Foreword

Apart from a number of original research papers, Volume 27 of the "Communications of the Geological Survey of Namibia" features such varied items as a couple of postgraduate studies carried out at the University of Namibia, a review of one of the Geological Survey's flagship projects of recent years and a report on a novel initiative to improve geoscience education and outreach. In addition to these current topics, in this issue we would like posthumously to pay our respects to an eminent colleague and for many years fixture of the Namibian geological scene, with an exposition on a little-known aspect of Namibia's multi-faceted geology lately discovered among his manuscripts. A tribute to Professor Klaus Weber of Göttingen, Germany, and an introduction to this so far unpublished part of a lifetime's work spent largely among the lower regions of the stratigraphic column, has kindly been provided by J. Walter and T. Becker (Füllgraf), themselves connoisseurs of Namibian geology.

Ute Schreiber, Martin Pickford (Editors)
Windhoek, July 2024

Professor Klaus Weber *4. 12. 1936 † 18. 10. 2010

When Prof Dr Klaus Weber passed away in October 2010 at the age of 73, the geosciences lost a passionate and, up to the end, curious disciple who during his career initiated and played a key role in many important research projects. His work on the Rhenish Massif of western Germany, the German Continental Deep Drilling Programme (KTB), and, above all, the numerous research projects he headed in Namibia are amongst the most important milestones of his professional career. Even after his retirement from the Chair of Structural Geology and Geodynamics at the Georg-August-University of Göttingen, he remained committed to the geosciences. Never loath to explore new fields or propound unorthodox and "original" theories, he now widened his scope beyond structural geology and the Proterozoic.

Klaus Weber was introduced to the geology of Namibia and in particular to the Southern Margin of the Damara Orogen by Henno Martin during a joint research trip in 1975, as part of the University of Göttingen's Special Research Programme entitled "Earth's Crust" (SFB 48). This excursion turned out to be a crossroads, both scientifically and personally, for Namibia became his favourite destination and stamping ground. Henceforth, he initiated numerous research programmes on the geodynamic development of the Damara Orogen, supervising more than fifteen mapping projects as part of diploma (M.Sc.) and doctoral theses, which are now to be made available to the Geological Survey of Namibia.

Upon retiring, Klaus Weber's special passion for the Gamsberg motivated him to carry out the preliminary investigation of the supracrustal deposits of the Gamsberg Plateau presented in this volume - thus continuing the work on the Gamsberg earthquake cracks by Reinhold Wittig, another Göttingen geology guru. Initially, the results of this study, which sheds new light on the composition and stratigraphy of the younger rocks forming the plateau of this ancient granitic landmark, were shared only with a small but enthusiastic community of amateur and professional geologists on scientific excursions Klaus Weber guided in Namibia after his retirement, occasionally in rather audacious circumstances.

The original German text of this excursion guide has been translated into English to make it accessible to a wider readership, while annotated Google Earth images and a locality map were appended to provide a better overview of the study area. By publishing this part of his latter activities, we would like to commemorate Klaus, who was an important mentor for many Göttingen graduates of our generation, and who in the course of a distinguished career made a significant contribution to Namibian geology.

Jens Walter and Thomas Becker (Füllgraf), January 2024

The sedimentary and volcanic rocks of the Gamsberg Plateau

K. Weber †2010

(translated and modified extract from unpublished excursion guide, 2003)

Abstract :- This excursion guide describes and proposes an interpretation of hitherto little or unknown sedimentary and volcanic rocks of probably Early Cretaceous age, which overlie Mesoproterozoic granites on the Gamsberg Plateau, together with their major element composition and a preliminary radiometric age. Much of this erstwhile thick package of supracrustal rocks, for which the name Gamsberg Plateau Formation is suggested, has subsequently been eroded, and only isolated remnants and scree cover are available for study today. Furthermore, clays of probably Neogene to Quaternary age, which in turn overlie the quartzites and rhyolites, their mineralogy and pollen content are described.

Keywords :- Gamsberg, Quartzite, Rhyolite, Earthquake fissures, Clay, Neogene, Early Cretaceous

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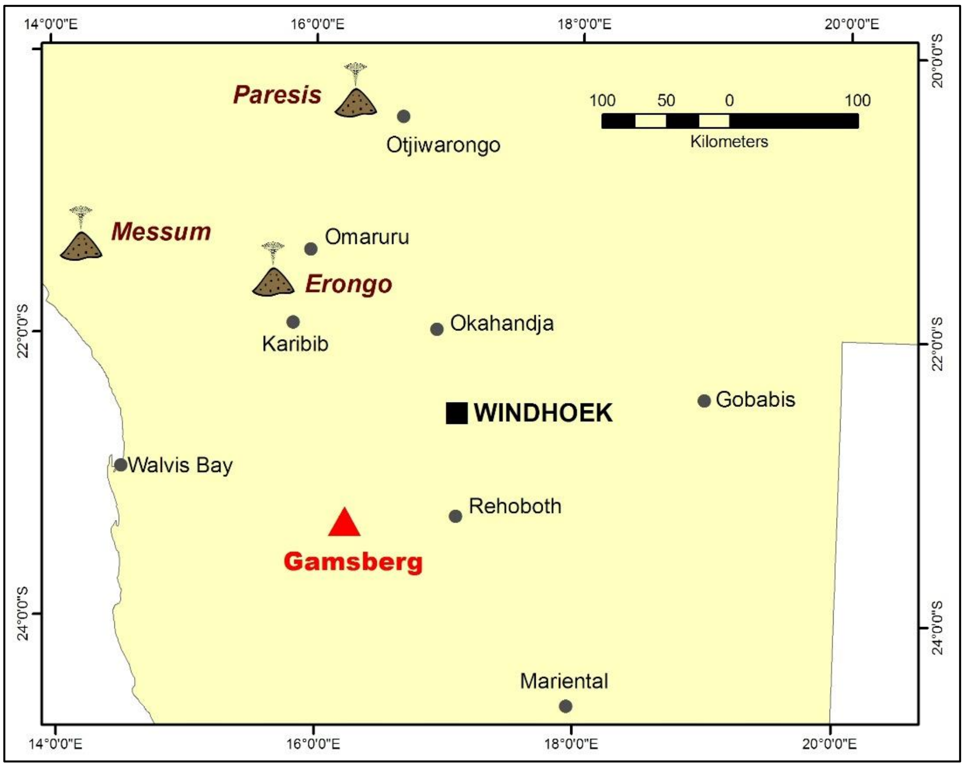

Figure 1. Locality map of central Namibia showing the relative positions of Gamsberg and Early Cretaceous eruptive centres of felsic volcanism (Erongo, Messum and Paresis)

Gamsberg quartzite

Gamsberg is a 2347 m high table mountain in central Namibia (Fig. 1), whose plateau is formed by quartzite (Fig. 2). These rocks have been lithostratigraphically correlated with the ca. 200 Ma Lower Jurassic Etjo Formation, which is similarly developed at Mount Etjo and Waterberg. However, for a number of reasons explained below, it seems more likely now that the Gamsberg quartzite is a correlate of the Twyfelfontein Formation of the Lower Cretaceous Etendeka Group in northwestern Namibia.

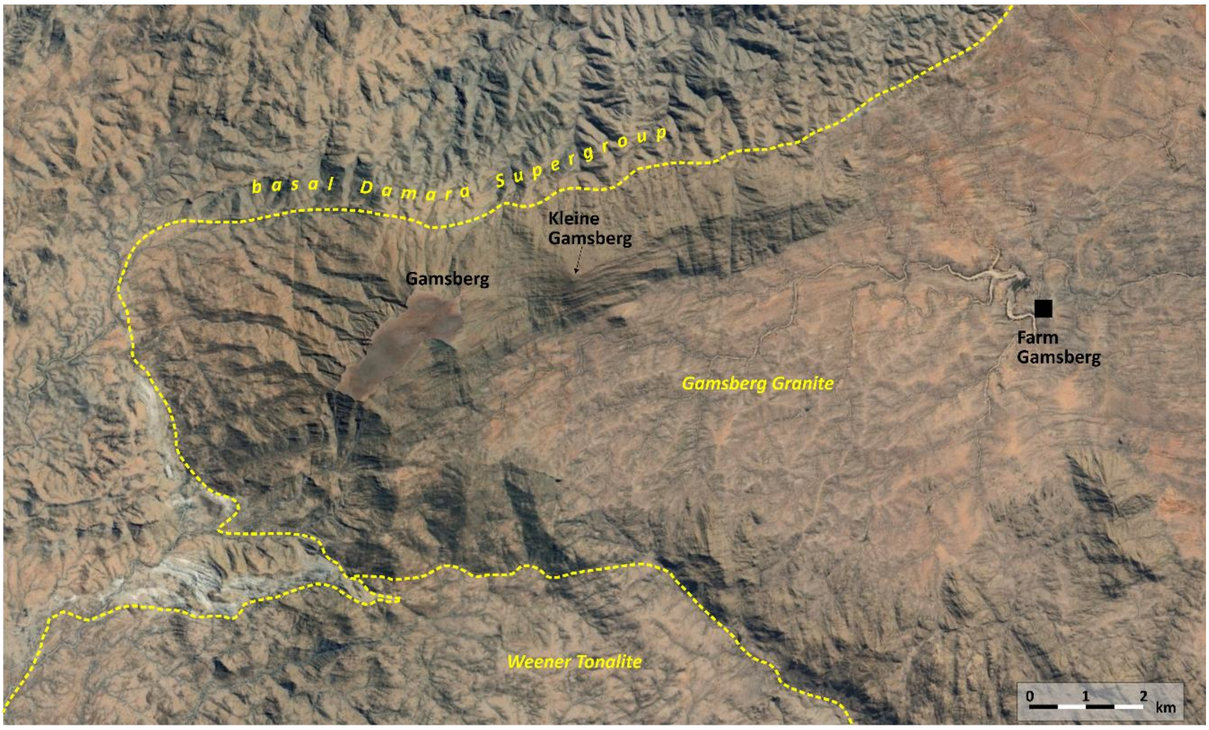

Figure 2. Aerial view of the Gamsberg area: the Gamsberg quartzite unconformably overlies Mesoproterozoic ca. 1.2 Ga granite gneiss of the Gamsberg Suite. The basal Damara metasediments west of the Gamsberg are outlined by bright bands of folded marble of the Samara Formation, while the pronounced foliation in the vicinity of Gamsberg and Klein Gamsberg results from differential weathering and erosion of the numerous intercalated, ca. 30° NW-dipping amphibolite dykes transposed parallel to the gneissic foliation.

At its base, the Gamsberg quartzite is developed as a medium- to coarse-grained, limnic-fluviatile, matrix-supported, conglomeratic sandstone with angular to poorly rounded, centimetre-sized clasts of the underlying Gamsberg granite and vein quartz. Apart from mudcracks (Fig. 3A), newly discovered trace fossils in the form of tubes and burrows (Fig. 3B) are present in places. There are also vertical tubular casts and carbonate-cemented cylindrical forms (Fig. 3C), which indicate temporary plant growth. Towards the hanging wall, the limnic-fluviatile sandstone changes into aeolian sandstone with large foresets typical of dunes (Fig. 3E). Numerous casts of gypsum crystals (Fig. 3D), such as those found in the Namib today, suggest an arid climate during the deposition of the upper levels of the Gamsberg quartzite, although the origin of the sulphur is unclear. Like many other sandstones formed in desert climates, the quartzite at the top of Gamsberg is strongly silicified (Fig. 3F), which probably contributed to the fact that this plateau right on the edge of the escarpment has survived to this day.

Gamsberg volcanic rocks

However, the intense silicification of the Gamsberg quartzite cannot be ascribed solely to palaeoclimatic conditions. In several places the sedimentary rocks are overlain by remnants of felsic volcanics, which to date had been unknown from the Gamsberg Plateau. They are very SiO_2-rich rhyolites, whose silica content probably also results from secondary silicification by a thicker package of originally overlying, now eroded, felsic volcanics.

The Gamsberg volcanic rocks are observed at the margins of three pans in the central and north-eastern parts of the plateau; in the satellite image they stand out in colour and texture from their surroundings (Fig. 4). In the interior of the pans they are covered by clays of Neogene age, or occur as angular fragments and blocks in and on top of these overlying, limnic-fluviatile deposits.

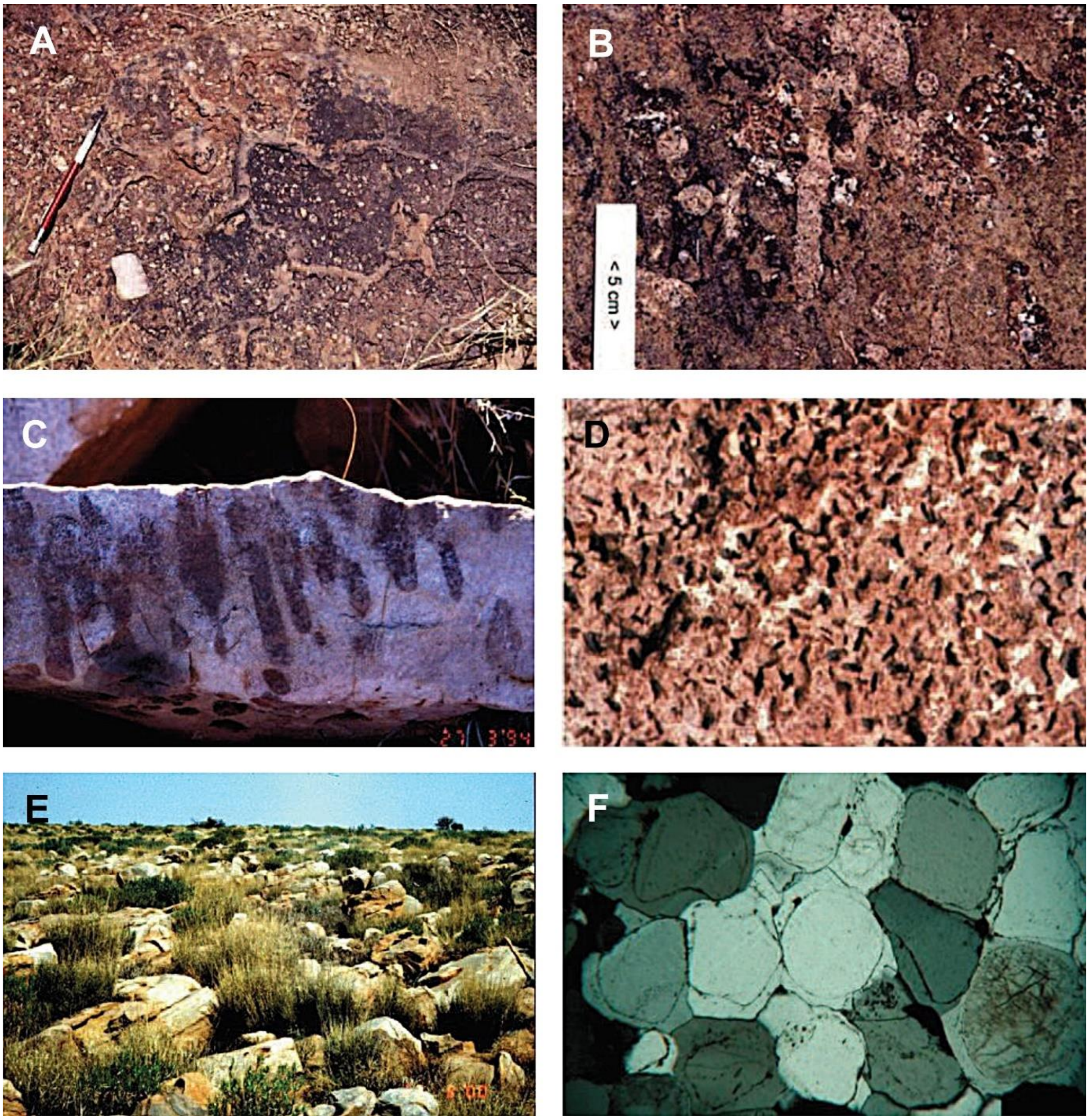

Figure 3. A) Mudcracks in the basal conglomeratic Gamsberg quartzite. In the lower left corner a large, rectangular vein quartz fragment can be seen; B) Trace fossils (burrowing and digging traces of worms, crabs or mussels) in the basal, limnic-fluviatile part of the Gamsberg quartzite; C) Dark, cylindrical forms of carbonate-rich sandstone, with a diameter of 1 to 2 cm, probably representing plant stalks. The colour results from weathering and the oxidation of traces of iron; D) Gypsum casts in Gamsberg quartzite (image width: 6 cm); E) Fossil dune cross-stratification in Gamsberg quartzite; F) Photomicrograph of the Gamsberg quartzite showing well-rounded quartz grains with opaque rims (iron oxides and hydroxides) typical of aeolianites. The grains are cemented by diagenetic quartz (image width: 3 mm).

The most conspicuous volcanic rock type is an autoclastic and/or hyaloclastic breccia (Figs 5, 6). Fine-grained, laminated pyroclastics locally show flow-banding (Figs 5A, B) or flow-folding (Fig. 5C). Flow-lamination is generally poorly developed, but in places can be very pronounced. All the Gamsberg pyroclastic deposits are extremely fine-grained and free of macroscopic pyro- and lithoclasts, suggesting deposition distal to the eruptive centre(s). The auto- or hyaloclastic breccias and the fluidal fabric of the silicified rhyolites indicate high temperatures of the fine-grained volcanic material, resulting in flow-deformation during or immediately after deposition. These deposits are interpreted as rheomorphic vitrified ash tuffs whose flow-foliation originated at an advanced stage of welding (McPhie *et al*., 1993). Further movement during subsequent cooling is recorded by synthetic Riedel shear planes, which developed under semi-ductile conditions (Fig. 5). These rocks and structures form in the internal, hottest parts of pyroclastic layers, while autoclastic and hyaloclastic breccias develop at the cooler surfaces and in aquatic environments, respectively.

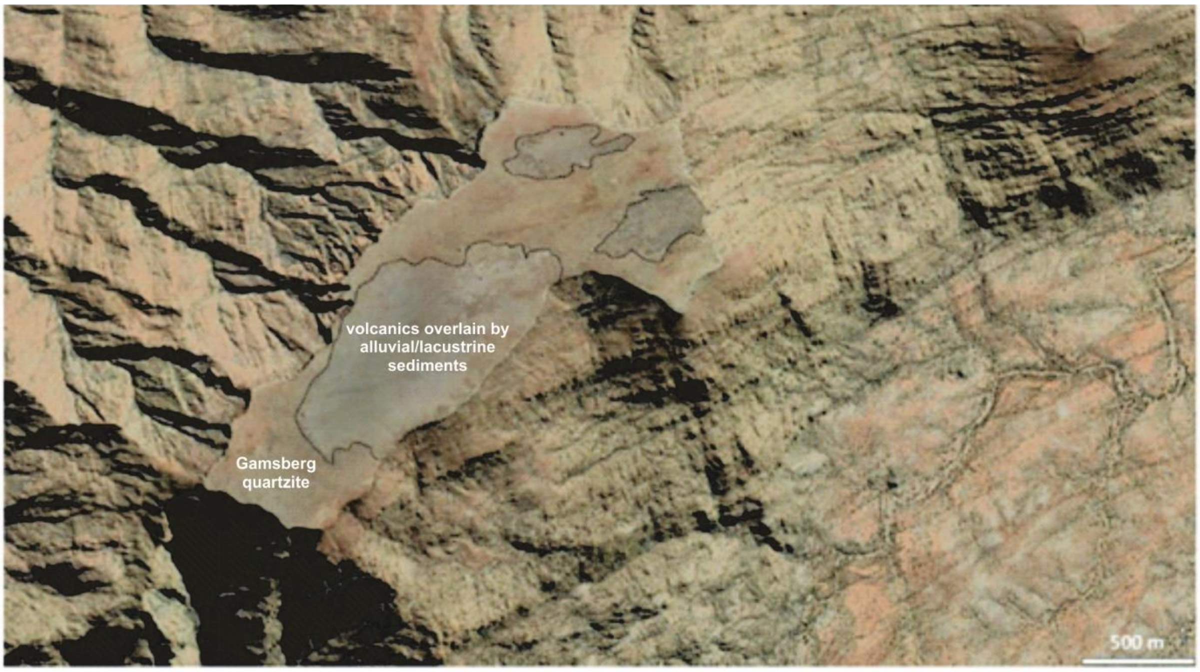

Figure 4. Satellite image (Google Earth) showing the distribution of rhyolitic volcanic rocks on the Gamsberg plateau, overlying Gamsberg quartzite and covered by Neogene limnic-alluvial sediments

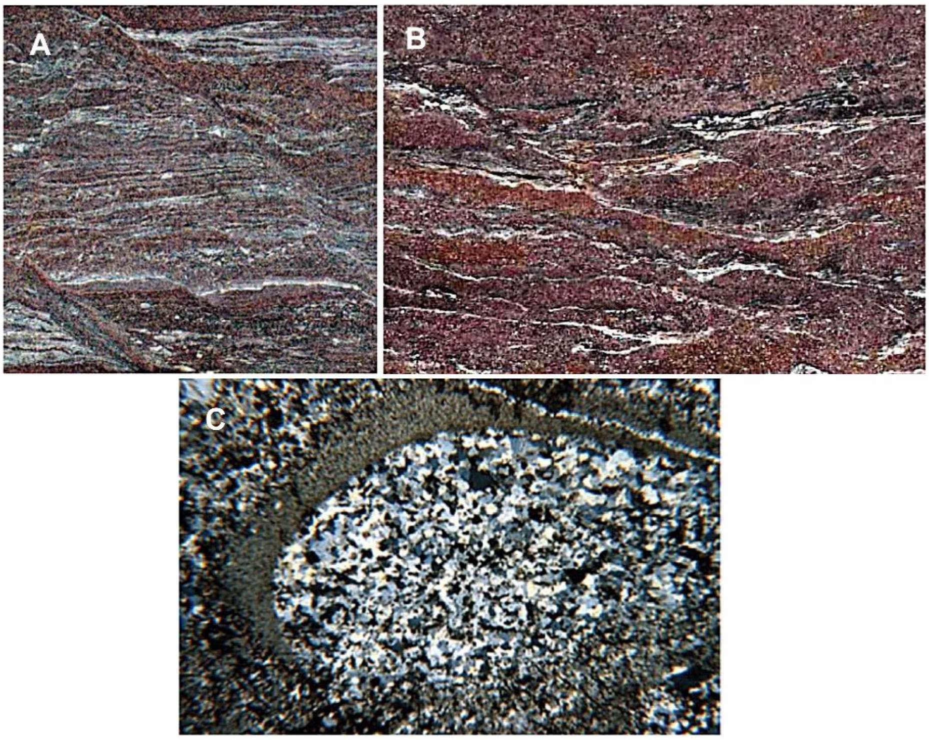

Figure 5. A-B) Gamsberg rhyolite with high-temperature flow-banding and Riedel shear planes developed under semi-ductile conditions during cooling. The light-coloured layers are rich in devitrified volcanic glass (pumice), image width B: 6 cm; C) Drop-shaped fluidal structure in Gamsberg rhyolite. The dark layer consists of devitrified glass (Xn λ/4, image width: 4.5 mm).

The Gamsberg volcanics often show lithophysae concentrically filled with chalcedony and clear idiomorphic quartz crystals up to several centimetres in size. In addition, nests occur of millimetre-sized, translucent actinolite (Fig. 7E), indicating temperatures of around 300°C in the meteoric fluids circulating through the volcanic rock. Patchy, post-magmatic actinolite is also found in less strongly welded, more porous parts (Fig. 7C), and in the matrix of the rhyolitic pyroclastic deposits (Fig. 7D). The relatively high post-magmatic temperature implies a considerable thickness of the volcanic pile that once must have overlain the Gamsberg quartzite; it is also responsible for the fine, recrystallised grain size, sericitisation of the glass fragments (Fig. 8), and the absence of Y-cracks in thin section. These conclusions are consistent with the result of apatite fission track analysis, according to which some 2000 m of Mesozoic rocks once lay on top of the Gamsberg granite.

In one rhyolite sample (Fig. 9) with a relatively weak flow texture, red-brown veinlets occur parallel to the flow. According to petrographic and geochemical analysis, the vein consists of silicified rhyolite which does not differ from the host rhyolite in terms of major and trace element composition. The development of such veins with short apophyses into and containing small fragments of the lighter-coloured host rhyolite, argues for an intrusive association, which, however, to my knowledge is unusual in rheomorphic welded tuffs, and cannot be readily explained.

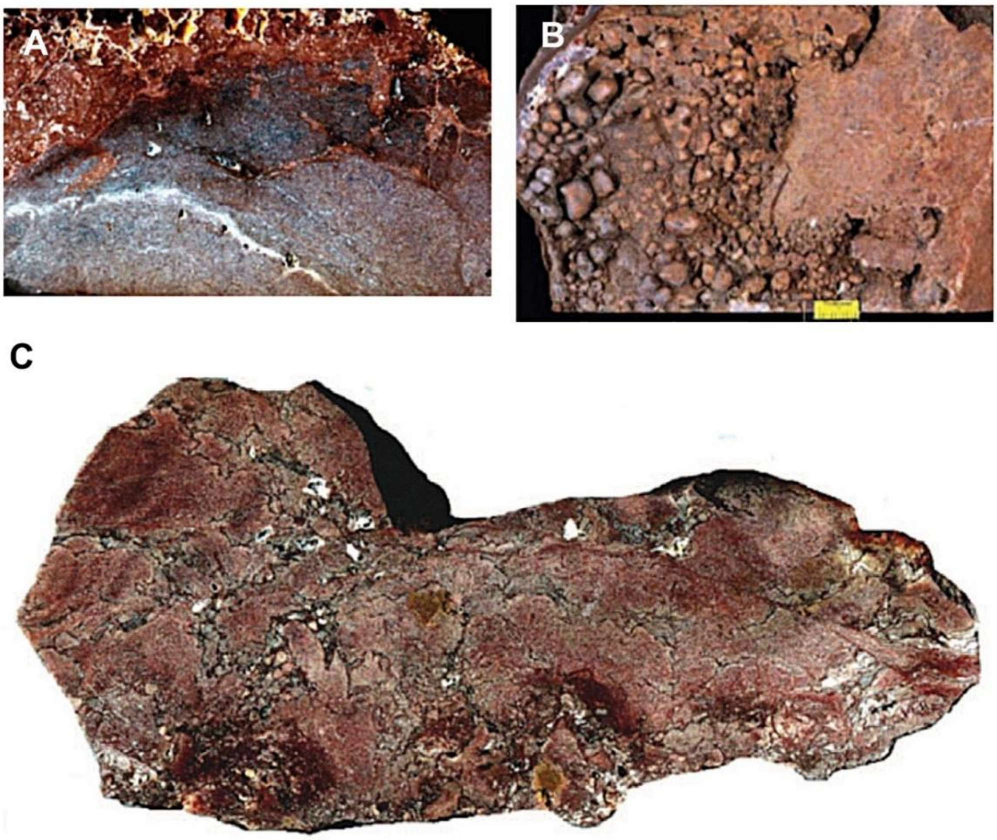

Figure 6. A) Auto- or hyaloclastic brecciation at the surface of Gamsberg rhyolite under a strongly altered pumice-like breccia (image width: 15 cm); B) Surface of an auto- or hyaloclastic breccia; C) Auto- or hyaloclastic breccia with quartz-mineralised vugs (white; sample length: 24 cm)

The volcanic rocks are underlain by one to two metre-thick, strongly silicified tuffitic sandstones, which in turn grade into the Gamsberg quartzite. The tuffitic sandstones are medium-grey when fresh and beige to reddish-brown on weathered surfaces. They are usually massive rocks that tend to show woolsack weathering, and because of their well-rounded (aeolian) grains and intense silicification have been considered part of the Gamsberg quartzite. However, petrographic studies show them to have a significantly higher feldspar content than the underlying quartzite, and also a high proportion of extremely fine-grained crystallised pumice and glass fragments; this is also expressed by geochemical composition (see 'Geochemistry of the Gamsberg rocks'). The proportion of clastic quartz grains in these tuffitic sediments varies from very high to very low, resulting in a complete transition from silicified tuffitic sandstone to silicified rhyolitic tuff, with scattered aeolian sand grains. The tuffitic sandstones presumably stem from aquatic mixing of aeolian sands and rhyolitic glass-ash tuffs, which is supported by the absence of aeolian cross-bedding in these epiclastic sediments. It is suggested that the aeolian sand grains originate from dunes in the area of the phreatic explosion and were transported together with the fine-grained ignimbrites to the place of deposition. In the Etendeka area, such aeolian sediments interlayered with volcanic rocks are common (Jerram *et al*., 2000), although they have not yet been reported from the rhyolitic volcanics of the Erongo Mountain, which is thought to be the probable source region of the Gamsberg rhyolites (Fig. 1).

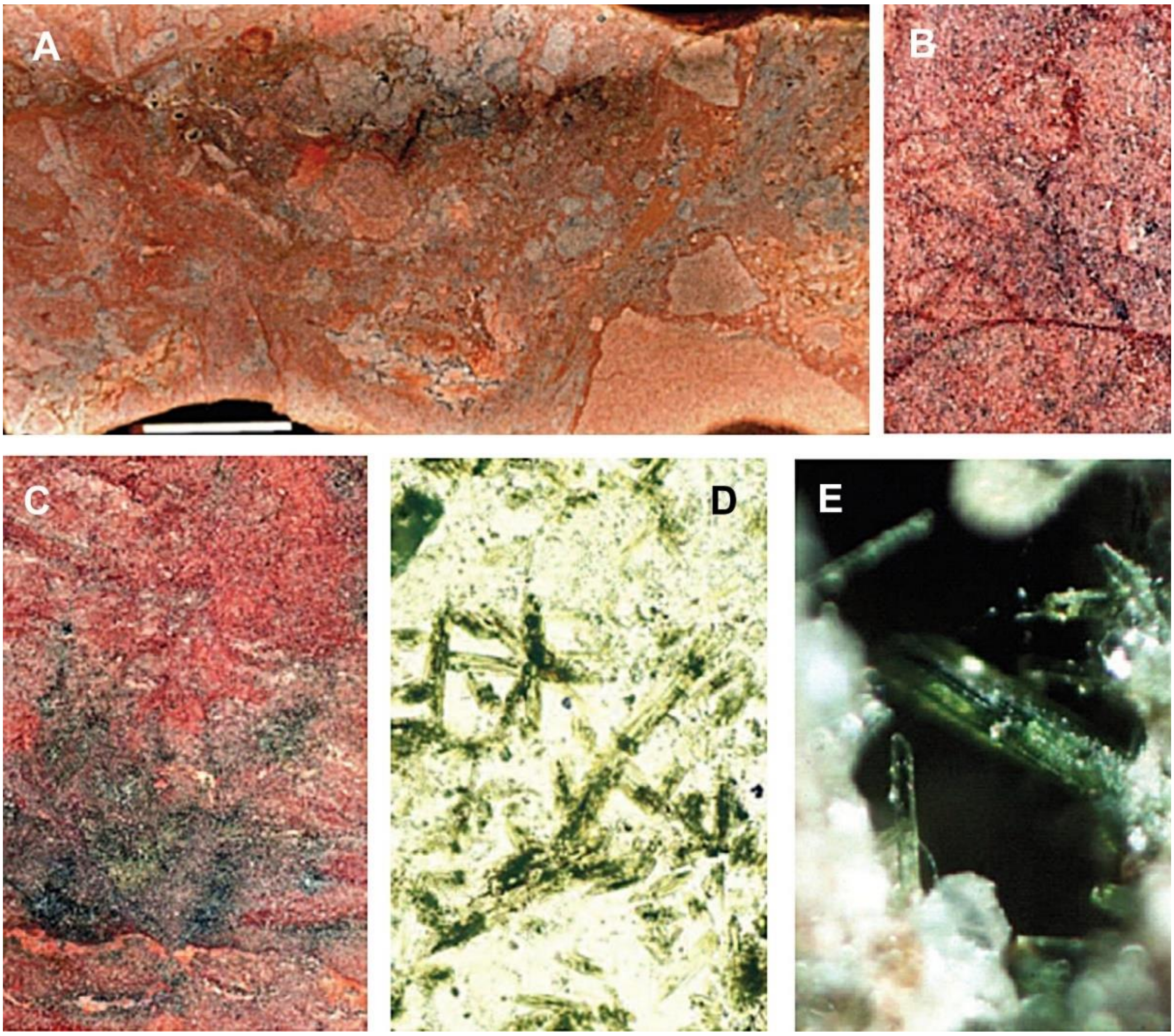

Figure 7. A) Rhyolite breccia from the Gamsberg; B) Incipient brecciation due to volume loss during cooling and devitrification of the welded tuff. The cracks are healed with quartz (chert; image width: 3 cm. C) Fine-grained rhyolitic tuff with light-coloured, devitrified pumice fragments and layers of pumice (fiamme; image width: 4 cm). Post-magmatic actinolite has grown in the grey-green and somewhat more porous, less welded parts of the pyroclastite; D) Photomicrograph of post-magmatic actinolite in rhyolitic tuff (Xn, image width: 2 mm); E) Photomicrograph of lithophysae with post-magmatic actinolite and quartz in Gamsberg rhyolite (image width: 2 mm)

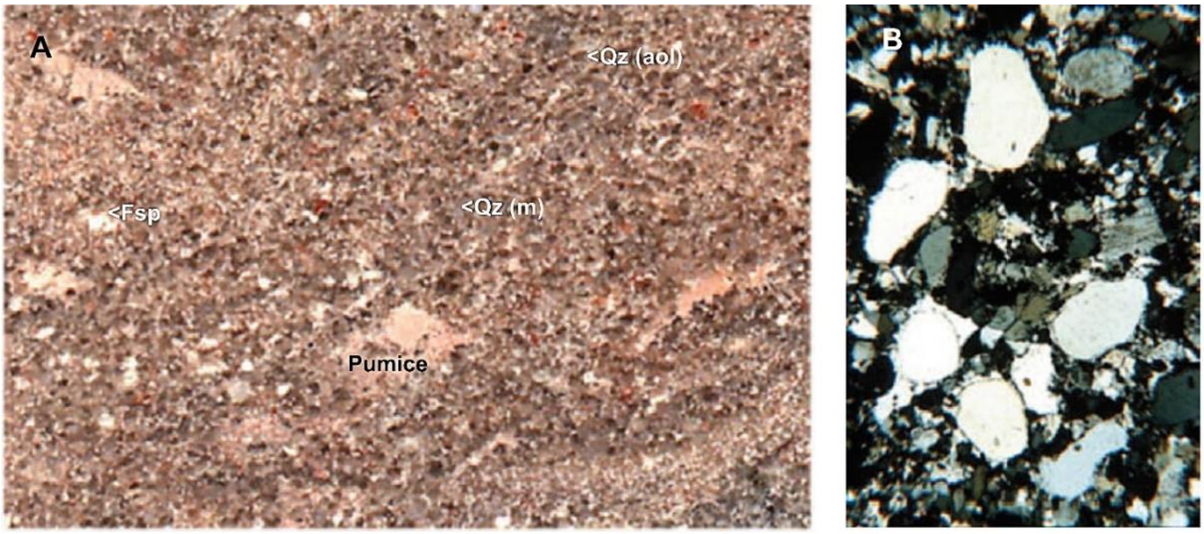

Figure 8. A) Silicified tuffitic sandstone from the uppermost part of the Gamsberg deposits with irregular, beige pumice fragments, white magmatic feldspar (Fsp), well-rounded aeolian (Qz aol) and angular, probably magmatic quartz grains (Qz m). Milky vein quartz grains are usually well-rounded; the very fine-grained, light-coloured grains are mostly feldspar and devitrified, variably sericitised glass fragments (image width: 17 mm, sample 22.8.00/5); B) Photomicrograph of aeolian quartz grains with opaque fringes in a finely crystalline, feldspar-rich rhyolitic matrix (Xn, image width: 2.15 mm)

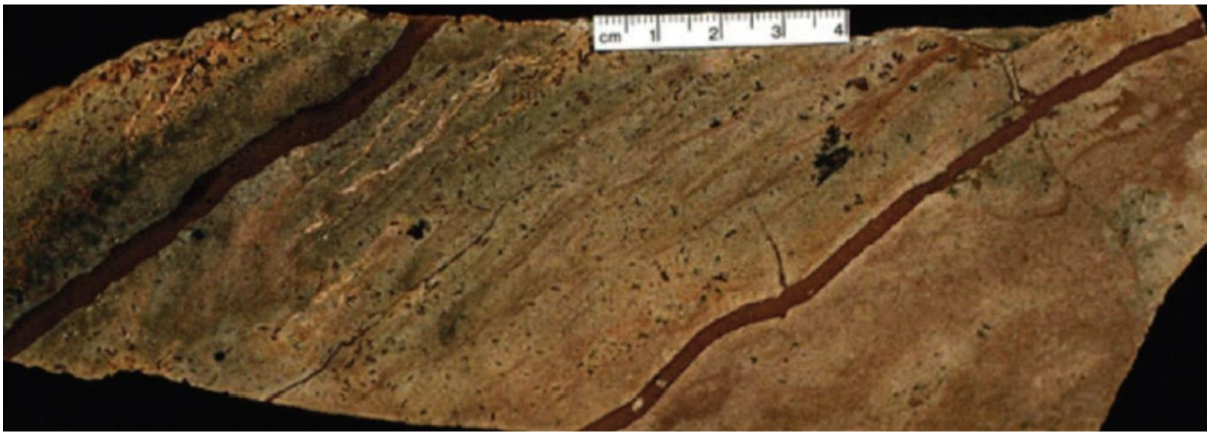

Figure 9. Fine-grained, red rhyolite veinlets within Gamsberg rhyolite, probably representing flow-parallel sills. From the sill on the right, small apophyses extend into the host rock. Also, two small fragments of the lighter-coloured host rhyolite occur within the right-hand sill (lower margin of the picture). The two rhyolites do not differ in geochemical composition.

Clastic dykes

Wittig (1976) described clastic dykes from the Gamsberg quartzite and the underlying Gamsberg granite (Figs 10-12). These dykes, which appear up to 240 m below the base of the quartzite in the Gamsberg granite, are interpreted as infill of earthquake fissures and divided into two types: a) dykes cross-cutting the basal (limnic-fluviatile) Gamsberg quartzite and the Gamsberg granite and filled with detritus of basal Gamsberg quartzite, and b) dykes cross-cutting the overlying aeolian, cross-bedded Gamsberg quartzite, filled with material from a higher, now eroded level. The garnet-rich dyke cutting the Gamsberg granite on farm Weener described by Wittig (1976) and cited by Schalk (1984) is not a clastic dyke with a garnet-rich sand-filling, but an igneous dyke with microcline, garnet and quartz as its main components.

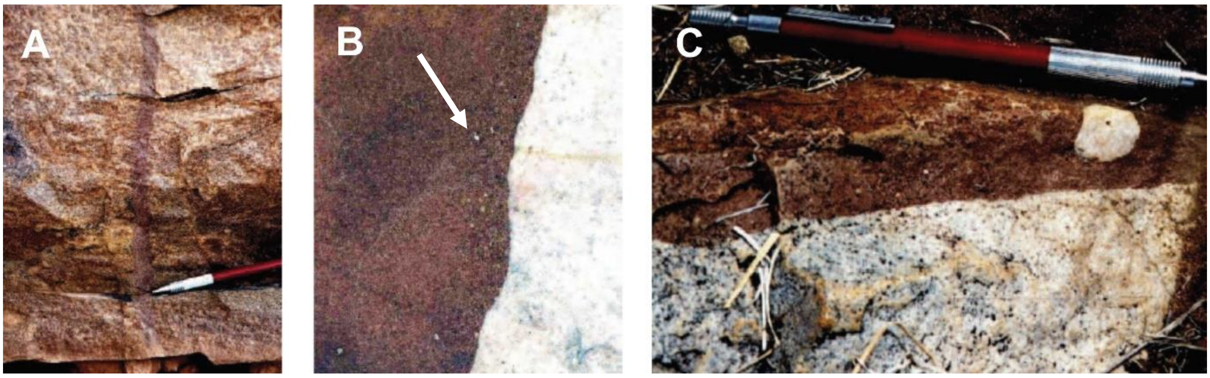

Figure 10. A) Clastic dyke of red tuffitic sandstone cross-cutting Gamsberg quartzite; B) Close-up of the contact between a clastic dyke (red) and light-coloured Gamsberg quartzite. The small, bright clasts in the clastic dyke are rhyolitic fragments (arrow, image width: 6 cm); C) Clastic vein (red) in Gamsberg quartzite with a large clast of light-coloured Gamsberg quartzite, demonstrating that the latter was already lithified at the time the clastic dyke formed.

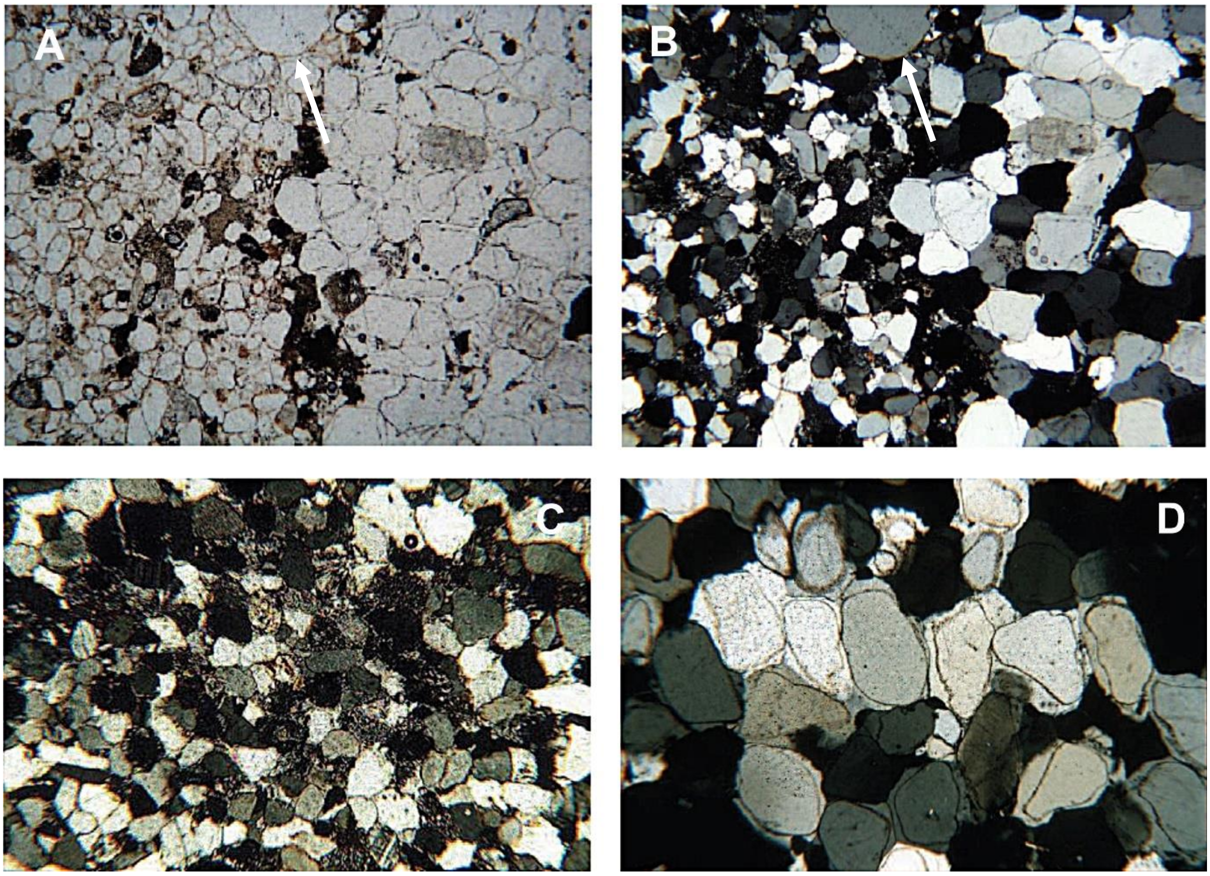

Figure 11. Photomicrographs of the contact between Gamsberg quartzite (on the right in each photo) and a clastic dyke (on the left) in A) planar-polarised light-PPL and B) cross-polarised light-Xn: grain size in the clastic dykes ranges from silt to fine sand. Aeolian grains (arrows) differ from the fluviatile ones by being larger and better rounded (image: width 5 mm.); C) Sample from the deepest clastic dyke below the top of the Gamsberg granite displaying fractured and subrounded quartz grains cemented by microcrystalline quartz (chert; image width: 2.15 mm); D) Gamsberg quartzite cemented by authigenic quartz (image width: 2.15 mm) for comparison with C)

The clastic dykes are clearly distinguishable from the hosting Gamsberg quartzite by their red to deep red colour (Fig. 10). Well-rounded, aeolian sand grains ca. 0.5 mm in size, as are present in the Gamsberg quartzite, also occur in varying proportions within the clastic dykes. However, most clastic grains are angular, range in size from silt to fine sand, and are of fluviatile rather than aeolian origin. While the Gamsberg quartzite - apart from the tuffitic transition layers below the rhyolitic tuffs - is a pure quartzite, the clastic dykes consist exclusively of tuffitic sandstones with high proportions of fine-grained feldspar and devitrified pumice and glass fragments, which excludes their derivation from the Gamsberg quartzite. Moreover, clasts of Gamsberg quartzite (Fig. 10C) occur within the tuffitic sandstone of the clastic dykes proving that it was already lithified at the time of dyke formation. The latter are massive and unstratified, locally displaying cloudy textures. Low-temperature meteoric waters probably circulated throughout the predominantly vertical fissure system, which according to Wittig (1976) has a preferred north - south orientation; these waters are thought to have washed in the sand fill, as well as provided the microcrystalline quartz (chert) cement. Microcrystalline quartz mineralisation is characteristic of low-temperature hydrothermal systems, while authigenic quartz, as in the Gamsberg quartzite, is of diagenetic origin. The deepest clastic dyke, with a width of 5 to 10 cm, was encountered some 240 m below the base of the quartzite in the granite.

Similar clastic dykes have also been found in the Etendeka volcanic rocks of northwestern Namibia, where they consist of aeolian and fluviatile tuffitic intertrap sandstones. Therefore, the intercalated red, tuffitic sandstones, which clearly differ from the Gamsberg quartzite in colour, petrographic composition, grain size and grain shape, are likewise interpreted as intertrap sandstones within the Gamsberg volcanics, which were deposited on top of the quartzite. Locally, larger vein quartz clasts are found in the clastic dykes, suggesting the presence of conglomeratic intercalations, similar to the ones observed in the Etendeka lavas, within the now eroded Gamsberg volcanics. These clastic dykes of tuffitic sandstone also are found in the Gamsberg rhyolites (Fig. 12A).

Figure 12. A) Clastic dyke of tuffitic sandstone with rhyolite clasts and numerous sericitised pumice fragments in brecciated Gamsberg rhyolite; B) Feldspar-rich clastic dyke (small light-coloured grains: feldspar and pumice fragments) in the Gamsberg quartzite with a large vein quartz clast, and smaller fragments of red rhyolite, devitrified volcanic glass (arrow) and silicified mudstone (image width: 6 cm); C) Clastic dyke cross-cutting Gamsberg granite

The clastic dykes which cross-cut the remnants of the Gamsberg rhyolites, the underlying tuffitic sandstones and Gamsberg quartzite, as well as the Gamsberg granite, are an archive of the sediments which once covered the Gamsberg Plateau. Grain size and shape show them to be of both fluviatile and aeolian origin, and it is likely that they belong to the Etendeka Group.

Geochemistry of the Gamsberg rocks

The Gamsberg volcanic rocks were analysed for main and trace elements. Further geochemical investigations were not carried out because of the strong silicification, hydrothermal overprinting and aeolian contamination. Results are shown in the tables and diagrams below. According to petrographic studies, samples with SiO_2 contents of 85 to ~88 wt% are volcanic rocks, including sample 9.4.90/4a (Fig. 9; 85.6 wt% SiO_2) from a fine-grained rhyolite vein within Gamsberg rhyolite sample 9.4.90/4. Sample 9.4.90/13b (89.9 wt% SiO_2) represents a clastic dyke of tuffitic sandstone with rhyolite clasts and sericitised pumice fragments cross-cutting Gamsberg rhyolite (Fig. 12A). The sand grains are predominantly of aeolian origin and were washed into the crack together with the tuffitic material. Table 1 shows the mean geochemical composition of the eighteen analysed Gamsberg rhyolites as compared to rhyolites from the Erongo Mountain (Emmermann, 1976) and average rhyolite (Duncan *et al*., 1984).

Comparison with the Erongo rhyolites was chosen as this Cretaceous volcano, located some 200 km to the north (Fig. 1), is the nearest source from which the Gamsberg rhyolites could have been derived. Geochemical composition of the Gamsberg rhyolites, together with petrography and magmatic texture, suggest a very silica-rich magmatic parent rock, which geochemically could have been a rhyolite (possibly rhyolitic glass ash tuff), as the Gamsberg rhyolites are free of magmatic phenocrysts. Of note is the relatively strong depletion of Al_2O_3, which, however, is probably due to the subsequent intense silicification (Table 1, Column B).

	A	B	C	D
SiO_2	87.10	73.00	73.10	72.82
TiO_2	0.23	0.51	0.40	0.28
Al_2O_3	5.60	12.47	13.40	13.27
Fe_2O_3	1.08	2.41	2.87	2.59
MnO	0.01	0.02	0.04	0.06
MgO	0.15	0.33	0.45	0.39
CaO	0.10	0.22	0.98	1.14
Na_2O	0.71	1.58	2.79	3.55
K_2O	3.58	7.97	5.24	4.30
P_20_5	0.03	0.07	0.23	0.07
	98.59	**98.59**	**99.5**	**98.47**

	A	B
Nb	7	
Zr	224	214
Y	28	
Sr	30	80
Rb	24	303
Pb	10*	
Ga	6	
Zn	13*	
Cu	25*	
Ni	18	
Co	<5*	
Cr	27	
V	30	
Ba	611	420
Sc	6*	

Table 1. Geochemical composition of the Gamsberg (Barge, 2001) and Erongo rhyolites (Emmermann, 1976). Left: major element composition (wt %) of A) Gamsberg rhyolite, mean values of 18 samples; B) Gamsberg rhyolite, values of column A recalculated to 73% SiO_2 due to silicification; C) Erongo rhyolite, mean values of 11 samples; D) Average rhyolite (after Duncan *et al*., 1984); right: trace element composition (ppm) of A) Gamsberg rhyolite, mean values of 18 samples (complete analytical results shown in Appendix I, *values below detection limit omitted as unreliable), and B) Erongo rhyolite, mean values of 11 samples (complete analytical results shown in Appendix II)

Aluminium, iron, titanium and sodium and potassium exhibit an almost linear decrease with increasing SiO_2-content (Fig. 13), i. e. from the volcanic rocks to the tuffitic sandstone of the Gamsberg fissures and the Gamsberg quartzite. This linear decrease is most obvious for Al_2O_3. Recalculation of the analysed average Al_2O_3-content (Table 1, column A) to 73 wt% SiO_2 (Table 1, column B) results in an Al_2O_3-content of 12.47 wt%. From this a "dilution factor" of 2.227 (12.47:5.6=2.227) for 73 wt% SiO_2 was determined, which is applied to the other major elements. Results show the immobile elements iron and titanium to be in relatively good agreement with the Erongo rhyolites, while sodium and calcium are depleted and potassium enriched relative to the Erongo rocks (Table 1, columns B and C). This can be attributed to the higher mobility of the alkali and earth-alkali elements during secondary alteration. As only Zr, Rb, Sr and Ba were analysed from the Erongo rhyolites (Emmermann, 1976; Table 1 & Appendix II), a comparison of trace element concentrations remains inconclusive.

SiO_2-contents between 90 (89.7 wt%) and 95 wt% have been determined for samples from a) clastic dykes, b) rhyolitic pyroclastic rocks with isolated aeolian quartz grains and c) tuffitic sandstones. Thus, the clastic dykes in the Gamsberg quartzite and the granitic basement differ from the quartzite geochemically as well as in terms of mineral content, grain size and grain shape, which excludes the latter, as already concluded from other evidence, as the source of the clastic dykes. The Gamsberg sedimentary and volcanic rocks show a continuous transition from silicified rhyolitic tuffs to pure quartzite. Between these end members the silicified tuffitic sandstones and clastic dykes occupy intermediate positions.

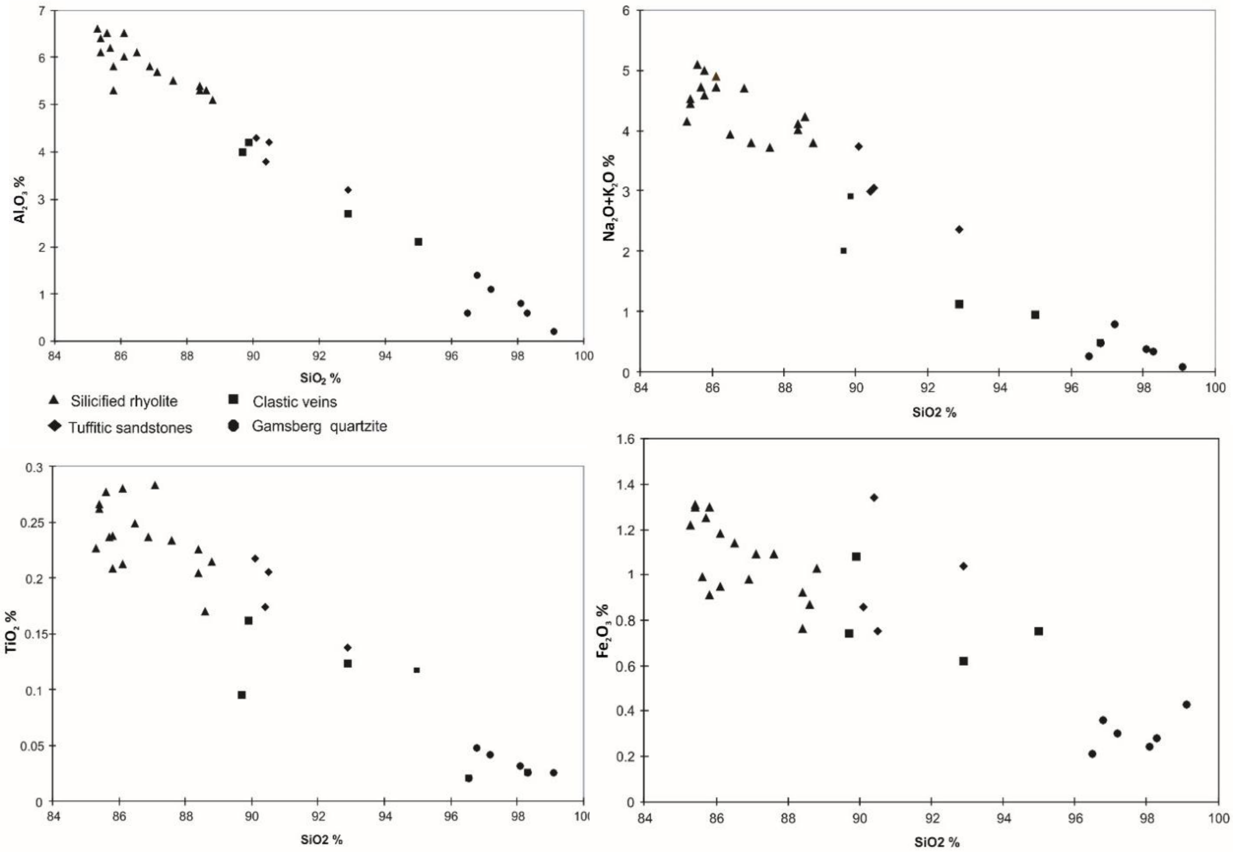

Figure 13. Harker (1909) diagram representation for some major elements of the Gamsberg rhyolite

Radiometric ages

Some 50 kg of a silicified rhyolite sample were processed for zircon separation but without success. Presumably, the expected very fine-grained zircons could not be isolated due to the strong silicification of the volcanic rocks. An attempt to prepare magnetically enriched fractions with diluted hydrofluoric acid also remained unsuccessful.

On sample 9.4.90/3, K/Ar ages were determined for the grain fractions <2 μm and < 0.2 μm (Table 2). The samples were crushed with a jaw crusher and briefly ground with a vibrating disc mill; the above grain fractions were obtained by the Atterberg process.

Compared to the total sample (K_2O = 3.91%), the K_2O-content of the grain fraction

<2 µm is significantly higher and probably results from an enrichment of potassium feldspar, as no mica was found in the fine fractions by X-ray diffraction. The preserved age (Table 2) is inconclusive and corresponds neither to the Karoo volcanics (170 to 180 Ma) nor to the Etendeka volcanics (132 Ma), but lies in between.

Due to the failed zircon dating and the uncertain K/Ar ages, reliable dating of the Gamsberg rhyolites is still pending. Assuming, however, that the Gamsberg volcanics, due to their rhyolitic chemistry, more likely correlate with felsic rocks of the Etendeka Group than with (the predominantly mafic) Karoo igneous province, one has to conclude that the Gamsberg rocks are younger than originally thought, i. e. that they are Lower Cretaceous in age. Recently found trace fossils in the limnic-fluviatile basal part of the Gamsberg quartzite on the other hand suggest a correlation with the older limnic-fluviatile layers of the Jurassic Etjo Formation, on the basis of which an unlikely duration of ca. 70 Ma would have to be assumed for the deposition of the rocks on the Gamsberg Plateau (Lower Jurassic to Lower Cretaceous).

Sample	Fraction	K_2O (wt%)	40 Ar*(nl/g) STP	40 Ar* (%)	Age (Ma)	2s- error (Ma)	2s-error (%)
09.04.90 / 03	<2 µm	7.46	41.46	94.35	164.7	3.5	2.1
09.04.90 / 04	<0.2 µm	5.62	30.13	88.47	159.1	6	3.8

Table 2. K-Ar geochronology of the Gamsberg rhyolite

Another conclusion, i. e. that both the Gamsberg quartzite and the overlying rhyolitic volcanics are younger than the Etjo Formation seems the more probable. This would suggest a correlation of the quartzite with the Twyfelfontein Formation, which Stollhofen (1999) places at the base of the Etendeka Group. The Twyfelfontein Formation also contains limnic-fluviatile deposits below the aeolian sediments (Jerram *et al*., 1999), for instance in the Huab Basin, which previously had been correlated with the Etjo Formation. Moreover, the very good Gamsberg outcrops give no indication of a hiatus between the deposition of the quartzite and the rhyolite. Rather, the outcrops as well as the geochemical data show that there is a continuous transition from pure quartzite via tuffitic sandstone to rhyolitic tuff. The tuffitic /epiclastic sediment fill of the clastic dykes further supports the existence of now eroded volcanic rocks as well as fluviatile and aeolian sediments, which, based on the presence of post-magmatic actinolites and apatite fission track analysis, must have had a considerable thickness. Therefore, the here described sedimentary and volcanic rocks should be awarded formation status (proposed name: Gamsberg Plateau Formation), and the unit tentatively placed in the basal Etendeka Group.

Cenozoic limnic-fluviatile sediments

The (provisional) Gamsberg Plateau Formation is overlain by grey clays, with a few intercalated gravel lenses of well-rounded vein quartz. The distribution of the clays on the Gamsberg Plateau, which largely coincides with that of the rhyolites, can be seen on the satellite image in Figure 4. The preserved thickness of these deposits is at least 1.20 m in the central area of their occurrence, as I was able to show by trenching. However, the original thickness must have been much greater, as indicated by the dense scree layer of well-rounded vein quartz clasts (Fig. 14A), compared to their prevalence in the *in situ* sediment. As there are no quartz veins on the isolated inselberg of the Gamsberg and the rounding of the vein quartz pebbles implies considerable transport distances, they are thought to belong to a limnic-fluviatile depositional environment connected with the metamorphic basement. As this question is of particular interest for the climate development, I took samples of these clays for pollen analysis and mineralogical investigation.

Asteraceae pollen dominate in the Gamsberg clays, but their proportion decreases very sharply in the lower part of the profile (Table 3). As the phylogenetic development of the *Asteraceae* only started during the Late Palaeogene, a Neogene maximum age of the clays is assumed. The samples contain numerous fungal spores, fungal oogonia and fungal hyphae, a number of algal cysts, some spores that cannot be identified, and a narrow spectrum of pollen. Particularly remarkable is the almost universal occurrence of *Asteraceae* pollen, especially of an extremely small form (generally < 10 μm). Much rarer are similarly small tricolpate and tricolporate forms (*Tricolpopollites liblarensis pusillus*-type or *Tricolporopollanites cingulum oviformis*-type). A few faecal pellet-like agglomerates of the former have been identified in the sample taken 75 cm below surface (insect faecal pellets?). A more detailed systematic determination is not possible. The two forms probably originate from the large family of Fagaceae.

Figure 14. A) Scree layer on top of the Gamsberg clay; B) Deflation plane with alluvial gravel on the Gamsberg Plateau

An important problem is whether the collected pollen represent recent contamination or a sediment-borne fossil record. The occurrence in the samples of forms such as *Betula* (birch) and *Alnus* (alder), which are not native to Namibia and also contain remnants of protoplasm, proves that there are impurities. However, in the case of the *Asteraceae* pollen contamination in the laboratory or during sample handling is unlikely. Although they may stem from the recent vegetation on Gamsberg, I would like to rule out contamination in the field, as the samples were collected from a fresh trench and immediately packed in plastic bags with zip fasteners. It remains to be noted that the pollen which cannot be clearly attributed to impurities, probably represent an *in situ* fossil record; thus, a Neogene to Quaternary age is assigned to the Gamsberg clays, as *Asteraceae* only form a notable component of the vegetation since the Neogene.

With more than 20,000 species, the daisy family is currently one of the most diversified families of seed plants worldwide. Vertical trends in the distribution of palynofacies elements are difficult to identify in the Gamsberg profile, excepting only the *Asteraceae* pollen which show a maximum in the middle and a sharp decrease in the lower part (Table 3). To a lesser extent the latter also applies to the pollen content as a whole. It is noteworthy that the fern spores (small trilete verrucate forms and monolete *Polypodiaceae* spores) are restricted to the uppermost four samples (< 65 cm depth), while mushroom spores and mushroom oogonia occur throughout the entire profile. Fungal hyphae also are common, especially in its upper part. Heavy minerals occur more frequently in the footwall than in the hanging wall.

Prof. Dr. Grüger of the Botanical Institute, University of Göttingen, who helped with the determination of the pollen, stated that the samples do not represent Quaternary or recent forms known to him. Also, the pollen associations found are not typical of today's local flora on the Gamsberg Plateau. Table 3 lists the results of the pollen analysis, which is thought to represent the fossil record in each of the samples.

The <2 μm and <0.2 μm fractions from the Gamsberg clays were isolated using the Atterberg method and examined by X-ray diffraction. Glycolised and non-glycolised oriented sections were used for clay mineral analysis. The Gamsberg clays contain very little illite in the particle size fraction <2 µm. Apart from kaolinite, they consist predominantly of expansive clay minerals (smectites). The quartz content in the fraction <2 µm is also very low, while the <0.2 µm particle size fraction is entirely free of quartz. The greyish colour of the clays, together with the predominant kaolinite and smectites, indicate a humid climate at the time of deposition. This would argue for a pre- to Early Miocene age, i. e. before the onset of the Benguela Current and the formation of the Namib Desert, with markedly arid climatic conditions.

Depth	15-20 cm	40 cm	50 cm	65 cm	75 cm	85 cm	93-96 cm	95-100 cm	100-105 cm
***Asteraceae* pollen <10 µm**	39	X	70	2	22	14		11	1
***Asteraceae* pollen >10 µm**	9	X	3	1		2		2	1
***T. cingulum oviformis* -type**			1	1	10		1		
***T. liblarensis pusillus* -type**	7	X	1		1 as faecal pellets				
***Betula* (recent)**					1				
***Alnu* s (recent)**						1			
***Chenopodiaceae* pollen**	2								
small trilete verrucate spores	14	XX		1					
monolete spores (*Polypodiaceae*)	2	X	1						
reticulate cysts	1	X	9	1		2			2
rugulate cysts	12	X	1						
algal cysts		X	XX	XX	XX	X			
fungi spores/ fungi oogonies		XX		XX		XX	X		XX
fungal hyphae		XXX		XX					X
resinite splinter		XX		XX		X	X	X	X
heavy minerals			XX	XX	XX	X	X	XX	XX
other pollen	3	X	2	2				3	
undetermined forms	3	3							
***Pterosphaeridia* - similar cysts**	3								
fine material		XX	XX						
Pinus								1	

Table 3. Fossil record of each profile section (cm below ground level). Numbers in the table represent counts per slide. In each case one slide was counted, which was screened completely. X = present, XX = common, XXX = very common

While digging the trench it was noted that the entire profile contained very few fragments of the underlying quartzite and volcanic rock, whereas the surface was covered by such rubble. The reason for this is the high smectite content of the Gamsberg clays. After the periodic rains, they swell so much as to make the terrain barely passable for vehicles. When it dries, deep hexagonal systems of shrinkage cracks form, the alternating volume increase and decrease leading to large rock fragments being transported to the surface, as happens also in periglacial soils. Due to this mechanism the volcanic rocks of the Gamsberg Plateau underlying the clays are frequently encountered as large fragments on the surface. However, it also reduces the reliability of the pollen analysis, as it allows contamination with recent pollen at least of the upper 20 to 30 cm of the profile by way of these deep shrinkage cracks.

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Appendix I. Major and trace element composition of the Gamsberg rhyolites analysed by X-Ray Fluorescence (Barge, 2001)

Sample No	09.04.90/ 01	09.04.90/ 03	09.04.90/ 04a	09.04.90/ 08	09.04.90/ 12	09.04.90/ 13a	09.04.90/ 20	17.08.92/ 08	14.09.94/ 1+1	14.09.94/ 1+2	14.09.94/ 1+3	12.04.00/ 05	12.04.00/ 06	12.04.00/ 08	12.04.00/ 11	12.04.00/ 12	12.04.00/ 13
Major elements (wt. %)																	
SiO_2	85.4	85.4	85.6	87.1	90.1	86.9	85.8	85.8	87.6	88.8	88.4	88.6	85.7	86.5	88.4	86.1	90.4
TiO_2	0.262	0.266	0.277	0.283	0.218	0.237	0.208	0.238	0.234	0.214	0.204	0.17	0.237	0.249	0.226	0.212	0.174
Al_2O_3	6.1	6.4	6.5	5.7	4.3	5.8	5.3	5.8	5.5	5.1	5.3	5.3	6.2	6.1	5.4	6	3.8
Fe_2O_3	1.3	1.31	0.99	1.09	0.86	0.98	1.3	0.91	1.09	1.03	0.76	0.87	1.25	1.14	0.92	1.18	1.34
MnO	0.007	0.007	0.009	0.02	0.006	0.01	0.009	0.013	0.009	0.009	0.01	0.004	0.004	0.006	0.005	0.004	0.05
MgO	0.17	0.25	0.13	0.16	0.03	0.06	0	0.91	0.23	0.09	0.05	0.04	0.05	0.15	0.07	0.03	0.05
CaO	0.19	0.11	0.2	0.13	0.03	0.11	0.03	0.21	0.11	0.06	0.04	0.06	0.05	0.17	0.03	0.03	0.08
Na_2O	0.72	0.61	1.13	0.8	0.17	0.58	0.3	1.46	0.87	0.91	0.76	0.94	0.61	0.83	0.6	0.82	0.34
K_2O	3.73	3.91	3.95	2.99	3.57	4.12	4.27	3.54	2.85	2.88	3.35	3.28	4.1	3.11	3.41	4.08	2.65
P_2O_5	0.045	0.032	0.029	0.045	0.018	0.015	0.018	0.031	0.017	0.012	0.016	0.021	0.014	0.053	0.022	0.013	0.016
Total	*97.92*	*98.30*	*98.82*	*98.32*	*99.30*	*98.81*	*97.24*	*98.91*	*98.51*	*99.11*	*98.89*	*99.29*	*98.22*	*98.31*	*99.08*	*98.47*	*98.90*
Trace elements (ppm)																	
Nb	12	9	6	7	7	9	6	5	7	6	8	5	7	7	5	5	12
Zr	233	225	286	290	280	267	134	274	235	213	159	161	201	228	251	235	141
Y	52	31	16	19	19	20	23	22	15	8	15	10	12	19	15	16	105
Sr	65	27	24	21	14	33	28	37	31	25	35	25	15	36	33	31	29
Rb	15	25	18	20	29	29	26	25	14	14	18	20	29	52	47	17	21
Pb	7	2	10	20	<5	10	2	7	3	3	8	0	0	0	0	9	18
Ga	8	7	7	6	4	6	5	7	6	8	7	5	6	7	6	6	3
Zn	10	14	15	11	9	16	11	21	0	9	16	3	1	3	0	7	11
Cu	16	26	29	29	12	31	20	30	<5	4	32	0	0	0	0	0	42
Ni	19	17	13	16	15	14	14	19	15	14	13	16	25	18	17	34	17
Co	3	3	<5	<5	<5	<5	1	3	<5	5	<5	2	1	1	1	0	0
Cr	33	30	23	23	26	24	30	24	26	23	26	24	35	32	26	27	26
V	34	20	26	33	16	48	33	21	10	16	24	23	13	31	17	37	91
Ba	1837	625	178	124	499	644	1059	522	626	459	878	286	344	278	250	773	732
Sc	2	1	4	3	4	6	4	6	2	1	1	3	2	3	6	0	7

Appendix II. Major and trace element composition of the Erongo rhyolites (Emmermann, 1976)

	Sills							Ignimbrites			Tuff
Sample No	**82**	**108**	**115**	**120**	**131**	**140**	**146**	**40**	**41**	**141**	**42**
Major elements (wt %)											
SiO_2	70.6	72.3	75.2	72.8	72.6	72.0	74.8	72.6	74.5	73.8	72.5
TiO_2	0.69	0.46	0.26	0.38	0.42	0.29	0.34	0.42	0.33	0.37	0.4
Al_2O_3	13.5	13.7	13.0	13.9	12.8	13.5	13.3	13.3	13.4	13.6	13.2
Fe_2O_3	4.00	3.22	1.72	2.50	2.80	4.20	2.59	2.86	2.34	2.43	2.96
MnO	0.03	0.06	0.01	0.05	0.04	0.05	0.05	0.03	0.04	0.03	0.03
MgO	0.76	0.80	0.25	0.58	0.30	0.22	0.35	0.50	0.37	0.46	0.40
CaO	1.65	0.95	0.91	0.67	1.06	1.4	1.04	0.62	0.95	0.86	0.62
Na_2O	2.87	2.85	2.95	2.57	2.74	3.10	2.70	2.69	2.44	2.64	3.10
K_2O	4.77	5	5.5	5.82	6.78	5.12	4.02	5.4	5.2	4.88	5.11
P_2O_5	0.23	0.26	0.24	0.22	0.2	0.06	0.26	0.26	0.3	0.25	0.25
LOI	0.96	0.73	0.42	0.69	0.52	0.54	0.58	1.22	0.48	0.72	1.37
Total	*100.06*	*100.33*	*100.46*	*100.18*	*100.26*	*100.48*	*100.03*	*99.90*	*100.35*	*100.04*	*99.94*
Trace elements (ppm)											
Rb	213	350	364	320	284	376	339	189	365	342	194
Sr	137	82	78	55	68	33	81	122	63	50	116
Zr	272	175	142	155	208	425	139	268	180	167	225
Ba	730	480	260	355	440	220	370	480	450	370	460