$^{40}Ar/^{39}Ar$ dating of the Klinghardt and Stalhart Phonolites, Namibia, and Comments on the Evolution of the Klinghardt Volcanic Field

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Abstract: Mineral separates from three phonolite samples have been dated using $^{40}Ar/^{39}Ar$ techniques. Nepheline from the Duruchaus Spitskop of the Stalhart phonolite volcanic field near Rehoboth in central Namibia yielded a plateau age of 52.6±0.3 Ma from 55% of the degassed ^{39}Ar. Sanidine from two samples collected on opposite sides of the Klinghardt volcanic field in SW Namibia yielded nearly identical plateau ages of 45.8±0.2 Ma and 46.6±0.2 Ma, each covering 98 % of ^{39}Ar released. In contrast to previously published ages indicating that Klinghardt volcanism might have persisted for up to 8 Ma, our results strongly suggests that the Klinghardt volcanic field was emplaced in a narrow time interval (< several hundred kilo-years) at ≈46 Ma, consistent with its character as a monogenetic volcanic field and geochemical evidence for the phonolites collectively being part of a single strongly differentiated magmatic system. These new ages are important in establishing a secure time-frame for understanding the geomorphological evolution of the Namib Desert and its Palaeogene deposits. In this regard we offer a critique of the paper of Pickford *et al*. (2013) and show that their misinterpretation of the nature of the Klinghardt volcanism has resulted in a misleading model for geomorphological evolution in this region.

Key Words: Klinghardt Volcanic Field; Stalhart Phonolite; Ar-Ar dating; southern Namib Desert.

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Introduction

Scattered small-volume occurrences of alkaline igneous rocks, mostly of Cenozoic age, are a feature of western southern Africa between Swakopmund in Namibia (latitude 22° S degrees) and Cape Town, South Africa (latitude 34° S). These intraplate volcanic rocks (including domes, plugs, short dykes, some lavas, pipes and diatremes) have been the subject of numerous investigations, mostly petrological, but also including age dating (e.g. Moore & Verwoerd, 1985; Reid *et al*., 1990; Whitehead *et al*., 2002; Verwoerd & De Beer, 2006). The available ages span a range from 29 to 65 Ma, with little evidence of any rational spatial pattern. Part of this may be due to ages being rather few. Other than the paper by Moore (1976) there is little attempt to understand the tectonic significance of the volcanism.

Many of the available ages were obtained by conventional K-Ar dating of whole rocks, the determinations being made many decades ago. Modern dating studies have demonstrated the unreliability of such old conventional K/Ar ages and a programme of modern dating by more reliable methods, such as $^{40}Ar/^{39}Ar$ on mineral separates and U-Pb dating of zircon, monazite and baddeleyite is required if a better understanding of these volcanic events is to be achieved. Here we make a contribution to this end by presenting recent results of dating phonolites from the Stalhart volcanic field (23°05' S; 17°00' E) near Rehoboth in central Namibia, and from the Klinghardt Mountains (27°15' S; 15°45' E) SE of Luderitz in southern Namibia. We also compare our results to the recent K/Ar dating of supposed Klinghardt phonolite cobbles in conglomerates reported by Pickford *et al*. (2013) and comment on what we believe is an erroneous view of the evolution of the Klinghardt volcanic field presented in that paper.

$^{40}Ar/^{39}Ar$ dating

The Stalhart phonolites (Marsh, 2010) are all slightly altered and none contained suitably fresh sanidine. However, fresh nepheline phenocrysts were separated from sample RP-56 collected from the prominent conical hill Duruchaus Spitskop (23º10' S; 16º58.6' E). Porphyritic Klinghardt phonolites (Lock & Marsh, 1981; Marsh, 1987) yielded very fresh sanidine and mineral separates from two samples were analysed: F14a collected in 1998 from the Porphyrkuppen (27º17' S; 15º41.7'E) in the northwestern part of the volcanic field, and KVR-309 collected in 1974 from a small dome at 27º20' S; 15º48' E along the SE margin of the field.

Mineral separates were prepared using standard crushing, sieving, washing and magnetic separation methods. The separates were hand-picked to greater than 99 percent purity and washed in diluted nitric acid, de-ionized water and acetone prior to being shipped for irradiation. Mineral separates were wrapped in aluminium foil packets and irradiated in a cadmium-lined aluminium vial, together with interspersed aliquots of the fluence monitor GA1550 (equivalent to MD2; age = 99.125 ± 0.076 Ma; Phillips *et al*., 2017). The irradiation canister was irradiated in position X33 or X34 of the ANSTO, HIFAR reactor, Lucas Heights (Sydney, Australia). The canister was inverted three times during the irradiation, which reduced neutron flux gradients to <2 percent along the length of the canister. $^{40}Ar/^{39}Ar$ analyses were carried out at the Research School of Earth Sciences, The Australian National University, using procedures similar to those described by McDougall & Brown (2006). After irradiation, aliquots of each sample were loaded into tin-foil packets for analysis and step-heated in a tantalum resistance furnace. $^{40}Ar/^{39}Ar$ step-heating analyses were carried out on a VG3600 mass spectrometer using an electron multiplier detector. Sensitivity was approximately 3 x 10^{-17} mol/mv. Mass discrimination was monitored by analyses of standard air volumes. ^{40}Ar production from potassium was determined from analyses of degassed potassium glass. Correction factors for interfering reactions are as follows: $(^{36}Ar/^{37}Ar)_{Ca}$ = 3.50 (±0.14) x 10^{-4} and $(^{39}Ar/^{37}Ar)_{Ca}$ = 7.86 (±0.01) x 10^{-4} (Tetley *et al*. 1980; Spell & McDougall, 2003); $(^{40}Ar/^{39}Ar)_{K}$ = 0.045 (±0.003) – present study. Data have been corrected for mass spectrometer backgrounds, mass discrimination, and radioactive decay. Unless otherwise stated, uncertainties associated with the $^{40}Ar/^{39}Ar$ results are 1 sigma uncertainties and exclude errors in the J-value estimates. Plateau ages are reported with 2 sigma uncertainties and include J-value estimates. Decay constants are those recommended in Steiger & Jäger (1977).

Results are presented in Table 1 and summarised in Fig. 1. The nepheline from RP-56 yielded a slightly discordant age spectrum, especially at the high-temperature end (high cumulative ^{39}Ar). However, there is a well-defined lower temperature plateau formed by 55% of released argon which yields a mean age of 52.6±0.3 Ma. This updates the age previously quoted for this sample by Marsh (2010). The age spectra from both Klinghardt samples yielded excellent age plateaux each spanning about 98% of argon released. F14a yielded an age of 45.8±0.2Ma and KVR-309 an age of 46.6±0.2 Ma which very nearly overlap within error.

Table 1. $^{40}Ar/^{39}Ar$ step-heating results for sanidine from Klinghardt phonolites and nepheline from the Rehohoth phonolite, Namibia. Notes: 1) Errors are one sigma uncertainties and exclude uncertainties in the J-value; 2) Data are corrected for mass spectrometer backgrounds, mass discrimination, radioactive decay and isotopic intereferences; 3) J-value is based on an age of 99.125 ±0.076 Ma for MD-2 (=GA1550) biotite (Phillips *et al*. 2017).

Temp (C)	^{36}Ar (mol)	^{37}Ar (mol)	^{39}Ar (mol)	^{40}Ar (mol)	% $^{40}Ar^*$	Ca/K	$^{40}Ar^*/^{39}Ar_K$	Cumulative % ^{39}Ar	Age (Ma)	± 1σ
Klinghardt Phonolite Feldspar F14a										
Sample weight = 1.2mg										
ANU52; J = 0.002633172 +/- 0.0000053										
700	5.274E-17	3.272E-17	1.497E-16	1.703E-14	8.5	0.415	9.628	0.2	45.17	9.92
800	1.559E-17	1.552E-17	1.251E-15	1.733E-14	73.1	0.024	10.129	1.9	47.49	0.29
850	1.415E-17	1.138E-17	3.305E-15	3.668E-14	88.2	0.007	9.787	6.3	45.90	0.19
900	1.418E-17	2.574E-17	5.924E-15	6.233E-14	92.9	0.008	9.77	14.2	45.82	0.14
950	1.637E-17	2.445E-17	6.047E-15	6.415E-14	92	0.008	9.764	22.3	45.80	0.18
1000	1.855E-17	3.032E-17	6.407E-15	6.855E-14	91.6	0.009	9.799	30.9	45.96	0.14
1050	2.358E-17	3.027E-17	6.35E-15	6.936E-14	89.5	0.009	9.781	39.4	45.88	0.28
1100	2.822E-17	3.132E-17	6.186E-15	6.888E-14	87.5	0.010	9.741	47.7	45.69	0.14
1150	3.511E-17	2.445E-17	5.514E-15	6.433E-14	83.5	0.008	9.741	55.1	45.69	0.17
1175	3.884E-17	1.997E-17	3.825E-15	4.902E-14	76.2	0.010	9.772	60.2	45.83	0.22
1200	4.256E-17	1.604E-17	3.297E-15	4.497E-14	71.7	0.009	9.78	64.6	45.87	0.37
1225	4.806E-17	2.219E-17	3.76E-15	5.126E-14	72	0.011	9.81	69.6	46.01	0.25
1250	5.473E-17	2.671E-17	5.219E-15	6.732E-14	75.6	0.010	9.756	76.6	45.76	0.21
1275	5.97E-17	3.777E-17	6.458E-15	8.086E-14	77.8	0.011	9.745	85.3	45.71	0.20
1300	5.05E-17	1.964E-17	4.053E-15	5.494E-14	72.5	0.009	9.83	90.7	46.10	0.34
1350	6.449E-17	2.201E-17	3.58E-15	5.427E-14	64.6	0.012	9.792	95.5	45.93	0.34
1400	7.67E-17	1.165E-17	2.07E-15	4.312E-14	47.2	0.011	9.837	98.3	46.14	0.51
1450	1.547E-16	4.557E-18	1.294E-15	5.778E-14	20.8	0.007	9.268	100.0	43.50	1.56
Total	8.088E-16	4.067E-16	7.469E-14	9.722E-13			9.772		45.83	0.27
Klinghardt Phonolite Feldspar KVR309										
Sample weight ~ 1.5mg										
ANU52; J = 0.002633172 +/- 0.0000053										
700	6.166E-18	1.025E-19	3.605E-17	2.181E-15	16.4	0.005	9.902	0.1	46.44	11.67
800	1.023E-17	3.738E-17	1.135E-15	1.465E-14	79	0.063	10.207	1.7	47.85	0.37
850	1.138E-17	3.769E-17	2.916E-15	3.252E-14	89.3	0.025	9.955	5.8	46.68	0.20
900	1.066E-17	4.939E-17	6.016E-15	6.323E-14	94.6	0.016	9.943	14.2	46.63	0.14
925	1.069E-17	3.397E-17	4.346E-15	4.653E-14	92.8	0.015	9.935	20.4	46.59	0.18
950	1.275E-17	2.694E-17	3.613E-15	3.991E-14	90.2	0.014	9.959	25.4	46.70	0.17
975	1.899E-17	2.352E-17	3.216E-15	3.774E-14	84.8	0.014	9.946	30.0	46.64	0.21
1000	1.8E-17	2.149E-17	2.647E-15	3.169E-14	82.8	0.015	9.919	33.7	46.51	0.23
1050	2.072E-17	2.63E-17	3.678E-15	4.274E-14	85.3	0.014	9.912	38.9	46.48	0.18
1100	2.704E-17	2.927E-17	4.272E-15	5.025E-14	83.7	0.013	9.849	44.9	46.19	0.20
1150	3.343E-17	4.22E-17	5.893E-15	6.846E-14	85.2	0.014	9.896	53.2	46.41	0.15
1200	3.945E-17	6.208E-17	7.54E-15	8.702E-14	86.2	0.016	9.951	63.8	46.66	0.16
1250	4.806E-17	8.08E-17	1.013E-14	1.155E-13	87.3	0.015	9.961	78.1	46.71	0.14
1300	6.264E-17	1.063E-16	1.314E-14	1.502E-13	87.3	0.015	9.979	96.6	46.79	0.14
1325	6.058E-17	1.555E-17	2.117E-15	3.886E-14	53.7	0.014	9.854	99.6	46.21	0.51
1350	6.113E-17	6.352E-18	3.014E-16	2.056E-14	12.1	0.040	8.224	100.0	38.65	2.73
Total	4.519E-16	5.993E-16	7.099E-14	8.421E-13			9.936	0.2	46.59	0.19
Rehoboth Phonolite Nepheline RP56										
Sample weight ~ 1.5mg										
ANU71; J = 0.0032724 +/- 0.0000098										
650	2.696E-17	1.204E-16	5.602E-16	1.147E-14	30.5	0.408	6.256	0.5	36.56	3.36
700	6.208E-18	4.049E-18	7.913E-16	8.782E-15	78.9	0.010	8.755	1.3	50.96	1.04
750	6.835E-18	2.761E-17	2.38E-15	2.341E-14	91.1	0.022	8.964	3.6	52.16	0.31
800	8.253E-18	2.194E-17	4.855E-15	4.649E-14	94.5	0.009	9.050	8.2	52.65	0.18
840	8.149E-18	1.659E-17	6.005E-15	5.674E-14	95.5	0.005	9.023	14.0	52.50	0.20
880	1.029E-17	4.178E-17	8.415E-15	7.957E-14	95.9	0.009	9.070	22.0	52.77	0.20
920	1.649E-17	2.545E-17	8.187E-15	7.926E-14	93.6	0.006	9.061	29.9	52.72	0.16
960	2.305E-17	2.3E-17	8.172E-15	8.103E-14	91.3	0.005	9.057	37.7	52.69	0.18
1000	2.492E-17	3.096E-17	6.269E-15	6.432E-14	88.3	0.009	9.060	43.7	52.71	0.20
1050	3.815E-17	2.89E-17	6.377E-15	6.884E-14	83.4	0.009	9.003	49.8	52.38	0.18
1100	5.22E-17	5.208E-17	6.045E-15	6.979E-14	77.7	0.016	8.969	55.6	52.19	0.22
1150	6.921E-17	7.229E-17	6.384E-15	7.814E-14	73.6	0.022	9.013	61.7	52.44	0.28
1200	9.255E-17	5.184E-17	8.587E-15	1.045E-13	73.6	0.012	8.962	70.0	52.15	0.26
1250	1.313E-16	6.526E-17	1.644E-14	1.849E-13	78.8	0.008	8.865	85.7	51.59	0.19
1350	2.26E-16	5.514E-17	1.399E-14	1.926E-13	65.1	0.007	8.969	99.1	52.19	0.30
1400	1.049E-16	3.151E-17	9.406E-16	3.973E-14	21.9	0.064	9.260	100.0	53.86	1.95
Total	8.455E-16	6.687E-16	1.044E-13	1.190E-12			8.978	0.3	52.24	0.26

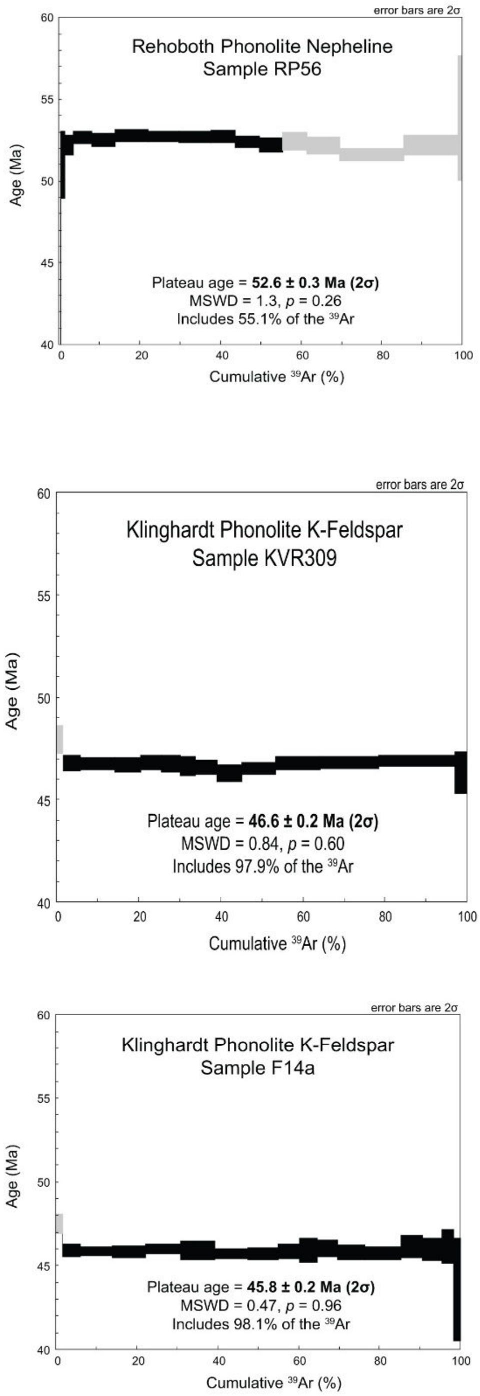

Figure 1. $^{40}Ar/^{39}Ar$ age spectra for step-heated nepheline from a phonolite in the Stalhart (Rehoboth) volcanic field and sanidine from two Klinghardt phonolites. Grey-coloured steps do not conform to plateau criteria and have been excluded from the plateau age calculation.

Discussion

As there are no previous age determinations for the Stalhart phonolites little can be said concerning the age reported here. The slight discordance in the age spectrum cautions against regarding the age of RP-56 as being thoroughly reliable. Further dating from other localities in the field is required. An interesting point in this regard is the 32±0.2 Ma Ar-age listed by Burger & Walraven (1976) for a phonolite at Aris, some 40 km N of Stalhart. No details of this age determination, which indicates that the Aris field represents a temporally different volcanic event from the Stalhart field, are given, but only additional dating with modern techniques can resolve this question.

The age of the Klinghardt phonolites is critical in understanding the evolution of the southern Namib Desert in terms of defining the erosion history of the area and the timing of the erosion surface and duricrust development, particularly with regard to the associated fossil assemblages. An old conventional K-Ar age of 37 Ma for Swartkop, a western outlier of the Klinghardt Volcanic Field, was reported by Kröner (1973). The Swartkop dome is built on a silicic duricrust and this age was long used as a time benchmark for younger deposits in the coastal region of southern Namibia.

The new ≈46 Ma age for the Klinghardt phonolites presents a revised benchmark for understanding the evolution of Cenozoic deposits in southern Namibia. It might be argued that the ≈9 Ma time gap between the old 37 Ma-age and the new 46 Ma-age is real and that Klinghardt volcanism may have persisted for that length of time. However, this is extremely unlikely. Firstly, conventional K/Ar ages commonly underestimate ages of feldspar-rich rocks due to the difficulty of complete degassing of samples in vacuum furnaces (Webb & McDougall, 1967). Secondly, the Klinghardt phonolite field is a classic example of a small monogenetic volcanic field (Németh & Smith, 2017), which are known from studies world-wide to be temporally short-lived. And thirdly, a detailed geochemical investigation (Marsh, 1987) has shown that the numerous phonolite bodies are genetically related to a single differentiating magmatic system, which, on thermal grounds, could not persist for long. Such systems rise and die over time periods of kilo-years not millions of years. In summary, all evidence, i.e. $^{39}Ar/^{40}Ar$ ages from samples taken at opposite sides of the Klinghardt Volcanic Field, petrology, geochemistry, and integration with modern volcanological research - place the Klinghardt phonolite eruptions into a narrow time window at ≈46 Ma.

Comparisons with ages presented in Pickford *et al*. (2013)

Pickford *et al*. (2013) presented ages for two phonolite cobbles from the Gemsboktal conglomerate thought to be derived from the Klinghardt Volcanic Field. Although their account refers to both K/Ar and $^{40}Ar/^{39}Ar$ dating, only conventional K/Ar ages are reported. The cobbles are from two localities: Black Crow (a porphyritic sample: NB10-1) and Granitbergfelder 15 (an aphyric sample: NB10-2 - abbreviated in the tables as Granitberg). It is not possible to gain a full understanding of their results as some information given in the text does not conform with that in their summary (their Table 2). Four ages were determined: three on NB10-1 - one whole rock age and two on sanidine and nepheline phenocrysts (according to the text, but not reflected in Table 2) - and one on the nepheline+sanidine ‘groundmass’ of the aphyric sample NB10-2 (wrongly labelled in Table 2). Collectively the ages range from 40.05±0.88 to 45.40±1.00 Ma with the highest (whole rock) and lowest (sanidine and/or nepheline phenocryst) age coming from the same sample NB10-1. Phonolites are feldspar-rich rocks and, as noted above, it has been long known that feldspars are notoriously difficult to outgas in vacuum furnaces (Webb & McDougall, 1967). Thus there is a strong possibility that conventional K-Ar ages of such rocks variably underestimate the true age. This should caution against placing significance regarding duration of activity based on ranges of conventional K/Ar ages. In this case there is a 5 Ma age difference in samples from the same specimen. We note the oldest K/Ar age (whole rock) overlaps with the $^{40}Ar/^{39}Ar$ ages we report and supports, along with inferences drawn from geochemistry and volcanology, our contention that Klinghardt phonolite volcanism was a short-lived event at about 46 Ma.

Comment on Pickford *et al*. (2013)'s account of the evolution of the Klinghardt Volcanic Field

In their evaluation of Palaeogene deposits in the northern Sperrgebiet, Pickford *et al.* (2013) misrepresent the volcanology of the Klinghardt Volcanic Field as described by Lock & Marsh (1981) despite citing this reference. We believe that this misunderstanding of Klinghardt volcanism impacts significantly on their account of the geomorphological evolution of the volcanic field and their proposal of the existence of a Klinghardt basement dome. It thus deserves comment.

Pickford *et al*. (2013) refer to the phonolite occurrences as consisting of "dozens of flows and intrusives", presumably by "flows" meaning lava flows. Furthermore they imply (p. 7), particularly in reference to Swartkop, that flows possibly travelled tens of kilometres from their presumed site of eruption. To summarise Lock & Marsh (1981), and in contrast to claims in Pickford *et al*. (2013), true sheet-like lava flows are very rare in the phonolite field; the vast majority of phonolite bodies are eroded endogenous domes, built by inflation of lava so viscous that "flowage to form more typical lava sheets did not take place" (Lock & Marsh, 1981, p. 2). The domes are sited immediately above their vents and only rarely (Quellkuppe and Kokerboom) was there limited flow of lava away from the vent to produce a coulée. There is also a small composite volcano, Höchster, with which some short lava flows are associated.

In particular, Swartkop is an eroded phonolite dome and not a remnant of a lava flow that has flowed far from its site of eruption. The spatial distribution of the phonolite bodies directly reflects the distribution of the volcanic vents. Generally, each dome represents a single eruptive event, but in some cases more than one eruption, or an eruption from a close neighbouring vent, results in coalescing domes, e.g. the Bakenberge. Intrusions are volumetrically minor and are represented by about a dozen short dykes. The domes were also emplaced in an area of considerable topographic relief and phonolite-basement contacts vary in both attitude and altitude with no systematic pattern across the whole volcanic field.

Pickford *et al*. (2013) have developed the notion of the "Klinghardt Dome", which proposes that the Precambrian basement has been uplifted (by at least 300 m) just prior to volcanism, followed at some stage by collapse of a small-diameter central portion of the dome. Despite claiming that "it is clear that the basement in the region of the phonolites has been updomed" (p. 6) they present no evidence to support this proposal. Evidence for a basement domal uplift (and collapse) 46 Ma ago can only rely on elevation differences of some pre-domal datum, such as a pre-domal horizontal sedimentary layer or other geological horizon. Pickford *et al*. (2013) link the idea of basement domal uplift and a central collapse to the explanation that the "main lava flows thereby form an irregular discontinuous ring-shaped outcrop around the central depression". This seems to imply that the supposed lava flows might represent such a datum. However, as emphasised above, there are no main lava flows or flow in the volcanic field. The distribution of the phonolite bodies simply reflects the distribution of their vents. Hence the distribution of purported "flows" cannot be used as evidence in support of the basement dome notion. In our field work over several weeks in the Klinghardt area we found no evidence of any basement doming prior to volcanism, nor did we find any geological horizon which could serve as a datum.

Finally, Pickford *et al*. (2013) claim that phonolites in the main volcanic field lie on basement strata and only those lavas that supposedly flowed "into the hinterland" overlie distal Palaeogene sandstones and conglomerates formed by erosion of the basement dome prior to volcanism. It is unclear what is meant by this proposal as the hinterland of the Klinghardt volcanic field lies to the east, whereas Pickford *et al*. (2013) are concerned with deposits lying to the west. Regardless, phonolite domes do overlie basement rocks in the Klinghardt Mountains but there are also several locations in the area where phonolite is observed post-dating conglomerate-covered erosion surfaces as noted by Lock & Marsh (1981), particularly in the Wartberg-Glasrücken-Stockenberg area

(Lock & Marsh, 1981, Fig. 1), almost in the very core of the supposed Klinghardt basement dome, and also along the NW margin of Kokerboom.

Conclusion

We present two new, tightly constrained ages of ≈46 Ma for Klinghardt phonolite volcanism in SW Namibia. These ages emphasize that Klinghardt phonolite volcanism was a short-lived volcanic event, consistent with this style of volcanism (a monogenetic volcanic field), and also supported by petrogenetic evidence that the phonolite magmatism represents a single magmatic system. The new ages provide tighter constraints on the age of a number of pre- and post-volcanic deposits in and around the Klinghardt area. We further comment on the notion of the 'Klinghardt Dome' as described by Pickford *et al*. (2013) and used by them as a geological framework to account for some of the Palaeogene deposits in the northwestern Sperrgebiet, Namibia. We suggest that the notion of the 'Klinghardt Dome' is a fiction as it arises from a misunderstanding of the volcanological character of the Klinghardt phonolites, and we further argue that there is no evidence for the supposed Klinghardt Dome and its development.

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