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On Chemical Magnetization in Some Permian Lava Flows of Southern Norway

By K. M. STORETVEDT and N. PETERSEN, Bergen[1]

Eingegangen am 23. April 1970

Summary: Thermal demagnetization analysis of the Brumunddal lavas of southern Norway suggests that their original thermoremanent magnetization has been substantially replaced by chemical magnetization of low temperature origin. Haematite is the dominating remanence carrier. Ore microscopy and studies of saturation magnetization versus temperature confirm this conclusion. The estimated magnetite remains constitute less than one per cent of total ore content. A single lava flow and in some cases a single specimen contain three different magnetization components of nearly equal thermal stability. These components are:

1) A reversed component which is supposed to represent the original or Permian field.
2) A reversed component of supposed Mesozoic origin.
3) A normal component which is antiparallel to component 2) and of supposed Mesozoic origin as well.

The Permian component is strongly overprinted by the subsequent magnetization processes. It is concluded that the remagnetization, which in part must have been simultaneously with the tectonism, has taken place below a sedimentary cover of the order of about one kilometer.

Zusammenfassung: Es wurden paläomagnetische Untersuchungen in Verbindung mit erzmikroskopischen Beobachtungen an den permischen Brumunddal Laven (Süd-Norwegen) durchgeführt. Die Analyse der natürlichen remanenten Magnetisierung nach schrittweiser thermischer Abmagnetisierung läßt vermuten, daß die ursprüngliche thermoremanente Magnetisierung weitgehend durch eine chemische Remanenz ersetzt worden ist. Träger der remanenten Magnetisierung ist fast ausschließlich Hämatit. Die erzmikroskopischen Untersuchungen und Messungen der Temperaturabhängigkeit der Sättigungsmagnetisierung bestätigen diese Folgerung. Der Anteil von Magnetit am gesamten Erzgehalt ist weniger als 1 %.

In den untersuchten Laven lassen sich drei verschiedene Komponenten der Magnetisierung von nahezu gleicher Stabilität nachweisen:

1. Eine Komponente mit umgekehrter Magnetisierung, welche wahrscheinlich das ursprüngliche permische Paläofeld wiedergibt.
2. Eine Komponente umgekehrter Magnetisierung, welche ihren Ursprung vermutlich im Mesozoikum hat.
3. Eine Komponente normaler Magnetisierung antiparallel zu Komponente 2., welche vermutlich ebenfalls ihren Ursprung im Mesozoikum hat.

Die permische Komponente ist weitgehend überprägt von subsequenten Magnetisierungsprozessen. Es wird die Folgerung gezogen, daß die Bildung der sekundären Magnetisierung teilweise gleichzeitig mit tektonischen Veränderungen und unter einer Sedimentbedeckung von etwa 1 km stattgefunden hat.

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1. Introduction

The sequence of sandstone and rhomb-porphyry lavas of the Brumunddal area, South Norway, was sampled for palaeomagnetic purposes with the prime intention to provide some more information about the origin of these rocks. However, it became clear even at an early stage of the investigations that the palaeomagnetic record concerned had a much more complex build-up than originally thought. In the lava flows, in particular, it became possible to study the fossil magnetization in fairly great detail, the results illustrating the problem of chemical remagnetization. It is believed that the magnetic complexity as posed by the Brumunddal rocks is not unique for this particular formation but of general importance in palaeomagnetism. Therefore, in this paper we are mainly concerned with remagnetization aspects leaving the geological implications of the findings to a separate account [STORETVEDT 1970b].

2. General geological description and sampling

The Brumunddal area is situated in the northernmost part of the Oslo graben at geographical co-ordinates of approximately 61° N, 11° E. The porphyry-sandstone succession of this region covers a total of 8.6 km^2. The latest and most detailed account on the geology of this formation has been given by ROSENDAHL (1929).

The lower part of the series consists of 4 rhomb-porphyry flows which petrologically are of the same type as the well-known Lower-Permian porphyries that are of wide distribution further south in the Oslo area. Three of the flows have a thickness of about 30 metres while the thickness of the fourth and uppermost one (flow 4) amounts to 100—200 metres. Layers of strongly red coloured sediments (up to 30 metres thick) occur between the lava flows but the major portion of sediments (red-yellow in colour) was laid down after the volcanic activity had come to an end. The preserved stratigraphic thickness of this uppermost sandstone sequence is 600—700 metres.

A rather long time elapsed between the eruption of flows 2 and 3 (the flows are numbered from bottom). During this time a slight tectonism took place but the main tectonic activity in the area, resulting in a general ESE dip of 30—40 degrees, post-dates the sedimentation of the upper-most sandstone.

The lavas and intercalated sediments which are the subject of the magnetic analysis of this paper were collected in a total of 22 oriented hand samples.

The area is strongly covered and suitable sampling sites were difficult to obtain. An exception is the uppermost flow which is extensively exposed in a recent road cut. This exposure represents the uppermost part of the flow. Unfortunately lava No. 2 is missing.

The rock units considered have sample numbers as follows:

Lava 4 (uppermost flow)	Nos. 32—38
Lava 3	Nos. 48—54
Intercalated sediments	Nos. 55—59
Lava 1	Nos. 60—63

3. Thermal demagnetization

Between 2 and 4 specimens from each sample were heated in air (as shown by the magneto-mineralogical results (see chapter 5) air is the most appropriate atmosphere for the rocks concerned) in zero field to progressively higher temperatures. After each heating step the specimens were cooled down to room temperature for measurement with an astatic magnetometer. After having studied the results of a detailed heating procedure on a number of pilot specimens it became clear that the interesting and important changes in the remanent magnetization occurred at the higher temperature ranges. Therefore, the subsequent heatings were largely concentrated on temperatures above 500 °C. In general intensity reduction as well as directional changes are negligible below this temperature. The heatings have been carried out in two different furnaces, a complete heating cycle lasting about one hour in both cases.

Examples of directional and intensity changes of remanent magnetization as a function of increasing temperature are shown in figs. 1—4 (see pag. 572—575). The results of altogether 16 specimens are presented.

It is evident from the figures that the magnetization of the lavas are strongly diverging from what should be expected in such rocks if they were to record the ambient geomagnetic field at the time of extrusion. If a substantial fraction of the original thermoremanent magnetization (TRM) is still preversed one should expect magnetite as a much more dominating magnetism carrier than haematite which in general is only slightly developed (if at all) at the deuteric stage of alteration. Instead, haematite was the only magnetic component which with certainty could be diagnosticated at this stage of investigation (see also chapter 5). An additional indication that magnetite does not play an important role in these rocks is provided in a more indirect way by the evaluation of the directional results obtained after demagnetization to low intensities (2×10^{-6} emu/cm^3—5×10^{-7} emu/cm^3). These directions show in general a so well defined behaviour that one is forced to rule out the presence of significant stray moments acquired during the experiments. Experience throughout some years suggest to the present authors that the natural remanence of magnetite bearing rocks do not in general allow thermal demagnetization analysis of such low intensity ranges unless the zero field cancellation during heating is ideal.

The most abnormal palaeomagnetic property is the presence of both normal and reversed directions of stable magnetization in the uppermost flow collection. Here, the two polarities are of about equal importance and there is no general magnetic stability difference. In addition, thermal demagnetization shows that the magnetization of many specimens is composed of two opposite directions (cf. for instance 36c, fig. 2). Thus, at a few tens of degrees below the Curie-temperature of haematite, 670 °C, normally magnetized specimens may become reversely magnetized while originally reversed specimens may change their magnetization directions towards a normal polarity. Such opposite polarity components appear in general during the analysis of the last few per cent of the remanence intensity. In the uppermost flow the groups of

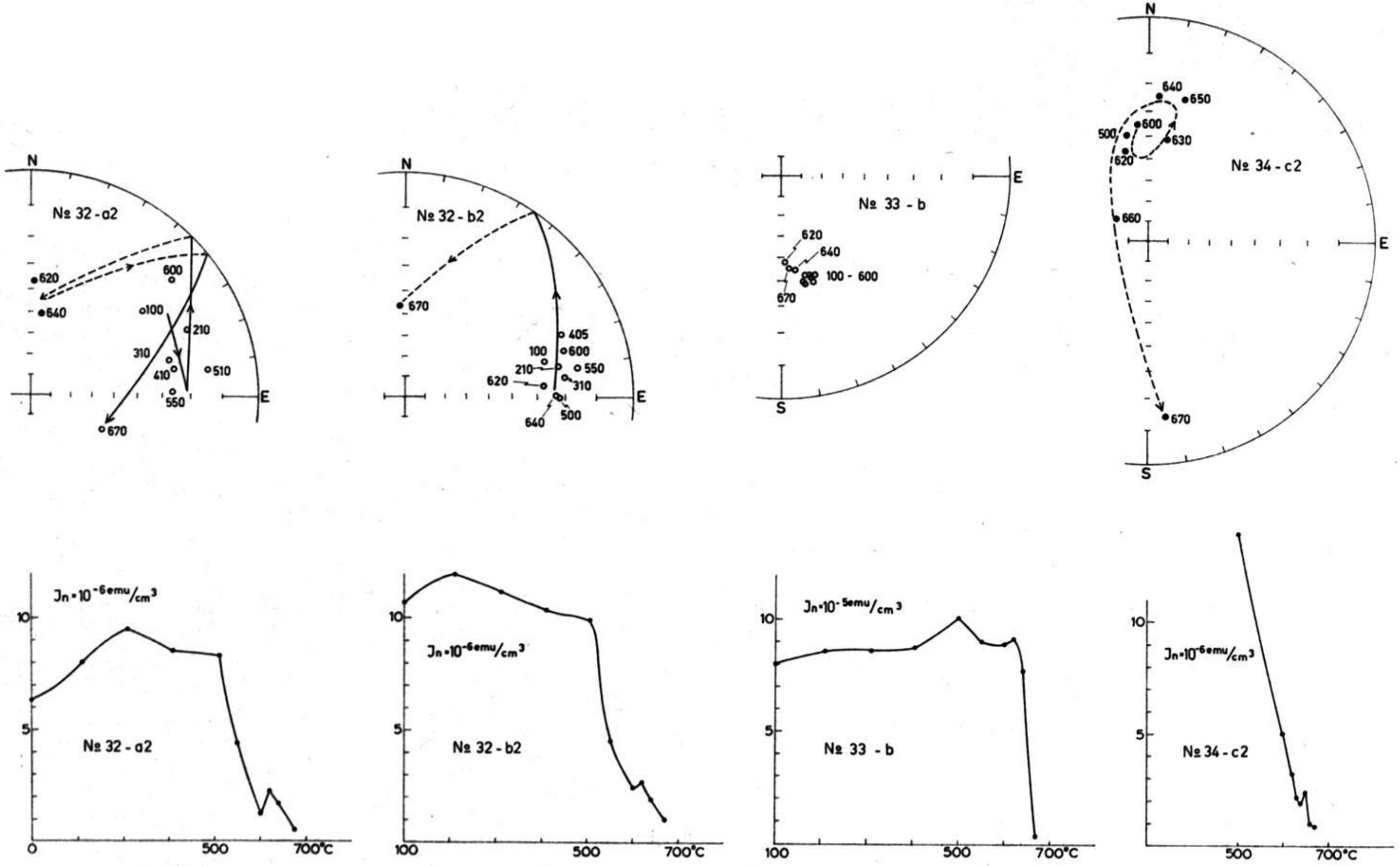

Fig. 1: Examples of remanent magnetism behaviour as a function of temperature. Directions are without tectonic correction. Full symbols are used for downward inclinations and open symbols for upward inclinations.

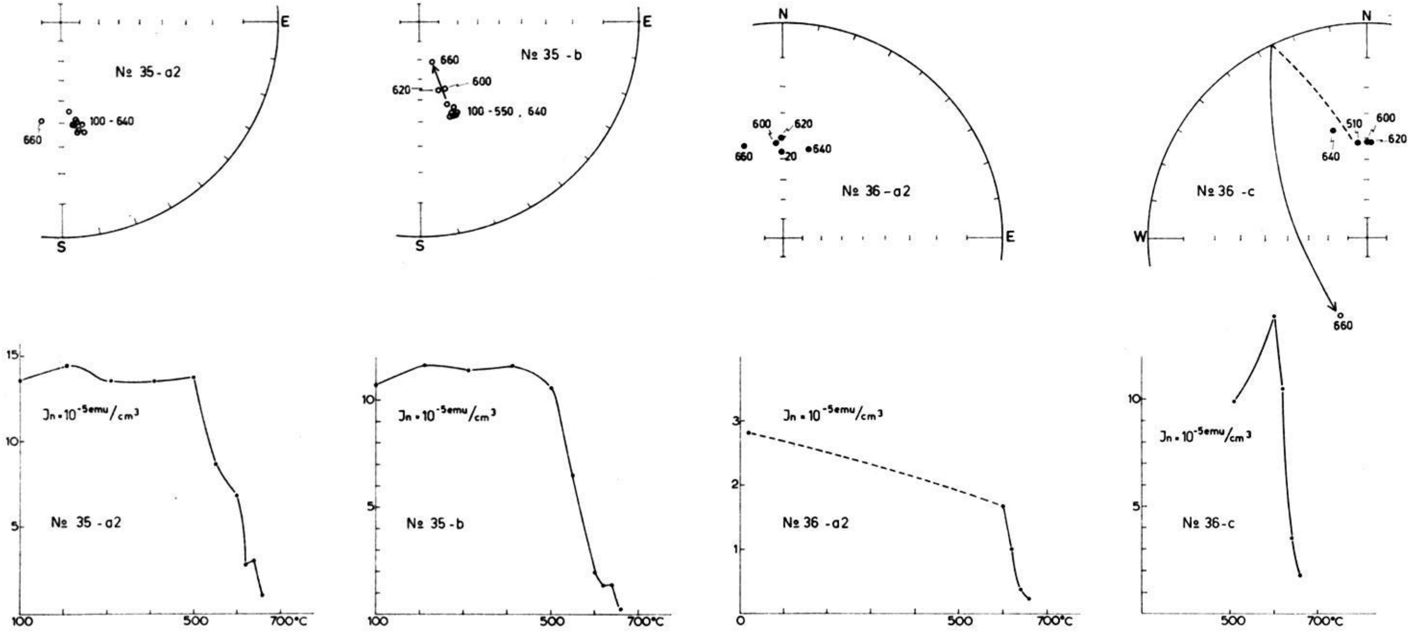

Fig. 2: Examples of remanent magnetism behaviour as a function of temperature. Directions are without tectonic correction. Full symbols are used for downward inclinations and open symbols for upward inclinations.

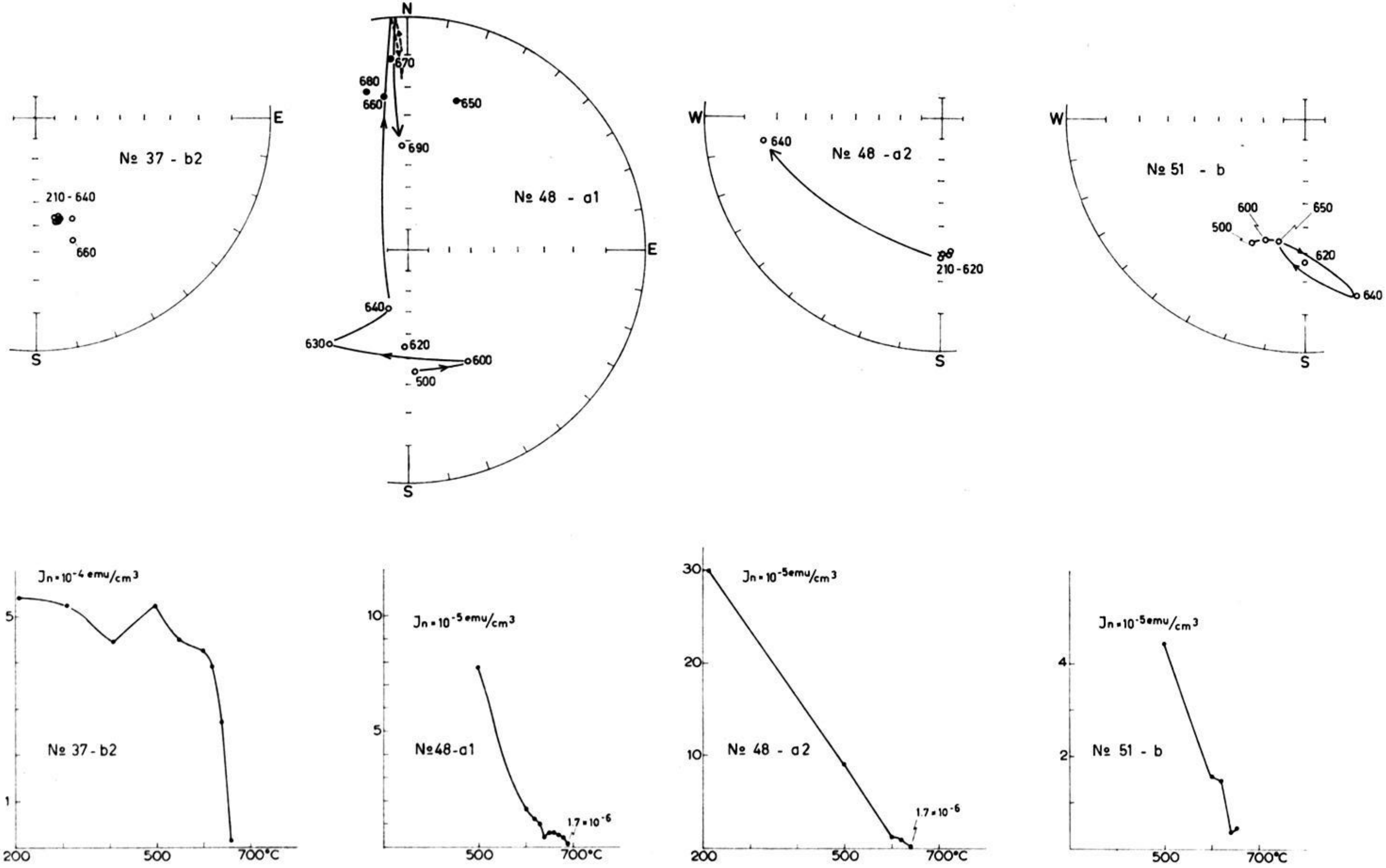

Fig. 3: Examples of remanent magnetism behaviour as a function of temperature. Directions are without tectonic correction. Full symbols are used for downward inclinations and open symbols for upward inclinations.

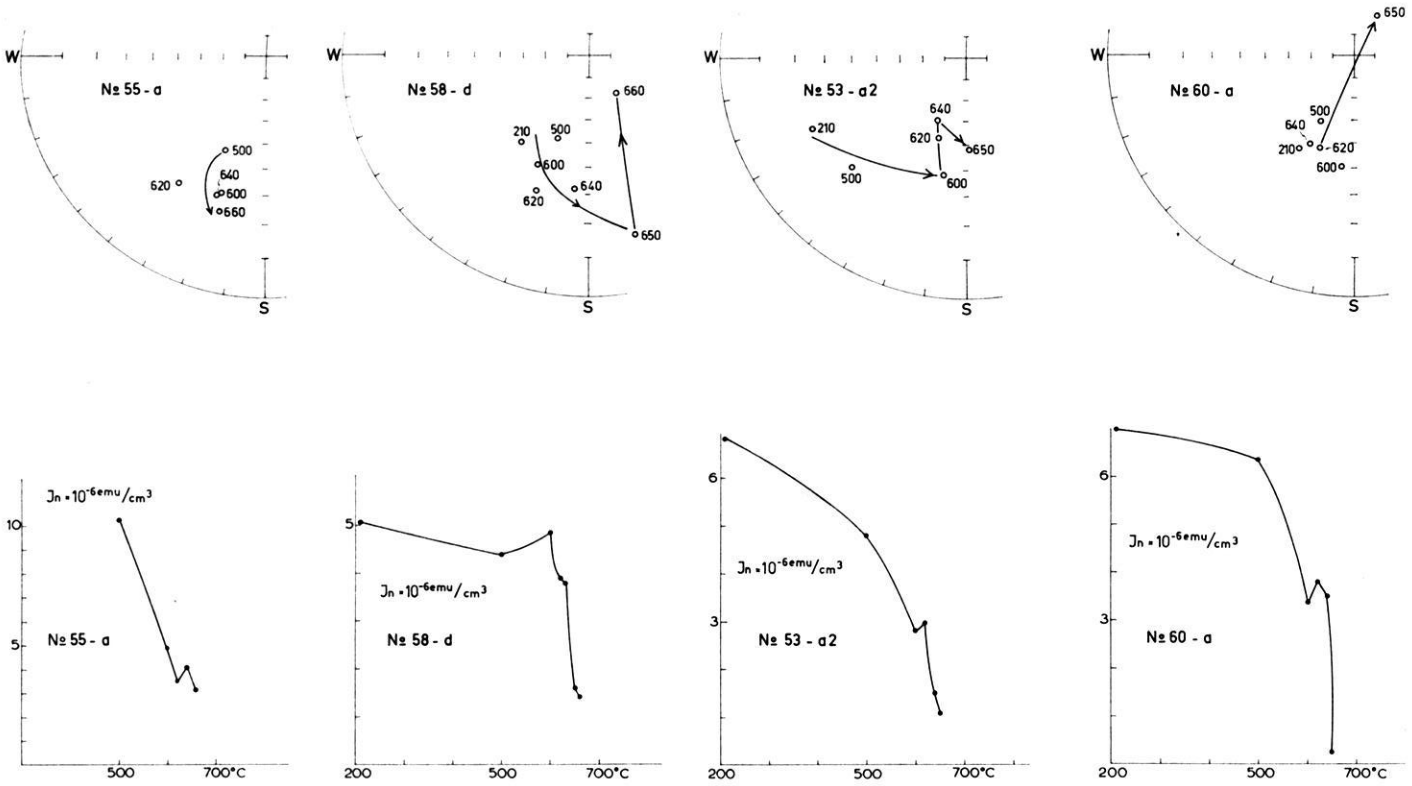

Fig. 4: Examples of remanent magnetism behaviour as a function of temperature. Directions are without tectonic correction Full symbols are used for downward inclinations and open symbols for upward inclinations.

directions (only specimens with well defined magnetization directions are considered) are antiparallel to within about 3 degrees (cf. fig. 5).

The remanent magnetization at lower stratigraphic levels is somewhat different from that of flow 4. Firstly, the reversed polarity magnetization is now entirely dominating, the existence of a normal component being only recognized through the directional changes of some specimens when demagnetized to higher temperatures (cf. for example 48al, fig. 3). Secondly, the magnetization of the lavas and sediments below flow 4 have a well defined spread of the magnetization directions towards shallower inclinations. This characteristic feature is shown both in the distribution of stable bulk magnetization (flow 3) as well as in systematic direction changes on demagnetization (cf. 55a and 58d of fig. 4). In the uppermost flow the tendency of obtaining the reversed component with the most shallow inclination is only observed in a few specimens.

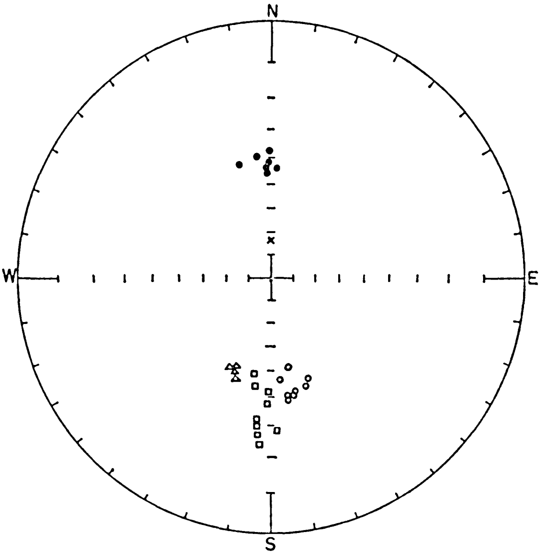

Fig. 5: Directions of stable bulk magnetization of separate specimens (cf. text). Only specimens with well defined magnetization directions (no systematic direction changes associated with the upper 90 per cent of remanence intensity) are included. Circles (open or closed) represent flow 4 specimens (results from six samples), squares are flow 3 data (results from five samples) and triangles are data from flow 1 (results from one sample only). The cross gives the direction of present axial dipole field at locality. Data are without tectonic correction.

The stable bulk magnetization directions are given in fig. 5. Each plot is a characteristic specimen direction (the direction normally encountered in palaeomagnetic papers) obtained by averaging the magnetization directions for a number of demagnetization steps. The directional estimates thus obtained must not be considered as representing a single magnetization direction but rather as a resultant of different directions. The observed direction changes at temperatures close to the Curie-temperature of haematite (low intensities) are interpreted as a splitting of this composite magnetization. As the blocking temperature of the different components seems to be largely overlapping one is not able to estimate any of the separate components with reasonable certainty. These high temperature directions are therefore set aside in the estimates of mean specimen directions given in fig. 5. On the other hand the majority of specimens investigated showed a remarkably well defined magnetization below about 600 °C. Several specimens (such as 55 a, 58 d, 48 al etc.) do not have a sufficiently well defined direction of bulk magnetization to be included in fig. 5. Nevertheless, also the latter specimens confirm the complex magnetization build-up as revealed by the more stable ones.

4. Interpretation of demagnetization data

Thermal demagnetization suggests that a single lava flow as well as a single specimen may contain up to three stable magnetization components. Their relative abundance may vary greatly. Because of this complexity and the fact that all components seem to be associated with haematite, it appears plausible to assume that the essential part of the original thermoremanent magnetization has been replaced by magnetizations of chemical origin (see also chapter 5).

As will be discussed in greater detail below the time span concerned in these processes seems to involve field reversals as well as relative polar wandering. This means that low temperature oxidation processes may be considered to have played an important role in the magnetization history of the Brumunddal lavas. Under such conditions it will be unrealistic to consider magnetization directions as palaeomagnetic spot readings. Even a single specimen is likely to represent the geomagnetic field over a very long time span and, provided no complications from field reversals or relative polar wandering are present, the magnetization of such a small piece of rock do certainly correspond much better to an ancient dipol field reading than to a palaeomagnetic spot reading.

As there are reasons for believing that the Brumunddal porphyries are of the same age as the porphyries in the district around Oslo, i. e. of Lower Permian origin, it is pertinent to ask whether any magnetization remains corresponding to this time can be traced. According to the foregoing such a possible component could either be associated with deuteric haematite or with haematite acquired by low temperature oxidation before any further relative polar wandering had become significant.

The characteristic magnetization of the uppermost flow as shown in fig. 5 is unlikely to represent the Permian field for two reasons. Firstly, the occurence of two polarities of magnetization is unknown for this period and secondly the pole position as calculated from these results after applying tectonic correction (tectonism occurred long after lava eruption), 129E, 54N (cf. table I), is anomalous compared with other Permian pole position of Europe. However, if remagnetization is as strong as the demagnetization experiments may indicate one should assume that any early Permian magnetization had a greater chance to survive in the lower parts of the succession. The reason for this may at least be twofold. Firstly, the older flows may have reached their ultimate oxidation stage at an earlier date than the uppermost flow, and therefore the magnetization of the latter one could be more strongly affected by later field changes. Secondly, the uppermost flow would be more strongly affected by post-eruption surface weathering than stratigraphically lower levels. Thus, flow 4 which has an average thickness of about 150 metres would provide a shielding effect on the under-lying rocks.

Whatever the explanation may be there is a difference between flows 3 and 4 as far as the directions of magnetization are concerned. In flow 3 the importance of a normal component is considerably diminished while the evidence of a second reversed component (with a shallower inclination) becomes stronger. However, because of an apparent overprint by later magnetizations, along steeper magnetization axes, the direction of this latter component can only be estimated very loosely (the suggested chronological sequence of these magnetizations is in harmony with the palaeomagnetic observations for Europe, i. e. the inclination of the axial dipole field is gradually increasing as one approaches the present time). From fig. 5 one can postulate a tectonically uncorrected magnetization direction of 180, —20 for the earliest (most shallow) component. An inclination of —20 degrees is probably an underestimate but thermal demagnetization results never give inclinations below —15 degrees. An average magnetization direction of about 180, —15 would, after tectonic correction, give a pole position corresponding fairly well to the Permo-Carboniferous field for Europe as recently suggested from the results of two dike systems, the Great Whin Sill [STORETVEDT and GIDSKEHAUG 1969] and the Kristiansand diabases [HALVORSEN 1970]. It is now suggested that the palaeomagnetic data from these dikes (W and Kr in fig. 6) are more reliable than the results from the Permian lavas because the latter rocks seem to pose the same general remagnetization problems (though not so well pronounced) as encountered in the Brumunddal formation [STORETVEDT 1970a].

Nevertheless, it appears reasonable to conclude that a magnetization component of Permian origin can be traced in the lower parts of the considered rock sequence being nearly extinct in the uppermost part of flow 4.

The characteristic magnetization directions of flow 4 constitute two nearly exactly antiparallel groups. The axis of magnetization is significantly different from that of the present day. It seems likely to assume that the geomagnetic field which affected the remanent magnetization of the uppermost flow (No. 4) so significantly, represents the last palaeomagnetic field axis of importance in the magnetization history of these rocks (there is no evidence of stable magnetizations imposed in more recent periods). By that time the oxidation of magnetite into haematite might have been completed whereby further chemical magnetization components became much more difficult to

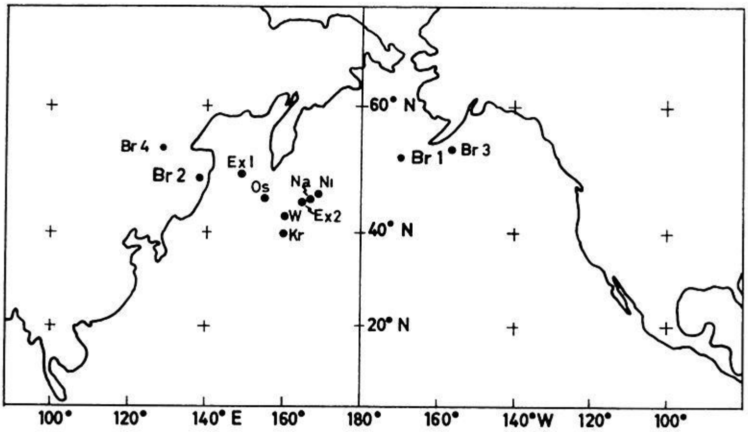

Fig. 6: Palaeomagnetic poles for Europe deduced from Permo-Carboniferous rocks which at least have been cleaned for low stability components. The rock formations concerned are: The Exeter lavas, Ex 1 and Ex 2 [Zijderveld 1967, Cornwell 1967], the Nideck volcanics, Ni [Roche et al. 1962], the Great Whin Sill, W [Storetvedt and Gidskehaug 1969], the Kristiansand diabases, Kr [Halvorsen 1970], the Oslo volcanics, Os [Van Everdingen 1960] and the Nahe volcanics, Na [Nijenhuis 1961]. The different pole positions given for the Brumunddal lavas (Br) are according to table 1.

impress. An alternative explanation of the apparent sharp cut-off of remagnetization processes may have been changes in climatic conditions for instance associated with the breaking up of the northern continents which apparently initiated at this time.

When two polarities of magnetization are present in a single specimen one should in general expect deviating directions (cf. 32a2 and 32b2 in fig. 1) as the components involved may not be exactly antiparallel. The resultant direction can be extremely stable as the different components may be of nearly equal stability. Therefore, in a case of chemical remagnetization an estimate or indication of a palaeomagnetic field can be quite troublesome; any answer has to be sought at low intensity levels close to the Curie-temperature of haematite. The general problem is illustrated in sample No. 32. However, apart from this sample no deviating or intermediate directions occur. This may be due to the following reasons:

a) One of the components, normal or reversed, is entirely dominating.

b) The two polarity components are of comparable strength but very closely antiparallel. Such an antiparallelism may occur if each component became acquired over a sufficient length of time to approximate the corresponding axial dipole field. Relative polar wandering must be insignificant.

Whatever the explanation may be the magnetization of flow 4 is likely to represent that of an ancient axial dipole. Based on the evidence of two polarities of magnetization together with a palaeo-inclination of about 25 degrees steeper than that estimated for the Lower Permian one feels tempted to suppose that a Mesozoic magnetization is considered. The immediate problem is, however, that neither the pole position based on a tectonically uncorrected magnetization nor that based on a corrected one falls into a suggested trend of relative polar wandering for Europe. On the other hand if one applies only half of the tectonic correction the estimated pole is in good agreement with the majority of Triassic palaeomagnetic poles for Europe.

Table I: Summary of results of stable bulk magnetization. *K* is the precision parameter of FISHER [1953].

Rock unit	Number of specimens	Direction of stable remanence		*k*	Pole no.	Pole position in present grids		Remarks
All lavas, uncorrected	29	180.5	−40.7	50	Br 1	52.2 N	169.7 W	Normal directions reversed when calculating mean direction
All lavas, corrected	29	217.2	−45.4	41	Br 2	47.8 N	137.7 E	
Flow 4, uncorrected	14	171.9	−42.8	168	Br 3	53.4 N	156.7 W	
Flow 4, corrected	14	219.2	−54.2	177	Br 4	53.8 N	129.3 E	

Table II: Summary of remanence polarity (normal or reverse) and type of inhomogeneity (lamellar or pockmark) in the Brumunddal lava samples. With one exception all samples containing ore grains with the lamellar structure are reversely magnetized.

Sample No.	Type of inhomogeneity	Polarity
32	P	N
33	L/P	R
34	P	N
35	L	R
36	L/P	N
37	L/P	R
38	P	R
48	L	R
49	L/P	R
52	L	R
53	P	R
54	L	R
63	P	—

Table I summarizes the palaeomagnetic results from the Brumunddal lavas (the intercalated sediments did not have sufficiently well defined magnetization) together with adequate polar estimates. These polar estimates in relation to other Permo-Carboniferous results for Europe are shown in fig. 6.

The important conclusions derived from this consideration are firstly that chemical remagnetization in the Brumunddal lavas continued at least into the Lower Mesozoic. Secondly, the remagnetization were in part simultaneous with tectonism. As the tectonic activity post-dates the sedimentation of the uppermost sandstone sequence the chemical alterations must have been operating through a sedimentary cover of the order of one kilometer.

5. Magneto-mineralogical investigations

A. Ore microscopy results

Polished sections of almost all samples have been studied under the ore microscope. The average ore content of the flows concerned is as follows:

Flow 1	10 volume %
Flow 3	9 volume %
Flow 4	11 volume %

Assuming a density of 5 for the ores and 2.5 for the silicate matrix an ore content of 10 volume % corresponds to about 18 weight %.

The ore mineralogy of the flows is very similar. All samples contain two sets of ore grains. The first set has an average grain diameter of 400 μ, while that of the second set is 40 μ. Fig. 7 shows the distribution of the ores in the silicate groundmass. All the ore grains are extremely inhomogeneous. Their shape, however, gives strong indication that they originally were titanomagnetite and to a small extent separate ilmenite. These primary phases are now completely transformed into a mixture which appears to be mainly haematite and rutile. Although the grains in all samples consist of the same mineral assemblage (haematite and rutile) one can, based on the texture of inhomogeneity within the grains, distinguish between two groups:

a) The "lamellar type". In these samples the ore grains consist of well developed lamellae systems. The structure of these lamellae resembles exsolution phenomena in titanomagnetite as they are developed for instance in basalts. A closer inspection under high magnification shows, however, that these lamellae are inhomogeneous as well, consisting of an extremely fine-grained intergrowth of haematite and rutile. A typical example is shown in Fig. 8. However, some grains of the lamellar type contain relics of a spinel phase (presumable exsolved primary titanomagnetite). An example of this latter case is given in Fig. 9. The total content of these spinel relics within an ore grain is less than 1%.

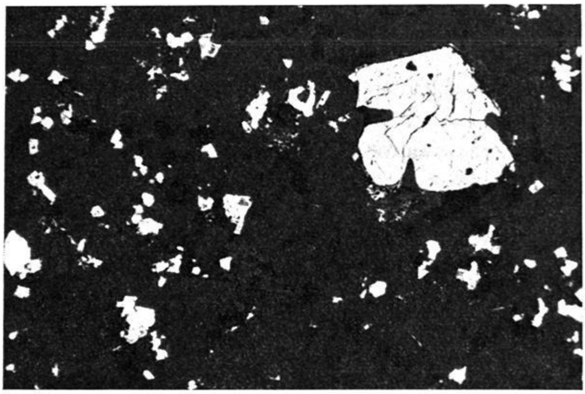

Fig. 7: A typical example of the distribution of ore grains (white) in the Brumunddal rhomb porphyry lavas. Magn.: 80×.

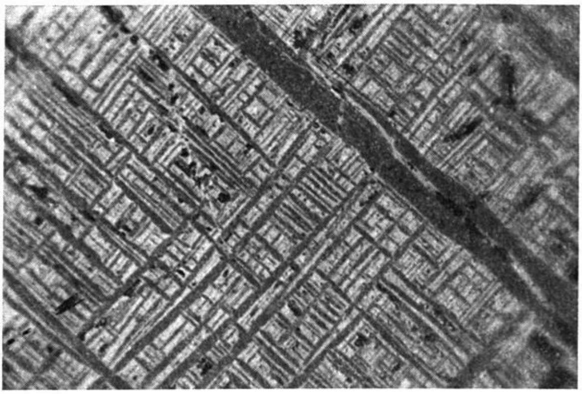

Fig. 8: An ore grain in sample No. 35. A complete pseudo-morphism of rutile (grey) and haematite (white) after ilmenite and exsolved titanomagnetite has taken place. The original exsolution structure is preserved. Magn.: 1200×, oil immersion.

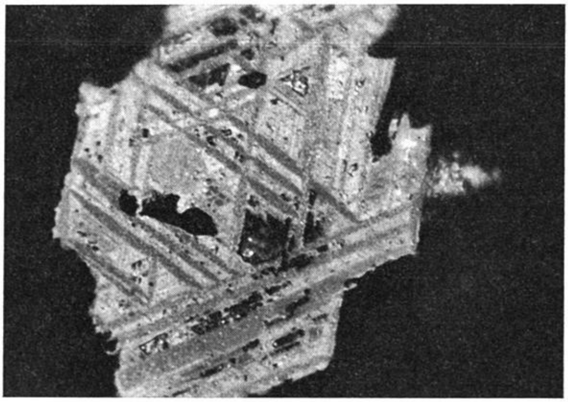

Fig. 9: Ore grain in sample No. 35. In addition to the general mixture of rutile (grey) and haematite (white) some relics of exsolved titanomagnetite (dark grey) can be observed in the centre of the grain. Magn.: 1200×, oil immersion.

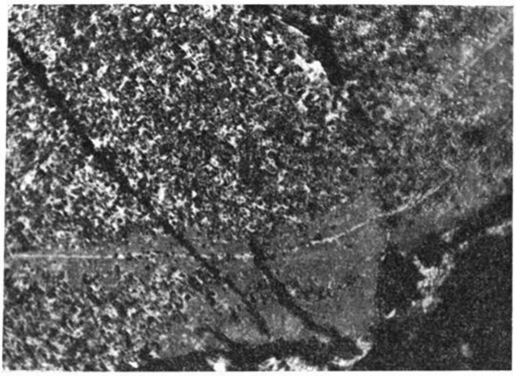

Fig. 10: Ore grain in sample No. 32. This is a typical "pockmark type" example. Irregular and extremely fine intergrowth of probably haematite (white) and rutile (grey). Magn.: 1200×, oil immersion.

b) The "pockmark type". These grains are characterized by an irregular inhomogeneity, the polished surfaces resembling pockmarks. Fig. 10 is a typical example of this type. The grains consist of the same material as in those of the lamellar type, i. e. a fine-scale mixture of haematite and rutile. Grains which are of the typical "pockmark type" do not contain any relics of a spinel phase. This latter observation has also been confirmed by measurements of saturation magnetization versus temperature (see below).

B. Temperature dependence of saturation magnetization

The saturation magnetization, I_s, as a function of temperature has been measured with a translation balance in an applied field strength of 8000 Oe. The measurements were carried out in air. The shape of the curves thus obtained suggests a distinction between two groups of samples:

a) Samples with two different Curie temperatures, one about 670 °C, the other about 570 °C. The former Curie point corresponds to that of haematite, the latter to that of magnetite (according to CREER and PETERSEN [1969] this magnetite is probably exsolved titanomagnetite). Heating and cooling curves are reversible at temperatures above 570 °C. Below this temperature the curves are distinctly irreversible, the cooling curve lying below the heating curve. Haematite is stable in air and this fact accounts for the reversibility of the heating and cooling curves above 570 °C where magnetite is in a paramagnetic state. Magnetite is very unstable in air at the temperatures concerned, being gradually oxidized to haematite which has a much smaller spontaneous magnetization than magnetite. Specimen nos. 35-b and 48-cl of fig. 11 are examples of this type of $I_s - T$ behaviour. Most samples with two Curie points are of the "lamellar type". In all, the $I_s - T$ curves confirm the microscopic evidence that magnetite (probably exsolved titanomagnetite) may still be present in these rocks but in an extremely small proportion.

b) Samples with a single Curie temperature around 670 °C. Specimen no. 34-bl in fig. 11 is an example of this type. Heating and cooling curves are reversible, indicating the absence of magnetite. The only magnetic component in these samples is obviously haematite. All samples of this group belong to the "pockmark type".

C. Amount of magnetic substances in the ore grains

If one assumes that the magnetic components have been saturated in 8000 Oe the amount of haematite and magnetite can be estimated. Samples that contain only haematite as magnetic mineral component have a saturation magnetization of about $5 \cdot 10^{-2}$ emu/g at room temperature. As the saturation magnetization of pure haematite is $5 \cdot 10^{-1}$ emu/g the haematite content must be around 10 weight %. As the total ore content determined microscopically is 18 weight % the magnetic measurements indicate that one average haematite occupies about 50% of the ore grains.

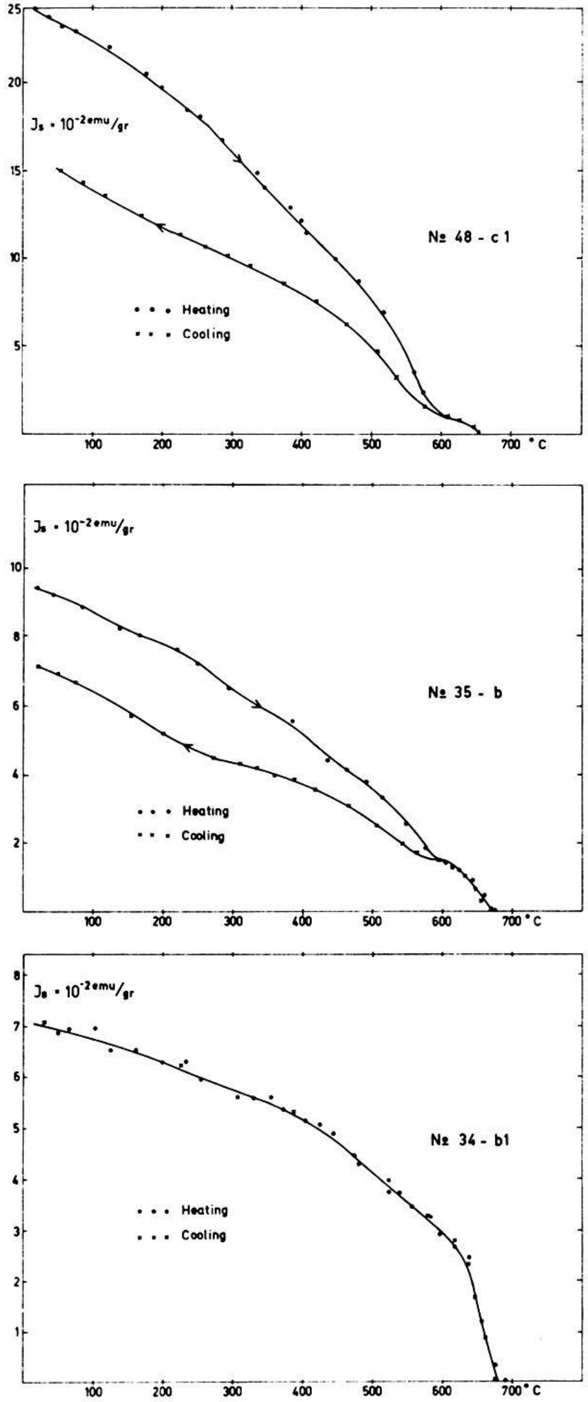

Fig. 11: Examples of saturation magnetization versus temperature.

The samples with two Curie temperatures show that at room temperature the saturation magnetization due to magnetite is of the same order of magnitude as that of the haematite component. As the spontaneous magnetization of magnetite is a factor 200 higher than that of haematite, the average magnetite content within an ore grain must be about 0.25%. This estimate is in good agreement with the microscopic observations.

6. Ore mineralogy in terms of remanent magnetization

According to CARMICHAEL and NICHOLLS [1968] the primary ore phases in basaltic rocks are titanomagnetites (members of the solid solution series ulvospinel Fe_2TiO_4—magnetite Fe_3O_4) with a chemical composition varying between 50 and 80 mol % ulvospinel coexisting with haemoilmenites (members of the solid solution series ilmenite $FeTiO_3$—haematite Fe_2O_3) with a composition varying between 80 and 99% ilmenite. The corresponding Curie temperatures vary between 0 °C and 300 °C for the titanomagnetites and between −200 °C and −50 °C for the haemoilmenites. CARMICHAEL and NICHOLLS [1968] conclude that basaltic rocks with Curie temperatures above 300 °C have undergone oxidation during or subsequent to extrusion (or intrusion). Thus, the very high Curie temperatures found in the Brumunddal lavas are in accordance with the extensive ore mineral alterations as revealed by the microscopic studies. The crucial question is at what temperatures these chemical transformations took place.

The lamellar structure in many of the samples studied resembles strongly the exsolution features that are common in basaltic lavas. Experiments on recent lavas [ANGENHEISTER et al. 1970] show that the well developed systems of exsolution lamellae are caused by oxidation during the initial cooling of the rock at temperatures higher than 500 °C. On the other hand, the ore grains of many basalts show also an extremely fine-scale exsolution similar to the "pockmark structure" of the present investigation. ADE-HALL [1969] calls this phenomenon "granulation" and ascribes it to a low temperature alteration. This suggestion is in agreement with some heating experiments carried out on different basalt samples containing homogeneous titanomagnetite (PETERSEN, unpublished results). These samples were heated for various times in air at temperatures ranging between 350 °C and 1100 °C. The exsolution bodies were very fine-scaled and irregular when the heat treatment was carried out at temperatures below 400 °C while well developed lamellae resulted at temperatures above 500 °C.

It is concluded therefore that samples of the lamellar type have already been oxidized during their initial cooling at temperatures probably above 500 °C. The samples of typical "pockmark type" have obviously escaped this early oxidation stage. However, the very fine-grained irregular disintegration which dominates the ores of the Brumunddal lavas so strongly (and overprinting the high temperature oxidation structure where it exists indicates an oxidation process at low temperatures. This low temperature oxidation has proceeded so far that a practically ultimate oxidation stage has been reached. The ore mineral assemblage present, haematite and rutile, is that which is stable in air at low temperatures [VERHOOGEN 1962]. Only some samples of the lamellar type have relics of the original spinel phase. Although this latter phase may carry the direction of original TRM is seems impossible in this case (because of the small amount precent) to estimate the remanent magnetization of this magnetite component which has a much lower magnetic stability than haematite. It can be safely concluded that the dominating magnetization component in the Brumunddal lavas must be of chemical origin and probably formed over a long time interval.

7. Conclusion

The ore mineral investigations have given very strong support to the conclusion reached from thermal demagnetization studies of the remanent magnetization. It appears that the low temperature oxidation in the Brumunddal lavas has continued throughout the Permian era and into Mesozoic times. The time span involved is probably more than 50 m.y., covering geomagnetic field reversals as well as relative polar wandering. Furthermore, the slowly growing chemical magnetization appears in part to have taken place during the period of tectonic activity. This should be a warning against a straightforward acceptance of tilt-corrected data in palaeomagnetism.

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