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Variation of magnetic properties and oxidation state of titanomagnetites within selected alkali-basalt lava flows of the Eifel-Area, Germany

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Abstract. In three lava flows from the Quaternary Eifel volcanic field, magnetic and petrologic properties were studied in four vertical and one horizontal profiles to obtain information concerning magnetic stability and possible effects for the paleomagnetic record in volcanic rocks. Only two of the profiles exhibited marked and correlating trends of high-temperature (HT) oxidation state, natural remanent magnetization (NRM) intensity, magnetic susceptibility and magnetic stability parameters. The variations may be interpreted to depend on the HT oxidation state of the titanomagnetites present in the lavas. In two other profiles, more complex variations of most petrological and magnetic parameters were found, probably due to combined effects of HT oxidation, maghemitization and variations of titanomagnetite volume content and grain size. Although the magnetic stability and dispersion of paleodirections show some relation to HT oxidation state, no evidence was found within a unit for systematic deviations of paleomagnetic directions from the paleofield. An apparent relation between directional trends and petrological and magnetic parameters in one of the lavas is interpreted to be due to viscous deformation or differential movement of parts of this flow as a result of interactions between almost solid and remaining liquid material overflowing it.

Key words: Paleomagnetism – Rockmagnetism – Lava flows – Volcanics – Oxidation state – Magnetic stability – Quaternary – Eifel (Germany)

Introduction

Since the 1950s paleomagnetism has become a tool widely used in geosciences, first in plate tectonics and later in a variety of applications, e.g. concerning the evolution of microplates and orogenic belts. Many results are from volcanic rocks which are thought to be the most reliable recorders of the geomagnetic field, due to the origin and stability of the remanence-carrying oxide minerals.

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Iron-titanium oxides have been intensely studied to understand remanence origin and stability and the effects of mineral alterations. Most of such studies used laboratory-grown minerals to obtain grains of controlled composition, size and form (e.g. Akimoto et al., 1958; O'Reilly and Banerjee, 1967; Hauptmann, 1974; Levi and Merrill, 1978; Tucker and O'Reilly, 1980; Keefer and Shive, 1981; Özdemir and O'Reilly, 1981, 1982; Nishitani and Kono, 1983; Özdemir, 1987). In other cases minerals were separated from natural rocks and subsequently conveniently prepared (e.g. Dankers, 1978; Harstra, 1982), but only few investigations used the same samples commonly used for paleomagnetic purposes (e.g. Watkins and Haggerty, 1965; Ade-Hall et al., 1968, 1971; Wilson et al., 1968; Grommé et al., 1969; Hargraves and Petersen, 1971; Lawley and Ade-Hall, 1971; Petersen, 1976; Kono, 1987). As reviewed by Moskowitz (1987), studies on synthetic materials show serious and systematic differences concerning even basic properties such as Curie temperature, cell size etc., which may be due to non-ideal starting material used in the experiments as well as to differing methods for evaluation of the experiments. Vincenz (1987) has pointed out that results from natural material diverge even more as its composition and structure apparently disagrees largely from laboratory-grown minerals.

Nevertheless, from the studies cited above, it follows that the magnetic properties of igneous rocks depend on factors such as magma composition, cooling history, reheating, etc. In particular, the high-temperature (deuteric) oxidation of titanomagnetites during the late cooling phase and low-temperature oxidation, which may occur any time later, may influence magnetic properties such as remanence intensity, magnetic susceptibility, Curie temperature, coercivity, and therefore may affect the paleomagnetic record.

High-temperature (HT) oxidation is characterized by a multiphase intergrowth of titanomagnetite (TM) with hemoilmenite or other phases. The development of such microstructures may be responsible for a reduction of the effective grain size, which in turn has effects on intensity of magnetization, coercivity, susceptibility, etc. (e.g. Graham, 1953; Watkins and Haggerty, 1965; Ade-Hall et al., 1968, 1971; Strangway et al., 1968; Larson et al., 1969; Evans and Wayman, 1974; Davis and Evans, 1976; Haggerty, 1976; Price, 1980). Tucker and O'Reilly (1980), on the other hand, ascribe changes of magnetic properties in the course of oxidation to the origin of interlamellar spinel phases, differing in composition from the initial TM and

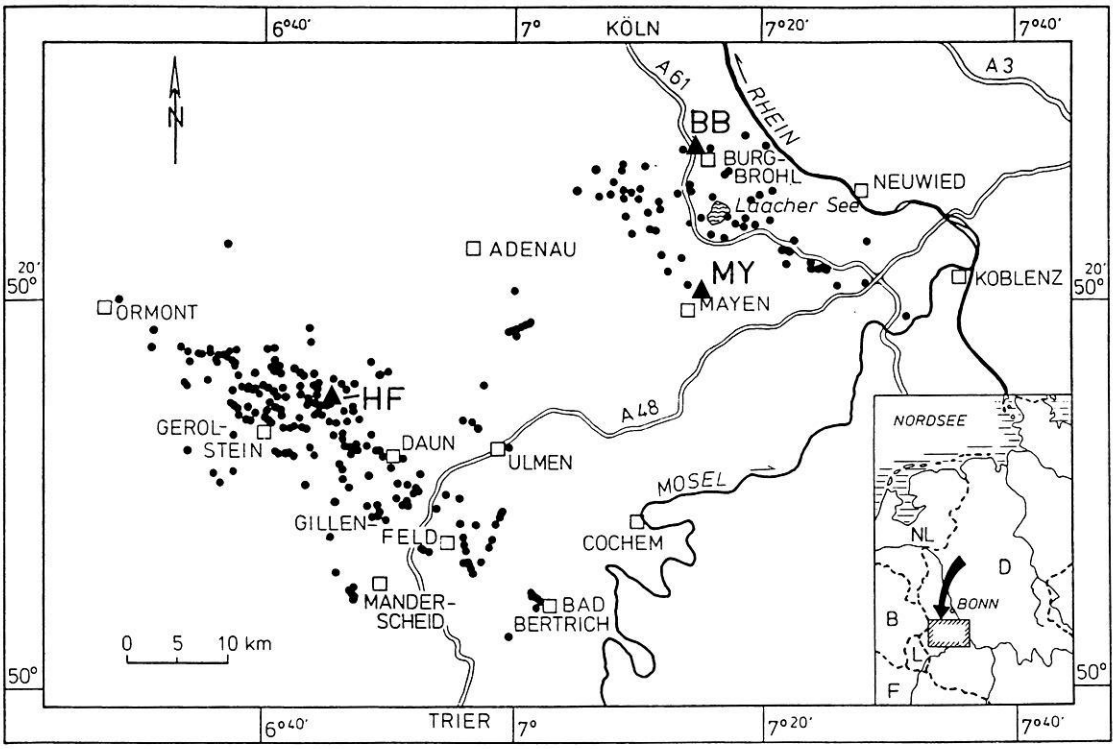

Fig. 1. Eruption centres in the quaternary Eifel area (*dots*) and the location of the lava flows studied (*triangles*): BB = Bausenberg, MY = Mayen, HF = Hohenfels/Mühlenberg. Modified from Büchel and Mertes (1982)

in the progressed oxidation states to the development of very fine-grain magnetite in hemoilmenite matrix.

Low-temperature (LT) oxidation (= maghemitization) normally occurs in igneous rocks at temperatures below the Curie temperature of the minerals present, and may proceed by addition of oxygen or by Fe migration out of the grains (e.g. O'Reilly, 1984). In any case, the structure and chemistry of the minerals changes, affecting most magnetic properties and, under certain conditions, the direction of remanent magnetization (e.g. Johnson and Merrill, 1972, 1974; Merrill, 1975; Petersen et al., 1979; Heider and Dunlop, 1987; Smith, 1987).

In an attempt to obtain data from material as used for standard paleomagnetic work, selected igneous rock lava suites from the Quaternary Eifel area (Fig. 1) were studied for their paleomagnetic, rock magnetic and opaque petrological properties.

Field and laboratory procedures

Samples were taken with a gasoline-powered corer at spacings of approximately 0.5 m on the vertical profiles and about 2.0 m on the horizontal profile and later cut into 25-mm-long specimens. A Digico magnetometer (Molyneux, 1971) served to determine intensity and direction of magnetization, a low-field susceptibility bridge (Bison 3101 A) to measure initial magnetic susceptibility. Specimens were stepwise alternating-field (*af*) demagnetized using a two-axis tumbler. Magnetic stability was investigated by applying different stability criteria: median destructive field (MDF); S_{200} (Wilson et al., 1968), considering directional stability as well as intensity variations; PSI (Symons and Stupavsky, 1974), giving information only about directional changes. Additionally, difference vector variations (Hoffman and Day, 1978) were analysed to look for stable directional endpoints.

The magnetic minerals, and their oxidation states, were identified by reflected light microscopy. Oxidation number M_{ox} was determined as described by Negendank (1972), using the classification scheme of Wilson and Haggerty (1966) and Ade-Hall et al. (1968); mean overall grain size was obtained using the counting method proposed by Wilson et al. (1968).

Specimens from the Hohenfels lava showed trends of remanent magnetization directions and rock-magnetic parameters along the vertical profile and were subjected to additional experiments to explain this observation: thermomagnetic curves were obtained with a horizontal magnetic balance (e.g. see Collinson, 1983) in fields of ca. 180 kA/m ($\simeq$240 mT); to reduce chemical alteration during the experiment, the sample region was continuously flooded by Ar gas; heating and cooling rate was 40° C/min, with maximum temperature errors during the whole cycle of about 10° C. Anisotropy of magnetic susceptibility was determined with a KLY-2 bridge, and high- and low-temperature variation of a strong artificial isothermal remanent magnetization (IRM) with a modified Digico magnetometer. The ore petrology was completed by scanning electron microscopy (SEM) using the backscattered electron method, which also allows semi-quantitative analyses of oxides and silicates, and, for selected specimens, by microprobe analysis of the titanomagnetites. Facilities for most of these measurements were available only after 1982, resulting in a delay of this study which had started in 1977.

The lava flows

The Eifel region comprises a Tertiary and a Quaternary lava suite. Figure 1 shows the distribution of Quaternary eruption centres and the location of the three lave flows studied for this paper, which are all of Upper Brunhes age.

From the Bausenberg (BB) volcano a basanitic lava flow extends about 4 km eastwards, comfortably exposed along a road cut, transecting almost perpendicular to the flow direction. At this exposure the flow thickness varies between 10 and 12 m, but the base was not accesible for sampling. Samples were taken near the flow base along a 200-m-wide horizontal profile on the eastern part of the exposure, at 9–10 m below the top of the flow. Two vertical profiles (total lateral spacing 2 m) were sampled at 0.2–9.9 m and 0.2–8.6 m below the top, respectively, separated about 50 m by the highway.

The Mayen lava flow (MY) is a leucite-nephelinite tephrite and has a thickness of about 15–25 m. The flow extends from the Ettringer Bellerberg about 3 km southward with lateral dimensions between 1.0 and 1.5 km. Samples were taken in two vertical sections with a lateral offset of about 8.0 m, covering a total vertical distance of 12.5 m.

The Hohenfels lava (HF) is one of the largest basalt lava occurrences in the Eifel (Fig. 2) with a thickness of around 10 m. Three quarries permit observations of lateral and vertical variations. In the northern part the melilite-nephelinite lava formed at the base a 1-m-thick layer of a dense rock with horizontal laminae, upwards followed by a 4- to 5-m-thick porous lava of 5- to 10-cm-thick laminae, inclined up to 30°. In this layer lava pillars with diameters up to 3 m are found, in contrast to the uppermost part with smaller vertically oriented pillars and no lamination.

In the southern part the lava flow shows a subdivision into a lower porous lava with partly inclined laminae, similar to the situation in the north, and an upper layer without stratification. The subdivision of the lava is pronounced by the orientation and diameter of the pillars being smaller in the lower part. Around the sampling location (Fig. 2) the orientation of the lava pillars beneath the transition zone is not vertical but protruding, suggesting a lava flow in a highly viscous state at the end of the lava cooling process. Possibly this can be explained by a late lava supply, not at the top but in the centre or lower part of the flow. In the southeast a contact between two lavas can be observed, leading to the idea that lava at first flowed to the southeast, forming a barrier for a subsequent erupting lava therefore extending more to the north. An alternative explanation would be the flow of viscous lava over irregular topography.

In conclusion from the field observations, probably the first lava outflow was in a southeastern direction until it formed a barrier. Subsequently delivered material resulted in an irregular flow and led to the deformation of the underlying and largely quenched but still viscous lava. Even a differential tilting of already solid parts may have occurred. Such deformations surely would have depended on factors such as lava thickness, temperature, degassing state, ground subsidence, etc. and, therefore, widely on the morphology of the flow basement. This could explain the varying lamination of the lower lava layer.

For the present study, samples were obtained from an inclined profile situated in the southern part of the complex

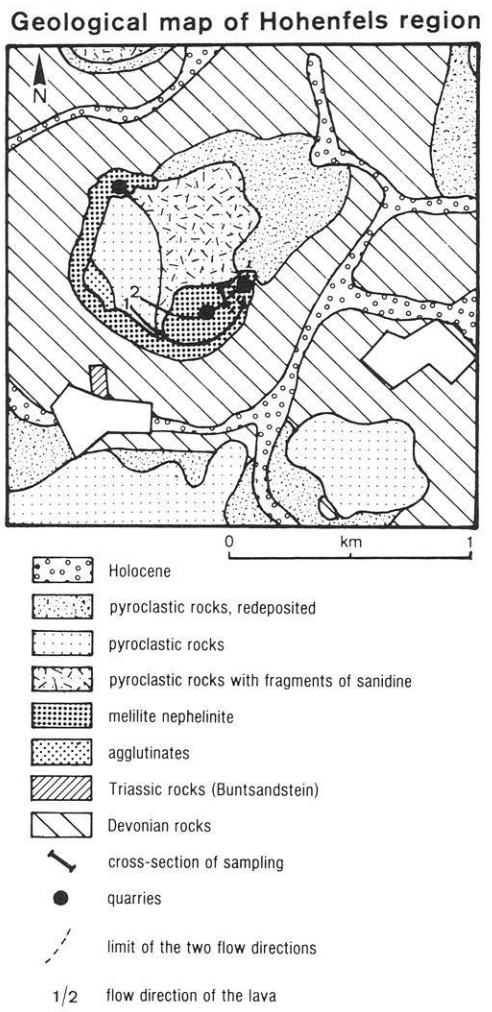

Fig. 2. Geology of Hohenfels lava flow according to Rahm (1956)

(Fig. 2), intersecting both layers over a vertical distance of about 9.7 m, and a horizontal distance of about 20.0 m. During the first field campaign in 1977 the extension of the quarries was neither big enough to give insight into the situation explained above, nor was sufficient attention paid to the uncommon lava pillar formation. A second sampling was performed in 1982, including more detailed field work in the meanwhile extended quarries, to explain the data obtained previously. Unfortunately, the quarried area had meanwhile been much extended and the lower section of the first profile had partly disappeared. The additional samples therefore are from a profile up to 10 m from the original one.

Results

Common to all lava flows studied is the dominance of titanomagnetites and their oxidation products. Besides HT oxidation, maghemitization mainly of low to intermediate degree was observed in 17% (BB-east) to 80% (HF) of the samples. Granulation was restricted to the BB-west and BB-horizontal profiles and occurred in about half of the samples. According to the age of the rocks and in contrast to the evidence cited by Ade-Hall et al. (1968, 1971), granulation here must have originated in a relatively short time

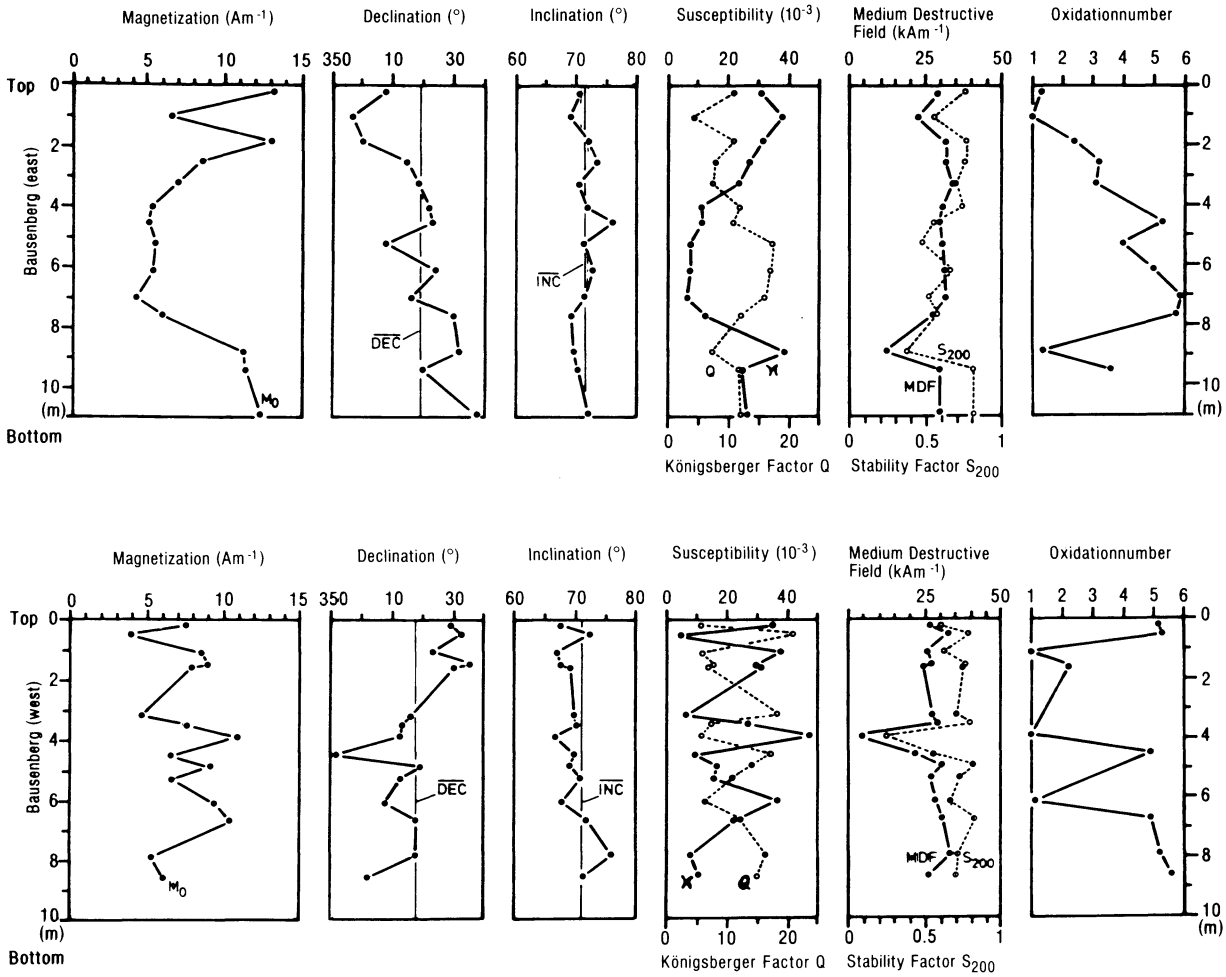

Fig. 3. Variation of magnetic and petrological parameters in vertical profiles of Bausenberg lava flow. See text for further explanations

span and without burial or substantial reheating of the flows.

Most TM had idiomorphic to hypidiomorphic habits. The volume content was rather similar for samples from BB-east, BB-horizontal, MY and HF, with means of $3.5\% \pm 0.4\%$ ($n=12$), $3.8\% \pm 1.2\%$ ($n=3$), $3.4\% \pm 0.6\%$ ($n=5$) and $4.1\% \pm 0.9\%$ ($n=3$), respectively. For most of these samples, mean overall grain size was determined, yielding values of 1.9 ± 0.3 μm to 4.7 ± 0.8 μm, which indicates single-domain (SD) and pseudo-SD particles as remanence carriers. No obvious trend of volume content and grain size was observed in any of the profiles studied.

Bausenberg and Mayen lava flows, vertical profiles

Figures 3 and 4 show the variation of paleomagnetic, petrological and rock magnetic parameters with the vertical position of the samples in the BB and MY lava flows.

The Bausenberg East profile exhibits similar trends for natural remanent magnetization (NRM) intensity and susceptibility, changing from high values near the top to lower values in the middle part and again high values approaching the base of the flow. In the Mayen lava a similar trend is visible but no increase of NRM intensity and susceptibility is seen towards the bottom of this profile, probably because the flow base is still several metres downwards. Intensity and susceptibility variations in these flows correspond to results, e.g., of Petersen (1976). In contrast, NRM intensity and susceptibility in the Bausenberg West profile exhibit irregular, though correlating, variations with depth.

Compared with NRM intensity and susceptibility, the HT oxidation number shows a reversed trend in BB-east and MY, with low values at the top and bottom of the profile and high values in the middle part. Watkins and Haggerty (1965) and Wilson et al. (1968) observed similar variations but, in contrast to our data, a strong correlation of NRM intensity and oxidation state. BB-west lava shows a contrary oxidation trend with high values at the upper and lower margin and low values in the central part of the flow; such variations are in accordance with data obtained by Hargraves and Petersen (1971) and Lawley and Ade-Hall (1971). Vertical variations of the stability parameters Q, MDF and S_{200} (Figs. 3 and 4) show similar trends but no obvious relation with other parameters.

Directions exhibited small variations along the profiles, resulting in parameters k and α_{95} of 111–397 and 1.4°–2.5°, respectively (considering all samples of a flow, even outliers). Minor apparent trends of declination with depth are not really important in view of inclinations $>70°$. Inclinations showed only small and statistical variations along the profiles.

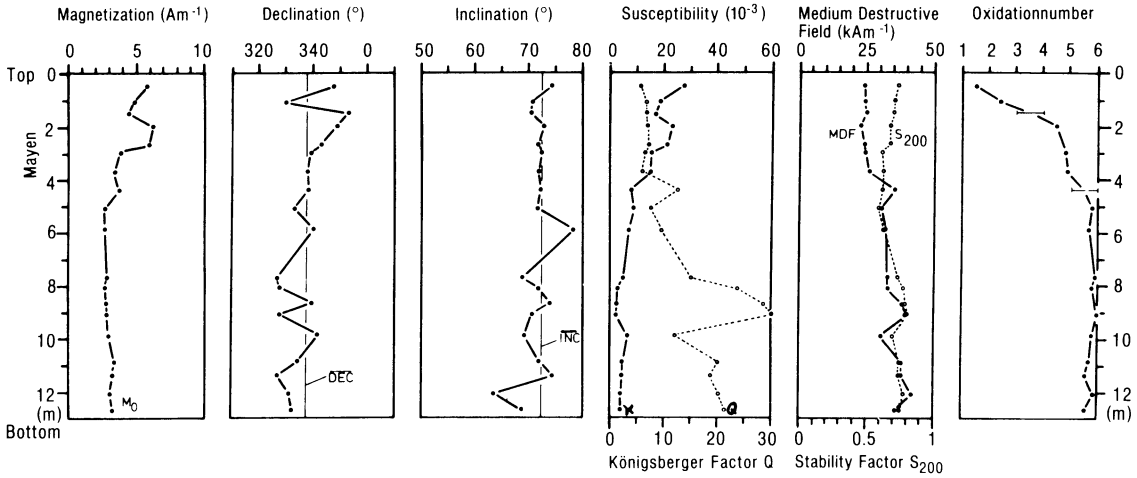

Fig. 4. Variation of magnetic and petrological parameters in a vertical profile of Mayen lava flow. See text for further explanations

Bausenberg, horizontal profile

Along the 225-m profile oxidation state varies largely, showing low values beneath the northern margin and several maxima and minima southwards (Fig. 5). No evident relation is observed with NRM intensity; however, susceptibility exhibits a negative correlation and the stability parameters Q, MDF and S_{200} a positive correlation with oxidation number.

Preliminarily, we may conclude that the four profiles show considerable and partly contrasting variations of most parameters. In some cases a correlation is probable between petrological and magnetic parameters. In particular, this may hold for the profiles BB-east and MY which exhibit similar and marked vertical variations of oxidation degree, NRM intensity M_0, susceptibility χ, with smaller variations of stability parameters. The correlation between oxidation state and M_0 and χ may be due to the increasing replacement of initial TM by less-magnetic and non-magnetic phases with increasing oxidation (e.g. Tucker and O'Reilly, 1980). Alternatively, the correlation may be accidental and the variations of M_0 and χ reflect variations of the volume content of TM. Besides the parallel trend of M_0 and χ, this interpretation is supported by the rather constant coercivity, given by MDF and S_{200}, which is thought to change during HT oxidation (e.g. Strangway et al., 1968; Lawley and Ade-Hall, 1971; Tucker and O'Reilly, 1980). As we have no TM volume content determinations from BB-east, the situation remains unclear. From the MY profile five evenly spaced determinations pointed to nearly constant TM volume content, 3.4 ± 0.6 vol%, favouring the hypothesis of an oxidation related variation of NRM intensity and susceptibility.

Profiles BB-west and BB-horizontal showed much more complex variations of most parameters. This may be due to combined changes of HT oxidation, TM grain size, TM volume content and LT oxidation, which were not determined in sufficient detail.

Hohenfels, vertical profile

The results from the Hohenfels profile exhibit a drastic change of most rock magnetic parameters at about 6 m below the top of the lava (Fig. 6). This level coincides with the transition from the "normal" upper part to the lower layer of porous lava with inclined laminae, and with a marked change of the HT oxidation state of the TM. Highly oxidized phases ($M_{ox} = 5$–6) were found in the upper part of the flow, coinciding with low values of NRM intensity and susceptibility, but high values of the Königsberger factor, MDF, and S_{200}. On the other hand, the bottom part showed low HT oxidation state ($M_{ox} = 1$), obviously causing reversed behaviour of the magnetic properties. The most interesting fact is that here, in contrast to the other lava flows, the paleodirections exhibited a strong trend which cannot be explained only in terms of scatter (Fig. 6). One might argue that these abnormal directions could be due to uncleaned secondary components present in the corresponding specimens. From Fig. 7 it can be demonstrated that this is not the case. Although we admit that the specimens exhibited low coercivities (MDF had values of 3–7 kA/m), the directional behaviour during the demagnetization procedure was univectorial or nearly so, leading to reasonably well-defined characteristic remanence directions.

In the lower part of the flow, most of the non-oxidized titanomagnetites are altered to maghemite at a moderate to high degree which may reduce magnetic stability (e.g. Akimoto and Kushiro, 1969; Merrill, 1975; Manson et al., 1979; Smith, 1987). Ellwood (1981), however, did not find any variability of intensity and directions in magnetically cleaned maghemitized samples compared with unaltered material. Prévot et al. (1981) found a strong dependence of magnetic properties on the grain size in maghemitized rocks, affecting susceptibility, Q factor and coercivity. According to these and other authors (e.g. Johnson and Merrill, 1972, 1974; Merrill, 1975; Heider and Dunlop, 1987), multi-domain TM may acquire a chemical remanent magnetization (CRM) during maghemitization. Since the bottom part contained a fraction of multi-domain grains, theoretically a CRM could have developed here, accounting for the large directional change. Considering the gradual directional change in the profile, this explanation could only be valid if the maghemitization protruded from the transitional zone downwards to produce a CRM recording a period of largely increased secular variation of the geomagnetic field. We regard this possibility as highly improbable.

Further magnetic properties were studied to look for

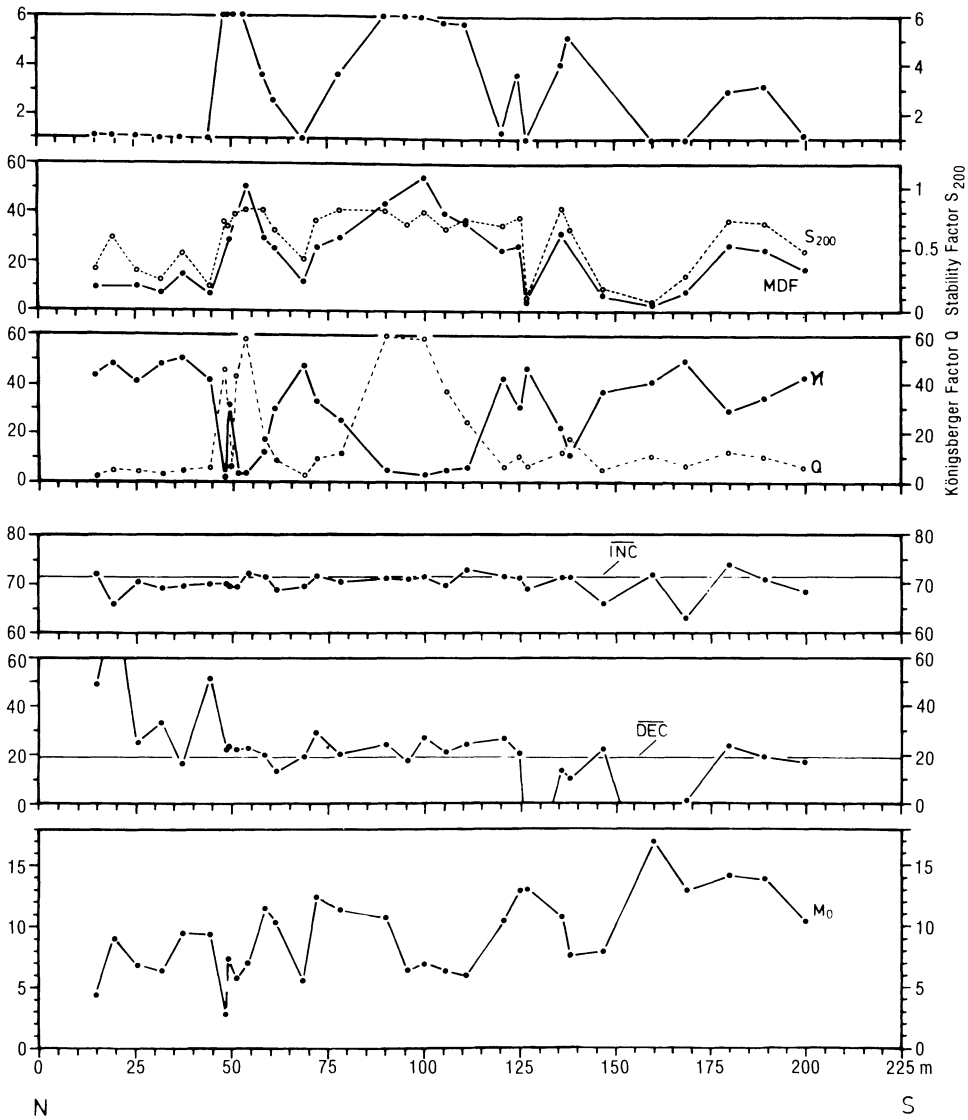

Fig. 5. Variation of magnetic and petrological parameters in a horizontal profile of Bausenberg lava flow, from N to S. See text for further explanations

possible correlations with the directional variations. All specimens were subjected to thermomagnetic analysis. Two distinct types of thermomagnetic curves were obtained, again corresponding to the vertical position (Fig. 8). The upper part exhibited thermomagnetic curves pointing to the presence of two magnetic phases with Curie temperatures T_c around 350° C and 560° C (Fig. 6, points and triangles, respectively). The lower Curie point corresponds to unoxidized TM which were observed in low concentration in the samples. These TM presumably were not maghemitized because of their small grain size (Petersen and Vali, 1987). The higher Curie temperature might be due to the exsolved magnetite of highly HT oxidized TM. Alternatively, it could point to the inversion of maghemitized TM of larger grain size than mentioned above. According to, e.g., Özdemir (1987), titanomaghemite inverts above about 250°–300° C to nearly stoichiometric TM and hematite or other non-magnetic oxides. Overall maghemitization degree should be low in our specimens ($z \leq 0.2$, see Özdemir, 1987) as no pronounced peak of saturation magnetization was observed at temperatures above inversion. The final inversion product had a lower Curie temperature than the first inversion product, and its saturation magnetization at room temperature was slightly stronger than that of the starting material, in agreement with results of Özdemir (1987).

Thermomagnetic curves for the lower part of the profile point to the presence of only one magnetic component with high Curie temperature, which in accordance with ore petrology is TM with low Ti content. As the curves were almost reversible with no indications of an inversion peak or increase of saturation magnetization (Fig. 8), the contribution of maghemite to the specimens magnetic properties must be rather low.

Microprobe studies on unaltered TM grains from specimens of both parts of the flow resulted in almost invariable Ti/Fe ratios of 0.13–0.16 (standard deviation 0.04), pointing to TM compositions of ca. $x = 0.35$–0.40 and Curie temperatures of about 320°–360° C. This agrees only with the lower Curie temperature in the upper flow part, as the lower layer specimens exhibited Curie temperatures typical for

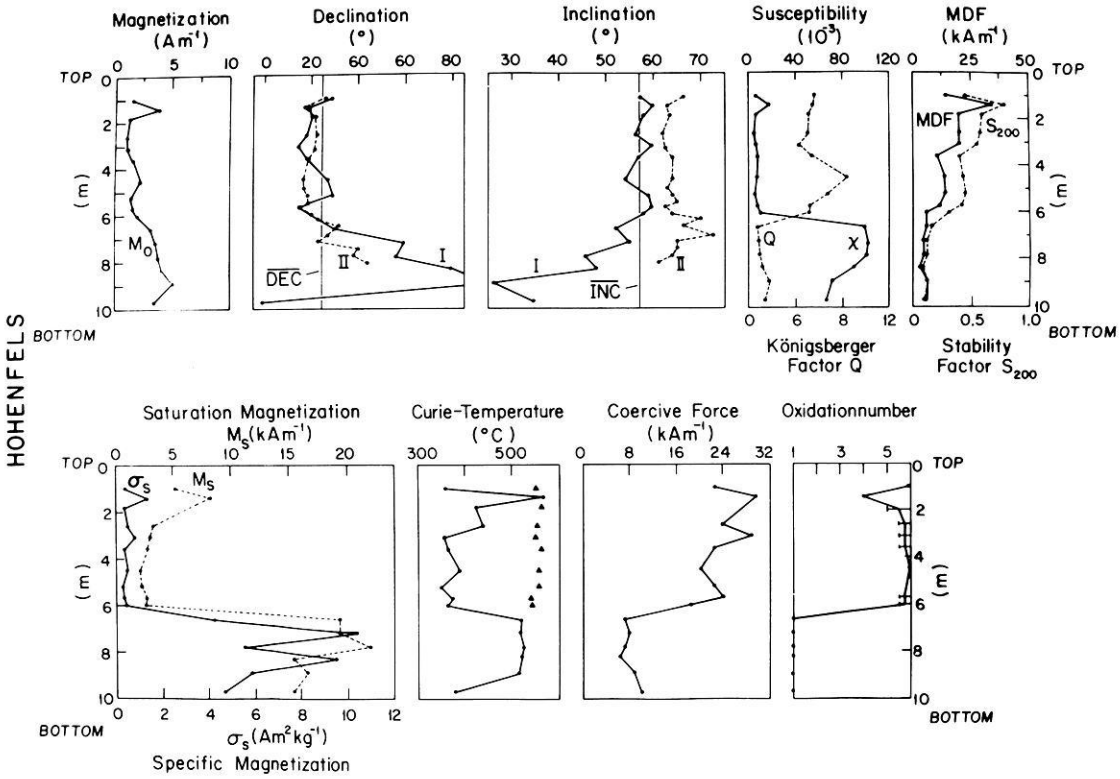

Fig. 6. Variation of magnetic and petrological parameters in a vertical profile of Hohenfels lava flow. Declination and inlcination curves marked with *I* and *II*, respectively, correspond to partly differing profiles sampled during field campaigns I and II. *Triangles* in the Curie temperature diagram indicate high-temperature Curie points. See text for further explanations

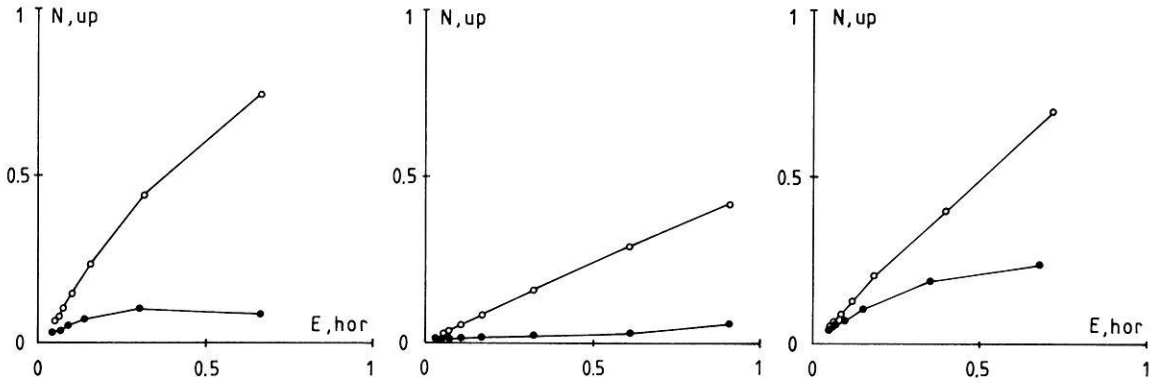

Fig. 7. Orthogonal vector diagrams (Zijderveld, 1967) for samples from the lower part of the Hohenfels profile. *Full* (*open*) *circles* represent the horizontal (vertical) component of remanent magnetization

Ti-poor TM ($x \approx 0$). The only explanation for this contradiction could be that the unaltered TM from the lower part does not represent the bulk magnetic properties.

The specific magnetizations determined with the magnetic balance correlated well with the NRM intensities. All magnetic components present in the specimens contributed to the observed magnetization which, therefore, corresponds to the original thermoremanent magnetization. Saturation magnetization and specific magnetization follow each other quite well in the upper part of the profile; in the lower part they show similar trends but some scatter. This may be explained by the much higher porosity of the lower layer and consequently varying density of the paleomagnetic specimens used for saturation magnetization measurements. Specific magnetization was determined on weighted material.

The changes of specific and saturation magnetization are related to the degree of HT oxidation. This is in accordance with results obtained by Grommé et al. (1969), Lawley and Ade-Hall (1971) and Tucker and O'Reilly (1980), indicating that these properties decrease during HT oxidation by a factor of 5 or more, due to a decrease of bulk TM and a corresponding increase of hemoilmenite.

Coercive force was high in the upper part and reduced by a factor of about 3 towards the base, obviously related to the degree of oxidation. Similar trends were observed by Tucker and O'Reilly (1980).

In order to look for possible inhomogeneities in the

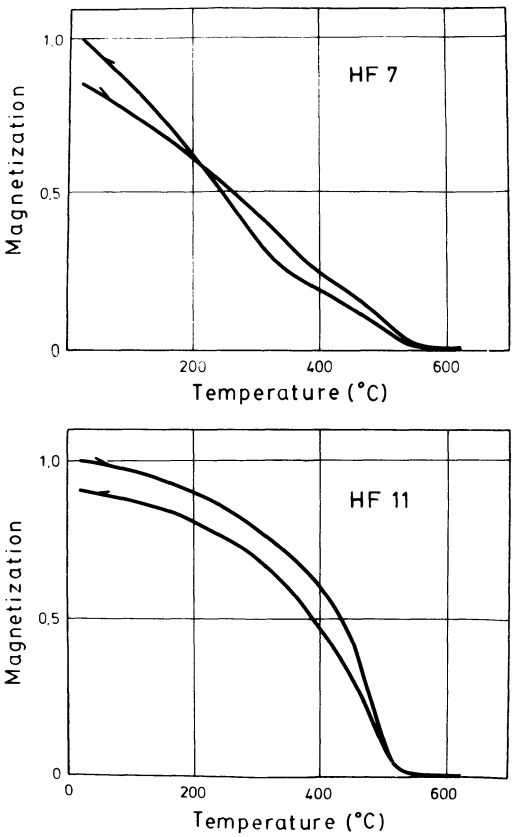

Fig. 8. Typical thermomagnetic curves for specimens from the Hohenfels lava flow

oxide grains, e.g. of the Fe distribution as a result of the migration of Fe ions during the maghemitization process (Petersen et al., 1979; Petersen and Vali, 1987), polished sections were SEM studied. The phase contrast photo (backscattered electrons) for a typical specimen from the lower part of the lava indicates a moderate maghemitization of the titanomagnetite reflected by the contraction cracks traversing the grain (Fig. 9a). The Fe- and Ti-distribution patterns (Fig. 9b and c, respectively) are very regular and exclude the origin of a CRM acquired later because of maghemitization progressing temporally and spatially. Apart from this aspect, the SEM results are very similar to those from the reflected light microscopy. However, the SEM could resolve unoxidized titanomagnetites of very small grain sizes besides highly oxidized titanomagnetites in the upper part of the lava. Maghemitization of the lower part was observed in the SEM, indicated as well by X-ray diffractometry.

Low-temperature variation of saturation isothermal remanence (SIRM) supported some of the above results. During cooling, specimens from the upper part of the flow (Fig. 10 HF 1) showed only a small variation of IRM but a significant decrease during rewarming which is characteristic of exsolved and maghemitized titanomagnetites (Dankers, 1978; Harstra, 1982). Specimens of the lower part (Fig. 9, HF 92), on the other hand, exhibited a strong decrease of SIRM cooling down to −196° C, and the pronounced gradient around −155° C points to the dominance of magnetite. On rewarming remanence recovered only moderately, which indicates an important contribution of multi-domain particles (Levi and Merrill, 1978). This interpretation agrees much better with the observed Curie temperatures than with the microprobe data.

Anisotropy of magnetic susceptibility (AMS) was measured to examine a possible relation with the directional variations. For interpretation we use the maximum, intermediate and minimum susceptibility magnitudes χ_1, χ_2 and χ_3, respectively, and their directions. The susceptibility magnitudes define the lineation factor $L=\chi_1/\chi_2$, foliation factor $F=\chi_2/\chi_3$ and anisotropy degree χ_1/χ_3 (e.g. see Hrouda and Janak, 1971); the latter with values between 1.002 and 1.022. Because of the relation of foliation and lineation, evident from Fig. 11, most specimens are characterized by the presence of more oblate than prolate magnetic particles. The axes of the anisotropy ellipsoids are plotted in Fig. 12 for the two parts of the lava flow. In the upper layer, the directions of the maximum susceptibility axes are well grouped and obviously define a local flow direction to the south. The lower part, in contrast, showed no well-defined anisotropy directions, although the maximum susceptibility directions appear to be mainly deflected to westerly directions. We interpret this phenomenon as the result of a (viscous?) deformation or differential tilting of these parts of the lava after acquisition of remanence, which would also explain the inclined laminae in this layer. The deflection to the west corresponds to a clockwise rotation, which is in accordance with the observed directional trend (Fig. 6). An alternative explanation would be that strain or stress, restricted locally within the lava, has produced the observed deflection of AMS and magnetization directions. Such phenomena are known from folded rocks rather than unfolded young lavas (see review of MacDonald and Ellwood, 1987), therefore we reject this possibility as unlikely.

The idea of a mechanical, rather than rock magnetic or petrographic, origin of the directional change is further supported by the paleomagnetic results obtained from the samples collected during a second field campaign. In the upper part sampling was possible more or less along the original profile, but below a depth of 6 m results come from samples which are displaced 5 m or more horizontally. Declinations and inclinations in this displaced sub-profile showed a similar but much less distinct change with depth. The viscous deformation or differential tilting obviously differed locally, which may correlate with the observed change of laminae orientation. Finally, reference samples taken separated from the profile near the flow base showed remanence directions which are in good agreement with the 'normal' upper layer specimens.

The extreme change of rock magnetic and petrographic parameters between the two parts of the lava flow in this interpretation is due to the complicated origin of the Hohenfels lava. The first outflow produced a low oxidized and slowly cooling layer. In contrast to, e.g., Grommé et al. (1969), high Curie temperatures and high specific/saturation magnetizations here are related to low and not to high degrees of oxidation. Consequently, the TM in this layer have a near-magnetite composition. In the upper part of the flow the TM were much Ti richer, resulting in ilmenite – titanomagnetite (Ti poor) exsolution by means of HT oxidation. This difference in composition may be due to some kind of temporal/spatial magma evolution which did not considerably change the whole rock chemistry but increased the amount of Ti in the later outflow.

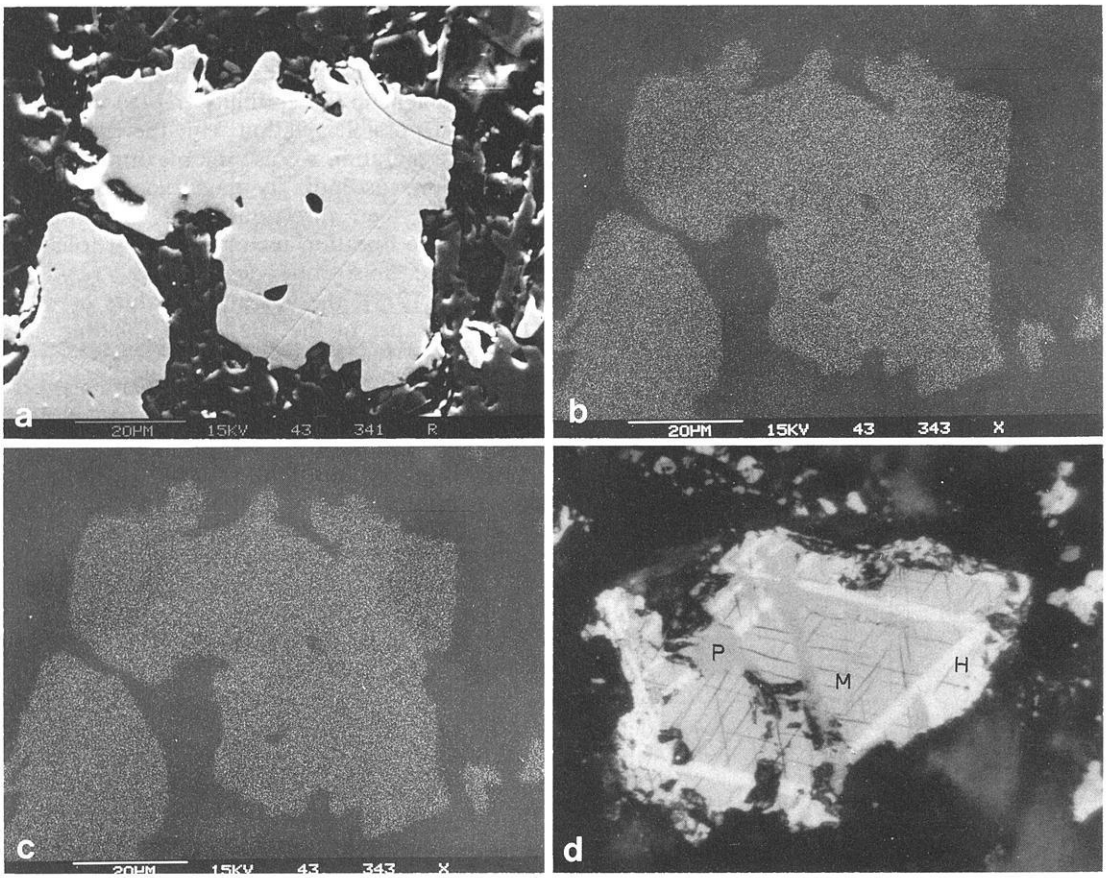

Fig. 9a–d. SEM micrograph (backscattered electron method) of **a** titanomagnetites in a sample from Hohenfels lava flow, and the distribution of **b** Fe- and **c** Ti-cations; **d**: large phenocryst ($d \approx 1$ mm), totally oxidized in the marginal zones to hematite (H) and pseudobrookite (P), with weakly altered titanomagnetite (M) in the centre of the grain

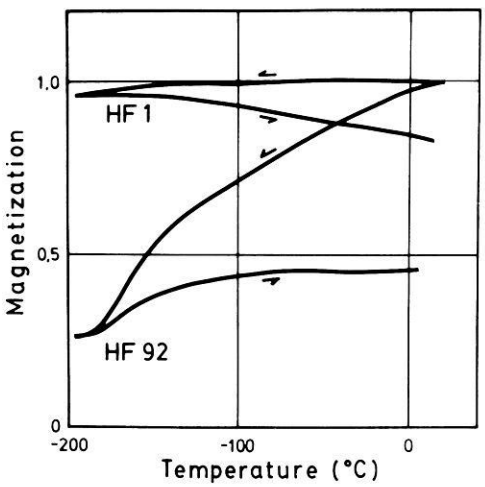

Fig. 10. Variation of strong artificial isothermal remanence (normalized) at temperatures between 20° C and −196° C for typical specimens from the upper (HF 1) and lower (HF 92) part of the Hohenfels lava flow

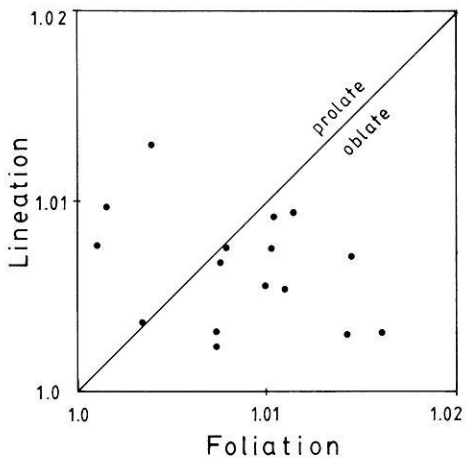

Fig. 11. The relationship between lineation and foliation for specimens from the Hohenfels vertical profile

Discussion

As shown above, the variation of petrological and magnetic parameters differs largely in the lava flows studied, and even varies between profiles of one flow (Bausenberg). Any correlation of magnetic and/or petrological properties derived from only one profile could represent local effects rather than give information about general relationships. We therefore compiled the results from all flows to look for correlations of HT oxidation, stability parameters and dispersion of magnetization directions with other parameters.

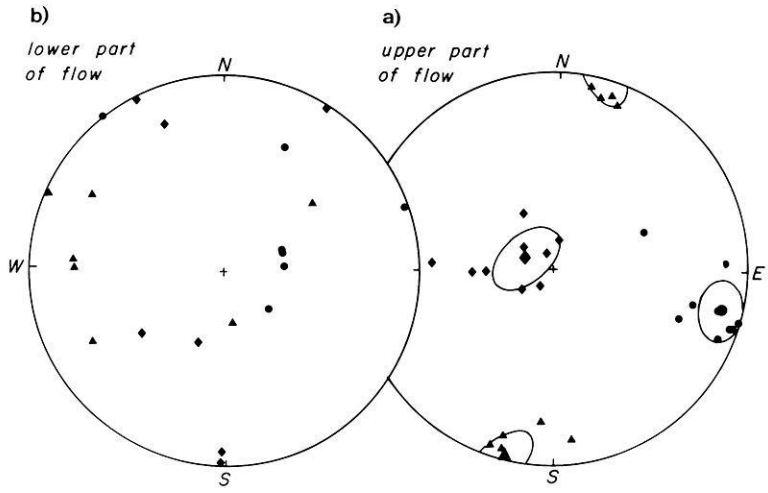

Fig. 12a and b. Equal area plot of magnetic anisotropy axes χ_1 (*triangles*), χ_2 (*full circles*) and χ_3 (*rhombs*) for specimens from **a** the upper and **b** lower part of the Hohenfels lava flow. Mean directions are shown by *bigger symbols*, with their confidence limits

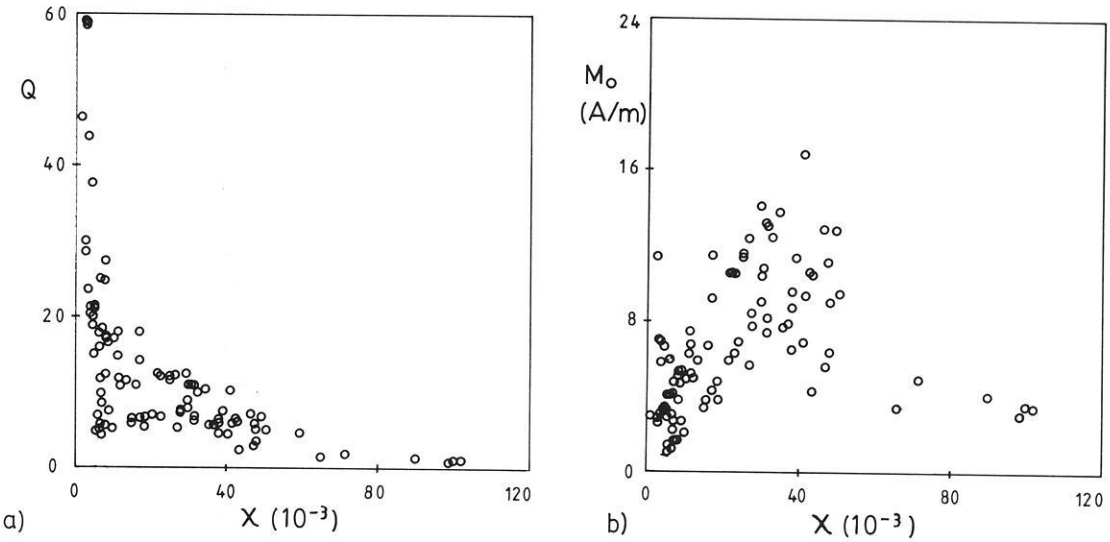

Fig. 13a and b. Relationship between susceptibility and **a** Königsberger factor Q and **b** NRM intensity M_o

Besides other properties (e.g. composition, oxidation degree), remanence intensity and susceptibility both depend on the volume content of TM. Assuming constant grain size and composition, remanence intensity and susceptibility should increase in parallel with volume content. Figure 13b shows such a correlation for low values. Revision of Figs. 3–6 indicates that low values are always associated with high oxidation numbers. Therefore, we believe that low NRM intensities and susceptibilities are due to an increase of weak or non-magnetic phases at the expense of initial TM during HT oxidation. The observed trend from low NRM intensities at high susceptibilities to high intensities at intermediate susceptibilities may be explained in terms of a reduction of the effective grain size during oxidation, resulting in higher coercivity and higher remanence because of exsolution of Ti-poor TM (e.g. Larson et al., 1969; Tucker and O'Reilly, 1980; Kono, 1987).

The Königsberger factor Q exhibits a large initial decrease with increasing susceptibility (Fig. 13a) and supports the above interpretation of reducing grain sizes. For a variation only of the volume content, Q would remain constant. We may conclude that NRM intensity and susceptibility variations are primarily related to other factors than TM content which, also according to microscopic observations, was rather constant.

In Fig. 14b the oxidation number M_{ox} is plotted versus susceptibility. With increasing oxidation, susceptibility first drops sharply and then decreases moderately but continuously. A similar variation was found, e.g., by Wilson et al. (1968) and Lawley and Ade-Hall (1971). The strong initial decrease may be due to stress developing within the grains, and/or incipient exsolution of ilmenite lamellae.

NRM intensity shows rather strong scatter, but an increase is recognizable up to intermediate oxidation numbers, followed by a decrease towards higher oxidation states (Fig. 14a). Similar variations were also found by Tucker and O'Reilly (1980), although our results show rather high NRM intensities for some highly oxidized samples ($M_{ox} \approx 6$). This may be due to the presence of unaltered TM within a highly oxidized ($M_{ox}=6$) surrounding (Fig. 9d), producing a much stronger than expected remanence. Alternatively, very small (≤ 1 μm) non-oxidized magnetites, occasionally observed within mafic phases of the groundmass (which are difficult to determine exactly by ore petrological methods), are responsible for such strong magnetizations.

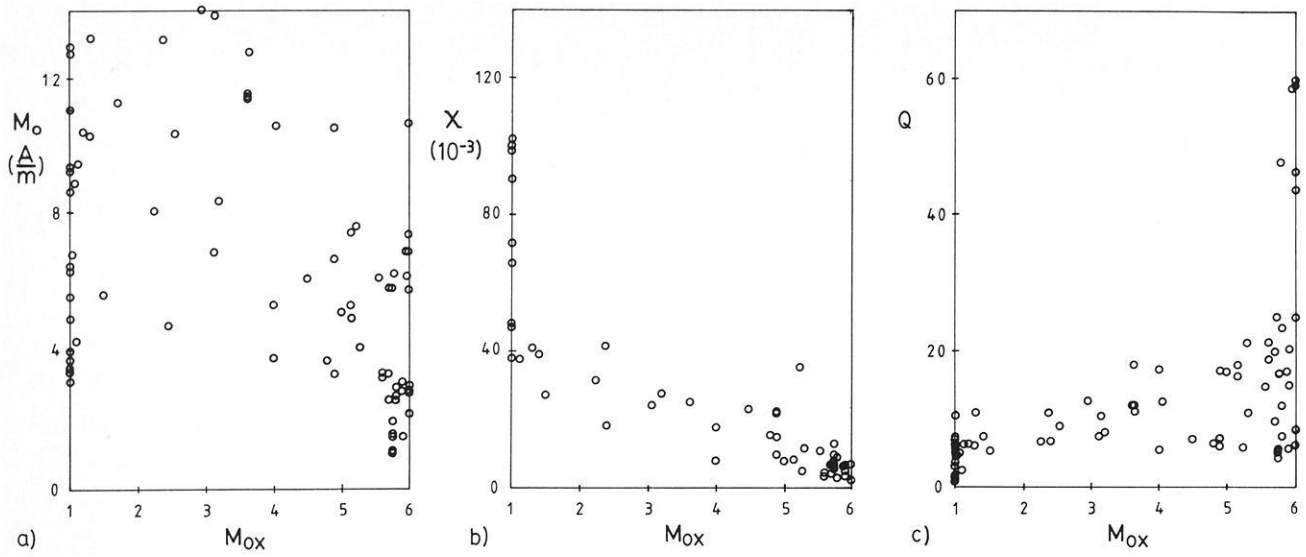

Fig. 14a–c. Relationship between oxidation number M_{ox} and **a** NRM intensity M_o, **b** susceptibility and **c** Königsberger factor Q

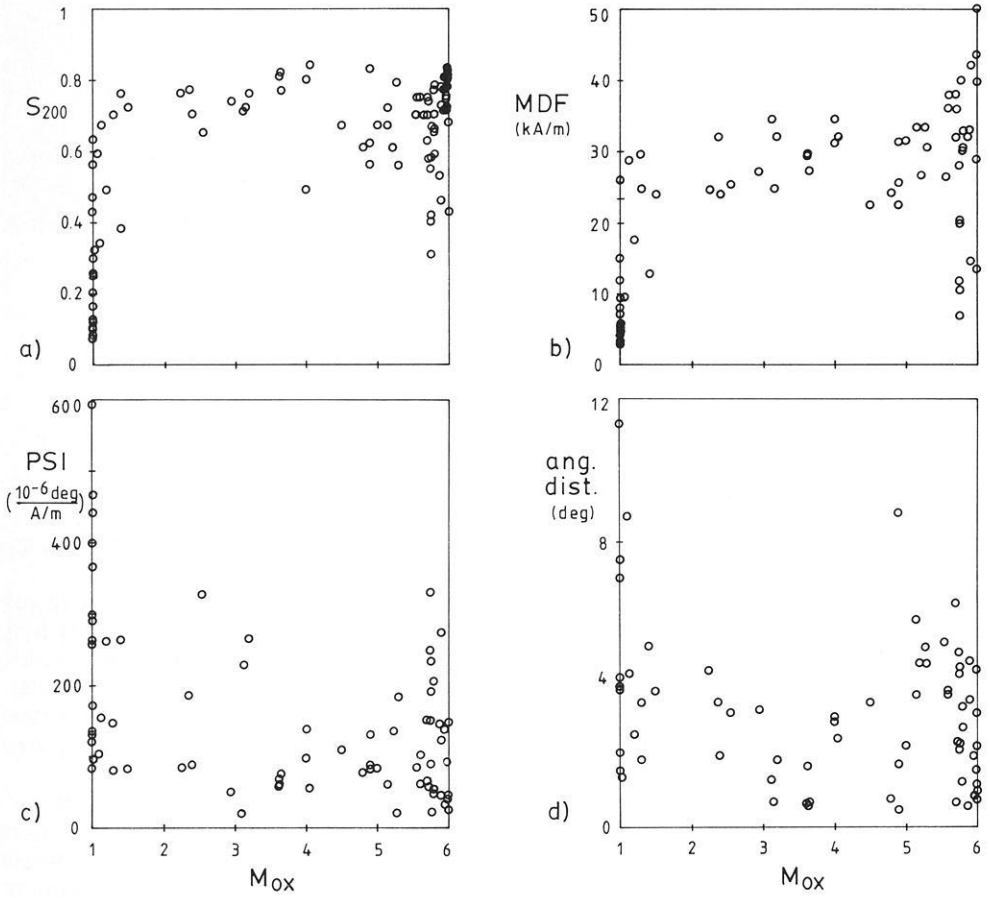

Fig. 15a–d. Relationship between oxidation number M_{ox} and **a** S_{200}, **b** MDF, **c** PSI, and **d** specimen's angular distance from profile mean direction (see text for further explanation)

It should be mentioned here that similar variations of NRM intensity were also observed as a result of LT oxidation (e.g. Petersen et al., 1979; Smith, 1987). Indeed, we have arguments against an important contribution of titanomaghemite to the bulk magnetic properties: according to Smith (1987), the Königsberger factor Q should sharply decrease with LT oxidation. In contrast to that, we observed an increase of Q with oxidation degree (Fig. 14c). This increase may be due to a reduction of the effective grain size (e.g. Price, 1980) and/or to the origin of very small-sized magnetite particles (Tucker and O'Reilly, 1980) with progressing HT oxidation.

Stability parameters S_{200} and MDF exhibit similar variations with oxidation degree (Fig. 15a and b). Stability is low at $M_{ox} \leq 1.5$ with rather high dispersion of S_{200} and MDF values. With increasing oxidation, up to $M_{ox} \approx 5$, stability is high and nearly uniform. For $5 < M_{ox} \leq 6$, MDF and S_{200} remain at this level but dispersion is again high.

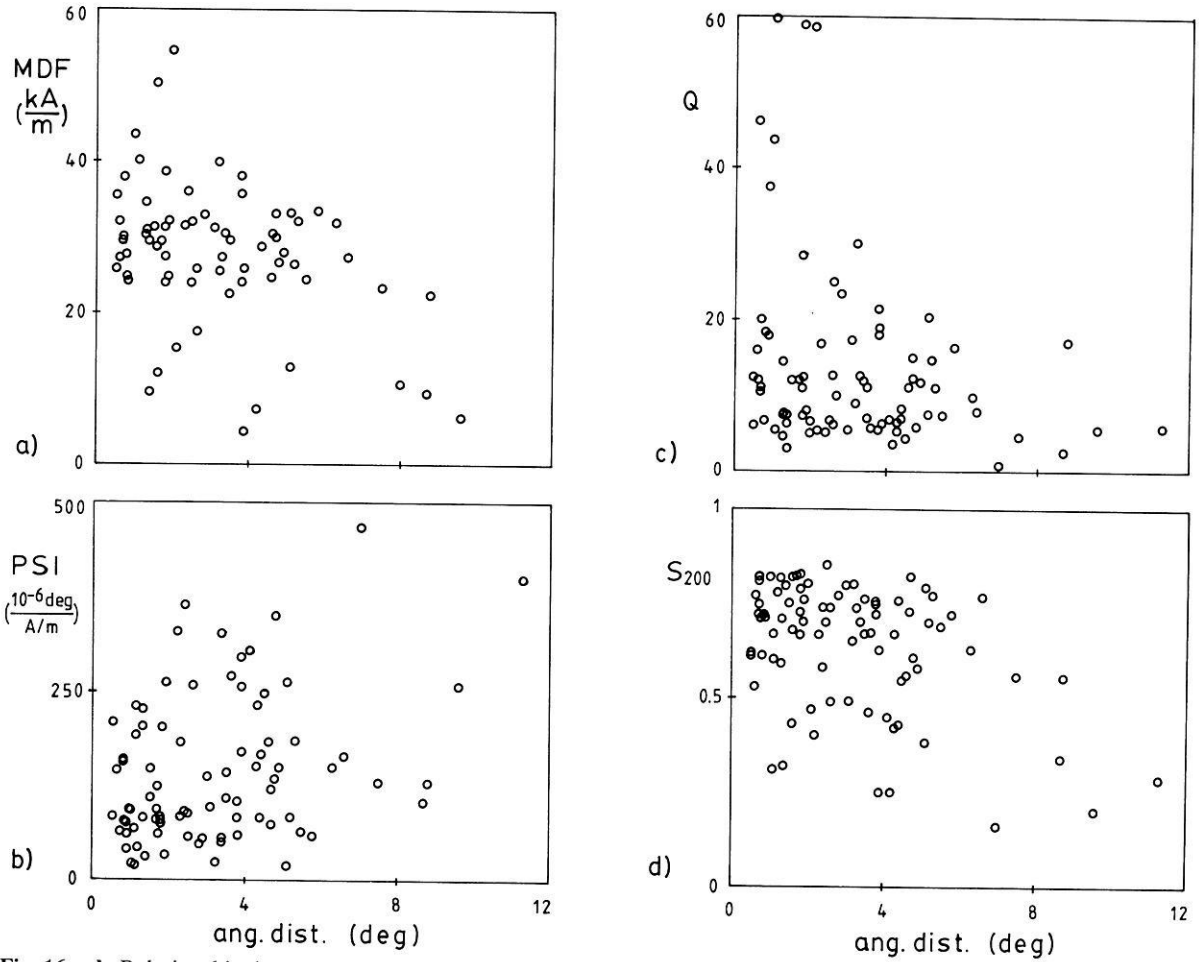

Fig. 16a–d. Relationship between specimen's angular distance from the corresponding profile mean direction and **a** MDF, **b** PSI, **c** Königsberger factor Q and **d** S_{200}

A few highly oxidized samples ($M_{ox} \approx 6$), all from the HF profile, showed nearly as low stability as non-oxidized samples. PSI exhibits a similar but, according to its definition, reversed trend with oxidation as S_{200} and MDF (Fig. 15c). The same highly oxidized samples characterized by low magnetic stability also exhibited low directional stability.

The angular distance of characteristic magnetization to the profile mean is plotted versus M_{ox} in Fig. 15d. Directional dispersion tends to diminish towards intermediate oxidation degrees ($M_{ox} \approx 3.5$) and to increase with further oxidation, probably related to changes in magnetic stability. Figure 16 shows that angular dispersion decreases with increasing MDF, Q, S_{200} and increases with decreasing PSI. Obviously, the directions of magnetically less stable samples deviate most from the profile mean direction. We believe that high-coercivity rocks acquire less secondary magnetizations whose coercivity spectrum may, additionally, be more separated from the thermoremanent magnetization (TRM) spectrum than in unstable rocks. These are favourable conditions for magnetic cleaning of NRM by af demagnetization to obtain the TRM direction.

We may conclude that the variation of magnetic properties, stability parameters and dispersion of paleodirections are related to the HT oxidation state of titanomagnetites. The observed relations are sometimes not marked, which may be due to interference of the measured properties with parameters and properties which are not known for part or even all of the samples or which were not determined quantitatively, such as degree of maghemitization, volume content and grain size of titanomagnetite, and saturation magnetization.

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