NIEDERSÄCHSISCHE STAATS- UND
UNIVERSITÄTSBIBLIOTHEK GÖTTINGEN

Werk

Jahr: 1975
Kollektion: fid.geo
Signatur: 8 Z NAT 2148:41
Digitalisiert: Niedersächsische Staats- und Universitätsbibliothek Göttingen
Werk Id: PPN1015067948_0041
PURL: http://resolver.sub.uni-goettingen.de/purl?PPN1015067948_0041

LOG Id: LOG_0064
LOG Titel: Rock magnetism of the Monti Lessini and Monte Berici volcanites and age of volcanism deduced from the Heirtzler polarity time scale
LOG Typ: article

Übergeordnetes Werk

Werk Id: PPN1015067948
PURL: http://resolver.sub.uni-goettingen.de/purl?PPN1015067948
OPAC: http://opac.sub.uni-goettingen.de/DB=1/PPN?PPN=1015067948

Terms and Conditions

The Goettingen State and University Library provides access to digitized documents strictly for noncommercial educational, research and private purposes and makes no warranty with regard to their use for other purposes. Some of our collections are protected by copyright. Publication and/or broadcast in any form (including electronic) requires prior written permission from the Goettingen State- and University Library.
Each copy of any part of this document must contain there Terms and Conditions. With the usage of the library's online system to access or download a digitized document you accept the Terms and Conditions.
Reproductions of material on the web site may not be made for or donated to other repositories, nor may be further reproduced without written permission from the Goettingen State- and University Library.

For reproduction requests and permissions, please contact us. If citing materials, please give proper attribution of the source.

Contact

Niedersächsische Staats- und Universitätsbibliothek Göttingen
Georg-August-Universität Göttingen
Platz der Göttinger Sieben 1
37073 Göttingen
Germany
Email: gdz@sub.uni-goettingen.de

J. Geophys. 41, 401–411, 1975

Rock Magnetism of the Monti Lessini and Monte Berici Volcanites and Age of Volcanism Deduced from the Heirtzler Polarity Time Scale

H. Soffel

Institut für Allgemeine und Angewandte Geophysik der Universität München

Received January 30, 1975

Abstract. In order to support the palaeomagnetic measurements (Soffel, 1975) on Tertiary volcanites from the Monti Lessini and Monte Berici, additional rock magnetic studies have been made. They show that the carriers of remanent magnetization of the basalts are members of the Titanomagnetite solid solution series. Intrusive bodies have homogeneous Titanomagnetites with Curie temperatures between 80° and 300 °C corresponding to phases richer in Ulvöspinel than in Magnetite. Subaqueous and subaerial basalts show features of high termperature oxidation with exsolution lamellae of Hemoilmenite within a spinel phase close to Magnetite (Curie temperatures between 470° and 520 °C). Also in the subaqueous and subaerial basalts, the primary ore phase before high temperature oxidation has been a member of the Titanomagnetite solid solution series with a high Titanium content. The ores in the basalts show almost no indications of a secondary low temperature oxidation. It can therefore be concluded that the investigated basalts possess a primary remanent magnetization acquired at the time of their formation.

Several rock magnetic properties have been correlated such as saturation magnetization and susceptibility ($K=0.845$), coercive force and ratio between saturation remanence and saturation magnetization ($K=0.800$), reciprocal coercive force and normalized susceptibility ($K=0.646$), Curie temperature and density ($K=-0.609$). No correlation ($K=0.03$) could be found between coercive force and Q ratio.

A comparison of the polarity of the lavas (Soffel, 1975) with the Heirtzler *et al.* (1968) polarity time scale of the geomagnetic field suggests that in the Monti Lessini two separate cycles of volcanic activity are present. An older cycle mainly between 52 and 46 m.y. and a younger cycle mainly between 40 and 32 m.y. Such two cycles of volcanic activity are also discussed for the adjacent Colli Euganei.

Key words: Rock Magnetism — Heirtzler Polarity Time Scale.

1. Introduction

This paper should be regarded as complementary to the previous paper by Soffel (1975) which contains the results of palaeomagnetic measurements on the Monti Lessini and Monte Berici volcanites of Tertiary age in Northern Italy. It has been disconnected from it and published as a separate paper within the same volume of Journal of Geophysics because of technical reasons.

The rock-magnetic and ore microscopic studies have been made in order to determine the nature and origin of the remanent magnetization of the rocks and to support the palaeomagnetic data. The aim was further to investigate whether the natural remanent magnetization is a primary one acquired by the rocks at the time of their formation or has been altered due to secondary processes like wheathering or other chemical changes at a later time of their history.

Table 1. Rock magnetic and mineralogical data. Meaning of the different columns: 1: site number, 2: susceptibility in 10^{-6} cgs units, 3: mean intensity of induced magnetization in μG (1 $\mu G = 10^{-6}$ Gauss), assuming a field of 0.48 Oe, 4: Q ratio for NRM, 5: saturation magnetization at room temperature in Gauss before heating, 6: saturation magnetization at room temperature in Gauss after heating, 7: type of J_s/T curve according to Fig. 1, 8: saturation remanence in 10^{-3} Gauss, 9: ratio between saturation remanence and

1 Nr.	2 $\chi(10^{-6})$	3 $J_i(\mu G)$	4 Q_{NRM}	5 $J_s(G)$	6 $J_s(G)$	7 J_s/T	8 $Rm_s(mG)$
1	865	415	5,56	0,534	0,569	10	67.2
2	4946	2374	0,33	4,164	3,768	3	923,1
3	4940	2371	0,85	3,173	3,125	6	313,5
4	3819	1833	0,59	2,117	3,472	9	411,0
5	2131	1023	4,88	1,473	3,001	8	331,5
6/1	1906	915	1,18	2,305	1,619	3	866,7
6/2	4955	2378	0,68	3,747	3,995	5	311,8
7	4596	2206	0,70	3,554	3,844	5	371,6
8	1954	938	3,74	1,825	3,160	8	364,6
9	3150	1512	1,94	1,052	1,635	7	161,9
10	6205	2979	0,65	3,025	2,847	3	386,2
11	2126	1021	1,90	1,010	1,284	8	147,0
12	3698	1775	12,96	0,523	2,077	7	100,3
13	3032	1455	5,63	1,252	2,133	7	258,3
14	354	170	16,24	0,209	0,278	7	83,4
15	3105	1491	0,61	1,940	2,720	8	336,4
16	2442	1172	4,39	1,360	2,060	8	160,5
17	2636	1266	2,13	1,480	2,310	7	218,9
18	924	443	2,07	0,750	0,810	2	127,6
19	773	371	6,84	0,540	0,330	3	171,8
20	838	402	5,62	0,360	0,320	3	106,2
21	217	104	5,76	0,210	0,210	1	43,1
22	1044	501	1,72	0,690	0,590	3	95,0
23	825	396	1,95	0,517	0,505	1	45,7
24/1	5315	2551	0,83	2,519	2,924	11	263,6
24/2	1220	586	4,43	0,417	1,545	7	93,9
25	523	251	15,86	0,285	0,949	9	30,3
26	1693	813	1,06	1,926	1,915	3	406,3
27	2455	1778	5,01	1,154	1,867	7	170,8
28	1637	786	33,33	1,185	1,768	9	316,9
29	2882	1383	2,32	1,221	2,131	7	136,6
30	2143	1029	2,31	1,099	1,773	7	158,9
31/1	802	385	5,10	1,337	0,739	3	704,3
31/2	338	162	4,84	0,289	0,251	3	98,6
32/1	1030	496	6,10	0,430	0,306	3	107,3
32/2	3090	1483	1,25	1,377	0,505	4	86,7
33	433	208	22,76	0,274	1,219	7	69,4

saturation magnetization at room temperature before heating in percent, 10: net coercive force in Oe, 11: Curie temperatures of the heating cycle. +: Pseudo Curie temperature of a Maghemite phase. 12: Curie temperatures of the cooling cycle, 13: class of high temperature oxidation according to Wilson and Haggerty (1966), 14: presence of primary Ilmenite. —: absent, +: traces, ++: rare. 15: presence of Maghemite. +: yes, —: no. 16: bulk rock density

9 Rm_s/J_s	10 H_c(Oe)	11 T_c(up)	12 T_c(down)	13 Oxid,	14 Ilm.	15 Magh.	16 σ(gcm^{-3})
12.6	70.0	500	520	3	++	—	2,76
22,2	167.2	530	500	1	++	+	2,90
9,9	43.0	200, 470	170, 470	1	+	+	2,96
19,4	61.7	300, 490	490	1	+	—	2,90
22,5	60.4	270, 480	490	1	—	—	2,90
37,6	340.0	560	530	4	++	—	2,72
8,3	48.4	530	520	1	+	+	2,83
10,5	56.8	520	490	1	+	+	2,90
20,0	58.8	250, 490	500	1	+	—	2,97
15,4	39.0	90	90, 430	1	—	—	2,99
12,8	30.3	510	480	1	+	—	3,02
14,6	48.1	320, 500	280, 520	1	++	—	2,68
19,2	22.0	80	80, 480	1	—	—	2,97
20,6	44.4	100	120, 470	1	—	—	2,93
39,9	80.0	290	540	1	++	—	2,65
17,3	63.2	250, 500	520	1	+	—	2,84
11,8	38.4	200, 480	510	1	+	—	2,58
14,8	42.0	220	470	1	—	+	2,83
17,0	82.4	530	530	4	++	—	2,65
31,8	244.0	580	560	4	++	—	2,34
29,5	266.0	580	560	4	++	—	2,39
20,5	200.0	540	530	5	++	—	2,72
13,8	86.0	540	530	2	++	—	2,72
8,8	59.6	530	520	2	++	—	2,75
10,5	51.2	350	490, 250	1	—	—	3,02
20,0	69.2	90	470	1	—	—	3,02
10,6	57.2	90, 490	90, 490	1	++	—	2,90
21,1	179.2	540	510	2	+	—	2,67
14,8	31.2	190	490	1	—	—	3,01
26,7	73.2	250, 490	490	1	—	—	2,84
11,2	27.6	190	500	1	—	—	2,94
14,5	32.0	160	500	1	+	—	2,93
52,7	543.6	560	530	4	++	—	2,67
34,1	397.2	570	540	4	++	—	2,31
25,0	164.0	550	550	4	++	—	2,32
6,5	57.2	350^+, 520	500	4	++	+	2,67
25,3	64.8	80	100, 480	1	+	—	2,84

An attempt was also made to get more precise data of the age of volcanism in the Monti Lessini and Monte Berici with the observed polarity distribution of the volcanic units and the Heirtzler, Dickson, Herron, Pitman and Le Pichon (1968) polarity time scale of the geomagnetic field.

37 volcanic units have been sampled in the Monti Lessini and Monte Berici. The sampling localities and the ages of the rocks can be taken from Soffel (1975) and the site numbers are the same as in that paper in order to facilitate the correlation between the rock magnetic data of this paper and the palaeomagnetic data of the above mentioned publication.

2. *Rock Magnetic Investigations and Ore Microscopic Studies*

Most of the rock magnetic data are listed in Table 1. The parameters which have been measured are: susceptibility χ in cgs units, induced magnetization J_i assuming an ambient field of 0.48 Oe (which is typical for the sampling area), Q ratio, saturation magnetization J_s of the natural sample in Gauss, saturation magnetization J_s after heating the sample up to 600 °C for the determination of the Curie temperature, saturation remanence Rm_s in 10^{-3} Gauss after saturation in a field of 8000 Oe, ratio Rm_s and J_s of the natural sample in percent, net coercive force H_c in Oe, Curie temperatures of the heating cycle, Curie temperatures of the cooling cycle (after heating up to 600 °C), degree of deuteric oxidation of the ore phase according to the nomenclature introduced by Wilson and Haggerty (1966), presence of Ilmenite and/or Maghemite, bulk density in g/cm^3.

2.1. Ore Microscopic Studies and Determination of Curie Temperatures

Ore microscopic studies revealed that the prevalent carriers of remanence are in general members of the Titanomagnetite solid solution series with variable Titanium content.

In some cases primary Ilmenite was found to be coexistent with primary unexsolved Titanomagnetite within the same ore grain or in the form of separate fine needles. Secondary Ilmenite is present in samples where the primary Titanomagnetite has been exsolved by deuteric oxidation of class 2—5 according to the nomenclature introduced by Wilson and Haggerty (1966). In general the ores are fresh and show no indications of subsequent low temperature oxidation due to wheathering or hydrothermal alteration. Some results of the ore microscopic studies have also been listed in Table 1. Information is given about the class of deuteric oxidation (class 1—5), the abundance of Ilmenite (++: rare, +: traces) and signs of subsequent low temperature oxidation (+: yes, —: no) leading to Titanomaghemite.

The Curie temperatures have been determined by measuring the saturation magnetization of a pulverized rock sample as dependent on temperature with a Forrer type horizontal balance as described by Petersen (1961, 1965). Measurement was made in air by heating the sample up to 600.°C and cooling it back to room temperature at a rate of about 15—20 °C per minute for each cycle. The saturation magnetization was measured digitally every 10—20° depending on the gradient of the curve. The Curie temperatures thus obtained for the heating and the cooling cycle are listed in Table 1.

Among the J_s/T curves of samples from the 37 sites 11 different types could be distinguished (Fig. 1). Their type is listed in Table 1 and will be discussed briefly with

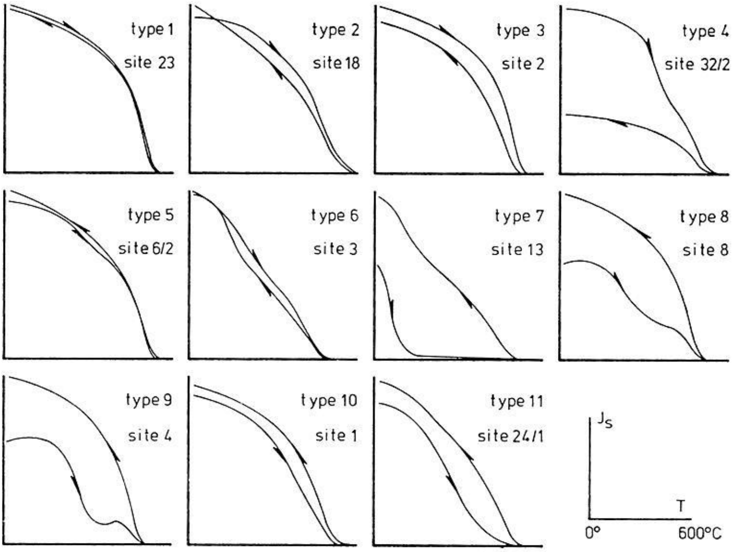

Fig. 1. Dependence of saturation magnetization (in arbitrary units) on temperature. Both heating and cooling cycle are shown and indicated by arrows. For absolute values see Table 1

respect to their main characteristics. Interpretation of the J_s/T curves has been combined with ore microscopic observation and rock magnetic properties (see Table 1) for the determination of the carrier of characteristic remanence in the rocks.

Type 1 (sites 21, 23): Exsolved Titanomagnetite due to deuteric oxidation of class 5 and 2 respectively. The slight drop of the Curie temperature and saturation magnetization of the cooling cycle may be due to a migration of Titanium back into the lattice of the cubic phase.

Type 2 (site 18): Exsolved Titanomagnetite and exsolved needles of Hemoilmenite due to deuteric oxidation of class 4. Change of Curie temperature and type of J_s/T curve due to diffusion of Titanium within the ores.

Type 3 (sites 2,6/1, 10, 19, 20, 22, 26, 31/1, 31/2, 32/1): Titanomagnetite with high Curie temperature either due to deuteric oxidation or due to primary low Titanium content. The large drop of Curie temperature and intensity of saturation magnetization of the cooling cycle is a consequence of Titanium diffusion and oxidation during the exderiment. Type 4 (site 32/2): Exsolved Titanomagnetite due to deuteric oxidation showing signs of subsequent low temperature oxidation (Titanomaghemite). Pseudo Curie temperature at around 350 °C is actually the temperature of desintegration of secondary metastable Titanomaghemite into stable Ilmohematite. Drop of the Curie temperature and intensity of saturation magnetization is a consequence of diffusion of Titanium and disappearance of metastable Titanomaghemite. Type 5 (sites 6/2, 7): Unexsolved Titanomagnetite with small Titanium content showing slight indications of a beginning low temperature oxidation. Almost reversible J_s/T curve. Small differences between heating and cooling curve are due to diffusion of Titanium.

Type 6 (site 3): Unexsolved Titanomagnetite with small Titanium content together with an anisotropic phase, possibly a member of the Ilmenite-Hematite solid solutions series. The Titanomagnetites show no indications of a beginning low temperature oxidation.

Type 7 (sites 9, 12—14, 17, 24/2, 27, 29, 30, 33): Unexsolved Titanomagnetite with high Titanium content, sometimes coexisting with Ilmenite, showing no signs of deuteric oxidation. Irreversible J_S/T curve due to oxidation of the Titanomagnetites during the experiment forming phases closer to Magnetite.

Type 8 (sites 5, 8, 11, 15, 16): Unexsolved Titanomaghemite with medium Titanium content. Desintegration (exsolution) of the primary ore phase by heating above 300 °C results in the production of a phase close to Magnetite with a Curie temperature of about 500 °C and a correspondingly large saturation magnetization.

Type 9 (sites 4, 25, 28): Similar properties as for type 8 but with a secondary maximum of saturation magnetization at around 400 °C. Material of such properties of the J_S/T curve is capable of a partial or complete self reversal of remanence when heated under certain conditions (Petersen and Bleil, 1973; Creer and Petersen, 1969).

Type 10 (site 10): Exsolved members of the Ilmenite-Hematite and Titanomagnetite, solid solution series as a result of exsolution. Cooling curve shows increased Curie temperature and saturation magnetization probably due to formation of new phases belonging to the Titanomagnetite solid solution series. Type 11 (site 24/1): Unexsolved Titanomagnetite with medium Titanium content, probably decomposing into two phases (one with $T_C = 490$ °C, another with $T_C = 250$ °C) after heating up to 600 °C in air.

The analyses of the ore phase indicates that the primary ore phase of the volcanites of the Monti Lessini and Monte Berici area is in most cases a member of the Titanomagnetite solid solution series with a high Titanium content. This is evident from the many sites with Curie temperatures below 300 °C. Predominantly the intrusive basalts of the investigated area fall into this group. Exsolved Titanomagnetites with higher Curie temperatures of the secondary phase of around 500 °C can clearly derived from primary low Curie temperature Titanomagnetites as a consequence of deuteric oxidation under subaqueous or subaerial conditions. The high Curie temperatures observed for some apparently homogeneous and unexsolved Titanomagnetites can be due to unobservable submicroscopic exsolutions. Low temperature oxidation due to wheathering or hydrothermal alteration immediately after the formation of the rocks is rare. Such features have been found to be much more abundant among the more acid volcanics of the Colli Euganei (Soffel, 1974) which had in general a much lower Titanium content in the Titanomagnetites. This suggests that the Colli Euganei magmas have assimilated much more crustal material than the Monti Lessini and Monte Berici volcanites during their way to the earth's surface.

According to the rock magnetic and ore microscopic studies the characteristic remanent magnetization (CARM) of all sites from the Monti Lessini and Monte Berici is a primary magnetization acquired by the rocks at the time of their formation. Only the samples from site number 32/2 seem to have suffered subsequent low temperature oxidation. As the characteristic remanent magnetization of this site groups very well (and so does already the natural remanent magnetization) and has the same direction as the subjacent flow it can be assumed that the slight mineralogical changes of the ore minerals are due to hydrothermal alteration immediately during or after the formation of the rock. In this case the palaeomagnetic result of site number 32/2 can be regarded as a reliable data (Ade—Hall *et al.*, 1971).

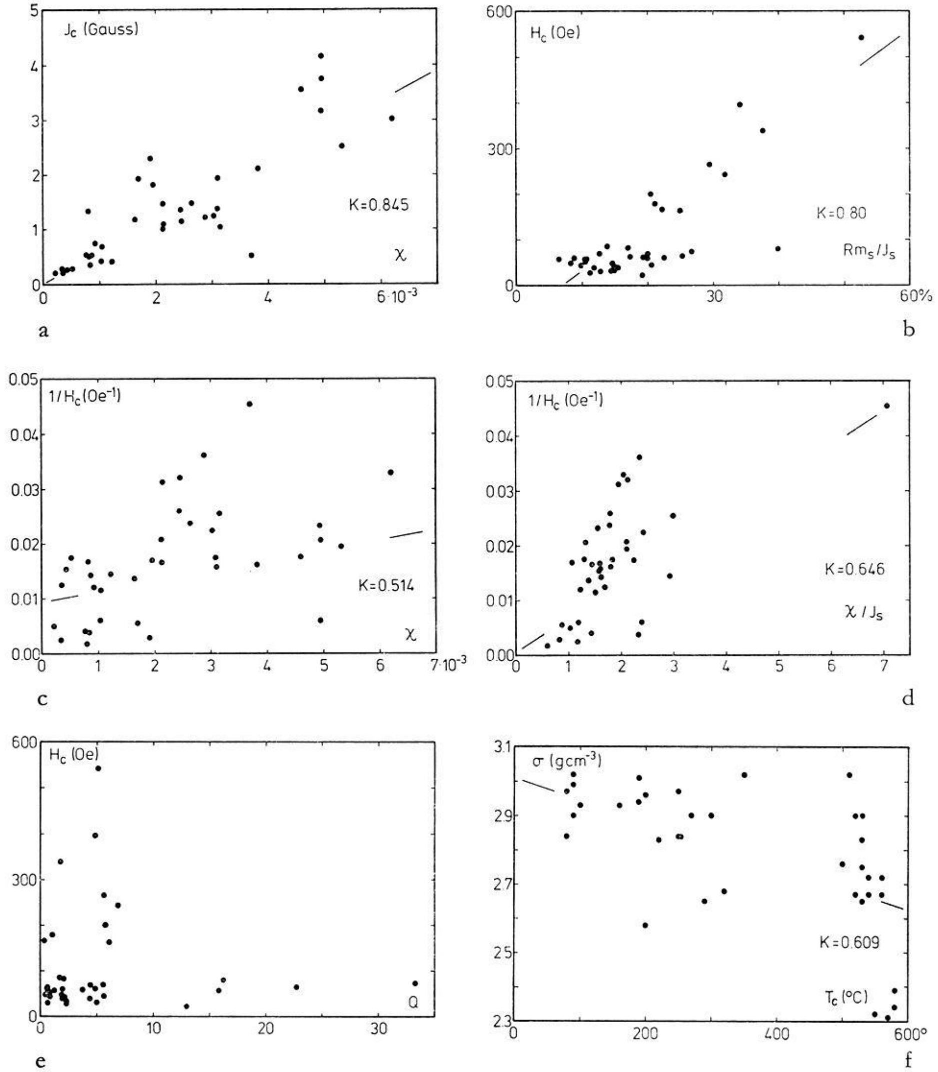

Fig. 2. Correlation between different rock magnetic parameters. a) Saturation magnetization J_s (in Gauss) versus susceptibility χ in cgs units. b) Coercive force in Oe versus the ratio between saturation remanence Rm_s and saturation magnetization J_s in percent. c) Reciprocal coercive force (in 1/Oe) versus susceptibility χ in cgs units. d) reciprocal coercive force (in 1/Oe) versus the ratio between susceptibility in cgs units and saturation magnetization J_s in arbitrary units. e) Coercive force in Oe versus Q ratio. f) Bulk density (in g cm^{-3}) versus Curie temperature

2.2. Correlation of Rock Magnetic Parameters

Some of the rock magnetic parameters which are listed in Table 1 and for which linear relationships are expected from the theory of ferro(i)magnetism have been correlated and plotted in Fig. 2. A good (Fig. 2a) correlation (correlation coefficient

$K = 0.845$) could be found between saturation magnetization and susceptibility. An even better correlation between these two parameters ($K = 0.917$) has been found for the Colli Euganei volcanites (Soffel, 1974). This indicates that the ore content of the Monti Lessini and Monte Berici volcanites is less homogeneous than in the Colli Euganei with respect to the chemical composition and grain size distribution. This is in fact the case. In the Colli Euganei (Soffel, 1974) there are in general acid volcanites with Titanomagnetites (exsolved as well as unexsolved) with low Titanium content. In the basic rocks of the Monti Lessini and Monte Berici Titanomagnetites with very low and very high Titanium content are present. Another good correlation ($K = 0.8$) could be found between the net coercive force and the ratio between saturation remanence (produced in a field of 8400 Oe) and the saturation magnetization at room temperature. For the Colli Euganei volcanites a value of $K = 0.84$ has been determined as correlation coefficient between these two parameters. All lava flows with unexsolved and large Titanomagnetite grains are found in the lower left part of this diagram (Fig. 2b) while the exsolved Titanomagnetites and the rocks with small Titanomagnetite particles are found in the upper right part of Fig. 2b. This is consistent with the idea that single domain and pseudo single domain particles have much larger coercive forces and Rm_s/J_s ratios than the large multidomain grains. A pretty bad correlation ($K = 0.514$) could be found between the reciprocal coercive force ($1/H_c$) and the susceptibility although a linear relationship should be expected between these two quantities (Fig. 2c) from the theory of ferro(i)magnetism based on the model of domain wall friction. However the correlation between the two parameters is disturbed by the variable ore content of the rocks which influences the susceptibility but not the coercive force. An improvement for the correlation between $1/H_c$ and χ could be obtained by plotting $1/H_c$ versus χ/J_s in arbitraty units. The diagram is shown in Fig. 2d. The correlation coefficient is now $K = 0.646$. No correlation ($K = 0.03$) could be found between the coercive force H_c and the Q ratio for the natural remanent magnetization (see Fig. 2e). This is surprising because for ore grains with large coercive forces a large remanent magnetization J_r and a small induced magnetization J_i is expected from theory of ferro(i)magnetism. $Q = J_r/J_i$ should therefore correlate to some extent with H_c. A good linear (and positive) correlation between H_c and Q has been reported by Kropacek (1974, private communication) for Tertiary basalts in northern CSSR. The bad correlation between H_c and Q for the Monti Lessini and Monte Berici basalts is probably due to the different polarity of the rocks and their different acquisition capacity for viscous magnetization components. The degree of deuteric oxidation, by which the Curie temperature of the ore minerals is increased, is expected to influence also the bulk density of the rocks. Intrusive basalts with low Curie temperatures are supposed to have higher densities than basalts formed under subaerial or subaqueous conditions with high Curie temperatures due to oxidation and/or exsolution. The density versus Curie temperature is plotted in Fig. 2f. The correlation between the two parameters is not very good ($K = 0.609$) but a tendency in the above mentioned sense is present.

3. Relations to the Heirtzler Polarity Time Scale of the Geomagnetic Field

A polarity time scale of the geomagnetic field for the past 80 m.y. has been determined by Heirtzler, Dickson, Herron, Pitman and Le Pichon (1968) with the help of the

Fig. 3. Heirtzler *et al.* (1968) polarity time scale of the geomagnetic field in the time interval between 30 and 50 m.y. Radiometric age determinations in the Monti Lessini and Monte Berici are indicated as well as the polarities of remanent magnetization of rocks. Black areas and dots: normal polarity, white areas and open circles: reversed polarities. Square: intermediate remanence direction

pattern of marine magnetic anomalies in combination with radiometric and paleontological data. The polarity time scale for the time interval from 30 to 50 m.y. is shown in Fig. 3. Black areas mean times of normal polarity, white areas are times of reversed polarity. The polarity of remanent magnetization of 6 lava flows (Soffel, 1975) are also shown together with their radiometric ages according to Piccoli (private communication, 1973). Two lava flows (36.2 and 37.0 m.y.) show reversed polarity (open circles) in agreement with the Heirtzler *et al.* (1968) polarity time scale. Good agreement could also be obtained for a flow with an age of 47.2 m.y. having normal polarity (closed circle). Among three lava flows aged 46.8 m.y. one has normal, another reversed and a third intermediate polarity (open square). This age seems to represent a time of transition from a reversed to a normal polarity, again in agreement with the Heirtzler polarity time scale. Two other age determinations (33.0 and 33.5 m.y.) were made on rocks not suitable for palaeomagnetic measurements.

4. *Tentative Age Determination of the Monti Lessini Volcanism with the Heirtzler et al. (1968) Polarity Time Scale*

Regarding the polarity time scale of Heirtzler *et al.* (1968) for the time interval between 30 and 50 m.y. (see Fig. 3) it can be seen that the times of normal and reversed polarity of the geomagnetic field are not equally distributed. Between 35 and 38 m.y. a reversed polarity is prevalent, while between 42 and 45 m.y. a normal polarity is predominant. The curve shown in Fig. 4 represents the average abundance of normal polarity in percent within a time interval of ± 1.5 m.y. around a given time according to the Heirtzler *et al.* (1968) polarity time scale between 25 and 60 m.y. As previously indicated there is a small abundance of normal polarity at around 36 m.y. (less than 20% of a 3 m.y. time interval) and a large abundance (almost 80% of a 3 m.y. time interval) at around 43 m.y. Assuming that the production of volcanic material happened at a more or less constant rate during several million years and that an equally well distributed sampling in the investigated area has been made, the ratio between lava flows of normal and reversed polarity should in some way reflect the polarity distribution at the time of active volcanism.

The palaeomagnetic data of the Monti Lessini volcanites (Soffel, 1975) demonstrate that almost all lava flows have reversed polarity. In an earlier section of this paper it could be shown that the CARM of the rocks is a primary magnetization acquired by

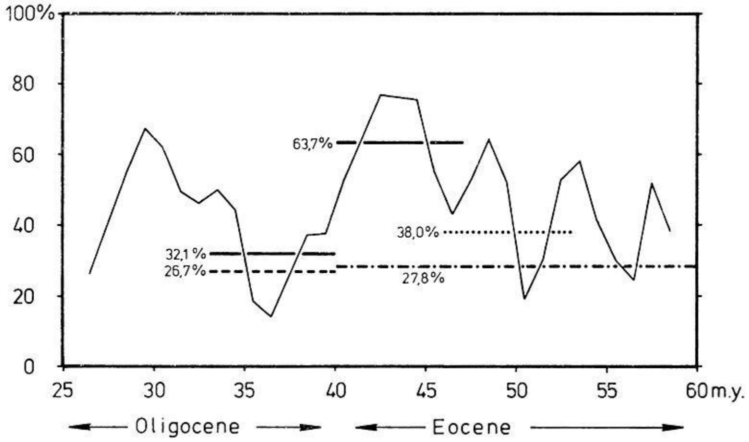

Fig. 4. Average abundance of normal polarity in percent within a time interval of ±1.5 m.y. around a given time according to the Heirtzler *et al.* (1968) polarity time scale between 25 and 60 m.y. For the meaning of the horizontal bars: see text

the rocks at the time of their formation. Selfreversals of natural remanent magnetization have most probably not occurred. It can therefore be concluded that a reversed polarity has been acquired by the rocks at a time where the geomagnetic field had a reversed polarity.

Among 15 volcanic units in the Monti Lessini which are of Oligocene age (according to radiometric or to biostratigraphic dating), 11 (73.3%) have reversed and 4 (26.7%) have normal polarity. This value of 26.7% (abundance of lava flows with normal polarity) is shown in Fig. 4 as a dashed horizontal line covering the time interval between 33 and 40 m.y. which is supposed to be the time of volcanic activity in the Monti Lessini and Monte Berici in Lower Oligocene. From the Heirtzler *et al.* (1968) polarity time scale an abundance of 32.1% (solid horizontal line in Fig. 4) can be computed for the same time interval (33 to 40 m.y.) in agreement with observation yielding a value of 26.7%. Other intervals like 33 to 39 m.y. (34.8%), 33 to 38 m.y. (33.0%), 32 to 38 m.y. (30.3%), 32 to 39 m.y. (32.3%) and 32 to 40 m.y. (32.8%) all including the radiometrically determined ages of 33.0, 33.5, 36.2 and 37.0 m.y. (see Fig. 3) yield roughly the same value of about 30% for the abundance of normal polarity.

An abundance of 63.7% for the normal polarity (solid horizontal line in Fig. 4) should be expected if the Eocene volcanism in the Monti Lessini had occurred between 40 and 47 m.y. However among the 18 volcanic units in the Monti Lessini of Eocene age (according to radiometric or to biostratigraphic dating), 13 (72.2%) have reversed and only 5 (27.8%, dash-dotted horizontal line in Fig. 4) have normal polarity. A comparatively small abundance of normal polarities (38.0%, dotted horizontal line in Fig. 4) is only present in the time interval between 46 and 53 m.y. which contains the radiometrically determined ages of 46.8 and 47.2 m.y. (see Fig. 3). Small abundances of normal polarities can also be expected in Lower Eocene between 54 and 58 m.y. (22.5%) and between 54 and 59 m.y. (36.0%).

The abundance of lava flows with normal polarity of either Oligocene or Eocene age therefore suggests that the Oligocene volcanism occurred between 32 and 40 m.y.

and the Eocene volcanism took place between 46 and 52 m.y. or earlier. According to the small abundance of lava flows with normal polarity ages between 40 and 46 m.y. are very unlikely. This implies that in the Monti Lessini a younger (Lower to Middle Oligocene) and an older (Lower to Middle Eocene) cycle of volcanism are present, separated by a time interval of about 6 to 8 m.y. in Upper Eocene with relatively small volcanic activity. A similar situation is also discussed for the volcanism of the adjacent Colli Euganei (Schiavinato, 1950).

Acknowledgement. The investigations have been made in the Institut für Allgemeine und Angewandte Geophysik, Universität München. Thanks are due to Prof. Dr. G. Angenheister, Dr. N. Petersen, Dr. J. Pohl, Dr. E. Schmidbauer, Dr. A. Schult and Dipl. Geophys. Ch. Schweitzer for many helpful discussions. The financial support of the Deutsche Forschungsgemeinschaft is gratefully acknowledged.

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

Creer, K.M., Petersen, N.: Thermochemical magnetization in basalts. Z. Geophys. *35*, 501–516, 1969

Heirtzler, J.R., Dickson, G.O., Herron, E.M., Pitman, W.C. III., Le Pichon, X.: Marine magnetic anomalies, geomagnetic field reversals, and motions of the ocean floor and continents. J. Geophys. Res. *73*, 2119–2136, 1968

Petersen, N.: Untersuchungen magnetischer Eigenschaften von Titanomagnetiten im Basalt des Rauhen Kulm in Verbindung mit mikroskopischer und elektronenmikroskopischer Beobachtung. Dipl. Arbeit, Inst. f. Angew. Geophysik, Universität München, 1961

Petersen, N.: Beobachtung einiger mineralogischer und magnetischer Eigenschaften dreier Basaltproben nach unterschiedlicher thermischer Behandlung. Diss. Naturw. Fak. Universität München, 1965

Petersen, N., Bleil, U.: Self reversal of remanent magnetization in synthetic titanomagnetites. Z. Geophys. *39*, 965–977, 1973

Schiavinato, G.: La provincia magmatica del Veneto sud-occidentale. Mem. Ist. Geol. Mineral. Univ. Padova *17*, 1–38, 1950

Soffel, H.: Palaeomagnetism and rock magnetism of the Colli Euganei volcanites and the rotation of Northern Italy between Eocene and Oligocene. Boll. Geofis. Teor. Appl. *16*, 333–355, 1974

Soffel, H.: The palaeomagnetism of age dated tertiary volcanites of the Monti Lessini (Northern Italy) and its implications to the rotation of Northern Italy. J. Geophys. *41*, 385–400, 1975

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

Prof. Dr. Heinrich Soffel
Institut für Allgemeine und
Angewandte Geophysik der Universität
D-8000 München 2, Theresienstraße 41
Federal Republic of Germany