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The Darfur Dome, western Sudan: the product of a subcontinental mantle plume

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Abstract Field investigations, K–Ar age determinations and chemical data were used to describe the development of an intraplate volcanic province, the Darfur Dome, Sudan. Magmatism started 36 Ma ago at a small subvolcanic complex (Jebel Kussa) in the center of the dome and was active in the same area between 26 and 23 Ma. Two major volcanic fields (Marra Mountains and Tagabo Hills) developed between 16 and 10 Ma. Volcanism started again at 6.8 Ma with a third volcanic field (Meidob Hills) and at 4.3 Ma in the Marra Mountains and with the reactivation of the center. Activity then continued until the late Quaternary. Having started in the center of the Darfur Dome, volcanism moved in 36 Ma 200 km towards the NNE and 100 km SSW. No essential difference in the alkaline magma types (basanitic to phonolitic-trachytic, with different amounts of assimilation of crustal material) in the different fields, was observed. Magmatism is thought to have been produced by a rising mantle plume and volcanism was triggered by stress resolution along the Central African Fault Zone.

Key words Darfur Dome · Mantle plume · Intracontinental volcanism · Alkaline magmas · K–Ar age data · Bouguer gravity anomaly

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Introduction

The Darfur Volcanic Province, western Sudan, in north-eastern central Africa (Fig. 1) is an area of about 400 × 100 km with Tertiary to Holocene volcanic and subvolcanic activity. It is comparable in size and magma types with other volcanic centers in North Africa such as Tibesti, Hoggar and the Cameroon Line, but as a result of difficult access to the area, it has not yet received much attention. Its origin has been ascribed to a mantle plume or a deep-seated laccolith (Francis et al., 1973; Bermingham et al. 1983) or to a failed arm of incipient continental rifting on a triple junction (Browne and Fairhead, 1983). The first investigations in this area date back to 1918 (see Vail, 1972). Only for the largest volcano, the Deriba Crater of the Marra Mountains in the SSW of the province, has a more detailed analysis of magma generation been undertaken (Wilson, 1983; Davidson and Wilson, 1989). New investigations on ages, magma types and volcanological features, combined with a Bouguer gravity map of north-west Sudan, allow the construction of a model for the development of an intraplate continental volcanic field. We compare it with other volcanic fields in north-east Africa and a geophysical model for the development of mantle plumes (Hill, 1991).

Regional geological history

Plume–lithosphere interactions strongly depend on the thermal state of the lithosphere. It is therefore necessary to outline the development of the basement for this volcanic province. Figure 2 shows the distribution of basement outcrops and volcanic occurrences in north-east Africa. The Darfur Dome is situated in a Pan-African mobile belt. It is not clear, however, to what extent pre-Pan-African elements from cratonic areas (Congo Craton, 'East Sahara Craton') form part of the crust, as little detailed information on the geochronology and the

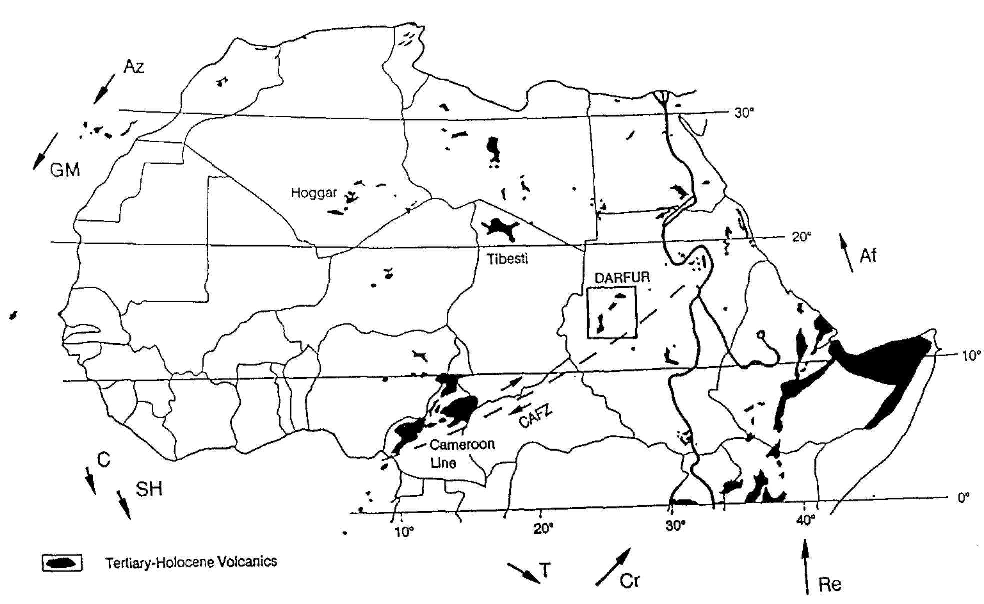


Fig. 1. Location of the Darfur Dome and distribution of Tertiary to Holocene magmatism in north Africa. CAFZ = Central African Fault Zone; arrows are directions of present plate motion of Africa (Schilling, 1991) in relation to suboceanic mantle plumes (Af = Afar; Az = Azores; C = Circe; Cr = Crozet; GM = Great Meteor; Re = Reunion; SH = Santa Helena; T = Tristan)

petrology of this basement in the immediate surrounding of the volcanic centers is available. Until the present work no age data for old Archean crust were reported from the basement of the Darfur Dome. The only possible pre-Pan-African age was reported by Coomer and Vail (1974), a Pb–Pb age of 1100 ± 200 Ma, determined on vein galena from the Marra Mountains. Harms (personal communication) dated a granite ('Kas granite') south of the Deriba Crater (Fig. 3) at 563 and 591 Ma (Rb–Sr biotite and whole rock ages). Approximately 100 km north of the Darfur Dome, a Late Proterozoic evolution of a fold and thrust belt was described by Abdel Rahman et al. (1990) and Harms (1989). There, Sm–Nd model ages on metabasites yielded 1150 Ma, K–Ar ages for amphibolite facies metamorphism between 740 and 860 Ma, and post-orogenic intrusions occurred at 565 Ma (Rb–Sr whole rock ages). Also, petrological work on the basement in the northern part of the Dome (Lattard et al., 1993) did not show any indications for a relict granulite facies event, which could be taken as a hint of older crust (c.f. the Uweinat area; Klerkx and Deutsch, 1977). The structure and the temperature at the base of the continental lithosphere are therefore probably more typical of a mobile belt than of an old craton.

Almost no geological record is given for the Paleozoic. About 100 km north of the volcanic province at Jebel Tageru, Silurian and Carboniferous sediments are exposed (Wycisk et al. 1990). Only anorogenic intraplate alkaline magmatism was reported for the eastern part of the Darfur Dome in the North Kordofan belt, for which ages of 442 Ma and 280 to 167 Ma were determined (Schandelmeier and Richter, 1991; Abdelbagi, personal communication). Petrographically similar but undated plutons were found south of the Marra Mountains. Therefore it seems likely that after crustal consolidation between 560 Ma and the Mesozoic the basement behaved as a stable area.

Rifting occurred in the southern Sudan rift system between the Late Jurassic and Albian (160–117 Ma) due to dominantly east–west extension; it continued from the Turonian to the Paleocene (90–60 Ma) with a more NE–SW directed extension, and from the Eocene to

Fig. 2. Areas of volcanic activity in north–east Africa since the Mesozoic. The Darfur Dome is outlined by the 600 m asl contour line (broken line). Precambrian basement outcrops (vertical ruling), volcanic fields (black) and isolated volcanic occurrences (dots) are marked

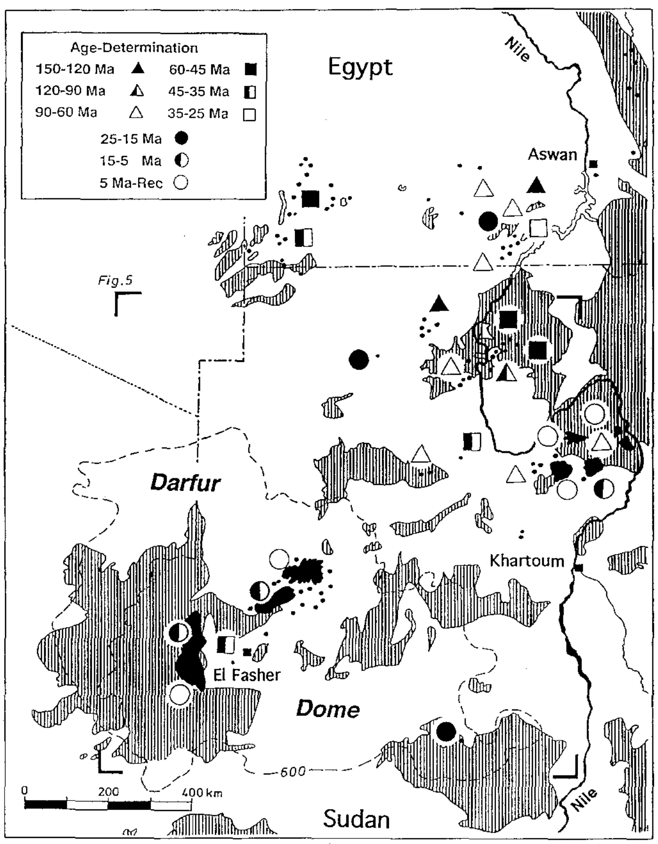
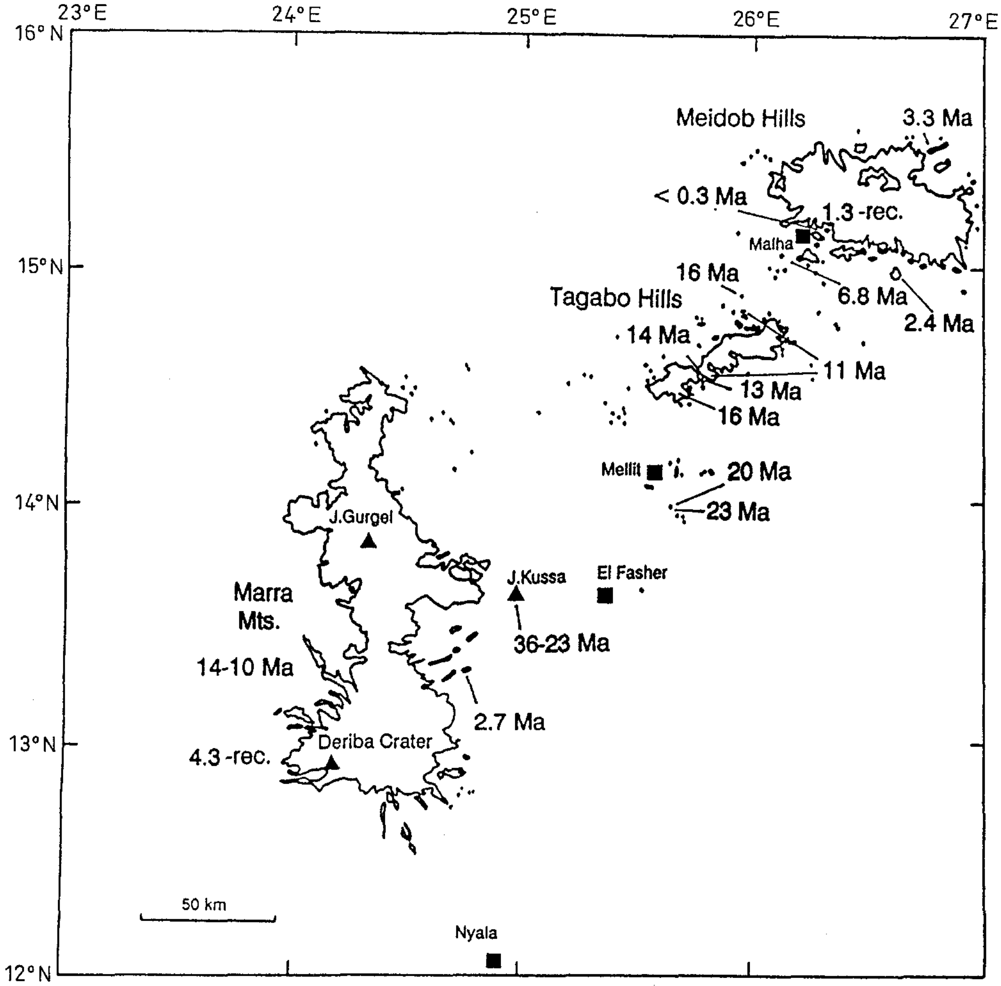


Fig. 3. The volcanic province of the Darfur Dome with the three major fields of the Marra Mountains, the Tagabo Hills and the Meidob Hills. Numbers are ages in Ma.



Miocene (55 to < 5 Ma) (Wycisk et al., 1990; Wilson and Guiraud, 1992). Sedimentation in the south-western part of this rift system started at least in the Valanginian (135 Ma) and in the east-central rift system with Kimmeridgian (155 Ma) sediments. Only minor volcanic activity is present in these basins: Wycisk et al. (1990) gave an age of 82 Ma for a 90 m thick dolerite sill. There is no obvious relation, neither in space nor time, between rifting and doming in the Darfur area.

In the vicinity of the dome, the basement is partly covered by a relatively thin (< 300 m) sequence of Cretaceous continental sediments (Hauterivian – Barremian to Santonian; Wycisk et al., 1990). In many places in the Darfur Dome excellent outcrops show that the basaltic flows extruded on these strata, which had already developed soil and weathering horizons. Therefore at the time of extrusion the dome was a topographic high. In Fig. 2, the 600 m asl contour line around the volcanic areas shows that this high still persists, indicating recent uplift of the dome. It comprises an area of about 1200 × 800 km, but volcanism is restricted to an area of 400 × 100 km. The highest mountain in the area is the volcanic edifice of Deriba Crater in the Marra Mountains, 3000 m asl and approximately 1800 m above the surrounding plain; in the NNE of the volcanic province other peaks (Jebel Gurgei, several in the Tagabo and Meidob Hills) rise to about 2000 m. The altitude of the contact between sedimentary and volcanic rocks lies at 900 m asl, whereas the general altitude of the peneplain in Darfur and Kordofan lies at about 600 m, and an uplift of approximately 200 – 300 m can be assumed.

Time sequence of magmatic activity

For our study we selected material for dating to obtain a regional overview for the time development for the whole Darfur Dome, with special emphasis on detecting the onset of magmatism. It was possible to select very fresh material for dating with the K – Ar method to limit the problems related to Ar or K loss during alteration. However, apparent ages which are too old may also result from excess Ar, which is usually found in alkali basalts carrying mantle xenocrysts, xenoliths and early cumulates or may occur in early crystallizing minerals such as pyroxenes and olivines (Funkhouser and Naughton, 1968; Kaneoka and Aoki, 1978; Fuhrmann and Lippolt, 1987).

Table 1. New age data on volcanic rocks from the Darfur Dome

Sample No.	Area	Rock type	K (%)	^{40}Ar rad (nl/g)	^{40}Ar rad (in %)	Age* (Ma)
W' El Fasher						
JK 1	J. Kussa	Trachybasalt (matrix)	3.196	4.42	71.51	35.8 ± 2.0 [+]
JK 1	J. Kussa	Trachybasalt (plagioclase)	0.639	0.91	76.87	36.2 ± 1.0 [+]
		Trachybasalt				
JK 13	J. Kussa	Syenite (biotite)	7.347	7.34		25.5 ± 0.7 [‡]
DF 6P	J. Kussa	Gabbro (biotite)	7.893	7.99		25.9 ± 0.7 [‡]
DF 14A	WSW' Tawila	Basalt	0.272	0.282	39.96	(26.5 ± 0.8) [§]
				0.307	40.94	(28.8 ± 0.9)
DF 14B	WSW' Tawila	Basalt	0.400	0.239	38.64	(15.3 ± 0.5) [§]
				0.250	36.36	(16.0 ± 0.5)
DF 1B	J. Sirati	Basalt	0.614	0.551	74.64	22.9 ± 0.7 [§]
				0.563	74.82	23.4 ± 0.7
DF 15A/1	J. Tina	Basalt	1.621	0.170	15.89	(2.69 ± 0.1) [§]
				0.187	16.10	(2.96 ± 0.1)
Mellit						
GK 2A	J. Kulla	Basaltic	1.436	1.30	77.54	23.1 ± 0.7 [§]
GK 2F	J. Kulla	Phonolitic	4.71	3.64	87.45	19.8 ± 0.6 [§]
GK 3	J. Kaskasna	Basaltic	1.773	1.51	84.93	21.8 ± 0.7 [§]
Tagabo Hills						
DT 24A	W' J. Abturnya	Phonolite	3.77	2.40	60.76	16.3 ± 0.5 [§]
				2.44	61.67	16.5 ± 0.5
DT 42A	NW' J. Somo	Phonolite	3.47	2.20	76.21	16.2 ± 0.5 [§]
				2.21	76.14	16.3 ± 0.5
DT 17A	J. Wigol	Hawaiite	1.702	0.91	13.71	13.8 ± 2.0 [+]
DT 4A	J. Mesma	Hawaiite	2.383	1.17	26.24	12.6 ± 1.0 [+]
DT 26A	NE' J. Agasagur	Basanite	1.362	0.78	59.05	(14.6 ± 0.4) [§]
				0.84	62.99	(15.8 ± 0.5)
DT 26B	NE' J. Agasagur	Basanite	1.495	0.80	54.22	(13.6 ± 0.4) [§]
				0.67	43.68	(11.5 ± 0.3)
DT 5	near J. Aunuga	Basanite	1.718	0.74	47.04	11.1 ± 0.3 [§]
				0.79	56.85	11.7 ± 0.4
DT 40A	NW' J. Somo	Basanite	0.931	0.385	45.55	10.6 ± 0.3 [§]
				0.386	41.30	10.6 ± 0.3
Meidob Hills						
ME 5	S Meidob	Basanite	1.705	0.451	61.47	6.8 ± 0.2 [§]
ME 2	S Meidob	Basanite	1.142	0.287	51.82	6.5 ± 0.2 [§]
GU 3	J. Kaboiji	Basanite	1.39	0.18	2.87	3.3 ± 0.3 [+]
GU 70	J. Silly	Basanite	1.23	0.12	1.65	2.4 ± 0.6 [+]
GU 91	J. Sireif	Phonolite (glass)	4.66	0.09	1.66	0.6 ± 0.2 [+]
GU 94	J. Sireif	Phonolite (glass)	4.31	0.23	1.52	1.3 ± 0.3 [+]
GU 95	J. Sireif	Phonolite (glass)	4.61	0.22	1.23	1.2 ± 0.4 [+]
DP 50A	Central Meidob	Phonolite (glass)	4.915	0.21	0.87	1.1 ± 0.2 [+]
DP 50C	Central Meidob	Phonolite (glass)	4.998	0.12	1.34	0.6 ± 0.15 [+]
ME 3A	Malha crater	Basanite	1.241	0.013	3.99	0.28 ± 0.05 [§]
ME 3E	Malha crater	Basanite	1.77	0.021	2.95	0.30 ± 0.05 [§]
ME 3G	Malha crater	Basalt	1.732	0.014	2.86	0.21 ± 0.05 [§]

* Calculated with IUGS decay constants; those in parentheses are apparent ages presumably resulting from excess argon (see discussion).
[+] Laboratory H. Ahrendt, Göttingen.
[‡] Laboratory Krueger Ent., Cambridge.
[§] Laboratory P. Pasteels, Brussels.

New K – Ar results are presented in Table 1 and shown in Fig. 3. For the oldest rocks (sample JK 1), care was taken to perform the K – Ar dating on the matrix and plagioclase, i.e. systems which crystallize at relatively shallow depth and therefore incorporate air argon only. Both the matrix and the separates from the same hand specimen yield concordant ages. The age of 36 Ma is therefore most likely a reliable age estimate for the earliest magmatic activity recorded so far in the Darfur Dome.

In other instances, repeated analyses were performed on aliquots from coarsely crushed whole rock material. This allows the presence of excess Ar to be detected if it is associated with minor phases (xenoliths or xenocrysts), or if it is irregularly distributed within the matrix. When repeated Ar analyses do not give the same result within the limits of error (age numbers in parentheses in Table 1), excess Ar may be inferred and the lowest apparent age is most likely to be closer to the extrusion age, though the ages do not differ very much. Samples DF14A and B come from the same outcrop, but their apparent ages differ by more than 10 Ma. They are contaminated with xenoliths and xenocrysts and have a low K content (enlarging the effect of contamination). These samples are therefore not considered in the discussion. The phonolite glasses DP50A and C also come from the same outcrop, a pyroclastic deposit. Their apparent ages differ between 1.3 and 0.6 Ma. The glasses are very fresh without microscopically detectable indications of recrystallization. It is therefore not clear whether they come from different eruptions, or if the difference might be due to analytical problems. These data are only used to testify a relatively young volcanic event.

The igneous activity began at 36 Ma at Jebel Kussa, a subvolcanic igneous complex considered to be the center of the dome (Fig. 3), which lies east of the main volcanic field of the Marra Mountains. Here, basaltic rocks were later intruded by gabbro and syenite (26 Ma, Table 1). The chemical and petrographic characteristics are similar to those of subvolcanic ring complexes, which are described as precursors to the main volcanic activity (e.g. Cameroon Line; Deruelle et al., 1991). In the vicinity of Jebel Kussa, a small isolated plug (Jebel Sirati) yielded an age of approximately 23 Ma. A lava flow (Jebel Tina, situated between Jebel Kussa and the Marra Mountains) yielded young ages of 2.7 and 3.0 ± 0.1 Ma. The volcanic activity in this central part of the Darfur Dome was therefore reactivated during the Pliocene.

Volcanism continued in the area north-east of El Fasher near Mellit (Fig. 3), where many isolated plugs of basalt and phonolite occur. Three of these were dated between 23 and 20 Ma (Table 1). These occurrences can be regarded as the outer areas of the Tagabo Hills, a largely eroded volcanic field north-east of the central Darfur Dome. In this field ages between 16 and 11 Ma years were obtained. Phonolites are 16 Ma, basanitic plugs 11 Ma old. Intermediate rock types are extremely rare in the Tagabo Hills and they yielded ages between 12 and 14 Ma. Ages between 14 and 10 Ma are also given by Wilson (1983) for trachytic and basaltic lavas of the southern and central part of the Marra Mountains. There, they form the major part of the field. This age period must therefore be considered as the most important period of magma production in the whole volcanic province. Ages for the northern part of the Marra Mountains are not available, but the erosional features are similar to the central area, and we assume that they are from this same period.

Voluminous magmatic activity of a younger age occurred mainly at the south-western (Deriba Crater) and north-eastern (Meidob Hills) ends of the Darfur Dome. In the Meidob Hills volcanic field, which forms the continuation of the Tagabo Hills towards the north-east, the oldest ages obtained so far are 6.8 Ma from eroded basanitic lava plugs (inselbergs at the south-west border of the field). Other determinations on basanites from inselbergs in the north-east and south-east yielded ages of 2.4 (Jebel Silly) and 3.3 Ma (Jebel Kaboiji), in accord with volcanic activity progressively moving towards the north-east. The extrusion of phonolites (1.3 – 0.6 Ma), which form the central part of the Meidob Hills, belongs to a young period of volcanic activity. However, maars with uneroded tephra rings and fresh pyroclastic deposits indicate an even younger volcanic activity. Thermoluminescence data (Wagner, personal communication) on trachytic pyroclastic rocks and ^{14}C data on lake deposits in maars (Pachur, personal communication) between 14000 and 5000 years prove that the Darfur Dome is a 'dormant volcano' (Vail, 1972). At the Malha maar crater (Meidob Hills), two basanitic lava flows were dated with K – Ar whole rock (Table 1): One which was cross-cut by the maar eruption and a second which flowed into the maar. Both yielded similar ages within the limits of error. The discrepancy between thermoluminescence and ^{14}C data and the K – Ar data is probably due to the fact that the conventional K – Ar method for such rocks with low K content is at the limit of resolution. However, it confirms that during a young period (< 3 Ma) basaltic to phonolitic – trachytic lavas were produced. Estimated from regional mapping the young rocks do not represent more than a few per cent of the magma production in the whole Meidob Hills volcanic field.

The activity at the south-eastern tip of the Marra Mountains was contemporaneous with this young phase in the Meidob Hills. Wilson (1983) reported ages between 4.35 and 0.06 Ma for a young phase of trachytic to basaltic volcanic rocks. Francis et al. (1973) dated carbonized wood at 3520 BP. The Deriba Crater represents the climax of this period and is deposited as a large shield volcano with a central caldera on the eroded 'Old Lava Series' (Davidson and Wilson, 1989).

Geochemistry

The rock types and their geochemical characteristics are broadly similar in all the volcanic fields. We present here a short description; a more detailed presentation of the results on magma genesis, including isotope data, is in preparation. The oldest rocks from Jebel Kussa (Fig. 4a) belong to two series: a highly and a moderately alkaline series. The latter includes a central quartz syenite intrusion. Some of the rocks are ultrabasic, but picrites have not been found. The rocks contain moderate amounts of MgO (< 11 wt.%), Ni (< 160 ppm) and Cr (< 400 ppm). Many rock types are subvolcanic and seem to be influenced by metasomatic processes.

The analyses are compared with those from the Marra Mountains (Fig. 4a; data from Davidson and Wilson, 1989). Rock types are broadly similar in the 'New' and 'Old Lava Series'. Magma genesis of the new series was investigated in detail (Davidson and Wilson, 1989) and is characterized mainly by the fractional crystallization of melts, which originated from a mantle source similar to ocean island basalts or to the Cameroon Line, and the simultaneous assimilation of crustal material at different

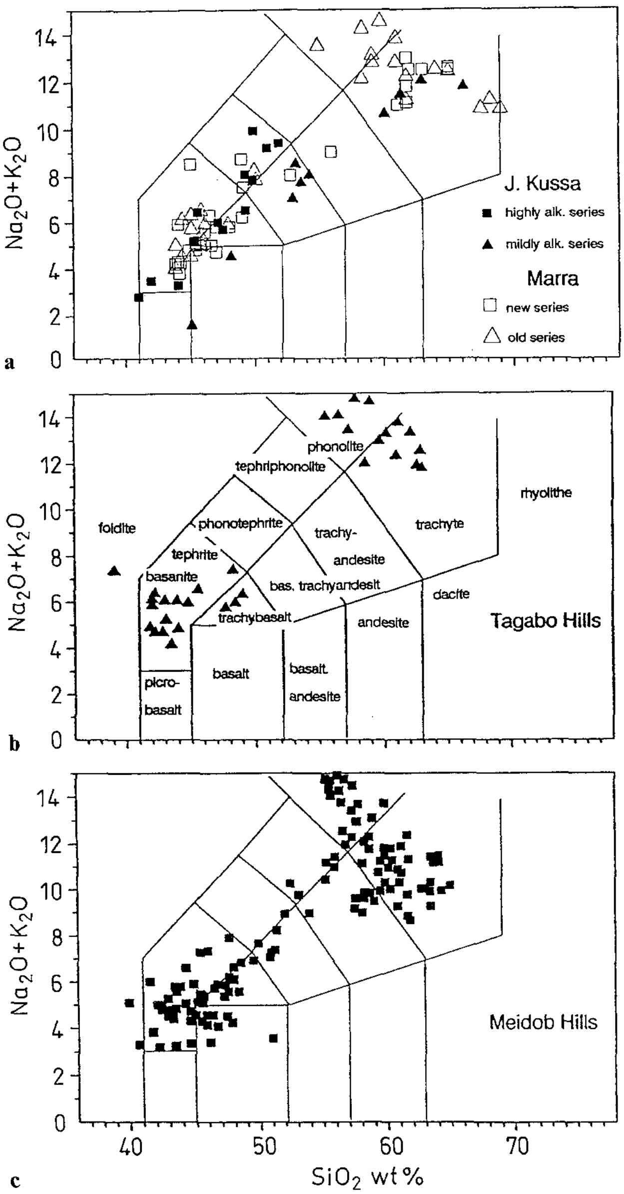


Fig. 4a–c. Comparison of magma composition for the three major volcanic fields. **a)** Marra Mountains (data from Davidson and Wilson, 1989) and Jebel Kussa; **b)** Tagabo Hills and **c)** Meidob Hills; IUGS-TAS nomenclature

levels. There is no obvious and significant difference in major element composition from the oldest to the youngest events.

In the Tagabo Hills, volcanism is essentially bimodal. The highly differentiated rocks are mostly undersaturated phonolites and nepheline normative trachytes (Fig. 4b), showing no or only minor contamination with crustal rocks, as suggested by Sr isotopes. Trace (including rare earth) element studies indicate melt generation in the garnet or enriched spinel lherzolite stability field. The lavas occur as plugs and flows and aerial photographs show that igneous dikes are the feeder sources for many of them (e.g. Jebel Teljo, the largest mountain of the Tagabo Hills, is a large dike-like structure of a phonolite). Dikes and dike-parallel fractures in the underlying sandstones are also common (Meissner and Ripke, 1989).

Major and trace element characteristics of the rocks from the Meidob Hills are typical of an alkaline rock sequence (Fig. 4c) and indicate a similar magma source and depth as in the Tagabo Hills. Differentiated rocks are phonolitic, and together with some intermediate rock types form only a small proportion of the whole magma volume. Trachytic rocks are mainly pyroclastic and show petrographic features such as xenocrysts, which indicate crustal assimilation. The volcanic field is built up of lava plateaus; several hundred scoria cones and other volcanic centers are the sources of the basanitic lave flows. Phonolitic lava domes (or mesa flows), with diameters between 0.3 and 3 km, rise a few hundred meters above the plateaus, representing a young stage in the development of this volcanic field. Deposits from plinian eruptions and ignimbrites are well preserved in the central Meidob Hills, recording the youngest magmatic event. Major and trace element as well as isotope data indicate a low degree of mantle melting and a HIMU-like component (Urlacher et al., 1994). No primary mantle-derived magma was found. Fractional crystallization as well as some crustal contamination (e.g. in the quartz syenite) has already influenced the magmas.

Tectonic features

Important factors controlling the type of volcanic activity are the regional uplift and the intraplate stress field caused by lithospheric plate movement. The stress field in the upper crust is recorded by tectonic lineaments and by volcanological features. Some data for the Darfur Dome are available from satellite and aerial photograph interpretation. The Meidob Hills are an east–west trending volcanic field where the youngest rocks in the central part and the scoria cones on the lava plateaus lie on this trend. A second subordinate trend is 160° NW–SE. These tectonic lineaments also clearly control the drainage system around the Meidob Hills.

In the Tagabo Hills, the east–west direction of the magma feeder dikes is well documented by Meissner and Ripke (1989). Two other directions (NE–SW and NW–SE to north–south) are also prominent. The east–west fractures have been interpreted as north–south tension gashes associated with dextral NE–SW movement along the Central African Fault Zone (CAFZ; Browne et al., 1985; Fig. 1) during the Tertiary (Schandelmeier and Pudlo, 1990). The CAFZ extends from the Cameroon Line into central Africa and marks the northern limit of some of the Sudanese rift basins. In the area between Tagabo and the Meidob Hills, volcanic activity is most likely related to this large-scale tectonic lineament.

The Marra Mountains extend in a north–south direction and the Deriba Crater is a central shield volcano rather than a fissure-type eruption (Davidson and Wilson, 1989), which covers the tectonic features responsible

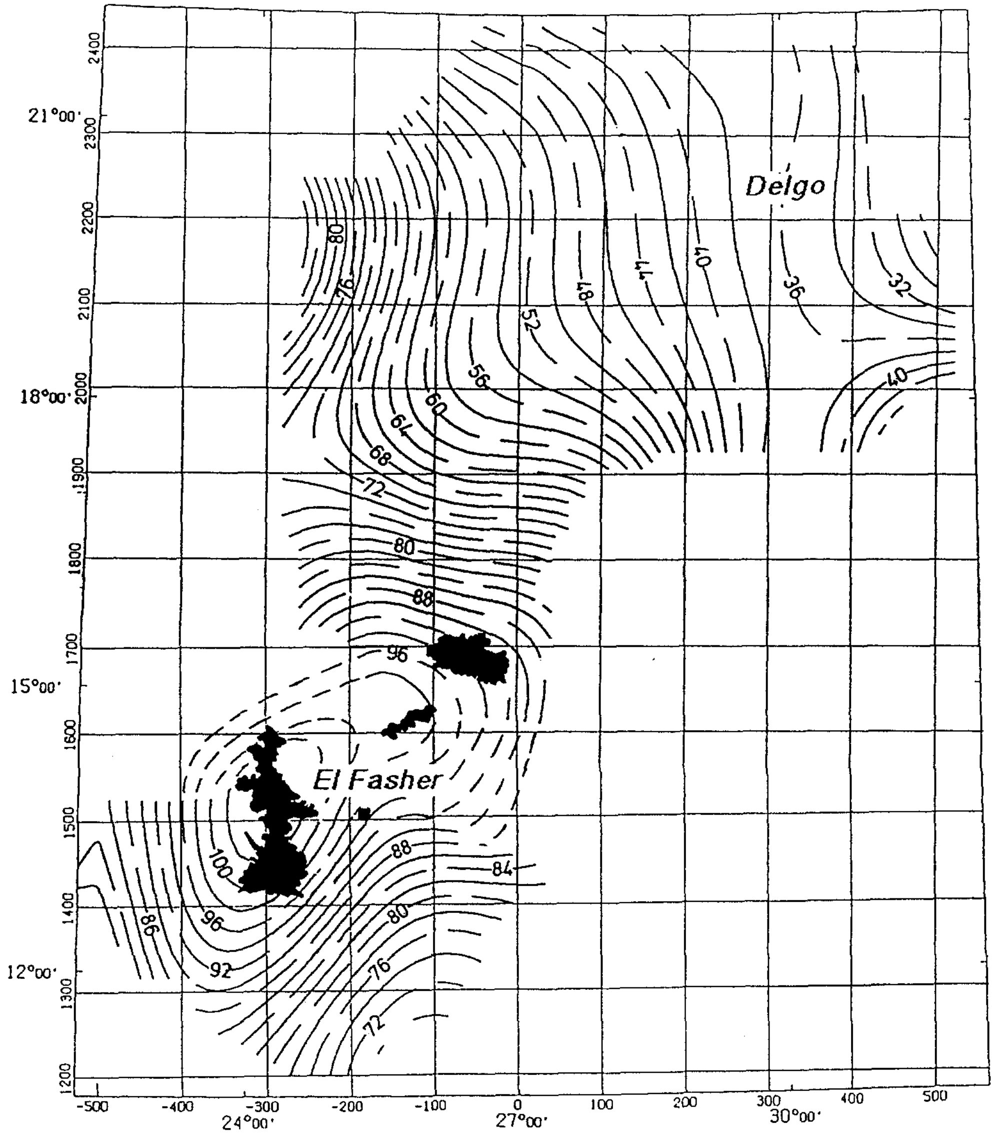


Fig. 5. Bouguer anomaly map for north – west Sudan, 400 km low-pass filter, 2 mgal isolines. The center of the anomaly is near the city of El Fasher, whereas the Delgo area (compare Fig. 2, a Cretaceous to Tertiary volcanic field) does not show a gravity anomaly

for the magma ascent. However, the geological map of Hildebrandt et al. (1990) also reveals the east – west direction of tectonic lines and a 140° to 160° direction of alignment of scoria cones. In all three volcanic fields there are therefore similarities in the tectonic directions.

We conclude that in the early stage of the development of the volcanic province the regional stress field was the major control on volcanic activity in the form of feeder dikes. During the later stages, when large magma chambers formed at high crustal levels, volcanism which produced maars, plinian eruptions and the large shield volcano of Deriba Crater was dominated by magma dynamics and local structural control.

Bouguer gravity data

All data from north-west Sudan (compiled by Robertson Research, unpublished report, Geological Research Authorities of Sudan), including a data set compiled by Leeds University for the Darfur Dome, were reinterpreted (Haußmann, 1993). The data were filtered in the space domain with a 400 km low-pass filter. An offset of 30 mgal between the filtered data sets was corrected and the isolines in the overlap area were smoothed by hand. The result is shown in Fig. 5, which also shows the areas of volcanic activity in the Darfur. There is a pronounced negative anomaly in the Darfur Dome, but none in the other areas, where volcanic activity was also observed (compare Fig. 2). The two distinct features of this anomaly are (i) its SW – NE direction (instead of SSE – NNW; Fairhead, 1979) parallel to the CAFZ and (ii) that it is centered in the central part of the dome west of the city of El Fasher. It coincides with the approximate center of volcanic activity and is also the location of the oldest volcanism observed so far. Fairhead (1979) modelled the anomaly center on an east – west profile under the Deriba Crater in the southern part of the field, which is, however, on the long axis of the elliptically shaped anomaly.

Conclusions: comparison with mantle plume modelling

The regional uplift, the time sequence of volcanic events and the Bouguer anomaly clearly indicate that a mantle plume is the most likely explanation for the volcanism in the Darfur Dome. There is no connection with the rift systems in southern Sudan, but instead with the CAFZ (Fig. 1), as indicated by the direction of the alignment of the volcanic fields in the Darfur (Fig. 3). This large-scale tectonic lineament is related to differential opening processes in the central Atlantic. The present day lithospheric stress field in the African plate is largely due to a rotation around central Africa (Schilling, 1991), and as palaeomagnetic studies indicate that there was no major drift for Africa during the Tertiary, the stress field was possibly similar during the whole period of magmatic activity in the Darfur Dome. This explains why the plate stagnated over the plume channel, so that the oldest ages for magmatic activity were observed in the center, from where ages decrease in NNE and in SSW directions. According to the thermal modelling by Hill (1991), the hottest zones of a plume are preserved both in the center and in the outer parts of the spreading plume head. Magmas are probably created at many stages of the development of the plume, but can extrude only if the stress configuration is appropriate. In the case of the Darfur Dome, resolution of the stress, created by rotation of the African plate, along the CAFZ opens extensional fractures as pathways for magma ascent.

Our field observations in the Darfur Dome are in good agreement with the first stages of the model by Hill (1991). They are schematically shown in Fig. 6 and summarized as follows:

1. When the plume head reaches a depth of 500 km, regional uplift starts, possibly associated with fluid-rich magmas – this stage is represented in the Darfur Dome as the end of sedimentation during Albian – Cenomanian time (about 100 Ma).
2. After a period of 20 to 60 million years, the plume head spreads out horizontally and collapses, but due to replacement of the lithosphere by asthenosphere the uplift continues: neither magmatism nor sedimentation is recorded in Darfur between 100 and 36 Ma.
3. When the plume head reaches a depth of 120 km, volcanism starts in a zone above the plume channel with picritic lavas – basic to intermediate volcanism occurred at Jebel Kussa at 36 Ma, followed by fluid-rich gabbroic to syenitic magmas at 26 Ma, and continued with basaltic and phonolitic rocks at 20 Ma. However, no picritic lavas were found, and these oldest rocks are subvolcanic, some of them with significant crustal contamination. This area is also near to the center of the negative gravimetric anomaly (Fig. 5) and therefore considered as the center of the plume.
4. The main stage of volcanism occurs when the plume head is at a depth of 70 km – the large volcanic fields of the Marra Mountains (14 to 10 Ma) and Tagabo Hills (16 to 11 Ma) were formed, triggered by north – south extension and NE – SW shearing, moving approximately 100 km towards the NNE and SSW from the plume head center.
5. After a delay of 1 – 10 million years heat conduction from the mantle into the crust produces more melts; if plate motion and arrangement are appropriate, true continental break-up may occur. In the Darfur area volcanism continued above the outer parts of the plume head with the development of the large shield volcano (Deriba Crater), with important assimilation of crust (2 Ma to Holocene), and the Meidob field (6 Ma to Holocene); this was associated with minor

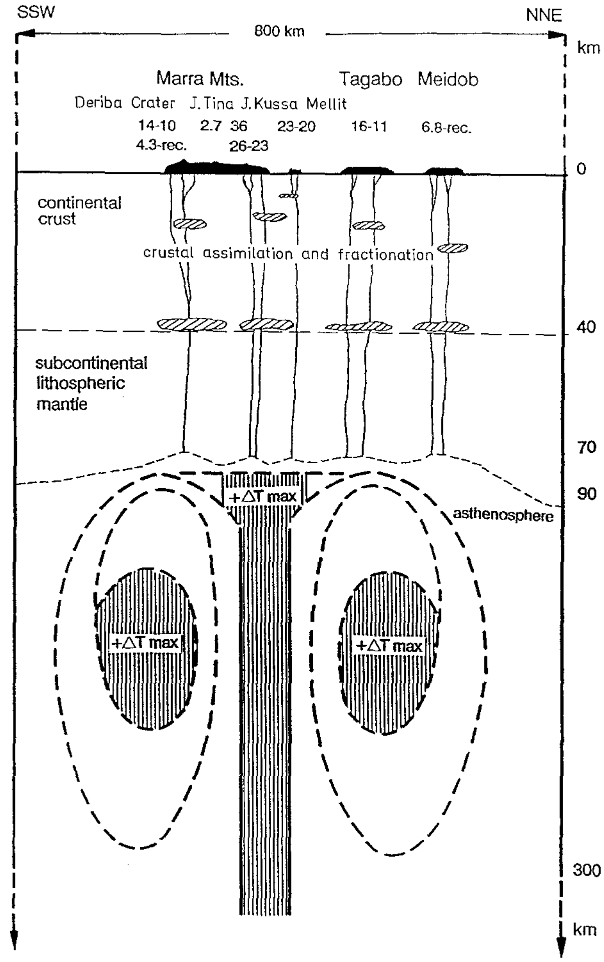


Fig. 6. SSW – NNE cross-section through the Darfur Dome showing the hypothetical present situation of the mantle plume. Ages of volcanism (in Ma) are indicated in the upper line. The lithosphere – asthenosphere boundary is correlated with the gravimetric anomaly (Bermingham et al., 1983), which ends north of the Meidob Hills and south of Nyala; its center lies near Jebel Kussa (compare Fig. 3). Temperature distribution (broken line, adopted from Hill, 1991, an intermediate stage in his Fig. 1 before and after spreading) in the asthenosphere is assumed to by symmetrical around a hypothetical plume channel of 100 km diameter. The area of regional uplift is about 800 km wide (see the 600 m asl isoline in Fig. 2), volcanic activity is restricted to about 400 km and the gravity anomaly fades out inbetween

activity in the center. Uplift continued, as shown by erosion between old and young lavas in the Meidob Hills and in the Marra Mountains by the erosional surface between 'Old' and 'New Lava Series' (Davidson and Wilson, 1989).

6. If in the model calculations the initial lithosphere is hot (700 °C), rapid extension is possible; if it is cold (500 °C), uplift ceases. In the Darfur area, the continental crust is Pan-African and therefore the initial lithosphere is neither 'cold' as for an Archean craton, nor 'hot' as for a Phanerozoic belt. Therefore both possibilities are open, but the plate motion of Africa is not appropriate for rifting due to rotation (Fig. 1; Schilling, 1991). The later stages of a plume, with the possible production of continental flood basalts, cooling of the plume head and thermal subsidence are not reached in Darfur.

In summary, the Darfur Dome is an excellent example of a subcontinental mantle plume below a stagnant plate and it shows that intraplate volcanism here is the result of the interaction of a mantle plume with intraplate lithospheric stress produced by plate rotation. Though the agreement between model calculations and geological observations is fairly good, it does not hold for other plumes. We compiled the available data for the Cameroon Line (Deruelle et al., 1991; Halliday et al. 1990), a volcanic field which probably started above a mantle plume. There is no time dependence for the volcanic rocks. Ages scatter irregularly between 30 Ma and Holocene. In addition, the subvolcanic ring complexes, which are regarded as the precursors of the main volcanic events at 65 Ma, are far away from the inferred plume channel. However, the coincidence of mantle plume activity and a large-scale tectonic lineament is similar to the Darfur Dome.

It is difficult to relate the other occurrences of volcanic intraplate activity in north—east Sudan and in Egypt (Fig. 2) to specific plume activities because their ages scatter widely from Jurassic to Holocene in the whole area. The volcanic fields are small compared with the Darfur Dome and are not clearly associated with domal uplift. In the area of the Delgo Uplift, a Cretaceous volcanic field (Franz et al., 1993; Satir et al., 1991) situated at the eastern margin of the gravity anomaly map (compare Fig. 5), there is no Bouguer anomaly. The exact cause of the melting processes for all these occurrences is still a matter of debate.

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