Radio-isotopic age control for Palaeogene deposits of the Northern Sperrgebiet, Namibia

Martin Pickford[1,4], Yoshihiro Sawada[2], Hironobu Hyodo[3] & Brigitte Senut[4]

1. Collège de France, Paris, France, <pickford @mnhn.fr>
2. Professor Emeritus, Shimane University, Matsue, Japan, <yoshipikotan@nifty.com>
3. Research Institute of Natural Science, Okayama University of Science, Ridai-cho, Okayama 700-0005, Japan, <hhyodo@rins.ous.ac.jp>.
4. UMR 7207 (CR2P) du CNRS, Case postale 38, 8, rue Buffon, 75005, Paris, France, <bsenut@mnhn.fr>

The fossiliferous freshwater limestones of the Northern Sperrgebiet accumulated in epikarst depressions that formed in Proterozoic dolomites of the Gariep Group. Geological mapping and stratigraphic superposition reveals that they are younger than the Pomona Quartzite, but older than the Blaubok Conglomerate and many other superficial deposits of Palaeogene and Neogene age, including the Klinghardt Phonolites. Age determinations of phonolite cobbles from the Gemsboktal Conglomerate and from occurrences of lava in the Klinghardt Mountains and at Swartkop indicate that volcanic activity spanned the period 42 – 37 million years. It is concluded from the stratigraphic and radio-isotopic evidence that the freshwater limestones were deposited during the middle Lutetian, ca. 47 - 45 Ma.

Keywords: Palaeogene, Namibia, radio-isotopic age, phonolite, limestones

Introduction

The discovery of rich assemblages of Palaeogene plants, invertebrates and vertebrates in freshwater limestones in the Northern Sperrgebiet (Silica North, Silica South, Chalcedon Tafelberg, Steffenkop, Black Crow, Gamachab, Eisenkieselklippenbacke) (Pickford *et al*., 2008a, 2008b) throws a great deal of light on the geological history and geomorphological evolution of southwestern Namibia because it provides constraints on the age of maturation of the Namib Unconformity Surface (Ward, 1987, 1988). The terrestrial gastropod fauna yields palaeoclimatic evidence, notably that the region enjoyed a summer rainfall regime at the time of deposition, but with a winter rainfall belt not far away. Some of the mammals (embrithopods, macroscelidids, todralestids) are more primitive than anything from the well known Late Eocene and basal Oligocene Fayum (Egypt) faunas, whereas others, notably the rodents and hyracoids share closer affinities with the North African faunas. The presence in Namibia, of a mammal with South American affinities is particularly intriguing.

The rodents and hyracoid, in particular, have been interpreted to indicate an age for the Namibian fossils close to the Late Eocene faunas of the Fayum, Egypt (Seiffert, 2010) but the other evidence suggests instead that these groups evolved more slowly than the embrithopods, just as they did in the Miocene of Africa, where large mammals tended to evolve more rapidly than rodents.
The aim of this paper is to investigate the stratigraphy and radio-isotopic age of rocks in the Sperrgebiet, with a view to resolving the debate about the age of the fossiliferous freshwater limestones. Phonolite clasts were derived from the Klinghardt Volcanic Province which lies 30-40 km to the east of the limestone deposits. The absence of phonolite clasts in all deposits older than the Gemsboktal Conglomerate indicates that eruptive activity did not commence in the Klinghardt Volcanic Province prior to the Middle Eocene some 42 Ma.

Freshwater limestones

The fossiliferous freshwater limestones in the Northern Sperrgebiet have yielded abundant and diverse plant and animal remains (Pickford *et al*., 2008b). In the main outcrops at Silica North, Silica South and

Black Crow (Fig. 1, 2) these limestones are unconformably overlain by the Blaubok Conglomerate (without phonolite clasts), which is in its turn overlain unconformably by the Gemsboktal Conglomerate (with abundant phonolite cobbles).

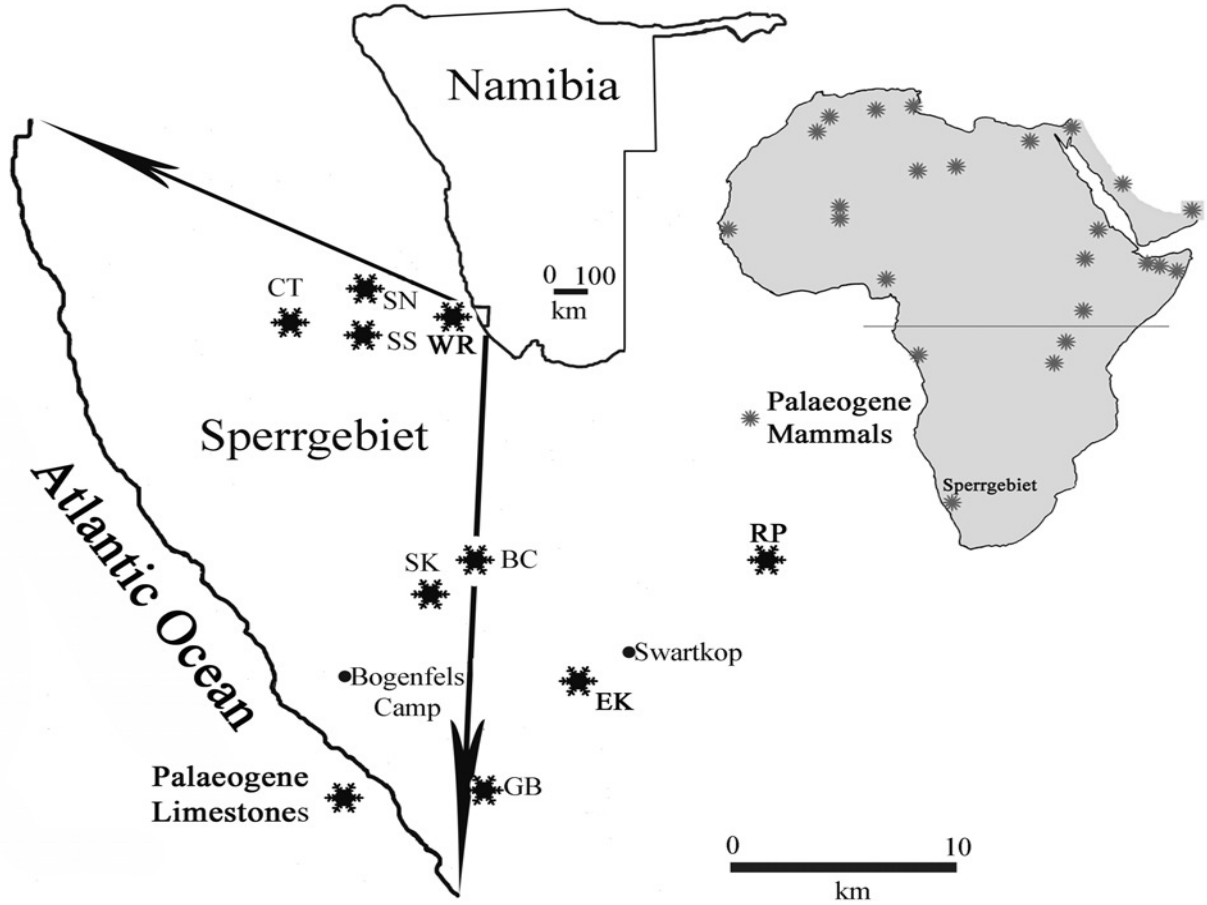

Figure 1: Location map, Northern Sperrgebiet showing Palaeogene terrestrial fossil localities in limestones. BC – Black Crow; CT – Chalcedon Tafelberg; EK – Eisenkieselklippenbacke; GB – Gamachab; RP – Reuning's Pipe; SK – Steffenkop; SN – Silica North; SS – Silica South; WR – White Ring.

Clast assemblages

In the Sperrgebiet in particular, but widely in Southern Africa and other parts of the World, clast assemblages have been studied in order to obtain information concerning the succession of geological events in a region. This is possible if the origin of the clasts can be determined because conglomerates with identifiable clasts must be younger than the stratum or rock unit from which the clasts were derived.

At Black Crow Depression, the Black Crow Carbonates not only underlie the Blaubok Conglomerate, but the latter unit also contains reworked blocks and clasts of Black Crow Carbonate, as well as boulders of Pomona Quartzite and Gariep Group Dolomites, and a variety of unidentified clasts. Some of the clasts in the Blaubok Conglomerate have been silicified, including Gariep Dolomite and Black Crow Carbonate, and this evidence indicates that silicification occurred prior to deposition of the Blaubok Conglomerate.

The Blaubok Conglomerate, which has no volcanic clasts, is widespread in the Sperrgebiet and includes important outcrops close to the Klinghardt Volcanic Mountains (at Graben and Reuning's Pipe for example, Fig. 1) which reveal that this unit was deposited prior to the onset of phonolite volcanism in the region (Fig. 3, 7). Unconformably overlying the Blaubok Conglomerate is another suite of conglomerates called the Gemsboktal Conglomerates, distinguishable

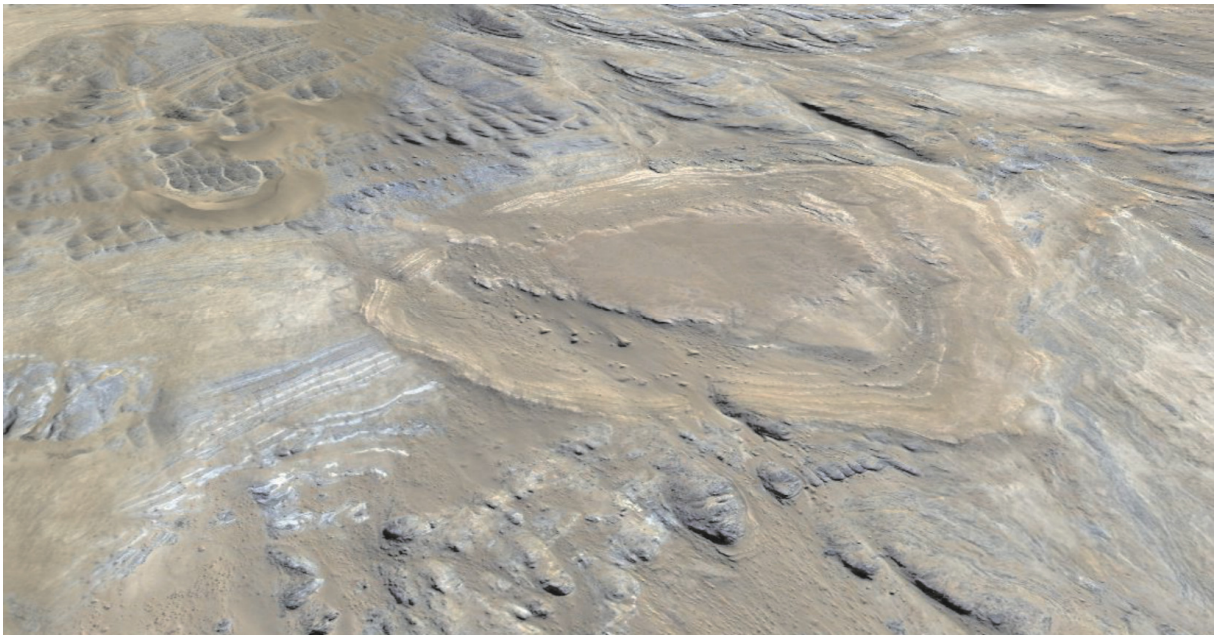

Figure 2: Well-bedded freshwater limestones at Silica South infilling a palaeokamenitza or palaeodoline eroded into Proterozoic Gariep Group Dolomites (grey tones). The well-bedded limestones are unconformably overlain by a cap of cliff forming Blaubok Conglomerate which has been cemented by the cupriferous Older Calc-crust. Note also the extant barchans dunes. The greatest diameter of the oval outcrop of limestone is ca 400 metres. Oblique view towards the north.

from the Blaubok unit by the abundance of phonolite clasts that it contains (Fig. 4, 7). The Gemsboktal Conglomerates must therefore be younger than the onset of Klinghardt volcanism.

Figure 3: Outcrop of Blaubok Conglomerate cemented by the older cupriferous calc-crust. This widespread sedimentary unit contains abundant honey-coloured silicified limestone pebbles, quartz, quartzite and other basement rock types but no phonolite.

At Black Crow, phonolite clasts are confined to the floors of shallow valleys that incised the countryside after the deposition of the Blaubok Conglomerate. Elsewhere, the Gemsboktal Conglomerates are mapped in superposition above the Blaubok Conglomerate, as for example at Granitbergfelder a few km north of Black Crow (Fig. 10). Radio-isotopic age determinations were carried out on phonolite clasts collected from the Gemsboktal Conglomerate at Black Crow and Granitbergfelder (Table 1).

Figure 4: Hamada capped by Gemsboktal Conglomerate rich in phonolite clasts (black pebbles). Note also the purple-brown cement which is the younger calc-crust.

The importance of determining the ages of clasts in conglomerates

It is sometimes considered meaningless (and a waste of funds) to determine the radio-isotopic ages of volcanic rocks in conglomerates. However, in certain geological and stratigraphic situations, the ages of volcanic clasts in conglomerates can provide precious information concerning the timing of geological events in a region. In situations like the one in the Sperrgebiet, where there is a clear differentiation between pre-volcanic and post-volcanic conglomerates, such ages can provide constraints on the ages of deposits older than the conglomerates in which they occur, even though they provide little information about the age of the conglomerate from which they were sampled, save to reveal that said conglomerate must be younger than the age of the clast.

A second excellent reason for determining the ages of volcanic clasts in conglomerates is that reliance exclusively on samples obtained from *in situ* occurrences such as lava flows and intrusions may bias understanding of the development of the volcanic province for two reasons. Firstly, early manifestations of volcanic activity may be subjected to rapid erosion, thereby leaving little or no material remaining *in situ* for researchers to collect, and secondly, as volcanic activity proceeds, earlier lava flows may be completely buried under later volcanic deposits, while intrusive masses of lava may be removed by later eruptions or become buried by later activity and thus be rendered inaccessible.

In the case of the Klinghardt Volcanic Province, previously published age determinations carried out on lava flows and intrusives were not from the main volcanic field but from occurrences some distance away from the Klinghardt Dome (Fig. 7, 8). The range of ages obtained spanned the period 29-37 Ma (Reid *et al*., 1990) and there is an unconfirmed age of 46 +/- 0.7 Ma (Marsh, 2010). The two phonolite clasts that we analysed yielded ages of 42.2 and 41.4 Ma confirming a Late Middle Eocene age of the on-

set of volcanism in the region.

It would therefore appear that the epikarstic carbonate deposits at Silica North, Silica Southand Black Crow which unconformably underlie the Gemsboktal and Blaubok Conglomerate formations are older than 42 Ma and possibly older than 45 Ma.

Silicification of superficial rocks in the Northern Sperrgebiet

Many of the superficial rocks in the northern Sperrgebiet have been silicified, and these include sediments as well as near-surface exposures of Gariep dolomites and quartzites of Proterozoic age.

Historically there has been much confusion about these silicified rocks, often pooled together under the name Pomona Quartzite. It was only recently that it became clear that the Pomona Quartzite is a composite unit comprising a wide variety of deposits of diverse age (Corbett, 1989). In its type area it is comprised of a series of conglomerates infilling shallow valleys that were silicified, producing valley silcretes, which, because they are extremely resistant to erosion, now stand proud of the surrounding countryside following the more rapid erosion of the Basement complex through which the valleys formerly coursed. Elsewhere, as for example at Black Crow and Swartkop, there are thin outcrops of well-bedded silicified sandstones, seldom more than a metre or two thick. Close to the margin of the Klinghardt Dome there is a series of well-bedded silicified limestones which have been folded into a series of basinal and domal structures. In many places throughout the Northern Sperrgebiet, outcrops of Gariep rocks show silicified surfaces, as for example at Black Crow, Silica North Silica South, Steffenkop and Eisenkieselklippenbacke. Most of these deposits comprise dark honey-coloured or olive-grey, very fine-grained siliceous rocks, probably formed by the silicification of ancient soil profiles, especially those parts which were close to the soilbedrock interface.

Eocene freshwater limestones at Silica North, Silica South, Chalcedon Tafelberg, Black Crow and Steffenkop, among others (Gamachab, Eisenkieselkippenbacke) have also been subjected to silicification (Fig. 5), but unlike the silicified limestones close to the Klinghardt Dome, they are generally incompletely silicified. The result has been the production of flaggy silicified limestone beds interlarded with pure limestone beds, irregular nodules of silicified limestone, vertical masses of silcified limestone cross-cutting bedded limestone and other irregular forms.

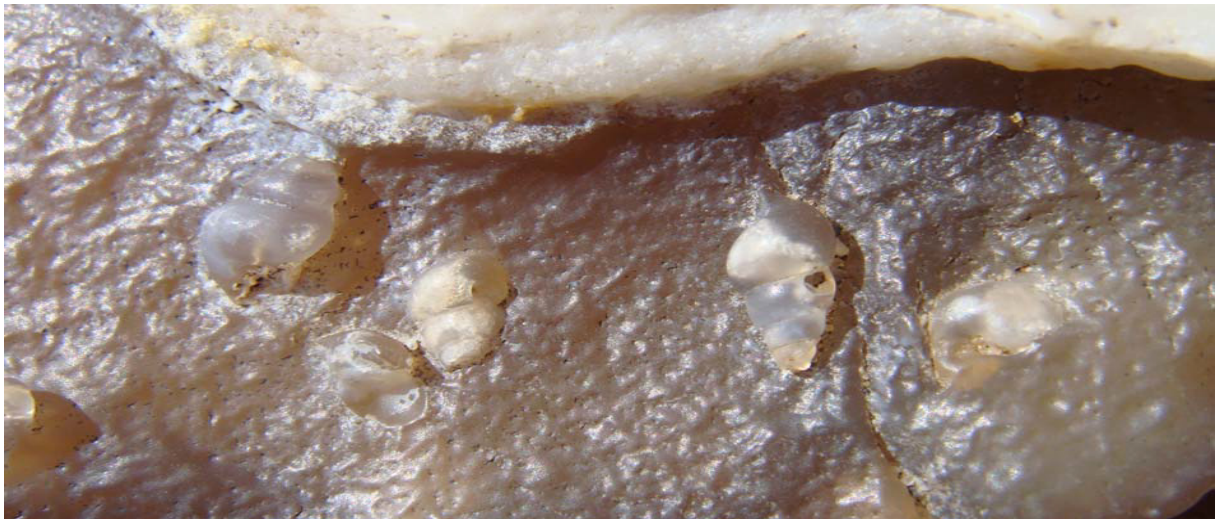

Figure 5. Silicified freshwater limestone containing shells of *Hydrobia*, a small freshwater gastropod, from Chalcedon Tafelberg, Northern Sperrgebiet, Namibia.

Although silicification of superficial deposits can result from a variety of processes and at different times, it is not impossible that most of the silicification observed in the Northern Sperrgebiet was due to the same relatively short-lived (ca. 1 Ma) process. The intensity of silicification decreases away from the Klinghardt Dome, which suggests that the silica was mainly of hydrothermal origin related to initial stages of activity in the Klinghardt Volcanic province. It is interesting to note that, if this is the case, then the silicification preceded the commencement of volcanic eruptions by several million years (perhaps 2-3 million years). This in turn suggests the emplacement of a magma chamber deep in the Earth's crust below what eventually became the Klinghardt Dome, and then the Klinghardt Volcanic Field, well before the commencement of surface volcanic activity. The silicification occurred after the deposition of the Black Crow and related feshwater limestones.

Cuprification of the Blaubok Conglomerate

The pre-volcanic Blaubok Conglomerate, which crops out widely to the west of the Klinghardt Dome, was calcified to a depth of a metre or so to produce the so-called "Older Calc-crust" which overlies unconsolidated to indurated conglomerate. In many outcrops, this "Older Calc-crust" shows a pale greenish tinge and sometimes stones caught up in the calc crust (notably quartz pebbles) show a similar colouration (Fig. 6). This is the only unit observed in the region which shows such colouring, and it is possible that the copper, which is responsible for the colour, was ultimately derived by hydrothermal processes related to theKlinghardt magma chamber. It is clear though, that this "copper" event preceded the beginning of volcanic eruptions, because its only manifestation is in rocks laid down prior to the onset of superficial volcanic activity.

Figure 6: Copper staining in the Blaubok Conglomerate at Silica North, Sperrgebiet, Namibia. Note the greenish tinge in the pale calc-crust cementing the conglomerate which contains pebbles of silicified limestone derived from the Silica North freshwater limestones, along with pebbles of quartz, dolomite and quartzite, but no phonolite.

Geomorphology of the Klinghardt Volcanic Field

The Klinghardt Mountains consist of dozens of phonolite flows and intrusives (Fig. 7, 8). The flows are often steep sided and repose on Basement rocks of the Proterozoic Gariep Fold Belt. It is clear that the Basement in the region of the phonolites has been updomed On its western edge the dome is bordered by a series of well-bedded silicified limestones of unknown age containing

traces of fossilised algae (Fig. 8). These deposits have been tectonised into a series of saucer-shaped bodies (Lock & Marsh, 1981) disposed around the western edge of the Klinghardt Dome from the southwest at Graben to the northwest at the so-called Klinghardt Breccia Pipe (which is in fact not a breccia pipe). The diameter of the Klinghardt Dome is approximately 24 km east-west by 23 km north-south, and the Basement rocks near the centre of the dome are ca 300 metres higher than its margins. It should be noted however, that the centre of the dome appears to have collapsed, thereby forming a large circular to slightly ovoid depression about 4 km in diameter in what formerly would have been the tallest part of the dome (Fig. 7). The main lava flows thereby form an irregular, discontinuous ring-shaped outcrop around the central depression.

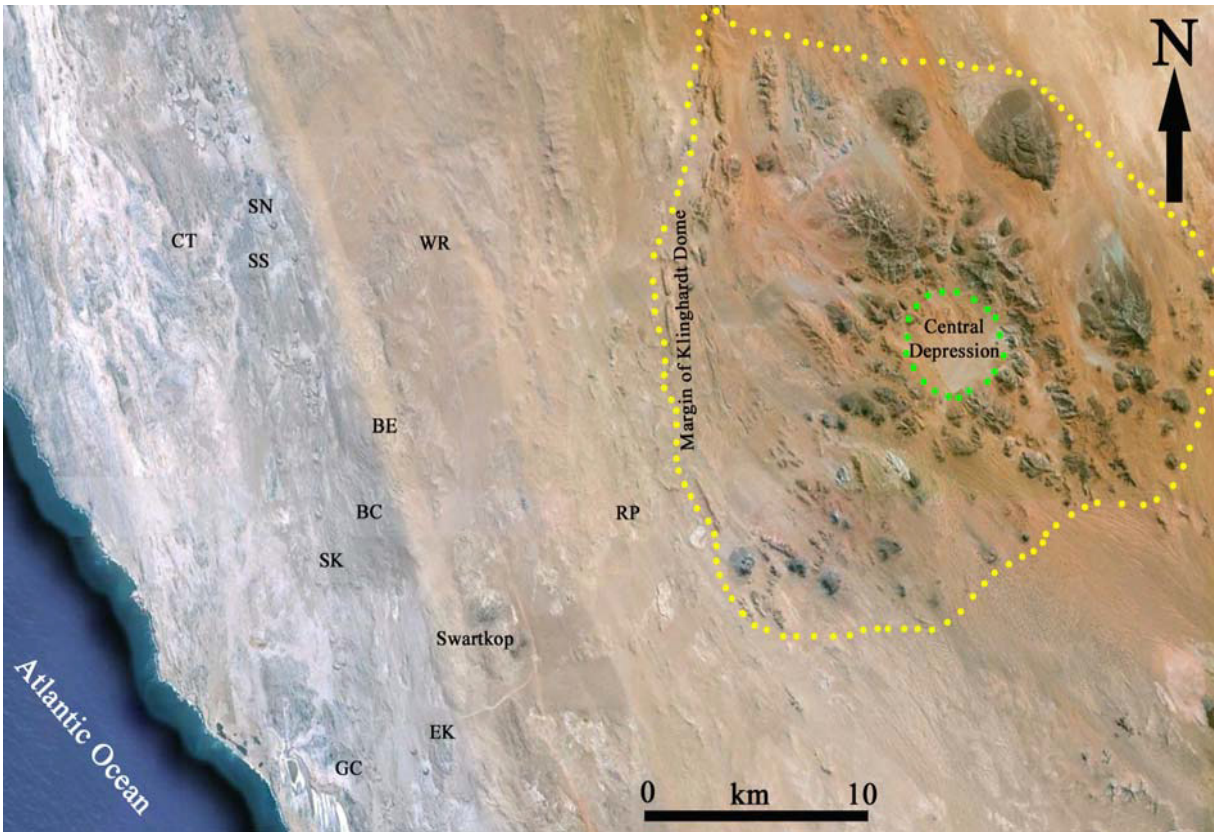

Figure 7: Geomorphology of the Northern Sperrgebiet, Namibia. Note the extent of the Klinghardt Dome (phonolite units are black) and the central depression. Middle Eocene freshwater limestone accumulated in depressions in Gariep Dolomites at BC – Black Crow; BE – Bull's Eye; CT – Chalcedon Tafelberg; EK – Eisenkieselklippenbacke; GC – Gamachab; RP – Reuning's Pipe; SK – Steffenkop; SN – Silica North; SS – Silica South; WR – White Ring.

Uplift of the Klinghardt dome appears to have started prior to the commencement of volcanic eruptions, because the Blaubok Conglomerate, which is widespread in the region west of the Klinghardts, extends right up to the edge of the dome, but nowhere does it contain volcaniclastic debris. The few places where flow direction can be observed, such as Reuning's Pipe (which is not a volcanic pipe), show that it was directed away from the dome.

The dome thus underwent erosion prior to the first eruptions, with the result that most of the phonolite flows in the main volcanic field directly overlie Basement rocks, in contrast to lavas that flowed into the hinterland which may overlie conglomerate and sandstone, as for instance at Swartkop, 24 km south-west of the centre of the dome. Because volcanic activity added to the topographic relief of the Klinghardt Dome, it continued to erode, but now shed huge quantities of volcanic debris into the fluvial systems flowing away from it. These younger

conglomerates, called the Gemsboktal Conglomerate, are widespread to the west of the Klinghardt Dome (Fig. 8), extending as far as Grillental, 60 km to the northwest and Buntfeldschuh 40 km to the southwest, and probably much further.

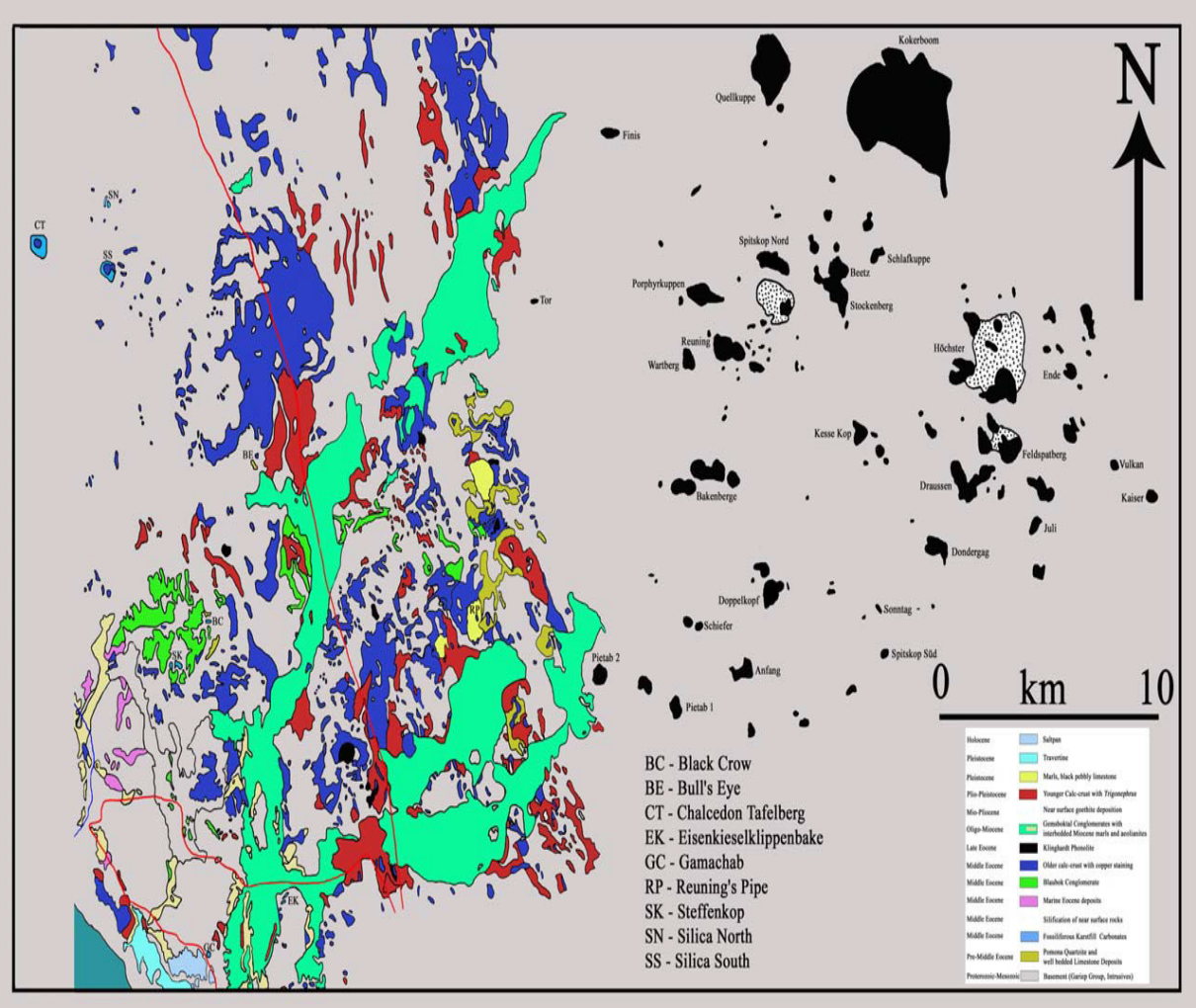

Figure 8. Geological map of Cainozoic deposits in the Northern Sperrgebiet, Namibia (Klinghardt geology based on Lock & Marsh, 1981; the remainder of the map based on Van Greunen's undated map and our own observations).

The Gemsboktal Conglomerates span a considerable period of time, some of the deposits dating from soon after the commencement of volcanic eruptions in the Eocene, and others forming during the Early Miocene (Elisabethfeld, 65 km northwest of the dome) the Pliocene and the Pleistocene. The Mio-Pliocene deposits comprise characteristic hamada topography of vast stone scattered plateaux bordered by scarp-like edges (Fig. 4), whereas the Eocene ones appear to have been confined to river valleys, such as one that cut through the Black Crow depression.

Radio-isotopic ages of Klinghardt Phonolites

1. Sample description and preparation

Two rock samples were analysed for K-Ar and 40Ar/39Ar age determinations (Tables 1, 2). (1) NB10-1: phonolite cobble from Black Crow. (2) NB10-2: phonolite cobble from Granitberg. Both specimens were collected from the Gemsboktal Conglomerate (Fig. 10). NB10-1 is fresh and highly porphyritic, and consists of phenocrysts of nepheline (Ne87.9 – 83.8 Ks16.2 – 12.1), sanidine (Or70.3 – 60.4 Ab39.3 – 29.4 An0.6 – 0.0) (up to 30 mm in

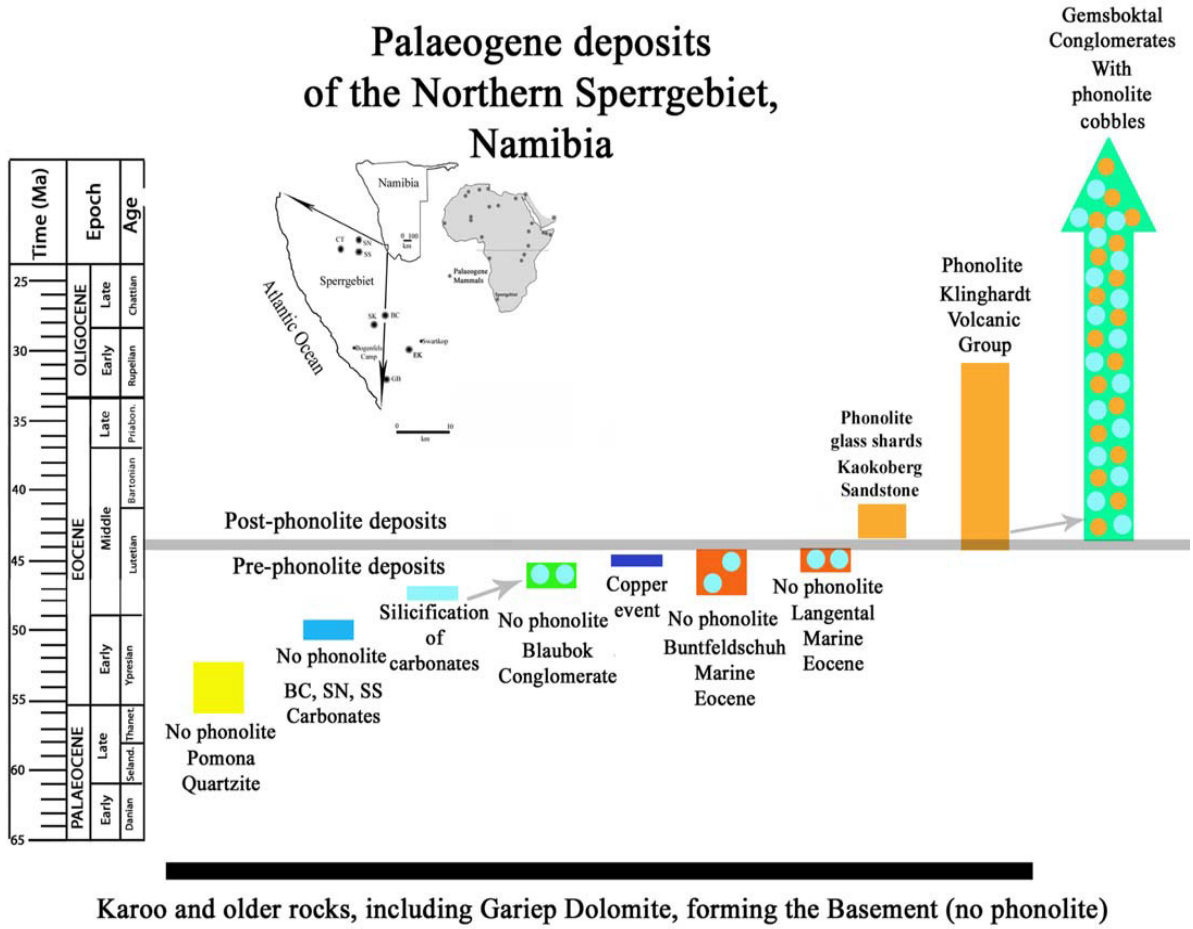

Figure 9: Succession of Cainozoic rocks in the Northern Sperrgebiet, Namibia. The historic basis is the work of Kaiser (1926) which we have modified or checked in the field on the basis of our own observations.

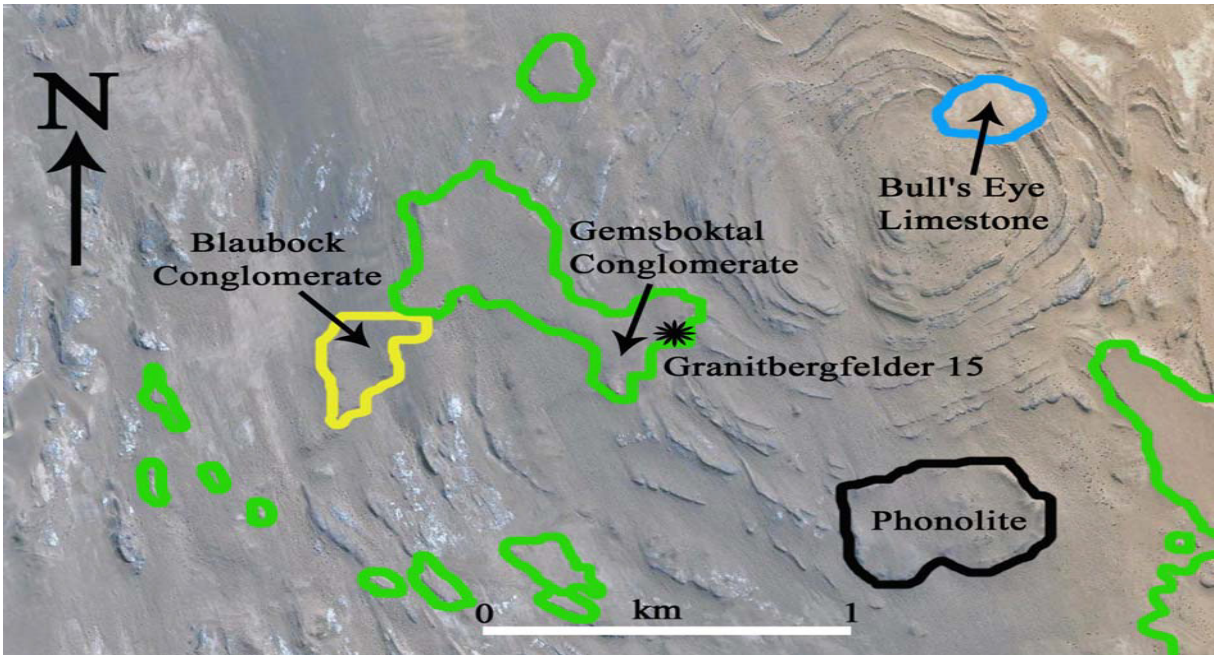

Figure 10: Satellite image of the Bull's Eye area, Northern Sperrgebiet showing the location where the Granitbergfelder 15 phonolite cobble (NB 10-2) was collected (star). The folded strata are dolomites of the Gariep Group, the blue outline is freshwater limestone that accumulated in a kamenitza or doline, the yellow outline is an outcrop of Blaubok Conglomerate unconformably underlying Gemsboktal Conglomerate (green outlines) which forms regionally extensive hamadas.

length), aegirine augite (up to 10 mm in length) and sphene with a groundmass of sanidine (Or65.0 – 62.4Ab37.4 – 34.8 An0.5 – 0.2), albite, aegirine augite, apatite, microlite and mesostasis. NB10-2 is aphyric and consists of a small amount of microphenocrysts of nepheline (Ne86.8 – 84.6 Ks15.4 – 13.2), sanidine (Or75.8 – 68.1 Ab31.8 – 24.2An0.1 – 0.0) (up to 6 mm in length) with a groundmass of sanidine, nepheline, albite, aegirine augite, apatite, zircon, microlite and mesostasis. Abundances of major elements and trace elements of NB10-1 and NB10-2 by X-ray fluorescence spectrometer analysis are shown in Table 1, 2. Both NB10-1 and NB10-2 are peralkaline phonolite. SiO_2, Na_2O and K_2O contents of NB10-1 are 53.72 wt%, 10.63 wt% and 7.24 wt%, respectively. SiO_2, Na_2O and K_2O contents of NB10-2 are 55.21-55.25 wt%, 8.93-8.96 wt% and 7.33-7.35 wt%, respectively.

Sanidine and nepheline phenocrysts and whole rock from NB10-1 and groundmass from NB10-2 were prepared by crushing and sieving for K-Ar age determination. The sieved fraction of 423-254 μm was cleaned in distilled and ion exchanged water then dried in an oven at 110ºC. The magnetic minerals were removed manually by magnet. The sanidine and nepheline grains were removed from the sieved samples by a Frantz isodynamic separator, heavy liquid (bromoform) and additional hand picking. The separated minerals were ultrasonically washed several times in ethanol and ion exchanged water for 10 minutes. The separated sanidine and nepheline (NB10-1Fd-M and NB 10-1L) and whole rock (NB10-1WR) samples were leached two or three times in HCl solutions (HCl : H_2O = 1 : 4) for 15 minutes in order to remove any argillaceous alteration products. The leached samples were cleaned by distilled and ion exchanged water about 20 imes to remove HCl then dried in an oven at 110ºC. A portion of the fraction was ground by hand in an agate mortar, and used for potassium analysis. Fresh coarse-grained sanidine and nepheline samples (0.5 - 1 mm in size) for 40Ar/39Ar age determination were separated by hand picking under a microscope.

2. Analytical procedure and results of K-Ar and 40Ar/39Ar age determinations

Analytical procedures for potassium and argon and calculations of ages and errors were based on the method described by Nagao *et al*. (1984) and Itaya *et al*. (1991). Potassium was analyzed by flame photometry using a 2000 ppm Cs buffer and has an analytical error of under 2% at 2σ confidence level. Argon was analyzed on a 15 cm radius sector type mass spectrometer with a single collector system using an isotopic dilution method and 38Ar spike.

Calibration of the 38Ar spike is accurate to within 1%. Multiple runs of a standard (JG-1 biotite, 91 Ma) indicate that the error of argon analysis is about 1% at 2σ confidence level. The sample was wrapped in aluminium foil, then preheated for a day or more at about 200 ºC in a vacuum to eliminate any absorbed atmospheric argon. Argon was extracted at 1600ºC on ultrahigh vacuum lines with an atmospheric 40Ar blank of less than 2.5x10-9 ccSTP. The clean up of reactive gas was done by two Ti-Zr getters, and the 38Ar spike added. The decay constants for 40Ar and 40Ca, and 40K content in potassium used in the age calculations are from Steiger & Jäger (1977) and are 0.581x10-10/y, 4.962 x 10-10/y and 1.167 x 10-4 (ratio of atomic abundance), respectively. The results of K-Ar age determinations are shown in Table 1. K-Ar ages of sanidine and nepheline from Black Crow (NB10-1) are 42.2 Ma and 40.1 Ma. The whole rock age is 45.4 Ma. Groundmass K-Ar age of the Granitberg sample (NB10-2) shows 41.4 Ma, and is close to the sanidine and nepheline ages of the phonolite cobble collected at Black Crow (42.2 – 40.1Ma).

Constituent	**NB10-1**	**NB10-2A**	**NB10-2B**
Major elements	Black Crow Namibia	Granitberg Namibia	Granitberg Namibia
SiO_2	53,72	55,25	55,21
TiO_2	0,33	0,40	0,40
Al_2O_3	21,67	20,14	20,13
Fe_2O_3	4,09	5,16	5,22
Total	**100,03**	**99,93**	**99,91**
Loss Ignition	2,21	4,06	4,06
Trace elements ppm			
Ba	114	346	347
Ce	357	344	342
Cr	<10	<10	<10
Ga	25	27	20
Nb	343	865	864
Ni	3	3	n.d.
Pb	39	23	23
Rb	207	183	182
Sr	849	492	493
Th	62	60	68
V	16	13	20
Y	31	15	16
Zr	1183	3060	3057

Table 1: Chemical analyses of two phonolite cobbles from the Gemsboktal Conglomerate, Namibia.

Speci-ment num-ber	**Formation**	**Rock type & occurrence**	**Local-ity**	**Material**	**Grain - size (um)**	**K content (wt.%)**	**Rad. 40Ar (10-8 ccSTP/g)**	**K-Ar age (Ma)**	**Non Rad. 0Ar (%)**
NB10-1Fd-M	Gemsboktal Conglomerate	Phonolite, cobble	Black Crow	Sanidine + nepheline	423-256	5,860±0,117	971,±9,3	42,22 ±0,93	1,2
NB10-1Fd-M	Gemsboktal Conglomerate	Phonolite, cobble	Black Crow	Sanidine+ nepheline	423-257	9,231±0,185	1450,6±14,1	40,05±0,88	1,3
NB10-1Fd-M	Gemsboktal Conglomerate	Phonolite, cobble	Black Crow	Whole rock	423-258	8,374±0,167	1492,6±14,5	45,40±1,00	1,7
NB10-1Fd-M	Gemsboktal Conglomerate	Phonolite, cobble	Granit-berg	groundmass	423-259	5,240±0,105	851,3±9,4	41,39±0,94	13,2

Table 2: Age determinations on phonolite cobbles from the Gemsboktal Conglomerate, Namibia

Discussion and conclusions

Previous geochronological research on the phonolites of the Klinghardt Mountains indicated a late Eocene to Early Oligocene time range for the samples analysed (Lock & Marsh, 1981; Marsh, 1987, 2010; Ried *et al*., 1990). However, the age determinations published by Kröner (1973) on which this age range was based were obtained not from the Klinghardt Mountains themselves but from isolated bodies of lava some distance away. Kröner (1973) published an age of 37 Ma for the Swartkop Phonolite (conventional K-Ar) (27°25'45.6"S : 15° 32'12.6"E), a flow that overlies silicified sand and conglomerate some 24 km west of the Klinghardt Dome (centre of dome is at 27°18'13"S : 15° 44'33"E) and an age of 35.7 Ma for the Schwarzerberg Nephelinite (whole rock) an intrusive body 33 km northwest (27° 08'47.9"S : 15°25'12.5"E) of the Klinghardts.

Marsh (2010) reported an unpublished age of 46.0 +/- 0.7 Ma (40Ar/39Ar plateau age on sanidine) from an unspecified phonolite in the Klinghardt Mountains (pers. comm. to Marsh by D. Phillips). As it stands, there seems to be no secure age determination from the Klinghardt Mountains themselves, unless the lava analysed by Phillips came from there. We here report additional radio-isotopic age determinations from two cobbles of phonolite collected from different localities in the Gemsboktal Conglomerate, a widespread sedimentary unit west of the Klinghardt Dome and the earliest such deposit to contain lava cobbles (the underlying Blaubok Conglomerate is devoid of lava clasts, even where it crops out close to the Klinghardt Mountains, and it evidently predates the earliest of the eruptions). Both samples yield ages in excess of 40 Ma, the Granitbergfelder 15 specimen an age of 41.39 +/-0.94 Ma (groundmass) and the Black Crow specimen ages of 42.22 +/- 0.93 (sanidine + nepheline), 40.05 +/- 0.88 (sanidine + nepheline) and 45.40 +/- 1.00 (whole rock).

We conclude that Klinghardt eruptive phonolite volcanic activity started somewhat earlier than previously estimated by Lock & Marsh (1981). Our results indicate an onset of volcanism during the Middle Eocene about 40 - 45 million years ago or even earlier, which may have continued until the Early Oligocene about 37 Ma. The age of 29 Ma for the young end of the range published by Ried *et al*., (1990) needs to be re-examined. The stratigraphic succession in the Sperrgebiet indicates that the prevolcanic strata in the region are older than 40 Ma. The Blaubok Conglomerate and the underlying freshwater carbonates at Black Crow, Silica North and Silica South (and elsewhere) are probably middle Lutetian in age (Fig. 9). A Middle Lutetian age was already estimated for these carbonates on the basis of the fossil mammals collected from them (Pickford *et al*., 2008a, 2008b).

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