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Palaeomagnetic and Rock Magnetic Investigations of Tertiary Volcanics in Northern Bavaria

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Abstract. Palaeomagnetic measurements were carried out on 26 Tertiary basalt occurrences for sites in the Oberpfalz (OPF), the Heldburg dyke swarm and several isolated occurrences between these 2 groups (HEB). The mean coordinates for all OPF sites are: long = 12.2° E, lat = 50.0° N, for all OPF + HEB sites: long = 11.4° E, lat = 50.1° N. After af-cleaning in fields of 8 to 16 kA/m (100–200 Oe) the mean directions of characteristic remanent magnetization (CARM) of OPF sites are: N = 16, dec = 12.7°, inc = 59,5°, α_{95} = 7.6°, of OPF + HEB sites: N = 22, dec = 12.4°, inc = 59.0°, α_{95} = 5.8°. Two thirds of the investigated sites have a reverse polarity. Sites with reverse CARM have shallower inclinations (OPF + HEB: −55.9°) than sites with normal polarity (OPF + HEB: +65.5°). This is explained by the presence of viscous components which cannot be erased completely by af-demagnetization. The pole position (northern hemisphere) for OPF sites is: long = 135° E, lat = 78° N, α_{95} = 9.4°, for OPF + HEB sites: long = 140° E, lat = 78° N, α_{95} = 7.2°. The OPF sites have radiometric ages between 19 and 24 My and the HEB sites between 16 and 41 My. Rock magnetic and ore microscopic investigations indicate that with the exception of a few sites, which have not been included in the averaging for the data given above, the direction of the CARM can be considered to be a good approximation to the direction of the primary magnetization.

Key words: Palaeomagnetism – Rock magnetism – Tertiary volcanics – Bavaria

Introduction

The Tertiary volcanic rocks in northern and northeastern Bavaria belong to the Central European volcanic provinces and are the result of cratonic igneous activity on the European plate. Palaeomagnetic data of a great number of these volcanic provinces have been reviewed by Duncan, Petersen and Hargraves

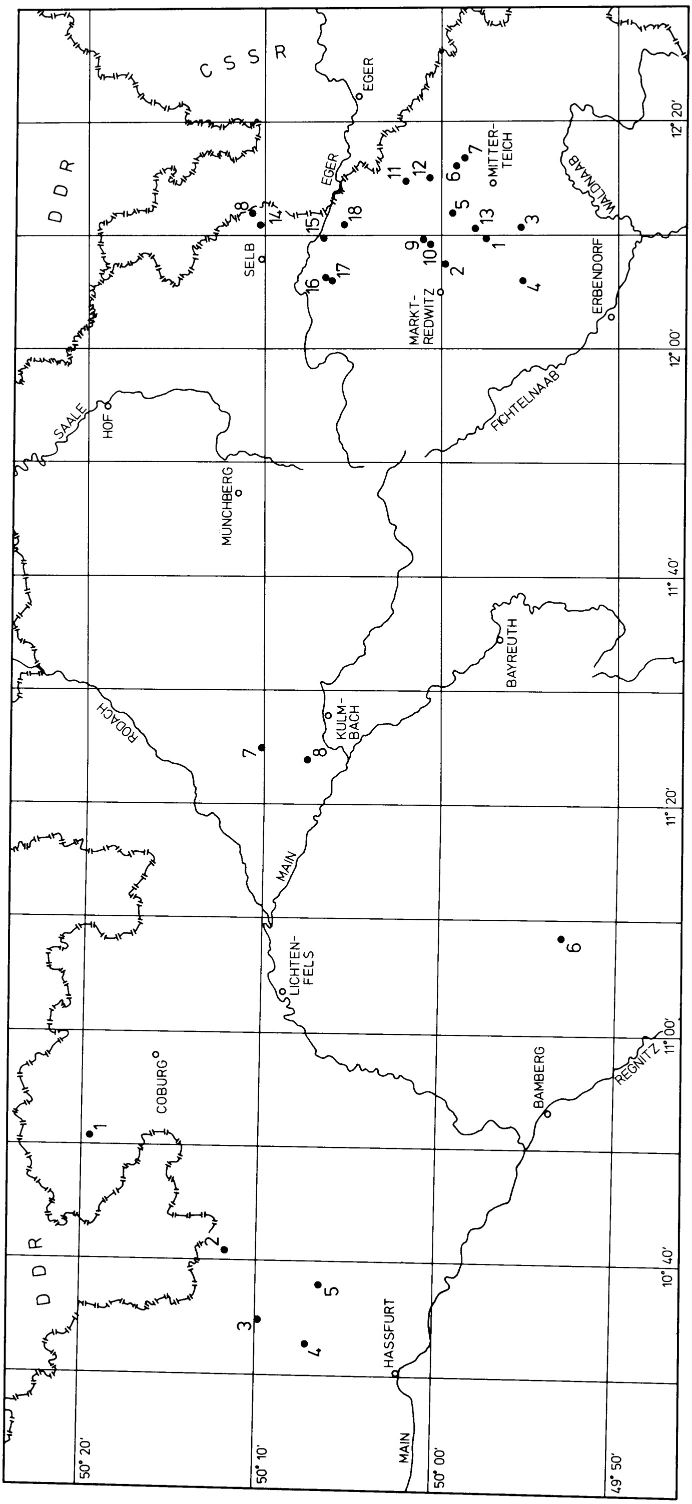


Fig. 1. Sampling sites. Sites east of Bayreuth are named OPF in text, tables and figures. Sites west of Bayreuth are named HEB

(1972). For the southern part of the volcanics in northeastern Bavaria some palaeomagnetic measurements have been made by Refai (1962) and by Soffel and Supalak (1968). In the present paper palaeomagnetic results of previously not investigated localities in northeastern Bavaria (Oberfranken and Oberpfalz), of part the Heldburg dyke swarm in northern Bavaria and of several small basalt occurrences between these 2 groups are presented. For part of these volcanic rocks radiometric age determinations have been made or are under work (Todt and Lippolt 1975; Lippolt, personal communication). They have confirmed the upper Tertiary age which was generally assumed on the basis of geological investigations (Schröder, 1962, 1965). The available radiometric ages have been included in Table 2.

In order to identify the carriers of magnetism in the investigated volcanics and to obtain a general idea of the reliability of the palaeomagnetic results, rock magnetic and ore microscopic studies were carried out. They are summarized in Section 4.

2. Sampling Areas, Petrology and Ages of the Volcanic Units

2.1. Oberpfalz Basalts (OPF 1–18)

The northeastern group of volcanics are called Oberpfalz basalts in the present paper (OPF 1–18, Fig. 1). They represent the western limit of the volcanic province of northern Bohemia which is associated with the Eger Graben. The Oberpfalz volcanic rocks are exclusively basalts, generally olivine-nephelinites and in part nepheline basanites (Richarz, 1920; Wurm, 1961; Noussinanos, 1973; Todt and Lippolt, 1975). They occur as isolated dykes striking approximately NE-SW, parallel to the Eger Graben, as effusive sheets and as lava filled vents which have resisted later erosion. Radiometric age determinations (Todt and Lippolt, 1975) on 19 basalts from the Oberpfalz indicate that the main eruptive phase was between 24 and 19 My, with a possible onset in upper Oligocene (28.8 ± 1.8 My for one site). However, an upper Pliocene or even Pleistocene age (≈ 3 My) was determined for Kammerbühl near the town of Eger (Fig. 1) indicating a younger volcanic phase in the same area.

For the present study 18 localities which had not been previously investigated palaeomagnetically were sampled in the northern part of the Oberpfalz basalts. Between 6 and 37 samples (drill cores) were collected at the different sites depending on the size of the volcanic unit. The samples were taken mostly in quarries, where fresh material could generally be found. Details for the localities are given in Table 1.

2.2. Heldburg Dike Swarm (HEB 1–5)

The Heldburg dyke swarm covers an area about 60 km in length and 20 km in width. The main part of the area is situated in E-Germany. On the Bavarian side only five suitable sites (HEB 1–5, Fig. 1) were found for sampling. In

Table 1. Sampling site coordinates and natural remanent magnetization (NRM, 1 A/m ≙ 10^{-3} G). N = number of samples, n = number of specimens, k = precision parameter, R = resultant vector, susceptibility: 10^{-3} SI units ≙ $80 \cdot 10^{-6}$ G/Oe, Q = Koenigsberger ratio for an inducing field of 47,000 nT (47,000 gamma)

Site No.	Locality	r	h	Topographic Map 1:25000, No.	N/n	NRM (A/m)	Dec (°)	Inc (°)	α_{95} (°)	k	R	Susceptibility (10^{-3} SI)	Q
OPF 1	Teichelberg	^{45}11900	^{55}35900	Waldershof, 6038	30/90	2.23	202.8	−49.7	5.7	21.7	28.7	66.4	0.97
OPF 2	Rehberg	^{45}09040	^{55}40040	Waldershof, 6038	20/63	0.91	44.6	+24.2	10.5	10.5	18.2	40.0	0.59
OPF 3	Triebendorf	^{45}12900	^{55}32160	Mitterteich, 6039	37/100	1.44	197.9	−55.4	10.1	6.4	31.4	48.7	0.77
OPF 4	Plössberg	^{45}07380	^{55}31940	Waldershof, 6038	7/18	1.38	356.8	+62.0	10.2	35.8	6.8	49.3	0.73
OPF 5	Hirschentanz	^{45}14400	^{55}39360	Mitterteich, 6039	12/38	1.36	200.6	−61.6	10.6	17.5	11.4	49.0	0.73
OPF 6	Gommelberg	^{45}19260	^{55}38900	Mitterteich, 6039	12/33	3.84	204.8	−61.7	4.0	117.6	11.9	31.9	3.15
OPF 7	Steinmühle	^{45}20000	^{55}38000	Mitterteich, 6039	14/42	2.25	191.5	−53.6	5.0	61.8	13.8	52.6	1.12
OPF 8	Längenau-E	^{45}13860	^{55}60300	Schönberg, 5839	10/28	1.36	196.9	−36.5	12.8	15.1	9.4	29.8	1.19
OPF 9	Brand-E	^{45}11540	^{55}42120	Marktredwitz, 5938	10/25	1.35	221.5	−55.7	5.9	66.7	9.9	21.7	1.63
OPF 10	Brand-SE	^{45}11160	^{55}41200	Marktredwitz, 5938	10/22	0.71	(195.1)	(−74.6)	46.2	2.0	5.7	45.9	0.41
OPF 11	Grün	^{45}17600	^{55}44180	Waldsassen, 5939	10/24	1.64	37.0	+72.5	8.2	35.5	9.8	39.3	1.09
OPF 12	Wolfsbühl	^{45}18020	^{55}41800	Waldsassen, 5939	9/22	1.00	193.7	+ 5.7	20.2	7.3	7.9	19.6	1.34
OPF 13	Steinhübel	^{45}12800	^{55}37000	Mitterteich, 6039	6/13	4.45	7.5	+66.4	4.3	242.2	6.0	9.5	12.29
OPF 14	Längenau-S	^{45}12980	^{55}59500	Schönberg, 5839	12/31	1.82	227.9	−28.2	7.7	31.9	11.7	32.5	1.46
OPF 15	Ruine Neuhaus	^{45}11680	^{55}52700	Selb, 5838	8/15	2.67	189.6	−41.8	7.4	56.4	7.9	20.8	3.35
OPF 16	Ruine Thierstein	^{45}07460	^{55}52420	Selb, 5838	7/15	4.29	134.4	+68.4	24.3	7.1	61.6	24.9	4.52
OPF 17	Thierstein (Stbr.)	^{45}07280	^{55}51940	Selb, 5838	11/31	3.23	42.6	+70.5	10.2	20.7	10.5	38.2	2.21
OPF 18	Steinberg	^{45}13125	^{55}50650	Waldsassen, 5939	10/18	1.12	(96.4)	(+14.1)	43.4	2.1	5.9	56.7	0.52
HEB 1	Grosswalbur	^{44}18120	^{55}77180	Meeder, 5631	3/6	2.02	–	–	–	–	–	40.2	1.3
HEB 2a	Zeilberg	^{44}06140	^{55}63140	Heldburg, 5730 und	17/43	1.22	217.2	−37.0	13.7	7.6	14.9	24.6	1.3
2b				Pfarrweisach, 5830	18/49	1.30	(215.0)	(−25.8)	24.8	2.9	12.1	27.5	1.2
HEB 3	Manau	^{43}93960	^{55}59520	Hofheim in UFr., 5829	7/13	1.17	185.3	−59.8	18.5	11.5	6.5	26.0	1.2
HEB 4	Hügel	^{43}96200	^{55}54700	Hofheim in UFr., 5829	11/23	1.99	23.4	+71.9	11.1	17.6	10.4	49.0	1.1
HEB 5a	Bramberg	^{44}02460	^{55}53330	Hofheim in UFr., 5829	7/15	1.25	218.0	+54.0	21.0	9.1	6.3	31.8	1.0
5b					7/20	0.57	(166.2)	(+5.5)	90	1.3	–	35.7	0.4
HEB 6	Oberleinleiter	^{44}38550	^{55}27875	Buttenheim, 6132	7/14	1.33	60.7	+28.9	14.3	18.5	6.7	43.8	0.8
HEB 7	Lösau	^{44}57675	^{55}59350	Kulmbach, 5834	6/11	4.43	8.1	+61.0	12.7	28.7	5.8	42.9	2.6
HEB 8	Veitlahm	^{44}56750	^{55}54925	Kulmbach, 5834	11/20	2.80	355.3	+65.2	5.0	82.0	10.9	22.3	3.3

Table 2. Characteristic remanent magnetization (CARM, 1 A/m $\hat{=}$ 10^{-3} G). $H\sim$ = alternating field used for af-demagnetization (8 kA/m $\hat{=}$ 100 Oe), k = precision parameter, R = resultant vector

Site No.	N	$H\sim$ (kA/m)	CARM (A/m)	Dec (°)	Inc (°)	α_{95} (°)	k	R	Polarity	Radiometric Age (My)
OPF 1	31	8	1.97	199.8	−52.2	2.7	89.8	30.7	−	21.4 ± 1.1
OPF 2	20	16	0.49	87.3	−69.9	3.4	93.0	19.8	−	
OPF 3	37	8	1.87	189.5	−63.1	2.3	103.0	36.6	−	
OPF 4	9	8	0.99	356.6	+55.0	7.2	50.8	8.8	+	
OPF 5	12	8	1.33	188.9	−64.9	4.4	97.5	11.9	−	
OPF 6	12	8	3.78	200.1	−65.6	3.6	142.8	11.9	−	
OPF 7	14	8	2.07	190.6	−59.0	4.6	75.1	13.8	−	
OPF 8	11	8	1.48	191.6	−51.0	5.5	68.8	10.8	−	
OPF 9	10	16	0.80	218.7	−62.6	6.4	57.5	9.8	−	22.8 ± 1.8
OPF 10	10	16	0.43	176.7	−78.5	12.6	15.4	9.4	−	22.9 ± 1.0
OPF 11	10	8	0.78	53.6	+59.2	4.3	123.1	9.9	+	
OPF 12	9	8	0.60	179.9	−22.6	12.6	17.5	8.5	−	
OPF 13	6	8	3.81	3.9	+65.3	2.2	891.5	6.0	+	
OPF 14	12	16	0.90	210.8	−49.5	6.1	51.1	11.8	−	
OPF 15	8	8	2.99	187.5	−52.5	3.1	314.3	7.9	−	
OPF 16	7	8	1.31	33.9	+80.3	7.4	67.3	6.9	+	
OPF 17	11	16	1.06	18.4	+68.7	4.6	99.3	10.9	+	
OPF 18	10	16	0.33	156.1	−48.1	6.2	61.5	9.8	−	23.0 ± 1.3
HEB 1	3	no stable remance		−	−	−	−	−		(24.0)
HEB 2	34	16	1.25	204.0	−46.8	3.4	50.7	33.3	−	(16.0)
HEB 3	7	8	1.21	199.8	−63.4	10.1	36.4	6.8	−	(41.6)
HEB 4	11	16	1.36	27.3	+58.9	4.8	78.9	10.9	+	(34.0)
HEB 5	14	12	0.09	180.8	−44.1	12.2	11.5	12.9	−	(16.0)
HEB 6	6	16	0.30	68.8	+20.6	6.8	70.1	5.9	+	(30.8)
HEB 7	6	6	1.60	2.6	+61.3	11.0	37.4	5.9	+	
HEB 8	11	10	1.37	352.9	+65.2	4.6	98.8	10.9	+	(26.9)

the sampled area the swarm consists mainly of dykes several dm to several m in thickness. The strike direction is parallel to the dominant NNE trend of the Rhine graben. Site HEB 2 (Zeilberg) is a large eruptive center. The petrological composition is basaltic for all sites. The age is estimated to be upper Miocene to upper Pliocene (Schröder, 1965). Preliminary radiometric ages are given in Table 2. The sampling of site HEB 1 was made in a weathered dyke about 60 cm thick. Site HEB 2 is a large quarry and sites HEB 3–5 are small abandonned quarries in broad dikes.

2.3. *Oberleinleiter Basalt (HEB 6)*

An isolated occurrence of nepheline basanite is found E of Bamberg. It is a small dyke striking in the same direction as the Heldburg dykes. A preliminary radiometric age is given in Table 2. Sampling was made in an abandonned quarry.

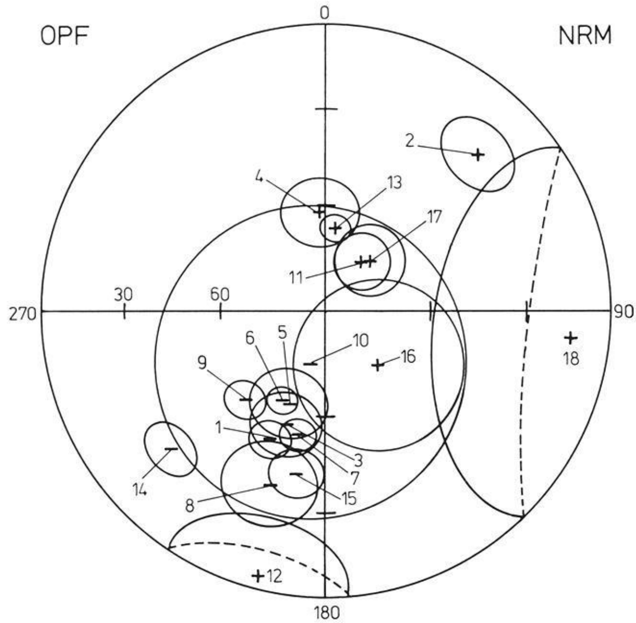
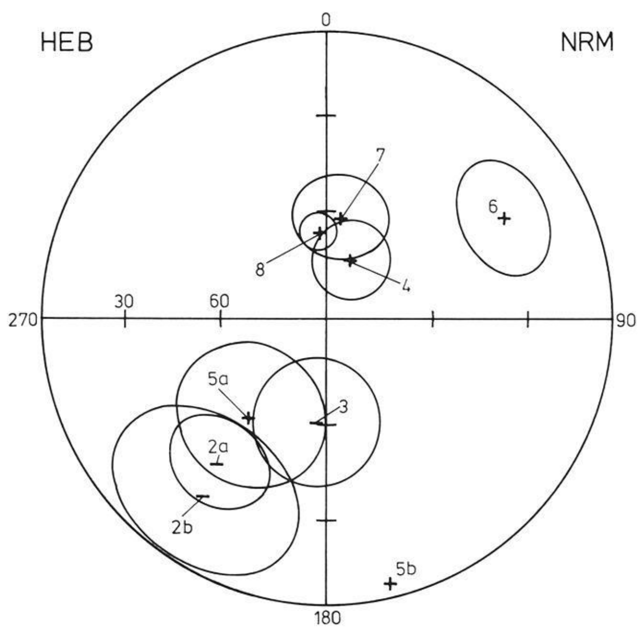


Fig. 2. Directions of the natural remanent magnetization (NRM) of OPF and HEB sites. Site mean values with the α_{95} angle of confidence ovals. Schmidt equal area projection



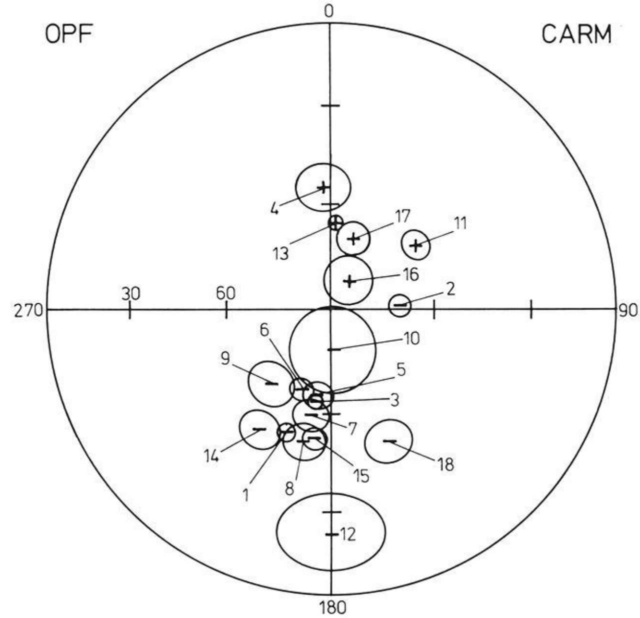
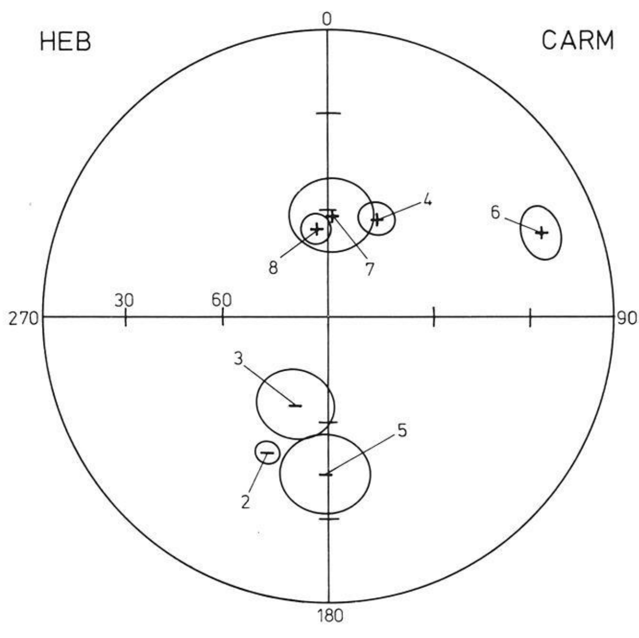


Fig. 3. Directions of the characteristic remanent magnetization (CARM) obtained after af-demagnetization. Site mean values with the α_{95} angle of confidence ovals. Schmidt equal area projection



2.4. Veitlahm – Grafendobrach Dykes (HEB 7–8)

Several small basalt occurrences are found N and NW of Kulmbach (Gudden, 1955). They occur as dykes several dm to several m large. The strike direction is 50–60° and is parallel to the Eger Graben. The age is estimated as Miocene (Dorn, 1930). Preliminary radiometric ages are also given in Table 2. Site HEB 7 is a dyke about 80 cm in width and site HEB 8 is an abandonned quarry in a dyke.

3. Palaeomagnetic Results

3.1. Natural Remanent Magnetization (NRM)

Measurements of remanent magnetization were made with a fluxgate spinner magnetometer. The data of the NRM are listed in Table 1. The site mean values were calculated from the mean values of the samples. Figure 2 shows the mean NRM directions of all sites together with the α_{95} cones of confidence for the OPF and HEB basalts respectively. The data are shown in equal area projection. The considerable scatter of the sample means of some sites (OPF 8, 10, 12, 16 and 18) in Figure 2 and in some cases the indication of a great circle distribution of the NRM directions reveals the presence of secondary magnetization components. With the exception of sites OPF 2, 12, 16 and 18 and site HEB 5 in Figure 2 the NRM already indicates the polarity of the characteristic remanent magnetization.

3.2. Alternating Field Demagnetization

A test of the stability of the NRM was done by demagnetizing two pilot samples from each locality in af-fields with peak values up to 80 kA/m (1000 Oe). The curves showing the variation of intensity of remanence during af-demagnetization were classified according to the schematic curves shown in Figure 4. In this classification scheme the letters A–D indicate increasing stability against af-demagnetization. One asterisk indicates the presence of a maximum and two asterisks indicate the presence of a relative maximum and a relative minimum as shown in Figure 4. The last 2 cases generally occur when the primary remanence is reversed and a viscous component in the direction of the present field is superposed on the primary remanence (assuming only 2 components of remanent magnetization). This is rather frequent among the basalts investigated here, the majority of which show a reversed primary remanence. The results of the classification are included in Table 4, together with the results of rock magnetic investigations described in Section 4.

From the af-demagnetization curves and the corresponding changes in direction of the pilot samples, the appropriate demagnetizing field for the remaining samples of a locality was determined. The demagnetization was then carried out in several steps and the characteristic remanent magnetization (CARM)

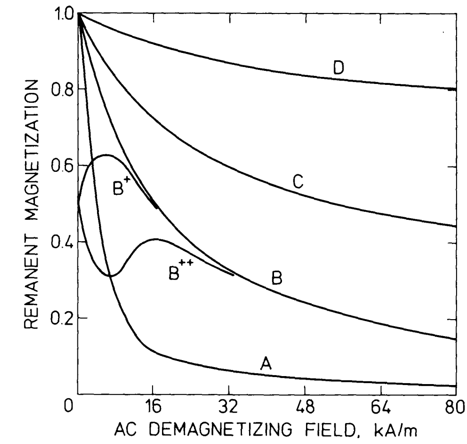


Fig. 4. Classification scheme used in Table 4 for the classification of af-demagnetization curves. Further explanations in the text (Sect. 3.2)

was taken from the demagnetization step giving the lowest amount of scatter, i.e. the minimum α_{95} angle of confidence In all cases alternating fields between 8 and 16 kA/m (100 and 200 Oe) gave the best results. The scatter of the directions of remanence could be considerably reduced for the individual sites (Figs. 2 and 3) and the grouping of the different sites around a mean normal and a mean reversed value was ameliorated. For site HEB 1 a CARM could not be determined because of unstable remanent magnetization.

The specific af-values used for the determination of CARM are listed in Table 2.

3.3. Characteristic remanent magnetization (CARM)

The site mean data of CARM are listed in Table 2. The mean directions together with their α_{95} cones of confidence are plotted in equal area projections in Figure 3. The majority of the sites have CARM directions which are in general agreement with palaeomagnetic directions obtained from other upper Tertiary rocks in Central Europe. A few sites have directions which deviate considerably from upper Tertiary directions (OPF 2 and 12 and HEB 6). As tectonic movements must be discarded, the deviating directions may be attributed to excursions of the magnetic field.

3.4. Mean Directions and Pole Positions

According to the geological descriptions (Schröder, 1962, 1965) and the radiometric age determinations (Todt and Lippolt, 1975) the main volcanic activity in the Oberpfalz and Oberfranken (OPF 1–18) occurred between 24 and 19 My. This corresponds to upper Oligocene and lower Miocene in the stratigraphic

Table 3. Mean directions, mean coordinates of sampling sites and pole positions. For the calculation of mean values of all sites the sites with reverse polarity were inverted to the other hemisphere.

Pole positions were calculated from the individual pole positions of the different sampling sites. Sites OPF 2 and HEB 6 were omitted because of too great departure from a Fisherian distribution, site OPF 13 was omitted because of a too low Curie temperature and site HEB 1 was omitted because of unstable remanence. k = precision parameter

Mean directions

Sites	N	Dec (°)	Inc (°)	α_{95} (°)	k
OPF	16	12.7	59.7	7.6	24.0
OPF + HEB	22	12.4	59.0	5.8	28.7
OPF normal	4	23.3	67.5	17.9	27.0
OPF + HEB normal	7	16.2	65.5	9.7	39.6
OPF reverse	12	190.2	−56.9	8.8	24.7
OPF + HEB reverse	15	191.1	−55.9	7.4	27.5

Mean coordinates of sampling sites

Sites	Long (°)	Lat (°)
OPF	12.2 E	50.0 N
OPF + HEB	11.4 E	50.1 N

Pole positions (North poles)

Sites	N	Long (°)	Lat (°)	α_{95} (°)	k
OPF	16	135	78	9.4	16.3
OPF + HEB	22	140	78	7.2	19.4
OPF normal	4	86	75	27.0	12.5
OPF + HEB normal	7	103	79	14.7	17.7
OPF reverse	12	152	77	10.1	19.0
OPF + HEB reverse	15	152	75	8.4	21.2

scale (Odin et al., 1975; Van Eysinga, 1975). Assuming that all the investigated basalts (OPF 1–18) erupted more or less within the same time interval, it is reasonable to calculate a mean direction and the corresponding pole position for the Oberpfalz basalts. Site OPF 2 is excluded because of too great departure from a Fisherian distribution and site OPF 13 because of the low Curie-point discussed in Section 4. The mean direction and the pole position for the northern hemisphere are given in Table 3 and Figure 6. The mean pole position was calculated from the pole positions determined individually for each site. As there is a characteristic difference between directions of normal and reversed sites, the mean directions of normal and reversed sites and the corresponding pole positions are also given in Table 3 and Figure 6. – For sites HEB 1–8 no pole position was calculated because of the small number of sites and the large time interval of the eruptions. Preliminary age determinations give ages between 16 and 41 My (Table 2). Some of these ages may be too high because of excess argon (Lippolt, personal communication 1976). – A mean direction and a mean pole position were calculated for all OPF and HEB sites, except OPF 2, 13 and HEB 6. The results have been included in Table 3 and Figure 6, which contain also the mean pole positions for all OPF+HEB normal and reversed sites respectively.

4. Rock Magnetic and Ore Microscopic Investigations

The results of rock magnetic measurements are presented in Table 4, which contains the following parameters:

– af-demagnetization curve type of NRM according to the classification described in Section 3.2

– coercive force H_c determined from a hysteresis curve with maximum magnetizing field of 96 kA/m (1200 Oe)

– magnetization M_{96} in the field of 96 kA/m (1200 Oe)

– ratio M_{rem}/M_{96} of the remanent magnetization obtained after magnetizing the samples in the field of 96 kA/m to the magnetization in this field. In a field of 96 kA/m the investigated samples were almost saturated, as could be seen from the measured hysteresis curves

– magnetization M versus temperature T curve type according to the partial classification scheme for basaltic rocks shown in Figure 5. The M-T curves were measured with a translation balance of the Weiss-Forrer type. Heating of the powdered samples up to 600° C and cooling was made in air within about 60 min. The applied magnetic field was 240 kA/m (3000 Oe).

– Curie-temperatures determined from the heating ($T_c\uparrow$) and from the cooling cycle ($T_C\downarrow$)

– ratio M/M_0 of the magnetization M in the field of 240 kA/m after the heating and cooling procedure to the magnetization M_0 before this procedure.

The ore microscopic data obtained with a magnification ×600 and oil immersion are also summarized in Table 4 with the following abbreviations:

– TMt indicates members of the titanomagnetite group

– LTO is the abbreviation for low temperature oxidation, characterized by the presence of titanomaghemite. A relative degree of LTO is indicated by 1 and 2 crosses, 2 crosses indicating that a substantial part of the titanomagnetite has been replaced by titanomaghemite (Ade-Hall et al., 1971)

– HTO is the corresponding abbreviation for high temperature oxidation. The roman numerals indicate the oxidation class according to Wilson and Haggerty (1966).

– Il_p indicates the presence of primary ilmenite

– Sf indicates the presence of sulphides, generally pyrite

– Crt means that part of the titanomagnetites have dark grey cores, which are considered to be remnants of a previous chromiferous spinel (Babkine et al., 1965; Wright, 1967)

– Diam indicates an estimated mean diameter of the magnetic ores in µm.

Table 4. Rock magnetic and ore microscopic characteristics. For explanation of the symbols see text (Sect. 4)

Site No.	a.f. type	H_c (kA/m)	M_{96} (A/m)	M_{rem}/M_{96}	M-T curve type	$T_c\uparrow$ (° C)	$T_c\downarrow$ (° C)	M/M_o	TMt	LTO	HTO	Il_p	Sf	Crt	Diam (µm)
OPF 1	B^+	6.4	4980	0.19	1a–2a	160–350	480	1.1–1.6	++	/–++	I–III	+	+		
OPF 2	C	4.0	4230	0.14	1a	240	520	1.59	++	+	I				30
OPF 3	B^+	3.2	5340	0.07	1a	260	510	1.43	++		I				15
OPF 4	B-C	4.8	4990	0.12	2a–3c	300–510	510	1.5–1.0	++	++	II	+			15
OPF 5	B^+	5.6	3000	0.17	2a	ca. 300	520	1.54	++	+	I				10
OPF 6	A^+	5.6	4570	0.15	1a	270	530	2.78	++	+	I				10
OPF 7	B^+	6.4	4170	0.15	3e	500	510	1.09	++	+	II	+			30
OPF 8	B^+	9.6	3360	0.33	2a	ca. 350	520	2.50	++	+	I				5
OPF 9	B^+	5.6	2780	0.18	1a	250	490	2.04	++	+	I				15
OPF 10	A^{++}-B^+	5.6	4450	0.16	2a	ca. 330	500	1.61	++	++	II	+			10
OPF 11	A	3.2	3170	0.10	2a	ca. 280	480	1.33	++	++	II				40
OPF 12	A	5.6	2440	0.22	2a	ca. 250	480	1.83	++	+	II	+			15
OPF 13	B	(8.0)	–	(0.22)	1a	ca. 50	480	–	++		I				40
OPF 14	A^+-B^+	5.6	3590	0.18	1a	190	530	1.67	++		I				5
OPF 15	C^+	9.6	2120	0.30	1a	180	470	1.72	++	+	I				5
OPF 16	A	5.6	2530	0.22	1a	190	500	2.08	++	+	I				20
OPF 17	A-B	8.0	2910	0.30	1a	200	500	1.96	++	+	I				20
OPF 18	A-A^{++}	4.8	5030	0.12	1a	220	480	1.34	++		I		+		40
HEB 1	A-A^+	5.6	5500	0.15	2a	ca. 350	550	1.15	++		I		+	++	15
HEB 2	B^+-B^{++}	7.2	3120	0.17	7a	ca. 500	480	1.19	++	+?	II	++	+		60
HEB 3	A^+	12.0	3720	0.35	2a	ca. 380	500	1.35	++	+	I		+	+	30
HEB 4	A	6.4	5700	0.08	3b	550	530	0.80	++	+	II	+	+	+	10
HEB 5	A	2.4	3170	0.08	1a	260	500	1.37	++		I	+			60
HEB 6	A^+	(5.6)	7690	0.13	3b	450	480	0.83	++		I			+	30+1
HEB 7	A	4.8	5070	0.12	4a	ca. 300	510	1.52	++		I		+	+	30
HEB 8	A	9.6	3120	0.21	4a	ca. 300	520	1.25	++		I		+	++	30+5

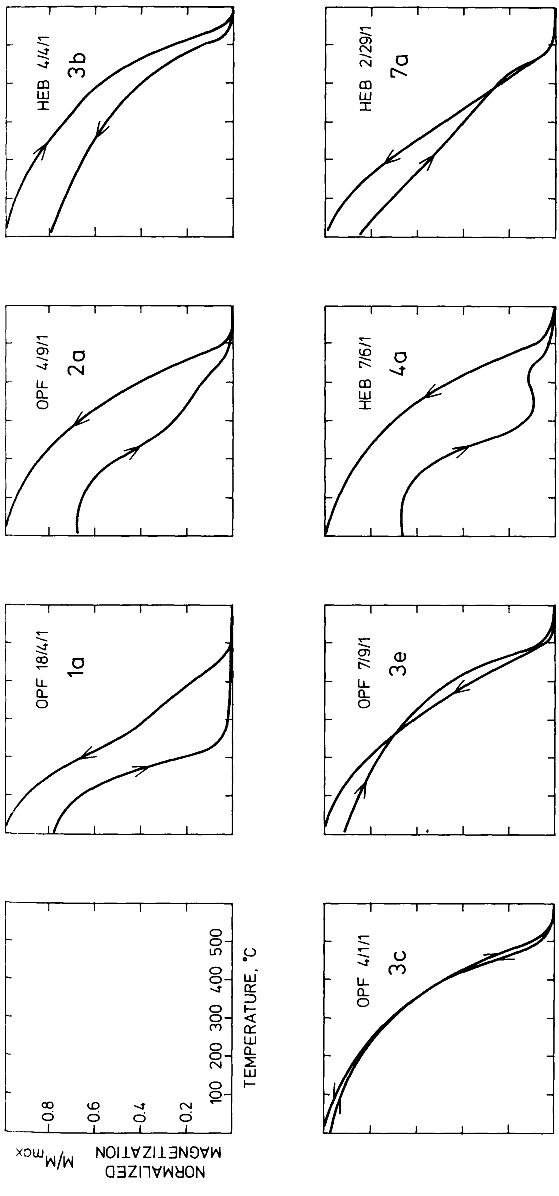


Fig. 5. Magnetization versus temperature curve (*M-T* curves) types found in the investigated basalts. Measurements were made in air and in an applied magnetic field of 240 kA/m (3000 Oe)

The ore microscopic and rock magnetic investigations show that titanomagnetites are the main magnetic phase. Most of the titanomagnetites exhibit a low temperature oxidation, but some appear to be very homogeneous as indicated by the *M-T* curves and the microscopic data. High-temperature oxidation is not frequent. We assume that high-temperature oxidation occurred during the original cooling of the lava in the generally isolated eruptions characteristic of the volcanism in the investigated areas. The time and the temperatures for the low-temperature oxidation are not so easily estimated. The Curie-temperatures measured in the apparently unoxidized or only slightly oxidized basalts are however around 200° C and it is therefore probable that low-temperature oxidation occurred below the Curie-point of the phase carrying the primary remanence. Thus changes of the intensity of the remanent magnetization but not of the direction can be expected (Marshall and Cox, 1971).

As a conclusion we can assume that the measured CARM generally represents a primary direction of magnetization. An exception is site OPF 13, which has a Curie-temperature of about 50° C. The remanent magnetization of this site is very close to the direction of the present geomagnetic field in the sampling area and is probably a recent thermoremanent magnetization acquired during heating by the sun.

5. Discussion

The palaeomagnetic measurements and testing procedures described above, as well as the additional rock magnetic and ore microscopic investigations summarized in the previous section show that, according to usual standards the palaeomagnetic results (CARM and Pole positions) can be considered as reliable.

The mean pole position for all sites, as well as for the OPF sites alone agrees well with the upper Tertiary pole position of McElhinny (1973) for continental Europe. The longitude $<180°$ given by McElhinny is confirmed and is in contrast to previous pole position determinations with longitudes $>180°$ (Fig. 6).

About two thirds of the investigated sites have a reversed polarity. For sites where the radiometric age is known, a comparison with a Tertiary polarity scale has been made by Todt and Lippolt (1975).

A remarkable feature is the difference in inclination between normal and reversed magnetizations (reversed magnetizations have shallower inclinations) and the corresponding difference of the pole positions (Fig. 6 and Table 3). This is apparently in agreement with similar differences between normal and reversed pole positions discussed by Wilson (1972) and by Wilson and McElhinny (1974).

We think that in the present case at least part of this difference can be explained by incomplete demagnetization of viscous components of the remanence. During af-demagnetization the directions of the remanence of many sites with reversed CARM move along a great circle which is defined by the present field direction, the NRM direction and the mean direction of the reverse CARM. This is particularly obvious for sites where the NRM direction strongly differs from the CARM direction. In these cases (Figs. 2 and 3) the CARM determined by the criterium of minimal scatter during af-demagnetization still lies rather far away from the mean CARM direction. Further af-demagnetization with higher fields yields no significant changes of the CARM direction. This suggests the existence of a viscous component in the direction of the present geomagnetic field, which could not be erased completely af-demagnetization. Thermal demagnetization might help in such cases. Incompletely erased secondary magnetiza-

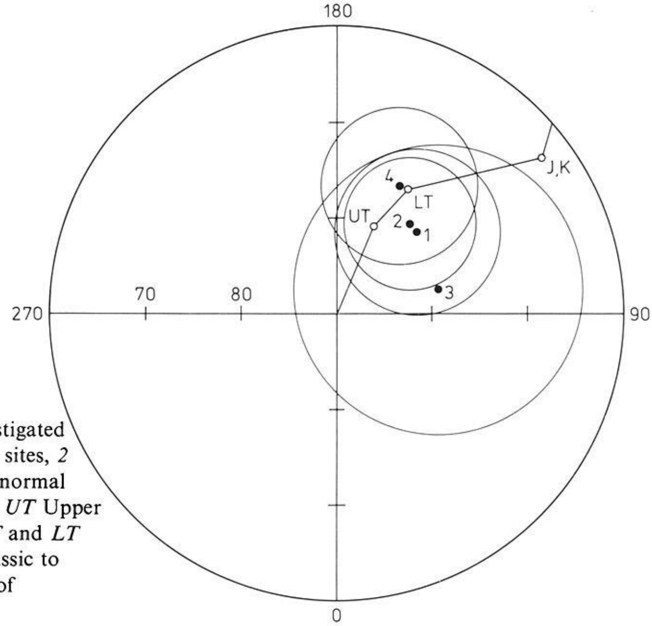


Fig. 6. Pole positions of the investigated basalts (see also Table 3). *1* OPF sites, *2* OPF+HEB sites, *3* OPF+HEB normal sites, *4* OPF+HEB reverse sites. *UT* Upper Tertiary, *LT* Lower Tertiary (*UT* and *LT* after McElhinny 1973), *J, K* Jurassic to Cretaceous (from a compilation of Schweitzer 1975)

tions in the direction of the present geomagnetic field produce shallower inclinations when the reversed primary magnetization has a shallower inclination than the present geomagnetic field at the sampling site and when the remaining secondary component is only a fraction of the primary magnetization.

The steeper inclinations of the normally magnetized sites cannot be explained by this mechanism. The number of sites may be too small in the present case to give a good Fisherian distribution and a satisfactory mean value of the inclination.

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References

Ade-Hall, J.M., Palmer, H.C., Hubbard, T.P.: The magnetic and opaque petrological response of basalts to regional hydrothermal alteration. Geophys. J. **24**, 137–174, 1971

Babkine, J., Conquéré, F., Vilminot, J.C., Phan, K.D.: Les spinelles des basaltes de Monistrol d'Allier (Chaîne du Dèves, Haute-Loire). Bull. Soc. Franc. Minér. Crist. **88**, 447–455, 1965

Bayerisches Geologisches Landesamt: Erläuterungen zur Geologischen Karte von Bayern 1:500000. München: Bayer. Geol. Landesamt 1964

Duncan, R.A., Petersen, N., Hargraves, R.B.: Mantle plumes, movement of the European plate, and polar wandering. Nature **239**, 82–86, 1972

Gudden, H.: Erläuterungen zur Geologischen Karte von Bayern 1:25000. Blatt Nr. 5834 Kulmbach. München: Bayer. Geol. Landesamt 1955

Marshall, M., Cox, A.: Effect of oxidation on the natural remanent magnetization of titanomagnetite in suboceanic basalt. Nature **230**, 28–31, 1971

McElhinny, M.W.: Palaeomagnetism and plate tectonics, 358 p. Cambridge: University Press 1973

Noussinanos, T.: Geochemie und Petrologie Oberpfälzer Olivinnephelinite, Nephelinbasanite und ihrer Ultramafiteinschlüsse. Dissertation, Fakultät für Geowissenschaften, Universität München. 94 S., München 1973

Odin, G.S., Hunziker, J.C., Lorenz, C.R.: L'âge radiométrique du Miocène inférieur en Europe Occidentale et Centrale. Geol. Rundschau **64**, 570–592, 1975

Refai, E.: Magnetic anomalies and magnetization of basalts in the area around Kemnath (Opf.). Z. Geophys. **27**, 175–187, 1961

Richarz, S.: Die Basalte der Oberpfalz. Z. Deut. Geol. Ges. **72**, 1–100, 1920

Schröder, B.: Zur Altersstellung der oberpfälzer Vorlandsbasalte. Geol. Bl. NO-Bayerns **12**, 1–15, 1962

Schröder, B.: Tektonik und Vulkanismus im oberpfälzer Bruchschollenland und fränkischen Grabfeld. Erlanger Geol. Abhandl. **60**, 90 S., 1965

Schweitzer, C.: Vergleich mehrerer Methoden zur Bestimmung der Intensität des Erdmagnetfeldes an rezenten Laven und ihre Anwendung auf mesozoische und paläozoische magmatische Gesteine. Dissertation, Fachbereich Geowissenschaften, Universität München, 157 S., München 1975

Soffel, H., Supalak, P.: Paläomagnetische Messungen am Basalt des Parkstein bei Weiden (Bayern). Z. Geophys. **34**, 287–296, 1968

Söllner, K.: Der Olivinnephelinit vom Teichelberg bei Groschlattengrün (Fichtelgebirge). Neues Jahrb. Mineral., Abhandl. **93**, 324–388, 1960

Todt, W., Lippolt, H.J.: K-Ar-Altersbestimmungen an Vulkaniten bekannter paläomagnetischer Feldrichtung. I. Oberpfalz und Oberfranken. J. Geophys. **41**, 43–61, 1975

Van Eysinga, F.W.B.: Geological time table, 3rd ed. Amsterdam: Elsevier 1975

Wilson, R.L.: Palaeomagnetic differences between normal and reversed field sources, and the problem of far-sided and right-handed pole positions. Geophys. J. **28**, 295–304, 1972

Wilson, R.L., Haggerty, S.E.: Reversals of the earth's magnetic field. Endeavour **25**, 104–109, 1966

Wilson, R.L., McElhinny, M.W.: Investigation of the large scale palaeomagnetic field over the past 25 million years. Eastward shift of the Icelandic spreading ridge. Geophys. J. **39**, 570–586, 1974

Wright, J.B.: The iron-titanium oxides of some Dunedin (New-Zealand) lavas, in relation to their paleomagnetic character (with an appendix on associated chromiferous spinel). Mineral. Mag. **36**, 425–435, 1967

Wurm, A.: Geologie von Bayern. Berlin: Borntraeger 1961

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