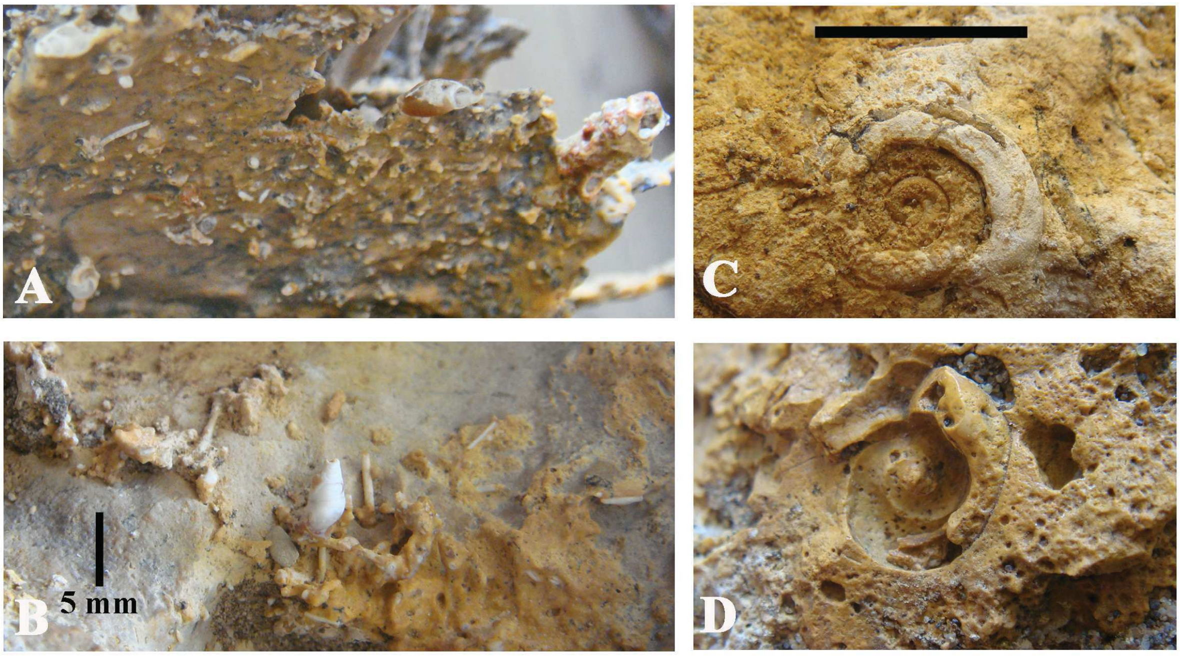

Figure 61. Freshwater gastropods preserved in partly silicified palustral limestone at Eisenkieselklippenbake. A-B) hydrobiids, C-D) large planorbids (scales 5 mm and 10 mm).

Dingle *et al.* (1983) correlated the Eisenkieselklippenbake and Buntfeldschuh marine deposits to the late Palaeocene-early Eocene high sea level stand (Ypresian), whereas Jacob *et al.* (2006) published an age of 42 Ma (Lutetian) for the Buntfeldschuh Formation and the Langental (Marine) Beds. In either case, the Ystervark Suite of faunas would be considerably older than thought by Pickford *et al.* (2008) as would the Sperrgebiet Silicification Event, on the grounds that not only are cobbles of Sperrgebiet silicified rocks common in the marine beds at all of these localities, but they overlie silicified rocks of the Ystervark Suite. Dingle *et al.* (1983) correlated the Langental *Turritella* Beds to the Priabonian on account of the nannofossils that they contain. This is more likely to be the age of the marine deposits at Eisenkiesel-klippenbake, and it is compatible with the biochronology of the Ystervark Formation. Further micropalaeontological survey is required to settle the issues.

We consider that the age of the Sperrgebiet Siliceous rocks can now be reasonably accurately constrained. At several localities (Eocliff, Eoridge, Chalcedon Tafelberg, Silica North, Silica South, Eisenkieselklippenbake, Steffenkop) silicified limestones have yielded abundant fossils including mammals at some of them (Fig. 45-46). Silicified and unsilicified limestones at Eisenkieselklippenbake contain abundant freshwater gastropods and aquaphile plants and are unconformably overlain by agate-bearing marine sediments (Fig. 47, 61). Similar marine deposits at Langental *Turritella* Site and Langental Shark Site yield Priabonian fossils. On this basis we conclude that the Sperrgebiet silicification process was active during the Late Bartonian.

Klinghardt Phonolites, Schwarzer Berg Nephelinite and other volcanic rocks

There was significant alkaline volcanic activity in the Northern Sperrgebiet during the Lutetian and Bartonian. The only places where superposition between lava and older rocks can be clearly observed are Werfkopje and Swartkop North Hill. At the former location two flows of olivine melilitite lava overlie Ystervark Carbonatite ash containing volcanic hailstones, which in their turn overlie altered granite. The latter occurrence shows Phonolite aged 37 Ma, overlying a quartz-rich conglom-erate which overlies silicified alterite (the chalcedony of Barbieri, 1968) containing pedotubules very similar to the Eisenkiesel-klippenbake outcrops 5 km to the south, and also close lithologically to the Steffenkop silicified limestones.

The Schwarzer Berg Nephelinite intruded alterite which is capped by White House Silcrete 1 km to the south of the intrusion. Radio-isotopic analysis of this intrusion yielded an age of 35.7 Ma (Kröner, 1973). Unpublished analyses of nephelinite from Schwarzer Berg yielded age determ-inations of 30-35 Ma (Phillips & Marsh pers. comm. in Miller, 2008b).

The Swartkop Phonolite overlies silicified alterite. Barbieri (1968) reported that a thickness of 34 metres of tuff overlies “silcrete”, “ferricrete”, marl and cong-lomerates, and is overlain by 3 metres of hornfels and chalcedony which is succeeded by 50 metres of phonolite.

Extensive outcrops of chalcedony south, west and north of Swartkop North Hill are overlain by a thin and discontinuous bed of conglomerate rich in quartz cobbles, which is in its turn overlain by Swartkop Phonolite. The chalcedony at this site contains pedotubules and is accompanied by opalized marl deposits similar to rocks that crop out at Eisen-kieselklippenbake 5 km to the south. Radio-isotopic analysis of the Swartkop lava yielded an age of 37 Ma (Priabonian) (Kröner, 1973) which is compatible with the Lutetian-Bartonian age estimate of the Eisen-kieselklippenbake fossils.

Phonolite lava from other areas (Black Crow, Granitbergfelder 15) yielded ages ranging from 45.4 Ma to 40 Ma (Lutetian to Bartonian) (Pickford *et al.* 2014) which is older than the Sperrgebiet Siliceous Suite. Unpublished age determinations of 45.67 +/- 0.1 & 46.52 +/- 0.1 Ma were reported by Phillips & Marsh (pers. comm. in Miller, 2008b) for unspecified outcrops of Klinghardt Phonolites.

In the Northern Sperrgebiet the presence or absence of phonolite cobbles has been used to distinguish between the Blaubock Conglomerate (which has no phonolite pebbles) and the Gemsboktal Conglomerate, which is rich in phonolite clasts (Van Greunen, unpublished map; Pickford *et al.* 2014). Most authors have concluded that the Blaubock Conglomerate must predate phonolite activity. Miller (2008a, 2008b) for example, concluded that the Blaubock Conglomerate was the oldest Cenozoic rock unit in the Sperrgebiet (pre-Lower Eocene) on the grounds that at Pietab 2 it is overlain by phonolite with an age of 46 Ma, whereas Jacob *et al.* (2006) thought it was 55 Ma. However, elsewhere in the vicinity of the Klinghardt Mountains (Eocliff, Kling-hardt’s Pan, Reuning’s Pan) the Blaubock Conglomerate overlies the Ystervark Carbonatite Complex and the Sperrgebiet Siliceous Suite (Late Bartonian to basal Priabonian) while in its type area north of Bogenfels, some of it overlies Priabonian marine strata. A possible solution to this enigma is that there could be more than one horizon called “Blaubock” Conglomerate. In order to resolve the apparent contradictions between these versions of the timing of events, further study of the contact between phonolite and subjacent rocks is necessary.

Figure 62. The Eocliff Limestone Mound reposes on a Late Eocene Land Surface which is concordant with the bases of several outcrops of Klinghardt Phonolites and well above the surfaces on which the Blaubock and Gemsboktal Conglomerates rest. View eastwards from the summit of Swartkop.

The Sperrgebiet Siliceous Suite

Prior to the accumulation of marine strata during the Priabonian, there was a widespread phase of silicification of near-surface rocks over a vast zone stretching from the Klinghardt Mountains to the coast and from Grillental in the north to Chameis in the South (Fig. 63-64). This phase of silicification was followed by a period of erosion, during which blocks of siliceous rocks were eroded, transported and deposited alongside Priabonian marine fossils. Because the silicification affected Bartonian limestones at Eocliff, it is concluded that the event occurred during the Late Bartonian. It occurred before the emplacement of the Swartkop Phonolite.

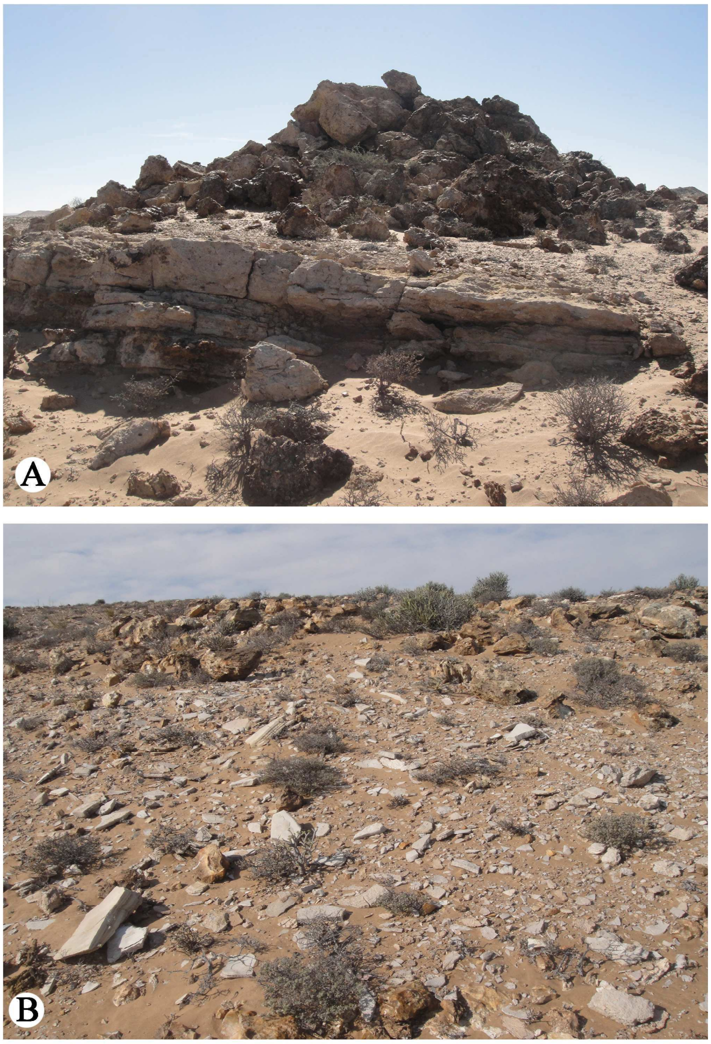

Figure 63. Silicified Ystervark Carbonatite Group rocks previously interpreted to be silcrete and attributed to the Kätchen Plateau Formation. A- Silicified Scoria Limestone overlying unaffected Plaquette Limestone at Eoknoll, B – Silicified limestone overlying Plaquette Limestone near Eocliff.

It is stressed that most of the rocks affected by this phase of silicification were near the ancient land surface, probably largely confined to the uppermost metre or two of soil and reg as shown by the presence of pedotubules and occasional gastropods. In some cases fractures in the bedrock show silicification which extends deeper into the country rock, but the majority of outcrops show a thin pellicle of silicified rock, usually less than a metre thick, overlying various rock types not so affected. In many cases the silicified masses overlie relatively fresh bedrock, but in other places they overlie alterite.

The variety of rocks affected by this silicification phase is truly amazing. Even though the process was homogeneous, the end result was highly heteromorphic depending upon which rock type was silicified.

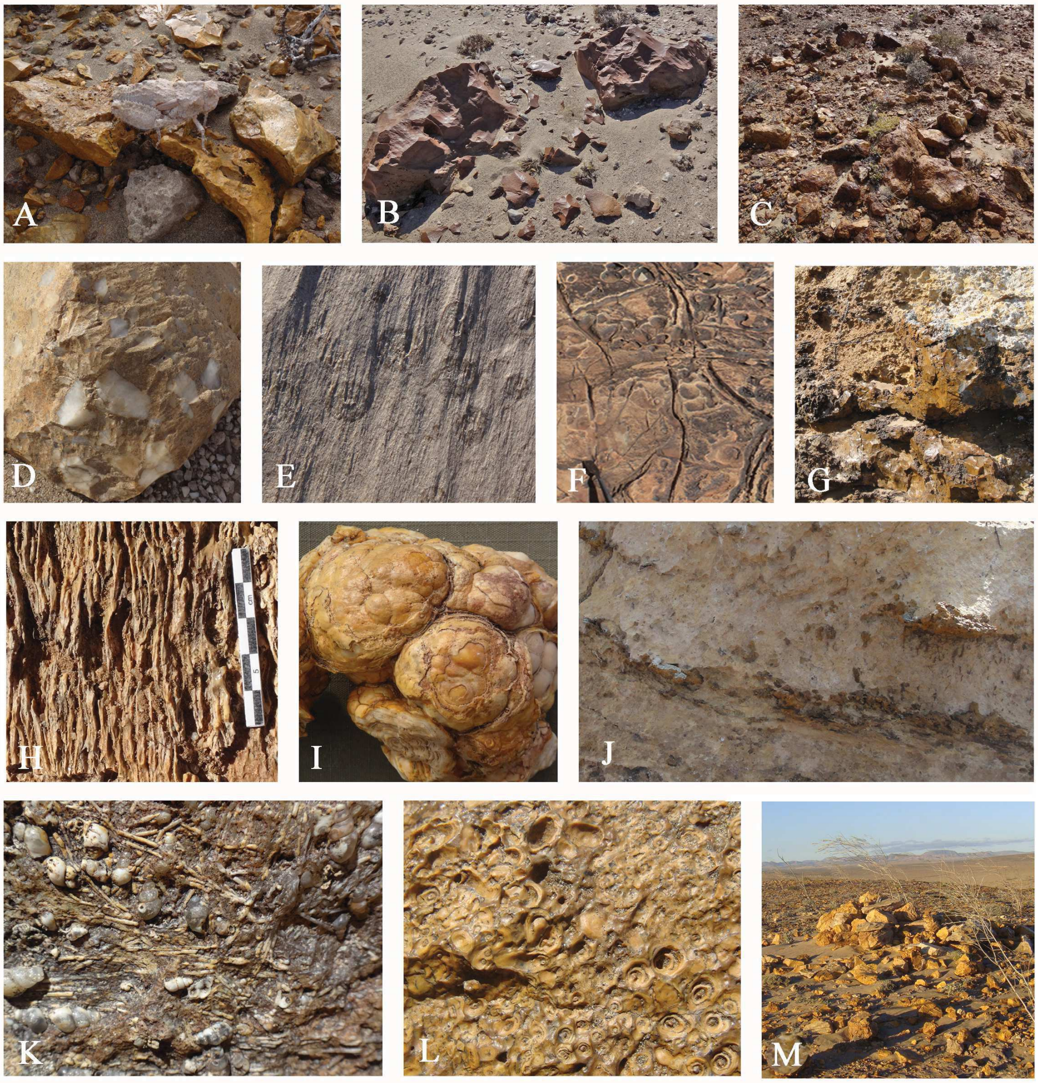

Figure 64. Selected specimens of the Sperrgebiet Siliceous Suite to demonstrate the enormous variety of rock types that were silicified during the Late Bartonian silicification phase. A – Silicified dolomite in a "Rondelle", B – Silicified ferruginised dolomite in Kleines Tal used as a source of stone tools, C – Silicified dolomite in a "Rondelle" built into a werf, D – Silicified deposits of the Kätchen Plateau Formation, E – Silicified sandstone containing round structures at Tafelberg Nord identified as lebenspurren, F – Silicified "sun-cracked" Plaquette Limestone near Eocliff, G – Silicified palustral limestone at Eocliff, H – Silicified phytoherm from Phytoherm Ridge, I – Silicified onyx from Phytoherm Ridge, J – Silicified algal mats in palustral limestone at Eocliff, K – Silicified fossiliferous limestone from Chalcedon Tafelberg, L – Silicified plant-bearing palustral limestone from Eisenkieselklippenbake, M – Honey-coloured silicified palustral limestone at the summit of Eisenkiesel--klippenbake.

Kaiser & Beetz (1926) recognised various types of silicified rock (verkieselung-massen) in the Sperrgebiet but did not call them silcrete. Since the 1940's however, virtually all researchers have interpreted the Sperrgebiet siliceous rocks to be silcrete and have inferred wide-ranging correlations to silcretes in other parts of the continent, and have proposed that these rocks comprise part of the African Surface of King (1949). Pether (1986) and Corbett (1989) demonstrated that some of the silicified rocks in the Sperrgebiet differed in their geochemical composition from genuine silcrete but their findings have generally been ignored by subsequent workers. By definition, silcrete (a pedogenic rock type) usually overlies altered bedrock (often kaolinite), which means that the Sperrgebiet Siliceous Suite should not be called silcrete. These siliceous rocks were formed by non-pedogenic processes millions of years later than the White House Silcrete which does overlie a deep weathering profile of Alterite, and which may comprise part of the African Surface.

Eocene and Oligocene Marine and Deltaic Deposits

The Eocene and Oligocene marine and deltaic deposits of the Northern Sperrgebiet have been widely discussed on account of the association of agates, chalcedony and jasper clasts with diamonds (Fig. 65) and the presence of a rich and diverse marine palaeontological record (Beetz, 1926; Böhm 1926; Böhm & Weissermel, 1913; Klinger, 1977; Siesser, 1977; Siesser & Salmon, 1979) which permits the age of some of the sediments to be determined. Apart from initial misinterpretations of the faunas as being of Cretaceous (Merensky, 1909; Range, 1910) or Miocene age (see map legends in Kaiser & Beetz, 1926) the Eocene affinities of the Langental *Turritella* Site fauna were soon established on the basis of studies of invertebrates by Böhm (1926) (see text legends for maps in Kaiser and Beetz, 1926). Much of the subsequent interpretation of the Sperrgebiet geological succession has been based on the positions of deposits relative to the Eocene Marine Beds. Thus, Rauff (1926) correlated the RvK Sponge Site northeast of Pomona to the Pre-Middle Eocene, Kaiser & Beetz (1926) correlated the Pomona Schichten (ie the Tafelberge Caps and underlying sediments) to the Pre-Middle Eocene and so-on (summarised by Miller, 2008d).

Recent discussions on the age of the Eocene Marine deposits hang heavily on the papers by Siesser (1977) and Siesser & Salmon (1979) who found microfossils at only one locality, the Langental *Turritella* Site, for which they proposed a Priabonian correlation. These deposits lie about 35 to 40 metres above present sea-level. The higher level deposits north of the *Turritella* Site, and elsewhere between 145 and 160 metres above sea level were either not studied (Eisenkiesel-klippenbake) or proved to be sterile (Buntfeldschuh). The assumption is that all these deposits accumulated during the Priabonian or earlier, yet the eustatic sea-level curve suggests another possibility, that the high level marine sediments more than 145 m asl, were deposited during a period of exceptionally high sea-level, possibly the Rupelian.

The proposal that the Buntfeldschuh deposits were older than those at Langental *Turritella* Site is not soundly based. No age diagnostic fossils were found in them, so the correlation proposed by Siesser (1977) and Siesser & Salmon (1979) was influenced by the altitude of the deposits, at 160 m asl well above any other marine deposits in the region. These authors proposed a correlation to the highest sea level known at the time of their study, which was the late Palaeocene one (Siesser & Dingle, 1981). Pickford (1998) considered this to be too old, and proposed a Lutetian correlation, but at the time of the study he had not had the opportunity to examine the outcrops in detail. The fact that the Buntfeldschuh delta deposits overlie outcrops of the Sperrgebiet Siliceous Suite, means that they are even younger than thought by Pickford (1998; Pickford & Senut, 1999) and must be Priabonian or Rupelian. Consideration of the altitude of the top of the delta deposits (ca 160 m) suggests that a Rupelian correlation is more likely than a Priabonian one.

The geological maps of Kaiser & Beetz (1926) indicate the distribution of agates, chalcedony, jasper and diamonds, the inland edge of the zone defining the shoreline of the Eocene Sea which, at Eisenkiesel-klippenbake (EKKB) was subsequently calculated to have transgressed to an altitude of ca 168 metres above modern sea-level (Siesser & Salmon, 1979; Miller, 2008d). The agate-bearing deposits at Eisenkieselklippenbake crop out, however, near the base of the EKKB palaeovalley where it opens into the Strauchpfütz valley at an altitude of ca 145 m asl and not at 168 metres, which is the altitude of the summit of the hill. At Buntfeldschuh, however, there is a 40 metre thickness of deltaic-marine deposits overlying a wave-cut surface 120 metres asl, implying a former sea-level at about 160 metres above present day sea-level.

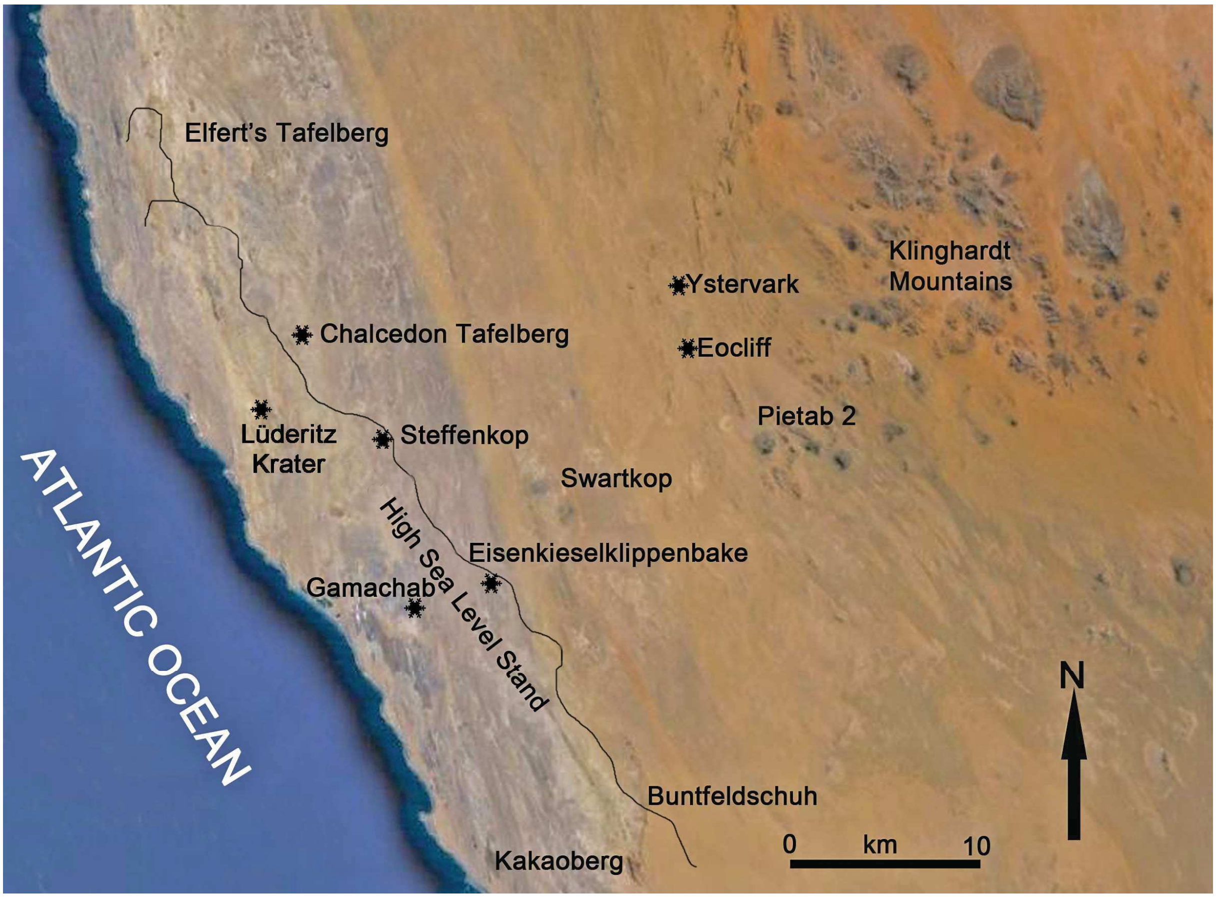

Figure 65. The limit of transgression of the sea during the Eocene as visualised by Beetz (1926) and Liddle (1971) (the northern extension to Elfert's Tafelberg) on the basis of the distribution of the agate, chalcedony and jasper clast assemblage. Note that most of the evidence of Ystervark Formation deposits has been removed from the seaward side of the ancient coastline, but remnants of the Sperrgebiet Siliceous Suite (fossiliferous silicified Ystervark Formation) at Gamachab, Eisenkieselklippenbake and Steffenkop partly resisted the marine and subsequent subaerial erosion and provide precious evidence concerning the timing of events in the region. Included in the figure is Lüderitz Krater.

The Buntfeldschuh sedimentary sequence is well exposed in a 5.5 km long north-south oriented, west facing scarp which exposes a thickness of just over 100 metres of sediment, for the most part overlying alterite without a silcrete cap (not 200 metres thick as reported by Kalbskopf, 1977). It overlies siliceous rock in the northern end of the escarpment (Corbett, 1989). The base of the scarp lies at an altitude of ca 120 metres and its summit at 220 m. Corbett (1989) measured sections in three places and concluded that there were two marine deposits each about 20 metres thick, separated from each other by an unconformity, and overlain by a coastal aeolian dune system 60 metres thick, overlain in its turn by 3-5 metres of calcrete (in fact the Namib 1 Calc-crust, not a "hardpan pedogenic calcrete" as thought by Corbett, 1989). We consider that the marine units of Corbett (1989) are delta deposits interfingering with layers of marine sediments (Fig. 66). There are lenses of agate, jasper and chalcedony pebbles in both of the "marine" units of Corbett (1989), each of which has yielded shark and fish teeth. The predominantly clastic deposits at Buntfeldschuh are radically different from the carbonate-dominated marls and limestones at Langental *Turritella* Site, and this has led to the suggestion that the deposits in the two areas accumulated at different times, with Buntfeldschuh generally being considered to be older than the Langental *Turritella* Site (Siesser & Salmon, 1979; Miller, 2008d; Pickford *et al.* 2014). However, the perceived difference in age of these deposits is based on a misundertanding of the nature of the Buntfeldschuh sequence, which is not an exclusively marine unit as frequently thought, but is a delta deposit with minor marine influence in the form of fossiliferous lenses of agate, chalcedony and jasper gravels. Our interpretation of the Buntfeldschuh deposits is that they are either co-eval with those at Langental *Turritella* Site which is Priabonian (Martini Zones NP 19 - NP 20) (Siesser, 1977) or they could be Rupelian, which was a period of exceptionally high sea-level (Fig. 67). This conclusion is supported by the observation that at the north end of the scarp, the Buntfeldschuh beds overlie Sperrgebiet Siliceous rocks (Corbett, 1989; Miller, 2008d) just as they do at Eisenkieselklippenbake. In addition, the supposed unconformity in the succession is likely to be of little chronological significance, because discordant surfaces are common in deltaic successions.

It is postulated that the Eocene marine deposits of the Northern Sperrgebiet span not only the Priabonian (at Langental *Turritella* Site) but also the Rupelian (at Eisen-kieselklippenbake, the Buntfeldschuh Delta and the high level deposits north of the *Turritella* Site). Sediments from the high level deposits need to be examined for microfaunal and microfloral remains in order to test this hypothesis, which is in the main based on correlation of the Sperrgebiet deposits to the highest part of the eustatic sea-level curve (Miller, 2009).

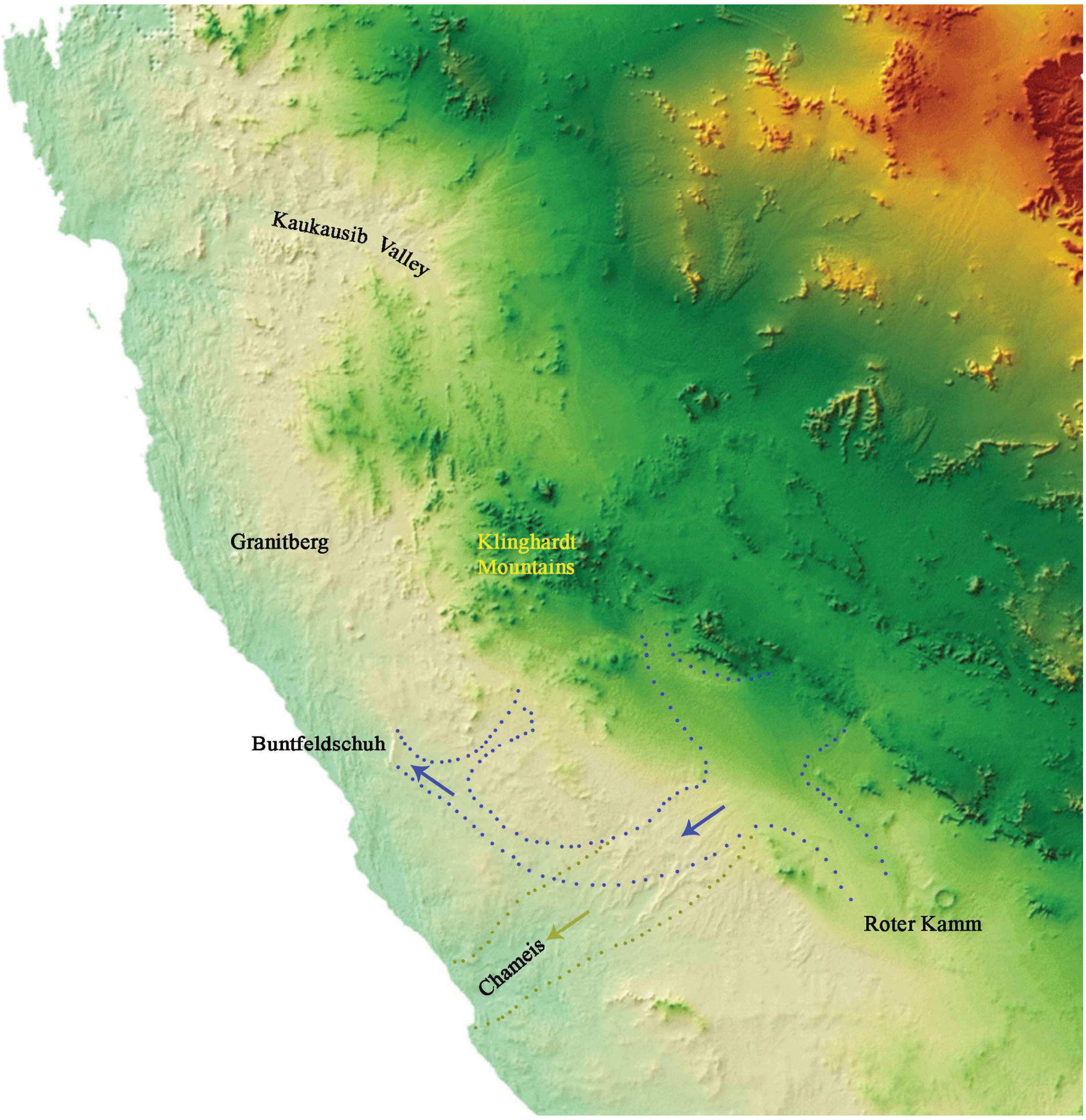

Figure 66. Hypothesis of the source of the Buntfeldschuh delta deposits showing a possible drainage network flowing from the hinterland towards the coast (blue dots). Today much of the area drains towards Chameis (brown dotted line). Most of this zone is blanketed by loose sand, which renders interpretation delicate.

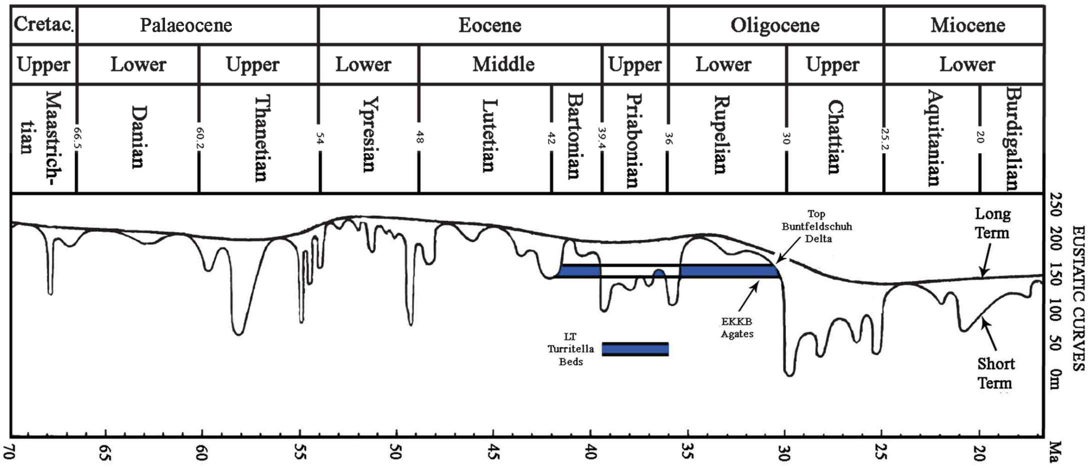

Figure 67. Eocene marine deposits of the Northern Sperrgebiet plotted onto the Eustatic Curve of Miller (2009) at the altitudes at which they occur. The highest level deposits at Eisenkieselklippenbake, Buntfeldschuh and the area north of the Langental *Turritella* Site have much less chance of being Priabonian than they do of being either Bartonian or Rupelian. Consideration of the Late Bartonian age of the Sperrgebiet Siliceous Suite, blocks of which occur in the marine deposits, means that the Bartonian correlation is unlikely, which favours the hypothesis that the highest deposits of agates, chalcedonies and jaspers accumulated during the Rupelian. The discovery of fossils in these high level deposits will settle the matter, but so far no serious attempt has been made to find them.

The Kakaoberg Aeolianite

Overlying the Buntfeldschuh delta deposits is a 60 metre thickness of green aeolian sands (Beetz, 1926; Corbett, 1989). Nowhere else in the Sperrgebiet, nor for that matter in Namibia, are there any comparable deposits to be found. The fact that the sands are dark green distinguishes them from the much younger Rooilepel Aeolianite of Early Miocene to Late Miocene age which are red, the Late Miocene Terrassenfeld Aeolianite which is brown to red, and the Plio-Pleistocene Fiskus Aeolianite which is brown to yellow.

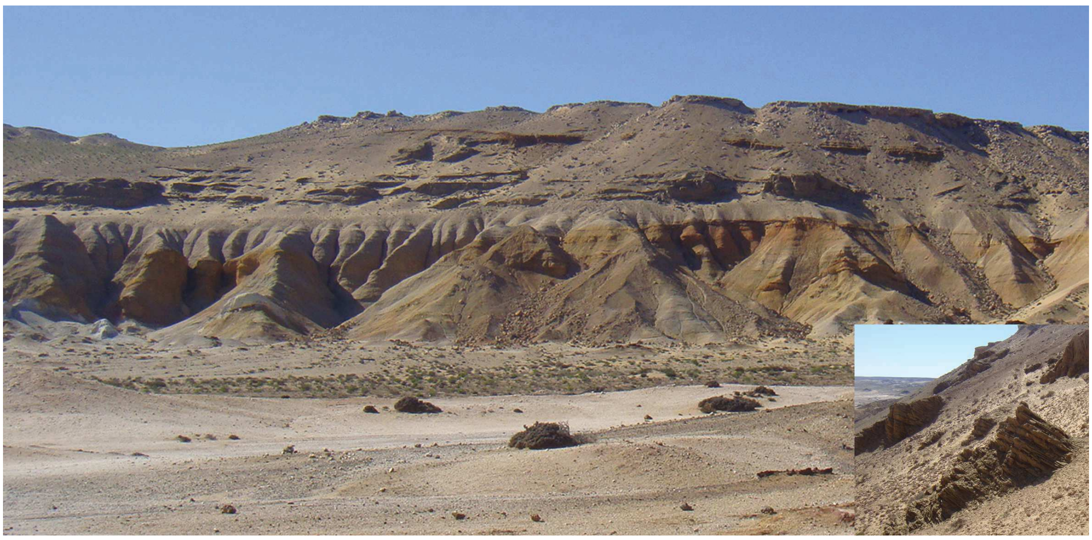

Figure 68. The Buntfeldschuh cliff exposes about 40 metres of deltaic and marine sands and gravels overlying altered Basement, overlain by a thickness of 60 metres of aeolian sand of the Kakaoberg Sandstone which is capped by a 3 metre thick Namib 1 Calc-crust forming the skyline. Note the super-bounding surfaces in the aeolianites. The inset shows steeply dipping slip-face bedding in the palaeodune deposits.

The Kakaoberg Sandstone (Fig. 68) displays steep slip-face bedding meaning that the deposits accumulated as dunes, a conclusion supported by the observation that there are super-bounding surfaces between layers of palaeodune material. The slip-face bedding indicates that the wind was southerly to westerly. Corbett (1989) identified phonolite clasts in the sand.

It is most likely that these aeolian deposits accumulated as coastal dunes, and as such they do not carry much significance for palaeoclimatology, other than the obvious one concerning wind direction. They are too localised in distribution to signify a Palaeogene proto-Namib phase of the Namib Desert as proposed by Ward & Corbett (1990).

The Blaubock Conglomerate and the underlying fossiliferous marls

Most previous maps of the Blaubock Conglomerate show a broad outcrop extending from the type area just north of Bogenfels, eastwards towards the Klinghardt Mountains (Beetz, 1926; Van Greunen, undated; Corbett, 1989).

Detailed mapping by the NPE north of Black Crow and Steffenkop reveals that there are important extensions of the conglomerate as far as Silica North (Fig. 69). In this sector, erosion has removed a lot of the conglomerate, but sufficient witness sections remain to reveal that most of the zone between Silica North and Bogenfels was once covered by this conglomerate. In several places small hamadas have resisted erosion, and provide sections showing that the Blaubock Conglomerate overlies variegated marls derived from altered bedrock. At Silica North, Silica South, Steffenkop and Black Crow they overlie Lutetian to Bartonian limestones of the Ystervark Formation. In the northeastern part of the area, similar conglomerates infill valleys cut into a low, north-south trending scarp. These valleys were likely incised into the pre-existing scarp during the Chattian low sea level stand, and are probably the same age as the much larger valleys at Grillental, Langental, Glastal and Fiskus (Pickford & Senut, 1999).

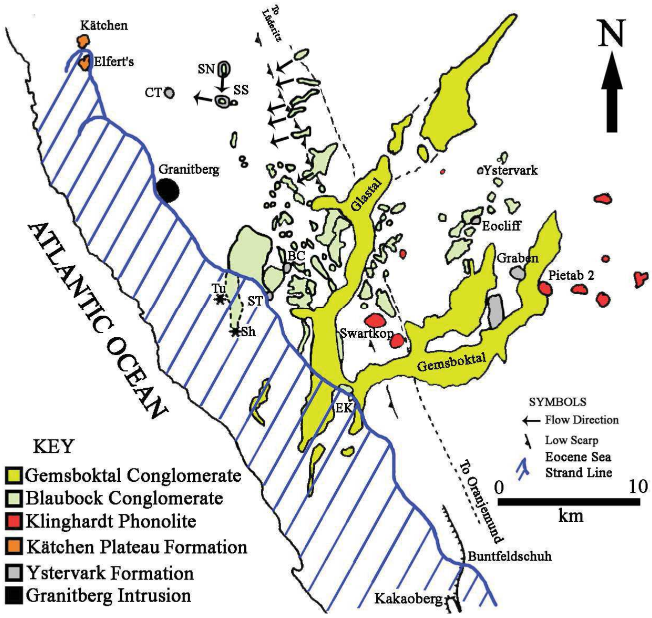

Figure 69. Distribution of outcrops of the Blaubock Conglomerate relative to the "Eocene Sea" highest strand line of Beetz (1926) and Liddle (1971) which is probably Rupelian. Note the scattered outcrops north of the type area at Blaubock Beacon, previously omitted from the maps. Note also the small palaeovalleys cut into a north-south trending scarp (arrows) with their infillings of Blaubock Conglomerate. The Blaubock Conglomerate beneath the Eocene Sea strand line was deposited when the sea level fell during the Chattian. It overlies Priabonian Marine Beds at the Langental Shark Site. The much younger Gemsboktal Conglomerate extends closer to the coast and the rivers responsible for its deposition evidently eroded away some of the Blaubock Conglomerate, especially in the Glastal region. (BC – Black Crow, CT – Chalcedon Tafelberg, EK – Eisenkieselklippenbake, Sh – Langental Shark Site, SN – Silica North, SS – Silica South, ST – Steffenkop, Tu – Langental *Turritella* Site).

During the Rupelian there was a period of weathering and local redistribution of marls derived from alterite. Some of these marls are variegated, probably as a result of pedogenesis, and they contain silicified tree trunks up to 10 metres long. Deposition of the Blaubock Conglomerate occurred during this period as shown by the observation, already noted by Beetz (1926) that the outcrops of Blaubock Conglomerate stop close to the Eocene Sea strand line. There are two outcrops of Blaubock Conglomerate however, that overlie Priabonian marine beds at the Langental Shark Site and at Eisenkieselklippenbake, but these occurrences probably represent a continuation of Blaubock Conglomerate deposition that occurred during the Chattian regression.

The Chattian Low Sea Stand triggered off deep incison of some of the valleys in the Northern Sperrgebiet, including Grillental and Elisabethfeld. Small valleys were incised into a north-south oriented scarp, and these are infilled with Blaubock Conglomerate as well. From this we infer that Blaubock Conglomerate was deposited over a substantial period of time (Priabonian to Chattian). Regionally, however, erosion appears to have been relatively modest during this span of time, as shown by altitude profiles of the Blaubock Conglomerate and the much younger Gemsboktal Conglomerate (Tortonian) (Fig. 70).

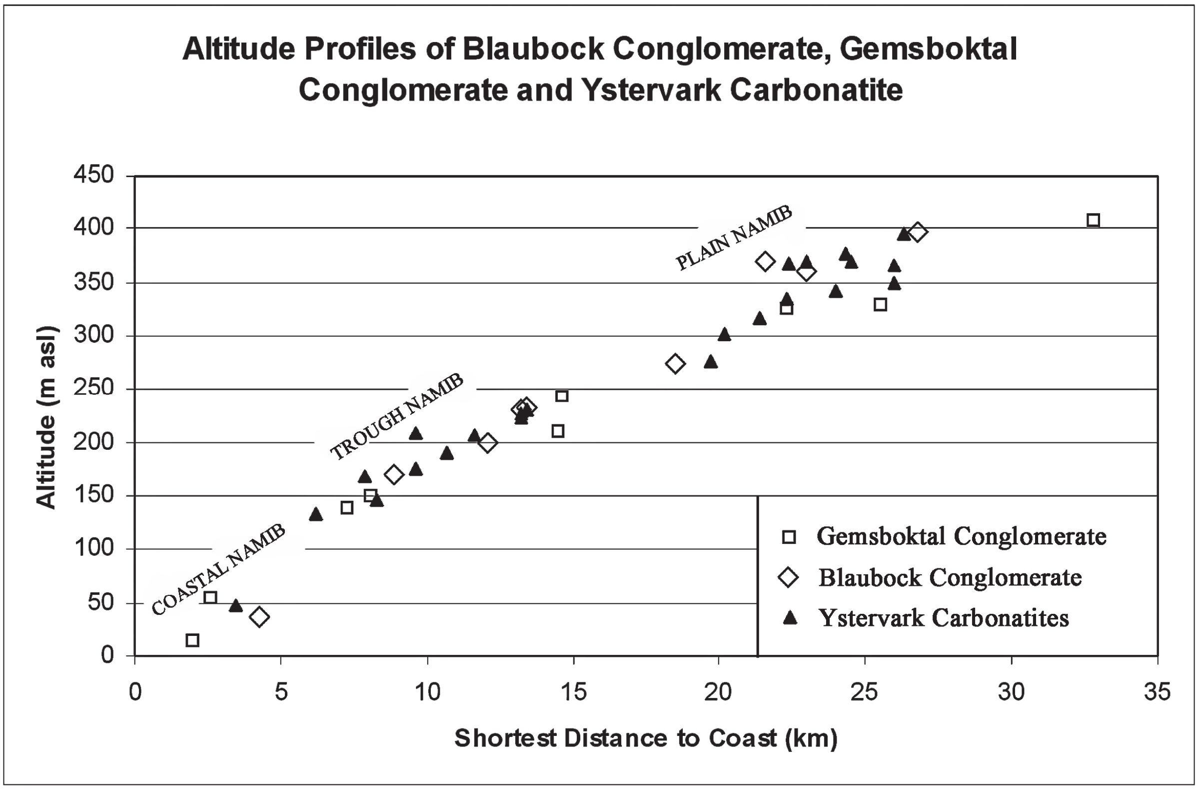

Figure 70. Altitude profiles of the Blaubock and Gemsboktal Conglomerates reveal that the top of the deposits are on average beneath the level of the base of the Ystervark Carbonatites (Lutetian – Bartonian) but with some deposits at the same altitude or slightly higher. At selected spots, such as Eocliff, the base of the Eocliff Limestone (Bartonian) is about 5 metres higher than the top of the Blaubock Conglomerate (Rupelian-Chattian). At other places such as Silica North and Silica South, Blaubock Conglomerate overlies the Plaquette Limestones of the Ystervark Carbonatite Formation.

Many of the outcrops of Blaubock Conglomerate north of Black Crow show slight greenish copper staining and they are variably indurated by carbonate and silica, but in the type area and at Eisenkieselklippenbake, the conglomerate is not indurated. The latter deposits were probably never consolidated because, being close to the sea, they were not influenced by the calc-crust processes that affected the outcrops further inland. Most outcrops of Blaubock Conglomerate contain abundant cobbles of Sperrgebiet Siliceous Suite indicating an age younger than the Late Bartonian.

It has been written that silicified tree trunks are preserved in the Blaubock Conglomerate (Miller, 2008d). However, the tree trunks that we have observed *in situ* lie in variegated marls underlying the conglomerate (Fig. 71-72). Downwasting of the unconsolidated gravels and marls during the Pleistocene to Recent has produced a secondary association between the petrified trees and the gravel. Evidence that the silicified tree trunks are older than the Blaubock Conglomerate is offered by two observations. Firstly, excavation beneath the silicified logs reveal that they lie within pebbly marly palaeosols, and secondly, the Blaubock Conglomerate sometimes contains small abraded chunks of silicified wood derived by erosion from the underlying marls and redeposited in the gravels nearby, as for example at Langental near the *Turritella* Site and at Reuning's Pan. The latter observation indicates a substantial time period bertween the deposition of the marl and the emplacement of the conglomerate, long enough to accomplish silicification of the tree trunks.

Figure 71. Fossil tree trunk # 1 secondarily associated with Blaubock Conglomerate between Langental and Black Crow. This specimen is 10 metres long and 75 cm in diameter. Excavation of the tree trunks in this area reveal that they lie within pebbly marls beneath the capping of Blaubock Gravel.

Figure 72. Close up view of a piece of silicified wood from Tree # 1 between Langental and Black Crow.

Ward (2000), Jacob *et al.* (2006) and Miller (2008d) wrote that the Blaubock Gravel is the oldest Cenozoic sedimentary deposit in the Sperrgebiet, the former authors giving an estimated age of 55 Ma.

Over most of its outcrop this is not the case. In the vicinity of the Klinghardt Mountains, not only does the Blaubock Gravel overlie the Lutetian-Bartonian Ystervark Carbonatite Suite but also, at Langental Shark Site it overlies Priabonian marine deposits. Some of it is therefore post-Priabonian.

According to Miller (2008d) the only place where it supposedly underlies phonolite agglomerate is at Pietab 2. Remapping of this occurrence is required, because if the reported superposition is true, then the Blaubock Conglomerate could encompass gravels of widely divergent ages, depending on the age of the Pietab 2 volcanic rock, which is thus far undated.

At Elisabethfeld, there is a coarse conglomerate beneath the fossiliferous early Miocene clays and silts. This conglomerate is probably a local representative of the Blaubock Formation while the rapid change in facies from conglomerate to overlying clay records the major marine transgression that heralded the Aquitanian stage (Basal Miocene).

Neogene alteration of older rocks

Ferruginisation of near-surface rocks in the Sperrgebiet

Widespread ferruginisation of superficial rocks occurred in the Northern Sperrgebiet sometime after the Priabonian (Fig. 73-75). This is evident from the fact that some specimens of Priabonian fossils have been found in ferruginised deposits at Langental *Turritella* Site. At Lüderitz Krater and elsewhere agates and other exotics have been incorporated into ferruginised masses. At Buntfeldschuh the Kakaoberg Ironstone Cap is younger than the Rupelian as it overlies and affects the Kakaoberg Aeoliantes which overlie Rupelian deltaic deposits. Near Klinghardt's Pan (formerly called the Klinghardt Breccia Pipe by Kalbskopf, 1977), the Blaubock Conglomerate has been ferruginised. At this locality the conglomerate is younger than the Ystervark Carbonatites and the Eocliff Limestones of Bartonian age. At Grillental VI, Early Miocene gastropods have been ferruginised and there are ferruginised masses of sediment and irregularly shaped nodules of iron oxides. Considering all the information, it appears that iron oxides were precipitated in porous near-surface deposits of the Sperrgebiet during the Late Oligocene to basal Middle Miocene, the end phase probably corresponding in timing with the Mid-Miocene

Climatic Optimum (Zachos *et al.* 2001). The ferruginisation occurred prior to the deposition of the Namib 1 Calc-crust, which overlies the ferruginised cap at Kakaoberg (Fig. 73).

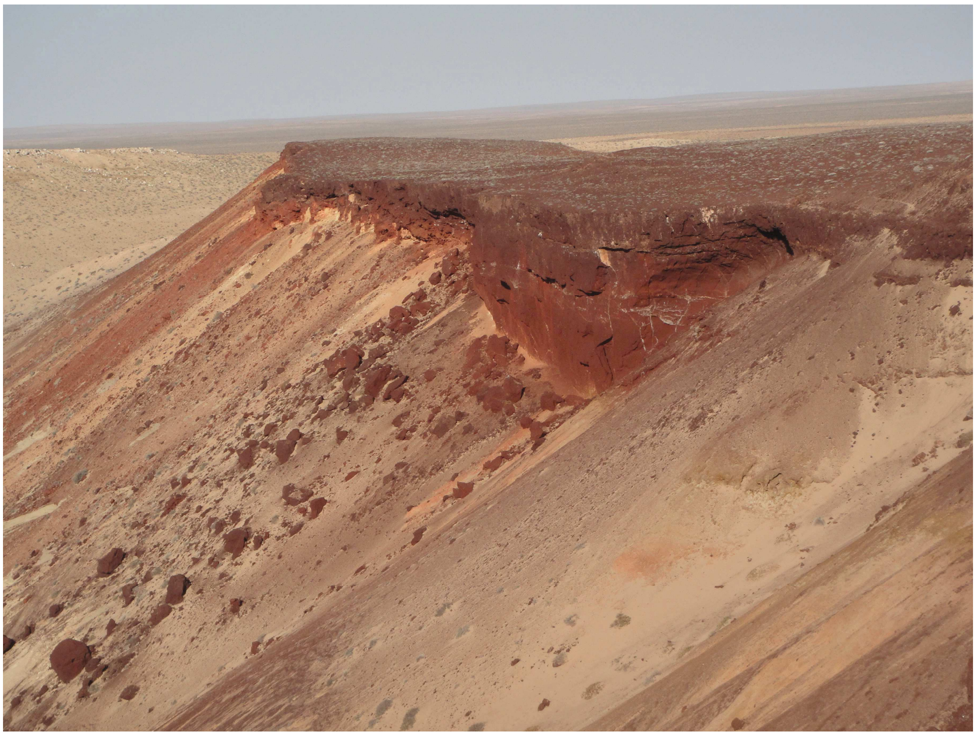

Figure 73. Ferruginised Kakaoberg Aeolianite near Buntfeldschuh.

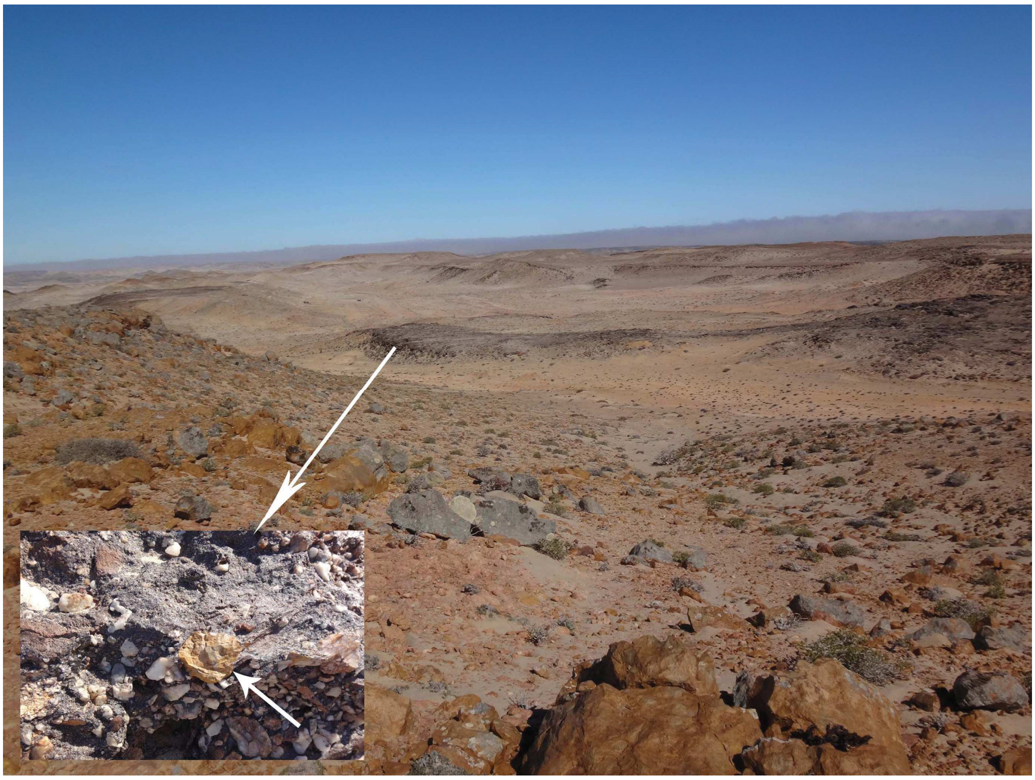

Figure 74. Ferruginised terrace deposits (arrow on main image) at Kätchen Plateau (foreground and background) hitherto interpreted as underlying the Pomona Quartzite, but in reality containing derived blocks of quartzite (arrow in inset image) incorporated into ferruginised terrace deposits during the Oligo-Miocene.

Figure 75. Ferruginised Blaubock Conglomerate east of Klinghardt's Depression. Inset is a close-up view of the conglomerate and its goethitic cement.

The products of this ferruginisation should not be confused with the Palaeogene iron oxide nodules (bohnerz) which were probably formed during the Early Eocene Climatic Optimum as part of the prolonged weathering that affected the Sperrgebiet. Other outcrops occur in the deflation basins at Idatal and Hexen Kesssel, indicating that these valleys existed much in their present form, before the Middle Miocene, probably downcut during the Oligocene low sea-stand. They were then filled during the Pleistocene by grey sand and onyx travertine, and deflated during the Late Pleistocene and Recent.

Miocene and Plio-Pleistocene Calc-crusts

There are widespread calc-crust deposits in the Northern Sperrgebiet, hitherto mapped as "Older Calcrete" and "Younger Calcrete" (Van Greunen, undated). Widely recognised in the Plain Namib, these Namib 1 (Miocene) and Namib 2 Calc-crusts (Plio-Pleistocene) extend deep into the Trough Namib, where they were previously mapped as Pomonakalke (Beetz, 1926) and considered to be of pre-Middle Eocene age.

In the Trough Namib, these calc-crusts often enclose blocks of Kätchen Plateau Quartzite, some of which are *in situ* (ie with cracks and fissures between quartzite blocks that have not been moved since their silicification, cemented by calc-crust) and some of which are not (downwasted and now reposing on terraces and floating in calc-crust). All previous workers mapped these outcrops as *in situ* Pomona Quartzite, but remapping by the Namibia Palaeontology Expedition reveals that about 80% of the supposed Pomona Quartzite outcrops comprise reworked blocks of quartzite which have been cemented by Oligo-Miocene ferruginous deposits and Mio-Plio-Pleistocene calc-crusts (Fig. 76).

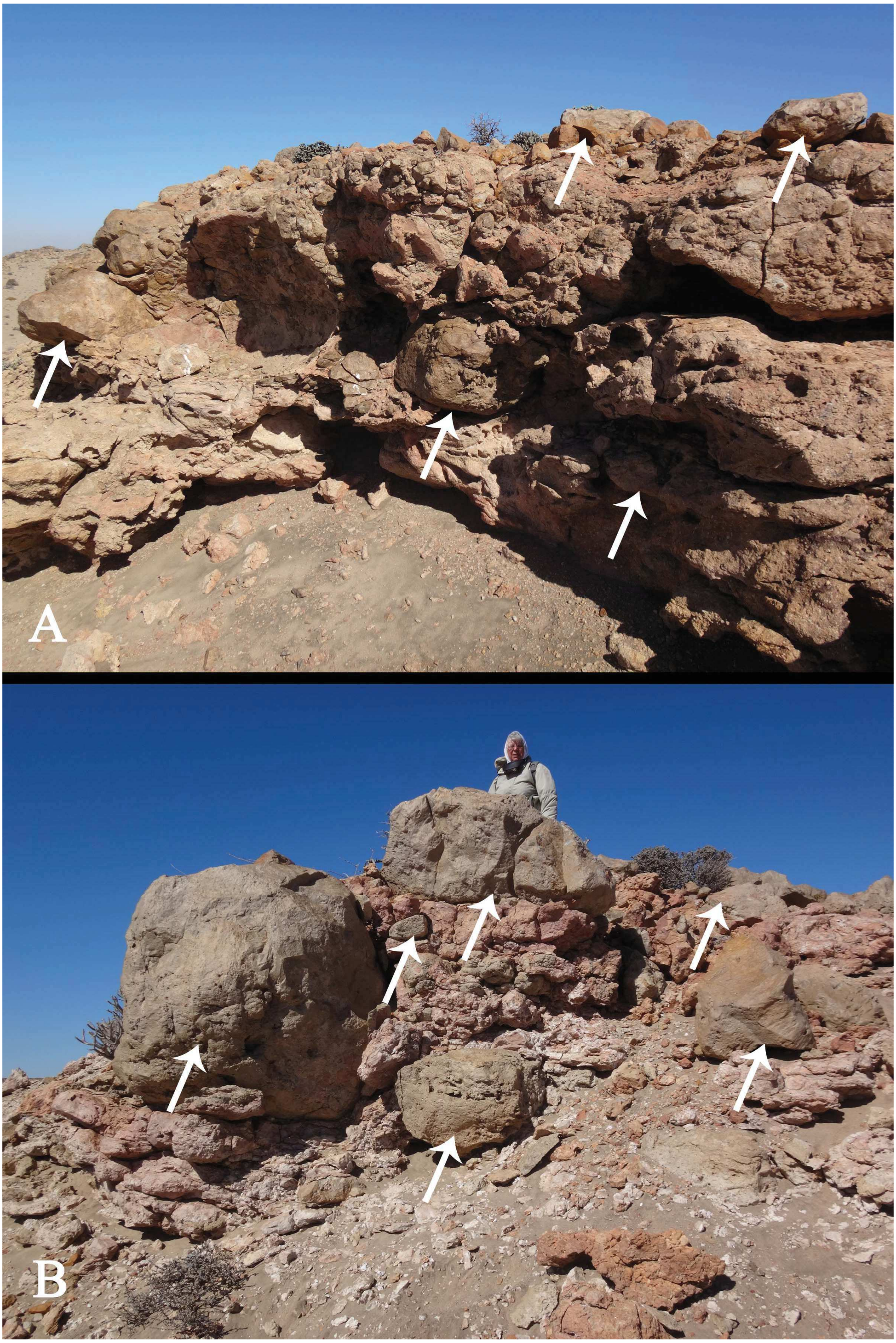

Figure 76. Blocks of Kätchen Plateau Quartzite (white arrows) floating in calc-crust matrices, A) at Langer Tafelberg with Namib 1 Calc-crust, and 2) near Kätchen Plateau with Namib 2 Calc-crust. These outcrops were previously mapped as *in situ* Pomona Schichten and correlated to the pre-Middle Eocene or even the Cretaceous, but are Miocene and Plio-Pleistocene respectively.

Intercontinental correlations

The announcement of the presence of Lutetian mammals in the Black Crow Limestone and at the Silica Sites (Pickford *et al.* 2008) caused a certain amount of comment, with several researchers reinterpreting the Namibian faunas as being much younger, closer in age to faunas from the Fayum, Egypt (Holroyd, 2010; Marivaux *et al.* 2011; Sallam *et al.* 2009, 2011, 2012; Seiffert, 2010a, 2010b; Seiffert & Simons, 2000; Seiffert *et al.* 2007) (Fig. 77). Continued survey of the Sperrgebiet limestones has led to the discovery of the Eocliff and Eoridge faunal sites which are younger than the Black Crow Limestones. Silica North and Silica South yield rodents that are similar to those from Eocliff, and these sites are therefore slightly younger than originally thought, but the Black Crow fauna appears to be as old as reported by Pickford *et al.* (2008).

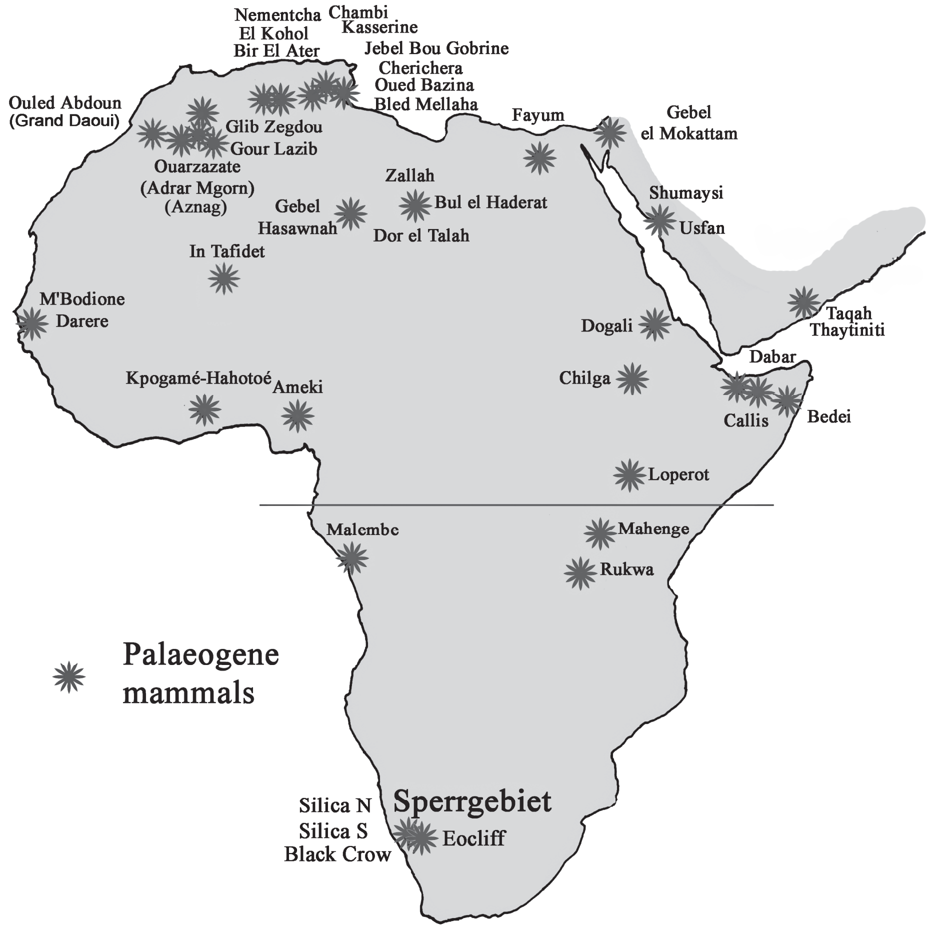

Figure 77. Location of Palaeogene continental fossiliferous localities in Africa with which the Ystervark Formation fossil localities are compared, notably the rich faunas from the Fayum Egypt, which are somewhat younger than the Sperrgebiet ones.

Of relevance to tying down the correlation of the Eocliff deposits is the observation that silicified portions of this unit are overlain unconformably by marine Eocene deposits which yield microfauna and macrofauna of Priabonian age (Martini nannoplancton zones NP 19 – NP 20) (Siesser, 1977; Dingle *et al.,* 1983). These Priabonian deposits contain reworked clasts eroded from the Sperrgebiet Siliceous Suite, meaning that the siliceous rocks must therefore be appreciably older than this zone. In the Fayum succession, Egypt, nannofossils of these zones occur in the Gehannam, Birket Qarun and Qasr el Sagha Formations (Underwood *et al.* 2013) which repose on the late Bartonian marine Wadi Rayan Formation and which are succeeded by the Rupelian Jebel Qatrani

Formation. The Eocliff fauna is therefore considered to predate the faunas from the Birket Qarun and Gehannam formations. If this is so, then the Black Crow fauna, which is older than the Eocliff one, would correlate with the Lutetian as originally deduced by Pickford *et al.* (2008) (Fig. 78).

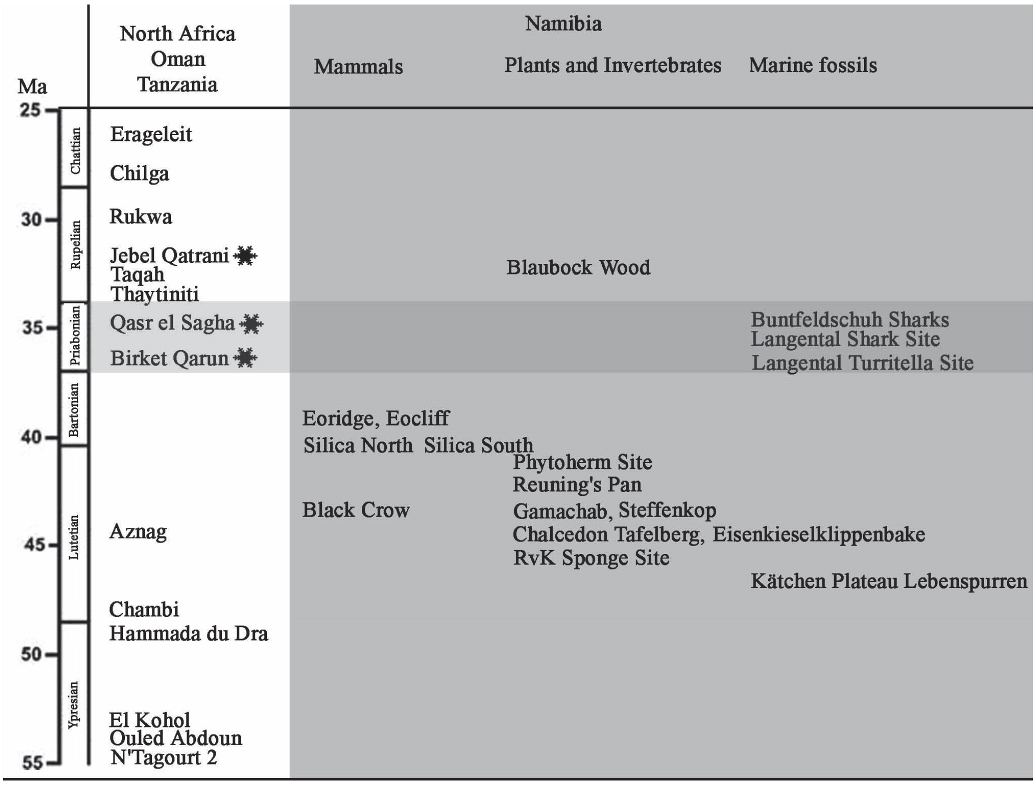

Figure 78. Correlation of the fossiliferous Palaeogene deposits of the Sperrgebiet, Namibia, to the international stratigraphic scale, and comparisons with the Fayum, Egypt, and other localities in North Africa, Oman, Kenya and Tanzania. The correlation with the Fayum (stars) is based principally on the positions of the strata relative to sediments containing Nannoplancton Zones NP 19 – NP 20 (Priabonian – dark horizontal grey line). All the Egyptian mammals are Priabonian or younger, all the Namibian mammal sites are older than the Priabonian.

Note that the Sperrgebiet faunas partly fill a lengthy time gap that existed between the Early Palaeogene faunas of Morocco and Algeria on the one hand, and the Late Palaeogene ones from Libya, Egypt, East Africa and Oman on the other. As such, the Namibian faunas will throw a great deal of light on the transition from the primitive Afrotherian faunas of the early Palaeogene, to the more modern looking African faunas from the Late Palaeogene. Preliminary work shows that the earliest known macroscelidids and afrosoricids occur in the Sperrgebiet, alongside arsinoitheres, hyracoids, primates and creodonts.

Discussion and Conclusions

The importance of fossils for unravelling Sperrgebiet geology was realised by Kaiser & Beetz (1926) who wrote that "It should be noted that the exact horizons in which the beds hitherto proved to be unfossiliferous are to be placed, will depend on the discovery of zone fossils in them". This sentiment applied particularly to the heterogeneous Pomona Schichten, the silicified rocks of the Sperrgebiet, the gravels later named the Blaubock and Gemsboktal formations and the calc-crusts (referred to in unpublished reports as Older and Younger calcretes).

The discovery of abundant and diverse plants, invertebrates and vertebrates in Palaeogene limestones and marls of the Northern Sperrgebiet in deposits previously referred to the Pomona Beds or to "Freshwater Limestones" permits a revision to be undertaken of the sequence and timing of geological events in the region (Fig. 79). The fact that the rocks yielding these fossils were frequently correlated to the Cretaceous or Palaeocene, means that a fundamental rethinking of the timing of the geological and geomorphological development of the area is required.

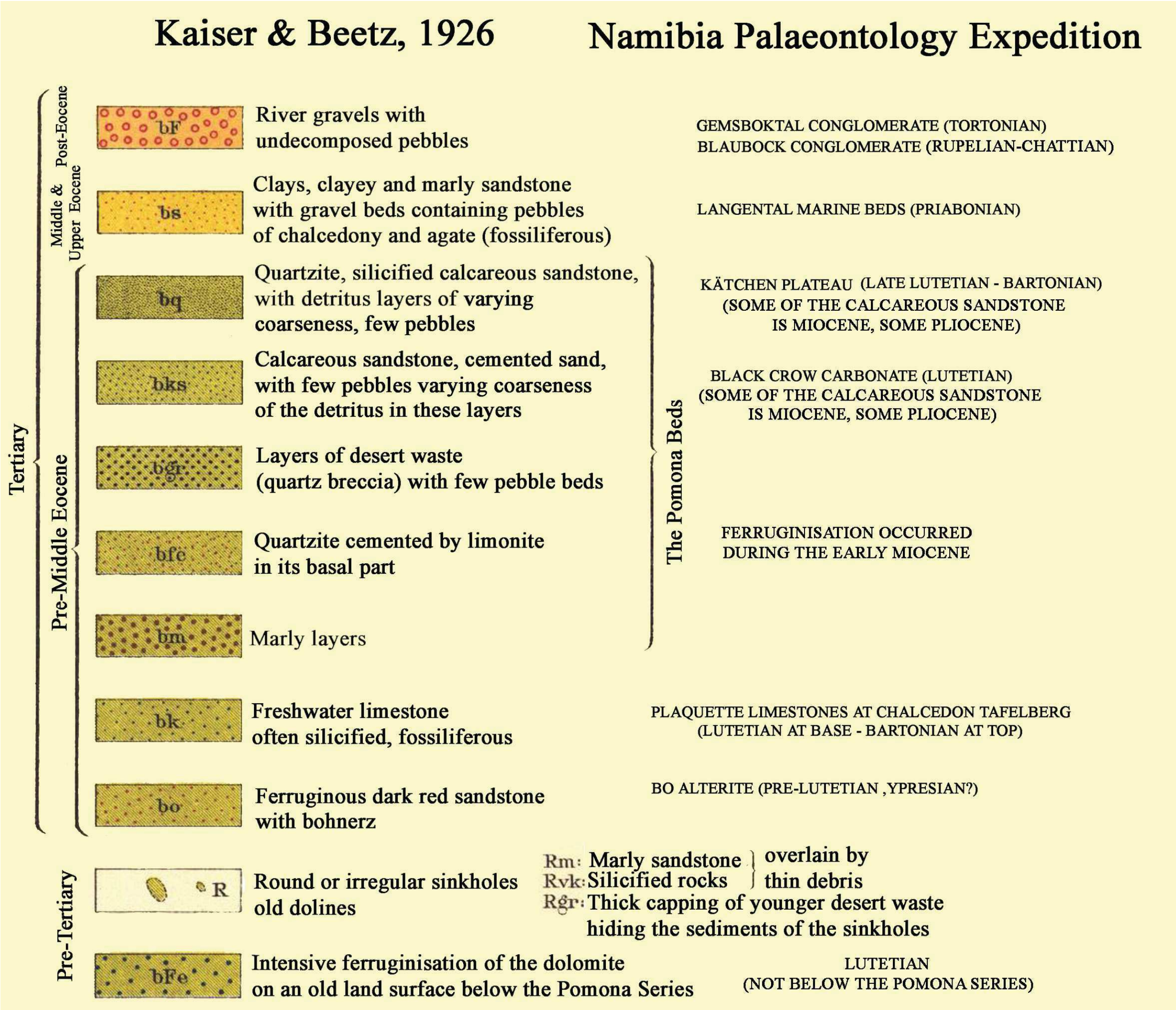

Figure 79. Comparison of the stratigraphic succession of the Northern Sperrgebiet translated from Map 4 of Kaiser & Beetz (1926) (in lower case letters) with that of the Namibia Palaeontology Expedition developed in this paper (in capital letters to the right of the chart). The succession of events is basically the same, but the timing of events and grouping of strata have changed somewhat. The Black Crow (bks) and Plaquette Limestones (bk) and some of the marly layers (bm) are attributed to the Ystervark Carbonatite Formation but the silicified quartzite (bq = Kätchen Plateau Formation) layers of desert waste (bgr = Pomona Beds) and limonitic quartzite (bfe = Pomona Beds) are excluded from it as are the "Pomonakalke", which are a localised expressions of the Namib 1 and Namib 2 Calc-crusts. The Bo Alterite (bo) and the intensely ferruginised dolomite (bFe) could represent the same alterite profile, silicified in parts (bFe) during the Sperrgebiet Silicification Event (Lutetian) and not in others (bo).

In many respects the pioneering researches by Beetz (1926) and Kaiser (1926a, 1926b) are more reliable than those of subsequent researchers (Liddle, 1971; Kalbskopf, 1977; Stocken, 1978; Miller, 2008d). This is because the German authors reported the field relations as they saw them, they relied on palaeontological data to anchor their interpretations of the subjacent older or younger deposits and they avoided the temptation to make correlations to events in other parts of the world without good evidence for doing so. In contrast many later authors imposed wide ranging correlations to continental erosion surfaces or eustatic history (Haq *et al.,* 1987) onto the rocks of the

Sperrgebiet without any real data to support their ideas (Dingle *et al.,* 1983; Partridge & Maud, 1989). By these dubious means the pre-Middle Eocene Pomona Schichten of Kaiser & Beetz (1926) were converted either into Middle or Late Cretaceous strata by subsequent workers (Liddle, 1971; Kalbskopf, 1977; Stocken, 1978; summarised in Miller, 2008d) or into basal Palaeocene units (Ward, 2000, Jacob *et al.* 2006). All the siliceous rock produced during the Sperrgebiet Silicification Event were erroneously considered by most authors to represent "silcrete" of Cretaceous age, usually correlated to the African Surface. Mapping by the Namibia Palaeontology Expedition and the discovery of fossils in these rocks reveals that most of them accumulated during the Lutetian and Bartonian and were partially or completely silicified by a widespread silicification event during the Late Bartonian.

Silcrete does indeed occur in the Sperrgebiet (here called the White House Silcrete) and it may well correlate to the African Surface silcretes mapped elsewhere in the continent, but it should not be conflated with the siliceous rocks formed during the Palaeogene which are here grouped into the Sperrgebiet Siliceous Suite.

The latter group of rocks is highly heteromorphic in terms of the mother rock being silicified, their colour, completeness of silicification, grain size, fossil content and hardness, yet all the varieties were produced by the same silicification process which was likely related to hydrothermal activity during the dying phases of the Ystervark Carbonatite Centre, or to similar activity during emplacement of the Klinghardt Phonolite Suite. The Ystervark Carbonatites, Klinghardt Phonolites, Werfkopje Olivine Melilitite and Schwarzer Berg Nephelinite are probably diverse aspects of the same deep seated volcanic processes.

The silicifying fluids altered many rock types close to the ancient land surface over an area extending more than 50 km from the centre, probably in the zone where alkaline groundwater containing dissolved silica rose towards the surface where it mixed with fresh, near-surface water, whereupon the silica precipitated. By this process, many rock types were silicified including all the major types of lithology in the Gariep Group (dolomite, schist, gneiss, quartzite), altered equivalents of the same (alterites comprising marls, iron oxides, sandstones and silts among other types) and Lutetian to Bartonian deposits (carbonatitic ashes, scoria breccia, phytoherms, palustral limestones, shallow marine sands and conglomerates).

Perhaps the most revolutionary findings of the present study are 1) the demonstration that the Pomona Schichten of Kaiser & Beetz (1926) comprise strata of Eocene (quartzite and sub-quartzite alterite), Oligo-Miocene (ferruginised levels), Miocene (Namib 1 Calc-crust) and Plio-Pleistocene age (Namib 2 Calc-crust), and 2) the realisation that the so-called "freshwater limestones" of Kaiser & Beetz (1926), Liddle (1971) and Kalbskopf (1977) are all linked in one way or another to activity at a carbonatite volcano close to the western margin of the Klinghardt Phonolite Cluster. Most of the limestones represent carbonatite ash that settled onto the countryside like snow producing well-bedded, finely laminated Plaquette Limestone, all of which remains today are roughly circular remnants infilling former depressions in the Lutetian landscape such as Chalcedon Tafelberg, Silica North, Silica South, Black Crow, Graben, Klinghardt's Depression, Klinghardt's Pan, Pietab 2 FWL Depression, Werfkopje and White Ring. There was some reworking of carbonate-rich ashes which were transported as clasts and as carbonate in solution into the depressions where they accumulated as palustral limestone, often extremely richly endowed with fossils. The Black Crow fauna, which is typical of the latter facies, reveals that palustral activity occurred during the Lutetian whereas the Silica North fauna shows that it continued into the Bartonian. A Bartonian carbonate deposit of a different kind occurs at Eocliff where a highly fossiliferous tufa dome grew around a lime-charged spring.

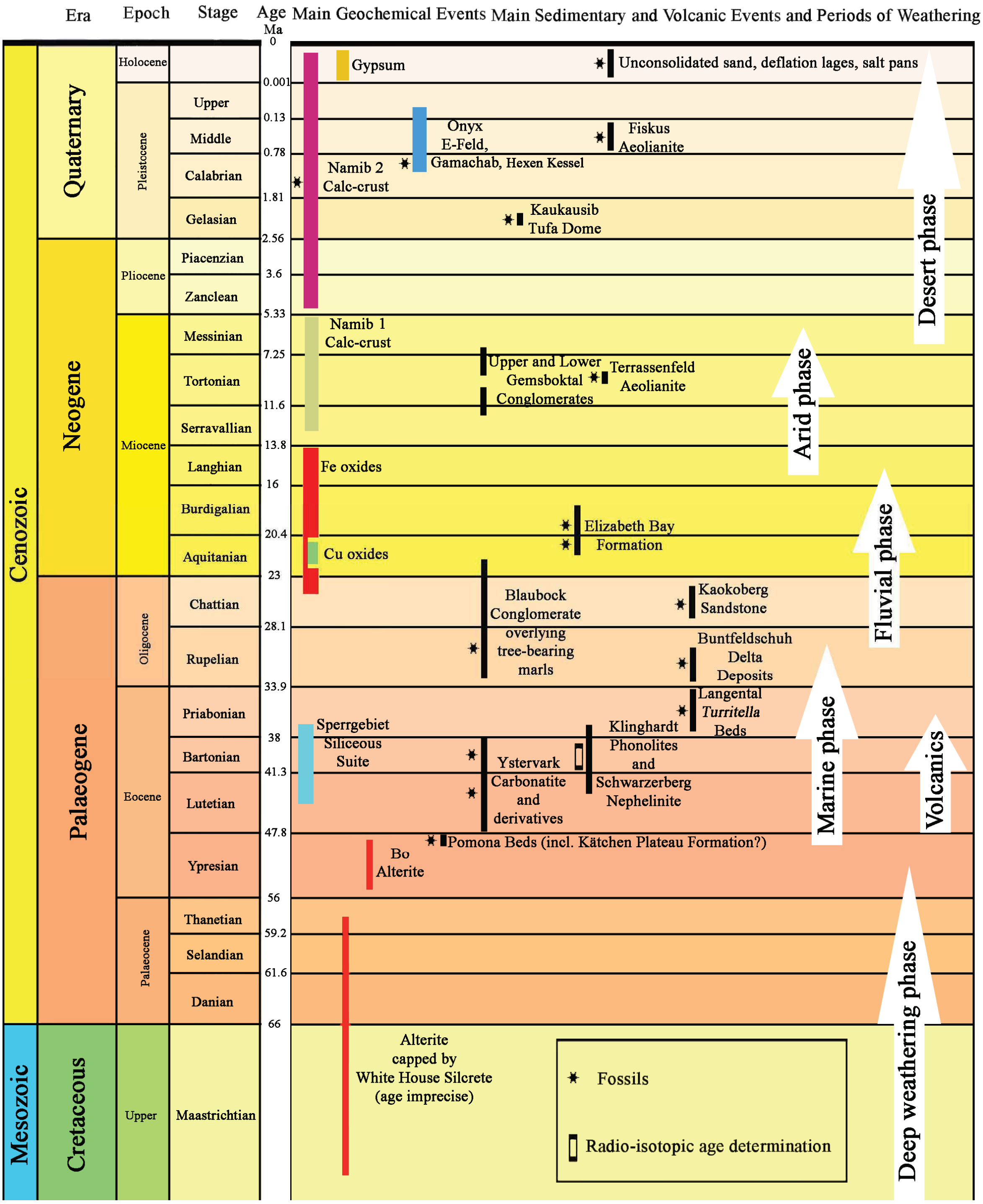

Figure 80. Summary of the main Cenozoic geological events in the Northern Sperrgebiet, Namibia, updated as a result of work by the Namibia Palaeontology Expedition. The timing of events is controlled by the fossil record, and by some radio-isotopic age determinations. The Lutetian and Bartonian witnessed important volcanic and associated sedimentary activity with penecontemporaneous silicification of surficial rocks, all of which interfered with the long term weathering and erosion processes that the region had been undergoing since continental break-up in the Mesozoic. The region was subjected to marine and fluvio-deltaic activity during the Priabonian and Rupelian. Since the Late Oligocene geological activity in the region has been dominated by sub-aerial processes, with minor marine incursions related to eustatic sea-level changes. Various diagenetic processes have been active in the area: silicification related to hydrothermal activity during the Bartonian, minor cuprification during the Aquitanian, ferruginisation, first during the Ypresian and secondly during the Chattian to Langhian, fog-driven carbonate crust formation (Calc-crust) during the Serravallian to Messinian and Plio-Pleistocene, and gypsum deposition during the Holocene (ongoing).

It is evident that the Northern Sperrgebiet records the interplay of many geological processes since continental break-up during the Mesozoic: weathering, erosion, transportation, deposition, volcanism, diagenesis, pedogenesis, tectonic activity and sea-level changes.

The long term weathering and erosional regime that the region has undergone since the Mesozoic, has been a permanent feature of the Northern Sperrgebiet, and is continuing today (Fig. 80). Climatic change has determined some aspects of the weathering processes, producing ferric alterites during climatic optima, silcretes and calc-crusts during more arid intervals. Sea-level changes such as the important Chattian low sea-level stand altered base-levels which led to incision of valleys during regressions. Transgressions led to drowning of the coastal strip during high sea-stands (Lutetian to Rupelian and Aquitanian to Burdigalian, and to a lesser extent during the Pleistocene). It is possible that high sea levels induced a concomitant rise in the level of the water table inland from the coast, which led to flooding of formerly dry depressions that were eroded during periods of low sea level stands. Palustral carbonate deposits accumulated during such periods, and have yielded immense quantities of fossils. Erosion has been of three major kinds; coastal related to wave action, fluvial due to surface waters on land, and aeolian. The last has been the most important since the Middle Miocene, and has predominated over surface water action. However, fluvial sheetwash activity was the dominant mode of sediment transport and deposition during the Rupelian-Chattian and Tortonian.

The most important interruption to the long-term weathering/erosion regime in the Northern Sperrgebiet was due to activity related to carbonatite and phonolite volcanism during the Lutetian and Bartonian (Fig. 80). Carbonatitic activity, in particular, intermittently blanketed the countryside in fine-grained ash, with up to 25 metres of deposits being preserved in former depressions in the Lutetian landscape. Widespread silicification of superficial rocks of many kinds, due to hydrothermal activity linked to the volcanism, "hardened" the superfical rocks and made them relatively resistant to weathering and erosion. Witnesses of this remarkable episode are found all over the Northern Sperrgebiet in the form of tafelberge (near Pomona) and widespread but always thin siliceous deposits (Verkieselungmassen of Kaiser & Beetz, 1926), distributed from Grillental in the north to Chameis in the south, a distance of ca 100 km, and from the coast up to the margins of the Klinghardt Mountains 30 km inland. Remnants of these deposits preserve evidence of the geomorphology of the region in the form of altitudinal profiles which slope gently from the interior of the Namib towards the coast.

As predicted by Kaiser & Beetz (1926) fossils would provide the key to determining the timing of geological events in the Sperrgebiet. Their prescient view has been amply confirmed by the discovery of many new fossil sites in the region, ranging in age from Lutetian to Holocene (Fig. 80). Lutetian fossils are common in carbonates deposited in depressions in the Palaeogene landscape, and they provide important evidence from which basis the timing of geological events can be determined. As a result of these discoveries, much that has been written about the development of "silcretes" and "freshwater limestones" in the Sperrgebiet needs to be modified, as do correlations of these units to the Cretaceous or Palaeocene, as does the hypothesis that the "silcretes" represent the local expression of the African Surface. Apart from the White House Silcrete, all the other siliceous rocks in the Sperrgebiet are of Lutetian to Bartonian age, and all the "freshwater limestones" (in fact carbonatite ashes and derivatives of carbonatitic activity which introduced vast quantities of calcium carbonate into the terrestrial and groundwater environments) span the same time range. These represent major advances in our understanding of Sperrgebiet geology.

A startling demonstration of the value of fossils for determining the age of strata concerns the Pomonakalke which was included in the Pomona Schichten by Beetz (1926) and as a result was considered to be Cretaceous by many authors, turns out to contain Plio-Pleistocene fossils at Marien Berg, the type area of the Pomonakalke (*Trigonephrus*) and at Elfert's Tafelberg (*Struthio daberasensis*), just south of Kätchen Plateau.

There remain, however, several problematic issues concerning the rocks of the Northern Sperrgebiet. The precise relationships between phonolite, nephelinite and olivine melilitite lavas on the one hand and the Palaeogene sediments of the Northern Sperrgebiet on the other, need to be elucidated. Available radio-isotopic age data indicate that the lavas were erupted or intruded during the Lutetian, Bartonian and Priabonian, suggesting that the Ystervark Formation sediments and Klinghardt lavas were broadly contemporaneous, as was recognised by Kalbskopf (1977) but so far very few places show contacts between the volcanic rocks and the sediments. One outcrop, Werfkopje, shows olivine melilitite lavas overlying Ystervark Carbonatite tuffs, and another outcrop, Chalcedon Tafelberg, shows monchiquite underlying Ystervark sediments, but the most telling outcrops are those at Swartkop North hill, in which a widespread terrace of chalcedony is overlain by conglomerate and then by phonolite lava dated 37 Ma (Kröner, 1973). Reports of phonolite at Reuning's Pan and Graben (Kalbskopf, 1977) need to be re-examined, because there are differences of opinion about the relationship of the lava to the subjacent bedded limestone (intrusive into the limestone or buried by the limestone).

Another significant problem concerns the chronological relationship between the Ystervark Carbonatite Formation and the Kätchen Plateau Formation. Are these units penecontemporaneous or not? Both overlie the Pomona Schichten in the restricted sense of the term as employed by Miller (2006c) defined as the sediments reposing on Basement Alterite and underlying the Kätchen Plateau Formation, and both underlie the Blaubock Gravels and Namib 1 Calc-crust. The Kätchen Plateau Formation pre-dates the formation of the Trough Namib but this does not resolve the question, because there are so few outcrops of Ystervark Formation in the coastal region and all but two outcrops are at altitudes higher than 175 m asl. If the quartzite at Granitbergfelder 15 and Black Crow corresponds to the Kätchen Plateau Formation, then this unit is older than the Ystervark Formation. This possibility is retained in figure 80, but the correlation needs to be tested.

A final conundrum that needs to be attended to concerns what happened at the interface between marine and continental realms during the Lutetian to Rupelian time span. In the marine realm there was active transportation of agate, chalcedony and jasper pebbles, depositing these clasts up to 160 metres above extant sea-level at the same time that, on land, the Blaubock Conglomerate was being deposited by rivers draining from the north and east. The gravels being transported down the Blaubock drainages came to rest along the ancient shoreline where impressive masses accumulated, but some of it was reworked by waves. However the precise nature of the interaction between the marine and continental deposits remains to be elucidated, as does the detailed timing of events, a problem that was evoked, with good reason, by Corbett (1989).

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Annex 1 – Localities surveyed by the Namibia Palaeontology Expedition.

Locality and lithology	Latitude : Longitude	Lithology, Fossil content	Age
Alte Lüderitzfelder Station west outcrop	27°18'14.2"S : 15°20'13.5"E	Loose blocks of silicified limestone	Lutetian derived into Miocene?
Bedded	27°23'08.0"S : 15°28'42.0"E	Plaquette limestone	Lutetian
Black Crow	27°22'38.3"S : 15°27'54.8"E	Palustral limestone, plants, gastropods, mammals	Lutetian
Blaubock Conglomerate Tree 1	27°22'33.7"S : 15°26'17.2"E	Silicified tree trunk	Rupelian
Blaubock Conglomerate Tree 2	27°22'30.9"S : 15°26'19.4"E	Silicified tree trunk	Rupelian
Blaubock Conglomerate Tree 3	27°22'32.0"S : 15°26'24.1"E	Silicified tree trunk	Rupelian
Blaubock Conglomerate Tree 4	27°22'56.7"S : 15°26'31.9"E	Silicified tree trunk	Rupelian
Blaubock Conglomerate Tree 5	27°22'56.4"S : 15°26'33.3"E	Silicified tree trunk	Rupelian
Blaubock Conglomerate Tree 6	27°22'55.3"S : 15°26'31.4"E	Silicified tree trunk	Rupelian
Blaubock Conglomerate Tree 7	27°22'52.2"S : 15°26'28.5"E	Silicified tree trunk	Rupelian
Blaubock Conglomerate Tree 8 and 9	27°22'50.5"S : 15°26'25.5"E	Silicified tree trunks	Rupelian
Blaubock Conglomerate Tree 10	27°22'45.2"S : 15°25'35.0"E	Silicified tree trunk	Rupelian
Blaubock Conglomerate Tree 11	27°22'39.1"S : 15°23'54.9"E	Silicified tree trunk	Rupelian
Blaubock Conglomerate Tree 12	27°22'40.8"S : 15°25'59.2"E	Silicified tree trunk	Rupelian
Blaubock Conglomerate Tree 13	27°22'32.3"S : 15°26'07.3"E	Silicified tree trunk	Rupelian
Blaubock Conglomerate Tree 14	27°22'36.5"S : 15°25'39.3"E	Silicified tree trunk	Rupelian
Bo Alterite	27°15'39.8"S : 15°22'45.8"E	Red sand with bohnerz	Ypresian ?
Bull's Eye	27°20'27.3"S : 15°28'25.9"E	Palustral limestone	Lutetian
Buntfeldschuh 1	27°35'12.2"S : 15°34'12.3"E	Sharks	Priabonian
Buntfeldschuh 2	27°34'42.7"S : 15°34'35.9"E	Sharks	Priabonian
Buntfeldschuh 3	27°34'42.6"S : 15°34'32.0"E	Sharks	Priabonian
Buntfeldschuh 4	27°34'48.0"S : 15°34'33.9"E	Sharks	Priabonian
Buntfeldschuh 5	27°34'47.4"S : 15°34'33.8'E	Sharks	Priabonian
Buntfeldschuh 5a	27°34'45.4"S : 15°34'31.2"E	Sharks	Priabonian
Cattle Post, Silcrete	27°18'00.9"S : 15°29'52.1"E	Silcrete overlying laterite	Pre-Ypresian
Chalcedon Tafelberg snails	27°16'06.5"S : 15°23'04.3"E	Silicified limestone, plants, snails	Lutetian
Contact Plaquette / Blaubock	27°20'29.9"S : 15°36'14.2"E	Plaquettes, Blaubock Conglomerate	Lutetian / Rupelian
Dauschkopf	27°11'58.9"S : 15°20'10.8"E	Brown silicified sand and rubble	Late Ypresian to Early Lutetian
Dicker Willem	26°28'S : 16°01'E	Carbonatite	Ypresian
E-feld	26°58'57.1"S : 15°15'54.6"E	Marly limestone, gastropods, mammals	Aquitanian - Burdigalian
Eisenkieselklippenbake limestone	27°27'37.7"S : 15°29'46.9"E	*Tomichia*, planorbids	Lutetian
Eisenkieselklippenbake silicified limestone and limestone	27°27'41.0"S : 15°29'47.6"E	Plants, Planorbids	Lutetian
Eisenkieselklippenbake N	27°27'37.5"S : 15°29'49.7"E	Gastropods, Plants	Lutetian
Elfert's Tafelberg	27°14'59.8"S : 15°29'12.4"E	Brown silicified sand and rubble overlain by Namib 1 and Namib 2 Calc-crusts	Late Ypresian to Early Lutetian, and Miocene, Plio-Pleistocene
Eocliff	27°21'00.0"S : 15°35'43.0"E	Limestone tufa dome, mammals	Bartonian
Eoridge	27°20'47.6"S : 15°36'42.8"E	Palustral limestone, gastropods, mammals	Bartonian
Ferruginised Blaubock Conglomerate	27°18'49.2"S : 15°36'41.4"E	Ferruginised Conglomerate	Chattian to Langhian Fe oxides
Fiskus	26°45'05.7"S : 15°14'40.7"E	Green clays, mammals	Aquitanian
Gabis Felder 1	27°19'32.1"S : 15°23'49.9"E	Olive Silicified Conglomerate	Lutetian-Bartonian
Gabis Felder 2	27°19'28.4"S : 15°23'49.9"E	Olive Silicified Conglomerate	Lutetian-Bartonian
Gabis Felder 3	27°20'05.1"S : 15°24'31.2"E	Olive Silicified Conglomerate	Lutetian-Bartonian
Gabis Felder 4	27°20'20.3"S : 15°24'33.9"E	Olive Silicified Conglomerate	Lutetian-Bartonian
Graben	27°23'02.3"S : 15°37'19.2"E	Carbonatitic limestone	Lutetian - Bartonian
Granitbergfelder 15	27°21'57.2"S : 15°28'24.9"E	Pale Green Quartzite Pomona Beds	Lutetian
Grillental VI	26°58'20.6"S : 15°19'35.5"E	Green clays, gastropods, mammals	Aquitanian
Hansenshöhe	27°11'09.1"S : 15°19'54.4"E	Brown silicified sand and rubble	Late Ypresian to Early Lutetian
Höhehagen	27°12'06.6"S : 15°19'30.0"E	Brown silicified sand and rubble	Late Ypresian to Early Lutetian
Hexen Kessel *Patella* site	27°17'30.6"S : 15°19'44.9"E	Grey calcified sand associated with onyx travertine	Pleistocene
Hexen Kessel *Vermetus* site	27°17'35.1"S : 15°19'46.9"E	Grey calcified sand associated with onyx travertine and alterite	Pleistocene
Kakaoberg	27°35'18.3"S : 15°34'15.8"E	Ferruginised aeolianite	Priabonian (Fe Chattian-Langhian)
Kätchen Tafelberg	27°14'03.5"S : 15°19'14.3"E	Brown silicified sand and	Late Ypresian to Early

		rubble, overlain by Namib 1 and Namib 2 Calc-crusts	Lutetian, and Miocene, Plio-Pleistocene
Karingarab	28°05'S : 16°12'E	Carbonatite (from Stocken 1978)	Unknown
Kaukausib Carbonatite	26°57'32.0"S : 15°35'55.4"E	Carbonatite	Unknown
Kaukausib Tafelberg	27°12'57.2"S : 15°19"04.1"E	Brown silicified sand and rubble	Late Ypresian to Early Lutetian
Kaukausib Tufa Dome	27°00'19.8"S : 15°36'47.7"E	Tufa Dome, mammals	Pliocene
Keishöhe	26°35'01.9"S : 15°52'09.4"E	Carbonatite	Unknown
Langental High Trench	27°23'21.0"S : 15°24'11.4"E	Mollusca, sharks	Priabonian
Langental Shark Site	27°25'00.1"S : 15°25'11.5"E	Sharks, Invertebrates	Priabonian
Langer Tafelberg	27°11'41.5"S : 15°20'11.7"E	Brown silicified sand and rubble, overlain by Namib 1 and Namib 2 Calc-crusts	Late Ypresian to Early Lutetian, Miocene and Plio-Pleistocene
Lästerkopf	27°13'21.7"S : 15°18'45.8"E	Brown silicified sand and rubble	Late Ypresian to Early Lutetian
Low Plateau	27°18'50.6"S : 15°25'56.5"E	Marls overlain by Blaubock Conglomerate	Rupelian
Lüderitz Krater	27°17'57.3"S : 15°21'42.8"E	"Pomona Beds" depression with agate infilling	Lutetian-Bartonian for base with Eocene infilling
Marien Berg	27°12'28.8"S : 15°21'33.5"E	Brown silicified sand and rubble overlain by Namib 1 Calc-crust and Namib 2 Calc-crust, the latter with *Trigonephrus*	Late Ypresian to Early Lutetian and Mio-Pliocene
Panther (Chameis)	27°55'S : 15°46'E	Carbonatite (from Stocken 1978)	Unknown
Phytoherm Hill	27°19'00.3"S : 15°36'05.3"E	Phytoherm limestone	Lutetian - Bartonian
Pietab 2 Freshwater Limestone Depression	27°24'35.1"S : 15°36'17.1"E	Carbonatitic limestone	Lutetian - Bartonian
Pietab 2 Phonolite	27°23'41.4"S : 15°38'37.7"E	Carbonatitic limestone	Lutetian - Bartonian
Pomona Tafelberg	27°15'16.6"S : 15°16'58.1"E	Brown silicified sand and rubble, overlain by Namib Calc-crust	Late Ypresian to Early Lutetian and Mio-Pliocene
Reuning's Pan Blaubock Conglomerate	27°22'55.7"S : 15°35'27.1"E	Silicified wood	Rupelian
Reuning's Pan Gastropod Limestone	27°22'47.3"S : 15°35'19.3"E	Limestone	Lutetian - Bartonian
Rheinpfalz Warte	27°11'28.9"S : 15°20'30.6"E	Brown silicified sand and rubble overlain by Namib 1 and Namib 2 Calc-crusts	Late Ypresian to Early Lutetian, Miocene, Plio-Pleistocene
Rondelles	27°14'00.2"S : 15°21'52.9"E	Round areas of silicified dolomite (? Tree root systems)	Bartonian
RvK Sponge Pit	27°10'45.6"S : 15°19'59.1"E	Silicified marl, sponge spicules	Lutetian
Schwarzer Berg, Silcrete	27°09'34.9"S : 15°25'42.4"E	Silcrete overlying laterite	Pre-Ypresian
Schwarzer Berg, Nephelinite	27°08'47.1"S : 15°25'16.6"E	Nephelinite intrusion	Bartonian
Scoria Hillock	27°19'26.8"S : 15°36'00.6"E	Carbonatite lava overlying Plaquette Limestone	Lutetian
Silica North	27°15'14.4"S : 15°25'06.5"E	Plaustral limestone, molluscs, Plants, mammals	Bartonian
Silica South	27°16'21.0"S : 15°25'01.1"E	Silicified limestone, plants, snails, mammals	Bartonian
Spider Tafelberg Nord	27°12'57.7"S : 15°20'17.1"E	Brown silicified sand and rubble overlain by Namib 1 and Namib 2 Calc-crusts	Late Ypresian to Early Lutetian, Miocene and Plio-Pleistocene
Spider Tafelberg Sud	27°13'23.0"S : 15°20'14.6"E	Brown silicified sand and rubble overlain by Namib 1 and Namib 2 Calc-crusts	Late Ypresian to Early Lutetian, Miocene and Plio-Pleistocene
Steffenkop	27°23'24.4"S : 15°26'38.1"E	Silicified limestone, gastropods	Lutetian
Strauchpfütz	27°29'53.7"S : 15°29'49.4"E	Gastropods in carbonate	Burdigalian
Swartkop	27°24'53.6"S : 15°31'28.2"E	Phonolite	Lutetian – Bartonian
Tafelberg Nord	27°12'42.8"S : 15°19'22.6"E	Brown silicified sand and rubble Lebensspurren	Late Ypresian to Early Lutetian
Tafelberg Sud	27°13'03.3"S : 15°18'56.5"E	Brown silicified sand and rubble	Late Ypresian to Early Lutetian
Terrassenfeld	27°28'16.4"S : 15°28'44.9"E	Sandstone, gastropods, Chelonia	Tortonian
Teufelskop	26°52'03.5"S : 15°46'12.5"E	Carbonatite	Unknown
Theodorshöhe	27°10'47.4"S : 15°21'40.8"E	Brown silicified sand and rubble	Late Ypresian to Early Lutetian
Werfkopje	27°13'37.4"S : 15°30'12.6"E	Carbonatite ash, hailstone lapilli / Olivine melilitite lava	Lutetian / Bartonian
White House Silcrete	27°30'21.5"S : 15°34'34.7"E	Silcrete overlying alterite	Pre-Ypresian
White Ring	27°16'16.2"S : 15°30'04.1"E	Plaquette Limestone	Lutetian
Ystervark Hill	27°19'16.0"S : 15°35'54.6"E	Carbonatitic breccia	Lutetian - Bartonian
Zwertafelberg	27°14'17.5"S : 15°20'32.7"E	Brown silicified sand and rubble overlain by Namib 1 and Namib 2 Calc-crusts	Late Ypresian to Early Lutetian, Miocene and Plio-Pleistocene

Annex 2. Translations and transcriptions of map legends on geological maps by Kaiser & Beetz (1926) and Van Greunen (undated)

The following lists provide translations of the map legends by Kaiser & Beetz (1926) taking into account the re-attribution of the so-called “Miocene” deposits to the Eocene as explained by these authors in their text. These legends provide some idea of the succession of events and the timing of events in the geological history of the Northern Sperrgebiet. Some rock units are represented in the maps only by colours or cross hatching, without any acronym – these are omitted from the lists below, but all are unconsolidated and probably of Holocene age. The legends in the six maps by Kaiser & Beetz (1926) vary from map to map, so translations of all the legends concerning the post-Basement rocks are provided. The lists are in the same order as printed on the maps. The lithological abbreviations (acronyms) employed on the maps can be confusing to persons not familiar with German grammar. In the abbreviations, nouns are generally, but not always, represented by a capital letter and adjectives by lower case letters. For example, “bFk” and “bFK” are not equivalent (“bFK” – freshwater limestone on terraces of the young rivers, not silicified; “bFk” – river gravels with unweathered pebbles, calcified). The original legends are in Old German, which, combined with the telegraphic way of presenting the units, renders some of the legends difficult to understand for non-native speakers of the language.

Map 1 Frohe Hoffnung – Buntfeldschuh

ALLUVIUM
Gy – gypsum terrace
al/cc – lagoonal silt and sand moderately thick covering quartzite and shale
al/cck – lagoonal silt, moderately thick, covering compact dolomite
al – clayey, damp sand on lagoonal mud
av – loam in pans (vleis)

DILUVIUM
dg – pebble beds of unknown age in old and young valleys
dw – old beaches
dm – shell banks in beaches and bays

ARID CLIMATE DEPOSITS : SUPERFICIAL DEPOSITS, PARTLY IN SITU, PARTLY COLLUVIAL, PARTLY AEOLIAN
esi/cq – banded calc-sinter on Cambrian quartzite
esi/cck – calcareous sinter covering compact dolomite ridges of the Konkip Formation
eg/esi – desert waste on calcareous sinter
es/cbd – sand, moderately thick, covering banded dolomite
eg/bk – thin layer of desert waste covering older calc-crust of the Plain Namib
es/cq1 – sand, moderately thick, covering Cambrian greenish shales
eg/cc – thin layer of desert waste covering quartzites and shales
eg/cck – thin layer of desert waste covering compact dolomite ridges of the Konkip Formation
eg/gc1 – thin layer of desert waste covering chlorite schists
ea – desert waste on slopes, blocks in the Buntfeldschuh area
esi – calcareous sinter
eD – mobile dunes, barchans
es – sand, fine to coarse, partly fixed by vegetation
ed – aeolian sand, locally accumulated bodies in bare sand drifts, mostly fixed by obstacles
ek – talus cone
egk – younger calc-crust covering and cementing desert waste
eg – coarse and medium-grained desert waste; angular, partly wind-worn detritus from the underlying rock, irregularly mixed with sand (partly “gravel” of the diamond deposits; partly recent desert waste)
eg1 eg2 – older desert waste terrace
ek1 – older desert waste terrace, calcified

TERTIARY
POST-EOCENE
bfe – ferruginised mass at Kakaoberg
bK – older calc-crust of the Plain Namib; partly silicified
bFK – freshwater limestone on terraces of the young rivers, not silicified
bs1 – sandstone, indicating a pause in the younger erosional activity

bFk – river gravels with unweathered pebbles, calcified
bF – river gravels, with unweathered pebbles

MARINE EOCENE
bs – Clay, clayey and marly sandstone with pebble banks; chalcedony and agate pebbles; fossiliferous

PRE-EOCENE
bqf – limonite-cemented quartzite of the Pomona Beds
bq – quartzite of the Pomona Beds
bQ – river gravels with weathered gneiss and phonolite pebbles

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Map 2 Bogenfels

ARID CLIMATE DEPOSITS : SUPERFICIAL DEPOSITS, PARTLY IN SITU, PARTLY COLLUVIAL, PARTLY AEOLIAN
ed/bF – thin sheet of wind-blown sand covering post-Eocene river gravels
ed/cbd – thin sheet of wind-blown sand covering Cambrian banded dolomite
ed/cck – thin sheet of wind-blown sand covering continuous compact dolomite ridges of the Konkip Formation
ed/gc1 – thin sheet of wind-blown sand covering dark greenish chlorite schist
eg/al – thin layer of desert waste covering lagoonal silts
eg/bF – thin layer of desert waste covering post-Eocene river gravels
eg/bs1 – thin layer of desert waste covering post-Eocene sandstone
eg/chd – thin layer of desert waste covering Cambrian main dolomite
eg/cbd – thin layer of desert waste covering Cambrian banded dolomite
eg/cq – thin layer of desert waste covering Cambrian greenish shale
eg/gc1 – thin layer of desert waste covering dark green chlorite schist
esi – calcareous sinter in large masses, overlying various substrates
eD – mobile dunes, barchans
ed – aeolian sand in local accumulations in barren sand drifts, mostly fixed by obstacles
es – sand, fine to coarse, partly fixed by vegetation
egk – younger calc-crust covering and cementing desert waste (partly "conglomerate" of the diamond deposits)
eg – coarse and medium-grained talus, angular, partly wind-worn detritus of the underlying rocks irregularly mixed with sand (partly "gravel" of the diamond deposits, partly recent desert waste)
egk1 – older desert waste terrace, calcified

TERTIARY
POST-EOCENE
bK – older calc-crust of the Plain Namib, partly silicified
bFK – freshwater limestone on terraces of the young rivers, not silicified
bs_1 – sandstone, indicating a pause in the younger erosional activity
bF – river gravels, with unweathered pebbles

bp – sediments of the Pomona Beds redeposited by marine processes

EOCENE
bs – clay, clayey and marly sandstone with pebble banks; chalcedony and agate pebbles, fossiliferous
bg – clay, clayey and marly sandstone with pebble banks; pre-Eocene river gravels reworked by marine processes
bp - Pomona Beds reworked by marine processes

PRE-EOCENE
bq – quartzite of the Pomona Beds
bks – calcareous sandstone with isolated pebbles of various grain sizes
bk – freshwater limestone, often silicified; fossiliferous
bQ – river gravels with weathered gneiss and phonolite pebbles

PERHAPS PRE-TERTIARY
v – Extensive silicification of an old land surface. For example : main dolomite and banded dolomite
R – circular or irregular sinkholes, old dolines. Rg : with pebbles and thin layers of desert waste

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Map 3 Granitberg

ALLUVIUM
al – clayey, damp sand of the lagoons overlying lagoonal sand
av – loam in pans (vleis)
ag – beach pebbles in ridges

ARID CLIMATE DEPOSITS : SUPERFICIAL DEPOSITS, PARTLY IN SITU, PARTLY COLLUVIAL, PARTLY AEOLIAN
esi/cq1 – sinter overlying shales in Cambrian quartzite
ed/cq1 – thin sheet of wind-blown sand covering Cambrian quartzite
eg/bs1 – thin layer of desert waste covering post-Eocene sandstone
eg/bK – thin layer of desert waste covering the old land surface of the Plain Namib
eg/bF – thin layer of desert waste covering post-Eocene river gravels
eg/cbd – thin layer of desert waste covering Cambrian banded dolomite
eg/ct – thin layer of desert waste covering Cambrian phyllitic shales
eg/cq1 – thin layer of desert waste covering Cambrian quartzite
esi – calcareous sinter in thick masses, overlying various rocks
eD – mobile dunes, barchans
es – sand, fine to coarse, partly fixed by vegetation
ek – talus cone
egk – young calc-crust covering and cementing desert waste (partly "conglomerate" of the diamond deposits)
eg – coarse and medium-grained desert waste, angular, partly wind-worn detritus of the underlying rocks, irregularly mixed with sand (partly "gravels" of the diamond deposits, partly younger desert waste)
egk1 – older desert waste terrace, calcified
eg1 – older desert waste terrace

TERTIARY
POST-EOCENE
bK/Ph – old calc-crust of the Plain Namib covering phonolite
bkQ – old calc-crust of the Plain Namib cementing desert waste of the Pre-Eocene river gravels
bkq – old calc-crust of the Plain Namib cementing desert waste of the Pomona Beds
bK – old calc-crust of the Plain Namib partly silicified
bFk – river gravels calcified
bs1k - calcareous sandstone
bs1 – sandstone, indicating a pause in the younger erosional activity
bFa – river gravels, containing quartzite of the Pomona Beds and agate
bFq – river gravels, containing quartzite of the Pomona Beds
bF – river gravels with unweathered pebbles

EOCENE
bp – Pomona Beds reworked by marine processes
bs – clay, clayey and marly sandstone with pebble banks; chalcedony and agate pebbles; fossiliferous
bg – clay, clayey and marly sandstone with pebble banks; pre-Eocene river gravels reworked by marine processes
Ra – cauldrons (old dolines) affected by marine activity; most containing agate pebbles

PRE-EOCENE
bq – quartzite, silicified calcareous sandstone; with varied grain-size desert waste and isolated pebbles (Pomona Beds)
bks – calcareous sandstone with isolated pebbles of varying coarseness
bsq – quartzite in pre-Eocene river deposits
bk – freshwater limestone, often silicified, fossiliferous
bQk – river gravels with weathered gneiss and phonolite pebbles, calcified
bQ – river gravels with weathered gneiss and phonolite pebbles

TERTIARY? PERHAPS PRE-TERTIARY
R – Circular or irregular depressions, old dolines
Rg – pebbles with thin layer of desert waste

Rm – marly stone with thin layer of desert waste
RvK – silicified masses with thin layer of desert waste

Map 4 Pomonahügel - Lüderitzfelder

ALLUVIUM
ag – beach pebbles
NaCl – thick salt beds covering lagoonal muds
al – clayey, damp sand, overlying silts
av – loam in pans (vleis)

ARID CLIMATE DEPOSITS : SUPERFICIAL DEPOSITS, PARTLY IN SITU, PARTLY COLLUVIAL, PARTLY AEOLIAN
esi/chd – thin layer of sinter (calcareous sinter terrace) covering Cambrian main dolomite
esi/cbd – thin layer of sinter (calcareous sinter terrace) covering Cambrian banded dolomite
esi/cq1 – thin layer of sinter (calcareous sinter terrace) covering Cambrian quartzite and arkose
ed/cq1 – thin sheet of wind-blown sand covering Cambrian quartzite and arkose
eg/av – thin layer of desert waste covering loam in pans
eg/chd – thin layer of desert waste covering Cambrian main dolomite
eg/cbd – thin layer of desert waste covering Cambrian banded dolomite
eg/cq1 – thin layer of desert waste covering Cambrian quartzite and arkose
eg/ct – thin layer of desert waste covering Cambrian phyllitic shale
esi – calcareous sinter in thick masses overlying various substrates
eD – mobile dunes, barchans
ed – aeolian sand in local accumulations, in barren sand drifts, mostly fixed by obstacles
es – sand, fine to coarse, partly fixed by vegetation
ek – talus cone
ea – desert waste (blocks)
egk – younger calc-crust covering and cementing desert waste (partly "conglomerate" of the diamond deposits)
eg – coarse and medium-grained desert waste; angular, partly wind-worn detritus from the underlying rocks, irregularly mixed with sand (partly 'gravel" of the diamond deposits, partly recent desert waste)
ek1 – older desert waste terrace, calcified
eg1 (eg) – older desert waste terrace, with sand
evw – Intensive weathering beneath older desert waste terraces

DILUVIUM?
dw – remains of old beaches
dg – pebble beds of unknown age in valleys

POST-EOCENE
bF – river gravels with unweathered pebbles

EOCENE
bs – clay, clayey and marly sandstone with pebble banks; chalcedony and agate pebbles

TERTIARY
PRE-EOCENE
bq – quartzite, silicified calcareous sandstone, with varied grain-size of desert waste and isolated pebbles of the Pomona Beds
bks – calcareous sandstone, cemented sand, angular desert waste and pebble deposits of the Pomona Beds
bgr – layers of desert waste, uncemented, with scarce pebble deposits of the Pomona Beds
bfe – limonite-cemented quartzite at the base of the Pomona Beds
bm – marly layers of the Pomona Beds
bk – freshwater limestone, often silicified; fossiliferous
bo – ferruginised dark red sandstone with bohnerz

PERHAPS PRE-TERTIARY
R – circular or irregular depressions, old dolines
Rm – marly sandstone with thin layer of desert waste
Rvk – silicified masses with thin layer of desert waste

Rgr – Thick, younger desert waste, covering the infillings of the depressions
bFe – Intensive ferruginisation of an old dolomite land surface at the base of the Pomona Beds

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Map 5 Rohrbachfeld

ALLUVIUM
agk – beach pebbles, occasionally cemented by lime
ag – beach pebbles
as – beach sand
av – fine sandy clay in depressions (pans, vleis)
al – clayey, damp sand, on silt, in old bays and lagoons, now dry

ARID CLIMATE DEPOSITS : SUPERFICIAL DEPOSITS, PARTLY IN SITU, PARTLY COLLUVIAL, PARTLY AEOLIAN
eg/cq1 – thin layer of desert waste covering quartzite and arkose
eg/cq – thin layer of desert waste covering greenish shales
esi – calcareous sinter in thick masses covering various substrates
eD – Mobile dunes (barchans)
ed – aeolian sand in local accumulations, barren sand drifts often fixed by obstacles
es – sand, fine to coarse, partly fixed by vegetation
ek – talus cone
egk – younger calc-crust, covering desert waste and sand, partly "conglomerate" of the diamond deposits
eg – coarse and medium-grained desert waste, angular; partly wind-worn detritus of the underlying rock, mixed with sand (partly 'gravel' of the diamond deposits, partly recent desert waste)
ek1 (ek2) – older desert waste terrace, calcified
eg1 (eg) – older desert waste terrace (eg1, eg2), with sand
evw (evwb) – intensive weathering beneath older desert waste terraces (evwb) with Bohnerz

?DILUVIUM
dg – pebble beds of unknown age in valleys

TERTIARY
PRE-EOCENE Terrestrial Deposition
bq – quartzite, silicified calcareous sandstone iron enrichment of the Pomona Beds
bks – calcareous sandstone, cemented sand, angular desert waste and pebble layers of the Pomona Beds
bgr – desert waste deposit with well-formed pebble layers of the Pomona Beds
bm – marly layers of the Pomona Beds

PERHAPS PRE-TERTIARY
Squiggle - Evidence of an old land surface
bFe – intensive ferruginisation of the dolomite on an old land surface at the base of the Pomona Beds
R – circular or irregular depressions, old dolines
Rg – containing sandstone with pebbles with thin layer of desert waste
Rm – containing marly sandstone with thin layer of desert waste
Rmv – containing marly sandstone, silicified with thin layer of desert waste
Rvk – containing silicified masses with thin layer of desert waste
Rgr – containing a thick capping of desert waste obscuring the sediments of the sinkholes
bt – intensively weathered old land surface partly with bohnerz

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Map 6 Elisabethfelder – Ginnestal

ALLUVIUM
al – clayey, wet sand, grading into mud in exposed marine bays or in depressions in the desert.

ARID CLIMATE DEPOSITS : SUPERFICIAL DEPOSITS, PARTLY IN SITU, PARTLY COLLUVIAL, PARTLY AEOLIAN
esi/g – thin beds of calc-sinter covering gneiss
eg/bFk – thin layer of desert waste overlying lime-cemented post-Eocene river gravels
eg/bF – thin layer of desert waste overlying post-Eocene river gravels
eg/bs1 – thin layer of desert waste covering Tertiary sands, clay and marl

eg/g - thin layer of desert waste covering gneiss
eD – mobile dunes, barchans
ek – talus cones
ed – aeolian sand, fine to coarse, locally present in sand drifts often fixed by vegetation and barriers
eg – angular, coarse to medium-grained desert waste, partly wind-worn detritus from the underlying rock, irregularly mixed with sand (partly gravel of the diamond deposits, partly recent desert waste)
egk – younger surface limestone covering and cementing desert waste (partly conglomerate of the diamond deposits)

TERTIARY and DILUVIUM
bsi – calc-sinter (onyx) in post-Eocene river gravels
bFK – lime-cemented post-Eocene river gravels
bF – post-Eocene river gravels
bs1 – sands, clay, green, red, clayey and marly, indicating a pause in the younger erosional activity.

Van Greunen (Legend from undated Geological Map. The lithological units are depicted by a combination of colours, dots, cross-hatching and small circles, but no alphabetical acronyms were used)

MIOCENE-RECENT
Lagoonal and Deflation Salt Pans
Calcsinter
Younger Calcrete
Younger Calcrete cementing Younger Gravels
Younger Calcrete cementing Older Gravels
Older Deflation Detritus
Shell Beds on Old Shorelines
Older Calcrete
Older Calcrete capping Phonolite
Older Calcrete cementing Younger Gravels
Older Calcrete cementing Older Gravels
Older Calcrete capping Chalcedonic Limestone
Younger Gravels with Phonolites or their Equivalent
Fluviatile Grits
Older Gravels without Phonolite

POST-EOCENE – MIOCENE
Marls, Clays and Sandstones
Phonolite / Trachyte (36 million years)

MIDDLE AND UPPER EOCENE (MARINE BEDS)
Clays and marly sandstones with chalcedony and agate gravels

LATE CRETACEOUS
Breccia Pipes with Kimberlitic affinities
Monchiquite (Limburgite, Melilite (sic) Basalt)
Marls, Grits, Rubble Beds silicified in part - Pomona Sequence
Chalcedonic Limestone (Freshwater Limestone) – Pomona Sequence
Kaolinization beneath Late Cretaceous Erosion Surface
Silicification and Ferrugination of Late Cretaceous Erosion Surface
Sinkholes in Late Cretaceous Erosion Surface infilled with marls, pebbles, sandstone

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