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Palaeomagnetism of Upper Cretaceous Limestones From the Münster Basin, Germany*

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Abstract. Marine, mainly flat-lying sediments of Late Cretaceous age are exposed throughout a wide area of the Münster Basin (NW-Germany). During the Cenomanian, Turonian, and Campanian fine-grained, grey, marly to pure limestones were deposited. The Campanian limestones carry magnetization components of unknown age due to the presence of secondary goethite and haematite. However, in the Cenomanian and Turonian rocks the natural remanent magnetization (NRM) is due to detrital magnetite and can be associated with the time of deposition. Fold tests confirm a Late Cretaceous age of magnetization in the magnetite-bearing limestones, since the NRM pre-dates latest Cretaceous deformation along the northern margin of the basin. The Münster Basin limestones provide one of the first reliable Cretaceous pole positions (Lat.: 76° N, Long.: 181° E) from stable Europe.

Key words: Palaeomagnetism – Limestones – Cretaceous – Stable Europe.

1. Introduction

In recent years two important polar wander curves for Europe have been compiled. That by Van der Voo and French (1974) covers the last 300 m.y. and that by Irving (1977) spans the last 375 m.y. Both curves show the same general trend with the pole moving apparently from low latitudes to its present high latitude position. However, the two polar wander paths differ significantly in their longitudinal position especially during the Jurassic and Cretaceous. This divergence is a result of the different compilation techniques used for the two polar wander curves. Mesozoic palaeomagnetic data from stable Europe are very scarce and a Mesozoic polar wander path can not be compiled from existing European data. The Van der Voo and French (1974) polar wander path for Europe relies heavily on North American palaeomagnetic data and

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the fit of Europe and North America using the Atlantic magnetic lineations. On the other hand, Irving's (1977) European polar wander path incorporates new Russian palaeomagnetic data, and relies on the premise that data from the Caucasus and east of the Urals are applicable to stable Europe.

The aim of the present study is to establish a reliable Cretaceous pole position for central Europe and to compare this pole position with those inferred for Europe by Van der Voo and French (1974) and by Irving (1977). The Mesozoic in Europe is documented by a great variety of sedimentary rocks, especially carbonates. Many recent investigations have shown that limestones can be reliable recorders of the ancient geomagnetic field, although their remanent magnetization is usually very weak. Nevertheless, since the development of superconducting rock magnetometers (Goree and Fuller 1976), it is possible to measure certain limestones with sufficient precision. Late Jurassic limestones from Germany (Heller 1977, 1978a) have recently given a well defined Jurassic pole position for stable Europe. The Upper Cretaceous limestones of the Münster basin (Fig. 1) are usually flat-lying and tectonically undisturbed, they outcrop over a large area of Westphalia, and are extensively quarried affording good fresh outcrop.

2. Geology

The development of the Upper Cretaceous Münster Basin (Fig. 1) commenced during the Albian and Cenomanian due to subsidence of the northern part of the Rhenish Massif. At this time the sea transgressed the Münster Basin from the Lower Saxony Basin in the north (Arnold 1964). Between Cenomanian and Campanian a huge pile of marine sediments – up to nearly 2,000 m – was deposited in water depths not exceeding 200 m (Arnold 1964). The facies vary from transgressional conglomerates, glauconitic sands, marls, and limey marlstones to pure limestones. The basinal facies is characterized by a marly-calcareous sedimentation with increasing carbonate content in the Cenomanian (Thiermann and Arnold 1964) ranging from interlayered marls and marl-limestone sequences ('Plänerkalke') to pure limestones. The Turonian is also represented by light-coloured, grey and mostly pure limestones with interlayers of calcareous marlstones. Beginning in the uppermost Turonian clayey marls were deposited continuously throughout the Coniacian, Santonian and Lower Campanian. During the Upper Campanian marl sedimentation continued, with intercalations of calcareous marls and limestones.

The sediments are flat-lying and tectonically undisturbed throughout most of the Münster Basin. Towards the margins, especially along the northern margin, movements occurred during the so-called 'Subhercynian' orogenic phase (Stadler and Teichmüller 1971) in latest Cretaceous times. This event caused steep tilting of the sedimentary layers, flexures, and even small scale overthrusts up to 500 m (Lotze 1953; Rosenfeld 1963) due to uplift of the North-Westphalian Block (Fig. 1). However, local fold axes are essentially horizontal and block rotations unlikely (Rosenfeld, personal communication).

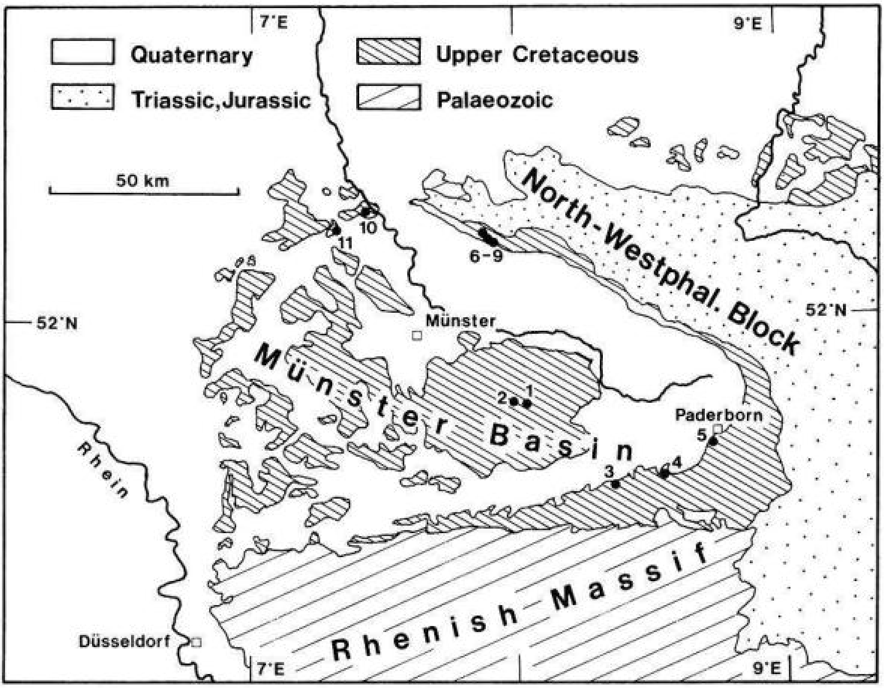

Fig. 1. Location of sampling sites (Nos. 1–11) in the Münster Basin

Since the marls were not accessible to palaeomagnetic sampling and fresh sandstone outcrops are rare, our investigations concentrate on the carbonate rocks which are quarried at many places. Eleven sites (Fig. 1) have been sampled which expose limestones of Cenomanian, Turonian, and Upper Campanian age.

3. Magnetic Properties

The natural remanent magnetization (NRM) of more than 500 limestone samples from the Münster Basin has been investigated. The initial NRM intensities vary between $4 \cdot 10^{-9}$ G and $5 \cdot 10^{-7}$ G with a mean value around $1 \cdot 10^{-7}$ G (Fig. 2). Although weak in intensity most of the NRM vectors could be determined with sufficient accuracy using the cryogenic magnetometer.

Depending on the NRM intensity, each sample was measured either in three or six different positions with respect to the instrument's triaxial detector system, thus allowing for three or six independent estimates of the remanence vector. These estimates were combined to give a mean value of the sample's magnetization vector together with some precision parameters (Heller 1978b; Lowrie et al. 1979) such as standard deviation of intensity and angular standard deviation of direction. Besides operator errors, the precision of measurement is influenced by the signal/noise ratio, sample shape defects, instability and

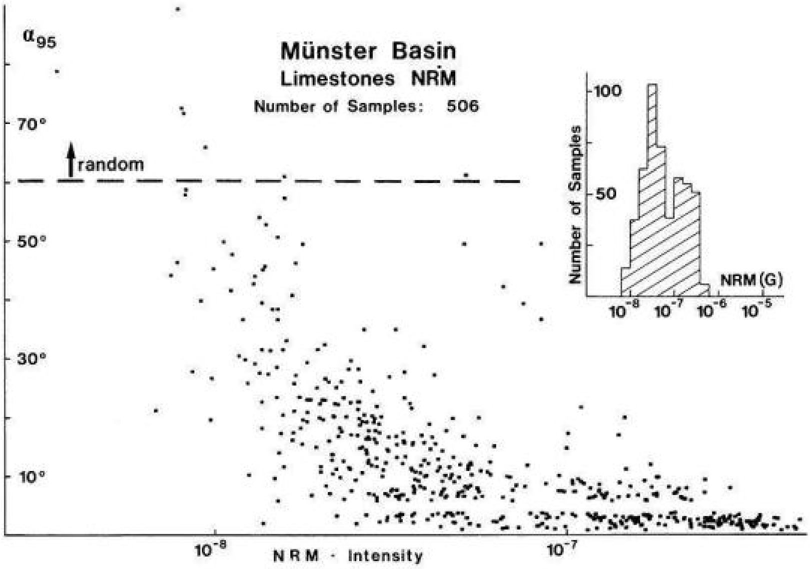

Fig. 2. The angular accuracy α_{95} from 3-position measurements for each individual sample plotted against the NRM intensity of that sample

inhomogeneity of remanence. When measuring in six positions, the inhomogeneity effects are minimized due to the completely symmetric measurement scheme.

Figure 2 shows the angular accuracy of measurement (α_{95}) of the NRM of each limestone sample to be largely intensity dependent. With decreasing NRM intensity (i.e., with decreasing signal/noise ratio) α_{95} increases, and signifies randomness (Watson 1956) at the 95% confidence level when values reach 57.2° for 6-position measurements and 60.2° for 3-position measurements. These values representing randomness usually occur in samples with intensities below $1 \cdot 10^{-8}$ G. Less than 2% of the NRM measurements had to be rejected by this criterion but much higher percentage of the collection had to be eliminated after demagnetization, when the intensities often fell below the critical limit.

For the palaeomagnetic investigations more than 300 samples have been subjected to AF-cleaning in fields up to 400 Oe. Many of these samples were subsequently magnetized progressively in fields up to 45 kOe in order to provide additional information on their magnetic mineral content.

Type 1 Limestone. The magnetic mineralogy of the limestones is highly variable. The predominant magnetic limestone type is characterized by the behaviour illustrated in Fig. 3. The NRM intensity steadily decays during AF-cleaning. A secondary component is removed by AC fields between 50 Oe and at most 200 Oe. Exceeding these field amplitudes, the projections of declination- and inclination-components run within experimental accuracy towards the origin. Thus no higher coercivity components are found in these samples. The IRM acquisition curves are saturated around $H = 2$ kOe and subsequent progressive

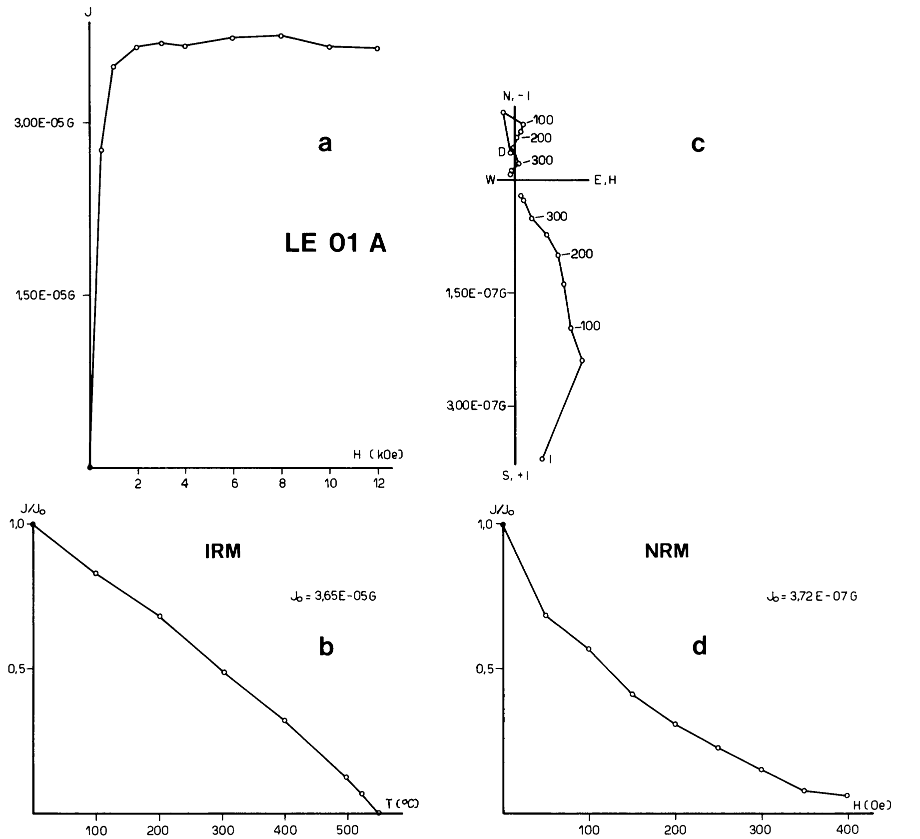

Fig. 3a–d. Type 1 limestones. **a** Acquisition of isothermal remanent magnetization (IRM) in increasing dc fields. **b** Stepwise thermal demagnetization of that IRM. **c** Vector diagram of declination (*D*) and inclination (*I*) during progressive AF demagnetization of the natural remanent magnetization (NRM). **d** The decrease in NRM intensity during progressive AF demagnetization

thermal demagnetization yields maximum blocking temperatures between 550° C and 575° C. All this evidence points to *magnetite* as the main carrier of remanence. Most of the limestones from sampling localities 5–11 (Fig. 1) qualify for this low coercivity type.

Type 2 Limestone. Magnetic high coecivity minerals predominate in a second type of limestone from the Münster Basin. The sample in Fig. 4 has an extremely stable NRM with a minor soft component which is removed by alternating fields of only 25 Oe. Up to 150 Oe (in other samples up to 400 Oe) no essential change of the NRM vector takes place. The IRM acquisition curve does not reach saturation even in fields as strong as $H = 45$ kOe. Upon thermal treatment 90% of the IRM is lost below 150° C. The extremely high coercivity and the low maximum blocking temperatures are attributed to *goethite*. The spontaneous magnetization of goethite occurring in limestones is very sensitive to temperature

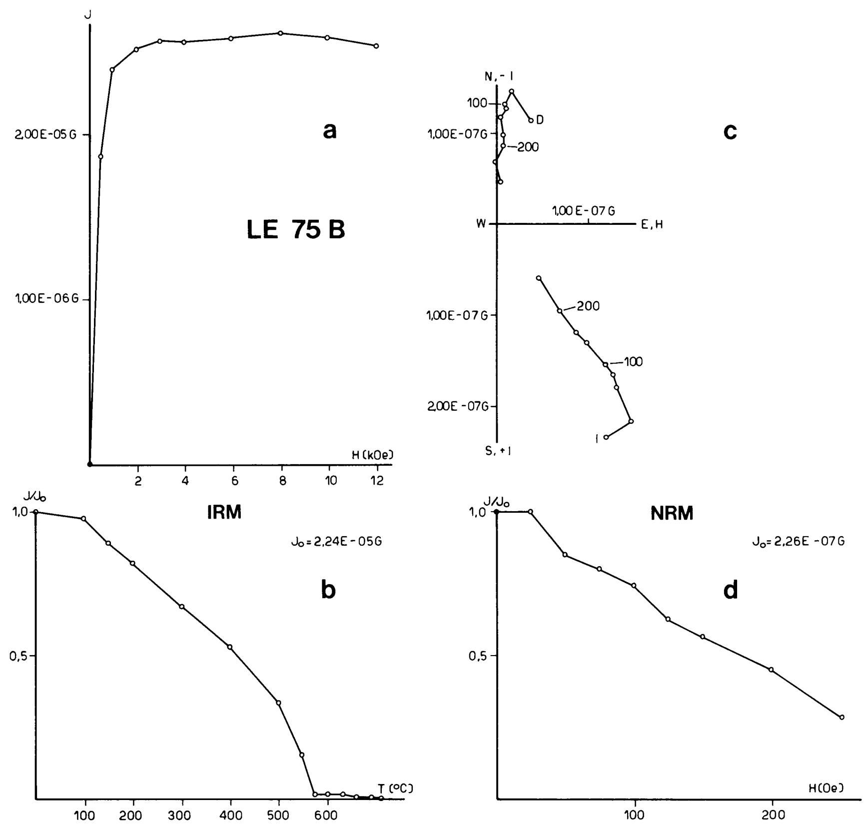

Fig. 3

fluctuation (Heller 1978a). This explains the partially erratic behaviour of the IRM acquisition curve. The IRM remaining after thermal demagnetization above 150° C may be due to the presence of either magnetite or hematite.

Type 3 Limestone. The sample in Fig. 5 again has a very stable NRM with only very little change of the magnetization vector during AF-cleaning. Having passed a small, very low intensity plateau below $H = 5$ kOe, the IRM acquisition curve again is not saturated at $H = 45$ kOe, the maximum field available. In this case, a much higher proportion of IRM is left after heating to 150° C. Since the maximum blocking temperatures of this portion lie well above 600° C (near to 700° C), it is concluded that besides *goethite, hematite* is a main contributor to the remanence of the sample. The stable level of the IRM curve between 2 kOe and 4 kOe as well as a small inflexion of the IRM thermal demagnetization curve near 550° C indicate a minor amount of magnetite to be present. Limestones of this type have been found mainly at the sampling localities 1–4 (Fig. 1).

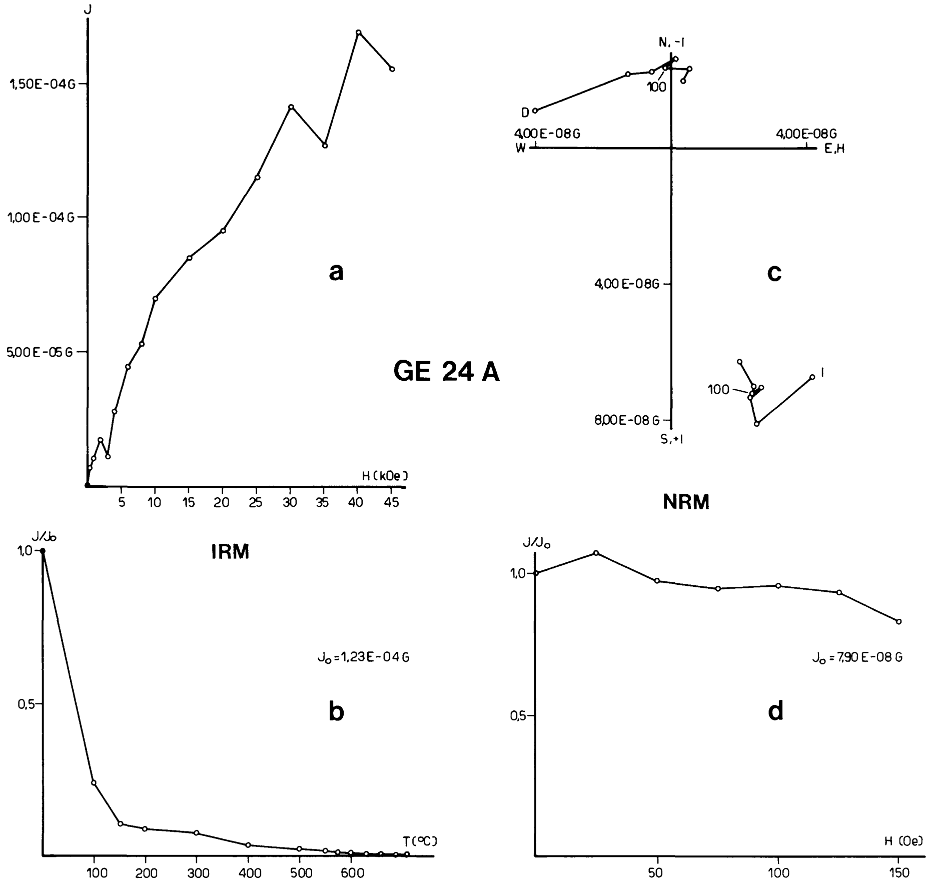

Fig. 4a–d. Type 2 limestones. **a**, **b**, **c**, and **d** see Fig. 3

Type 4 Limestone. The sample in Fig. 6 contains mainly *magnetite,* since the IRM intensity is mainly acquired in fields below $H=2$ kOe and a strong inflexion of the thermal demagnetization curve of IRM is found at 550° C. However, the IRM acquisition curve does not saturate below $H=3$ kOe, the maximum coercivity to be expected for magnetite, and a distinct IRM component survives heating to 575° C being totally obliterated above 625° C. Thus a substantial amount of IRM is contributed by *hematite.* The NRM contains again a soft component which is removed well below 100 Oe. Otherwise the directional stability of NRM is very high, but the trends of the projections of declination and inclination, although being straight lines within the limits of experimental error (note the low intensities), do not pass through the origin. This is caused by different magnetization directions in magnetite and hematite respectively.

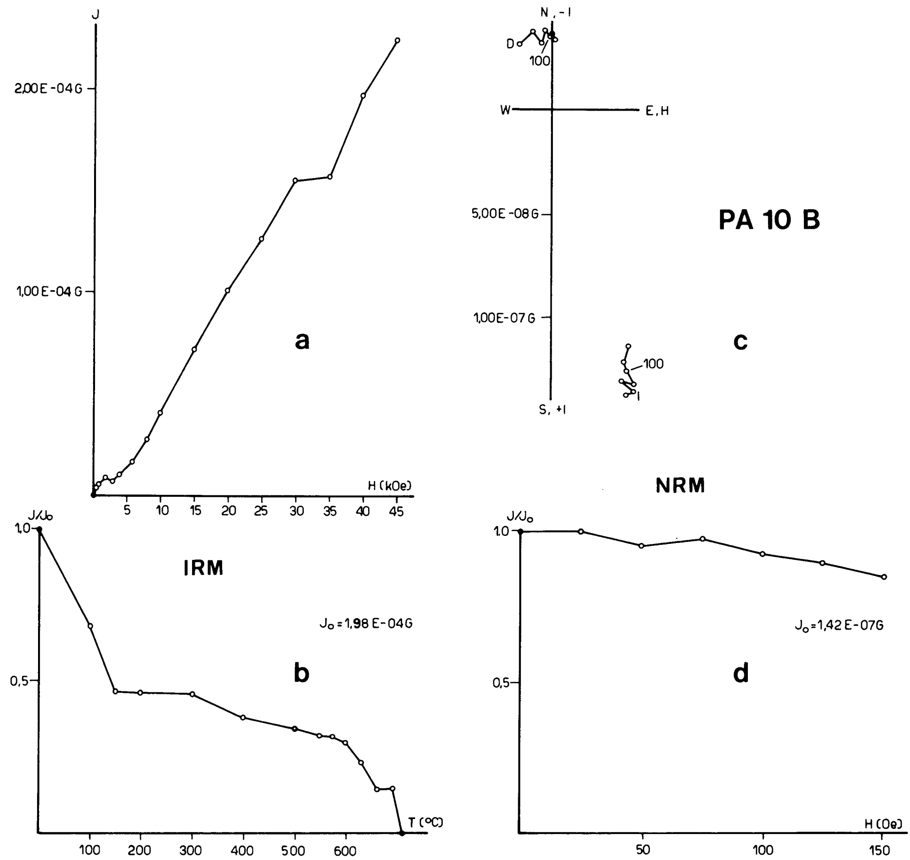

Fig. 5a–d. Type 3 limestones. **a**, **b**, **c**, and **d** see Fig. 3

4. Age of NRM and Selection of Reliable Palaeomagnetic Data

The magnetization history of a rock is often difficult to ascertain. Viscous remagnetization, oxidation and exsolution of thermodynamically unstable ferromagnetic minerals or secondary precipitation or recrystallization of magnetic minerals may lead to a complete overprint of more primary magnetizations.

The three ferromagnetic minerals magnetite, goethite and hematite which have been identified in the Münster Basin limestones by IRM studies, have been formed under different conditions. By analogy with deep sea sediments (Løvlie et al. 1971) and due to the fact that magnetite cannot precipitate by purely chemical reactions in seawater, it is generally agreed that most magnetite is of detrital, primary origin in carbonate sediments. The limestone NRM carried by magnetite therefore is assumed to be of synsedimentary origin, although viscous overprint cannot always be ruled out. However, two positive fold tests

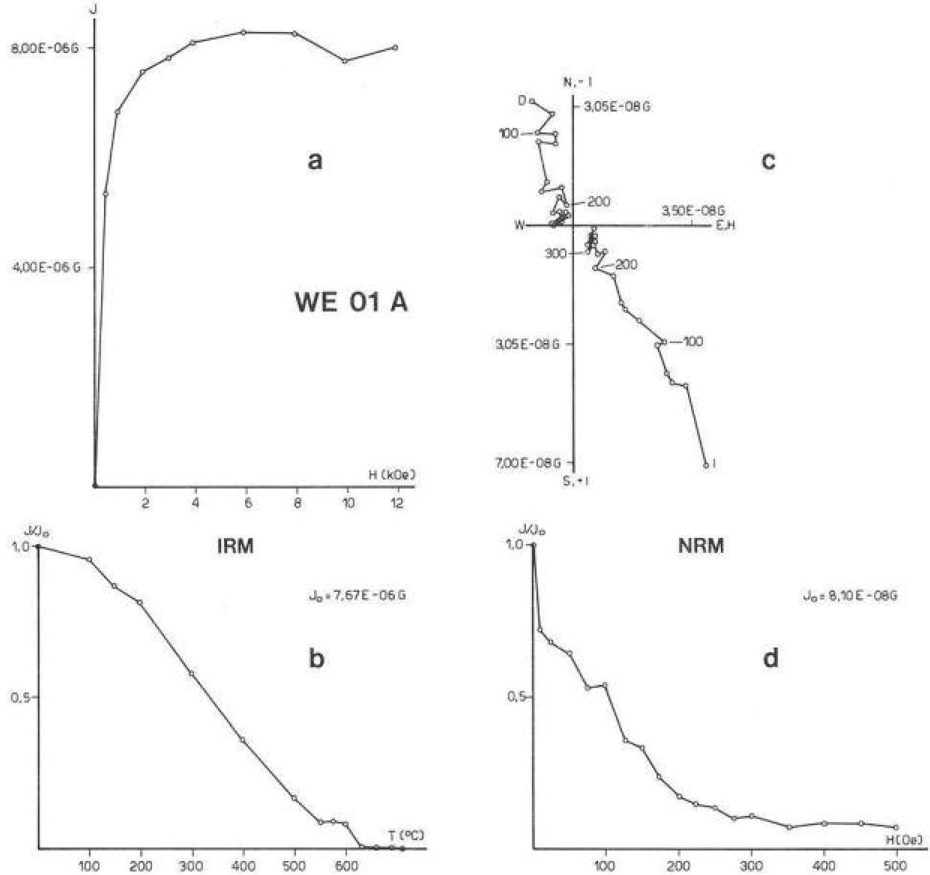

Fig. 6a–d. Type 4 limestones. **a**, **b**, **c**, and **d** see Fig. 3

(Fig. 7) allowed us to attest an early magnetization to the Münster Basin Type 1 limestones. The scatter of AF-cleaned, stable NRM directions is considerably reduced by unfolding of the limestone beds, and therefore a pre-folding origin of NRM is indicated. Since the main tectonic events in the area occurred during the so-called 'Subhercynian' orogenic phase in the latest Cretaceous, an Upper Cretaceous age of NRM can be established for this limestone type.

The age of the high coercivity magnetization components in limestone types 2–4 remains ambiguous, because no suitable fold tests could be conducted. There is evidence for later formation of goethite and hematite, the latter mineral being considered as a dehydration product of goethite (Berner 1969). During demagnetization of tilted mixed coercivity (Type 4) limestones, the magnetization components attributed to hematite often, but not always, have slightly different directions to those attributed to low coercivity magnetite (cf. Fig. 6). Although the NRM directions of the high coercivity samples (Types 2 and 3) are extremely stable during AF-cleaning and plot close to the low coercivity

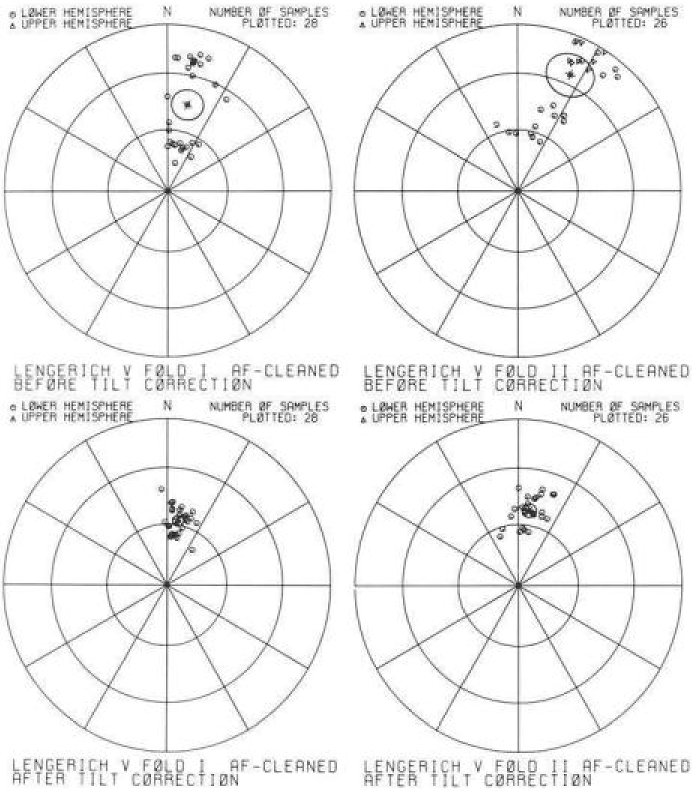

Fig. 7. Two fold tests on limestones from Lengerich (location 6,9; Fig. 1), indicating a pre-folding age for the AF-cleaned magnetization

directions, all samples of Type 2 and 3 have been discarded because of the likelihood that the high coercivity magnetizations were formed at a time much later than the deposition of the sediment. In the case of the mixed coercivity rocks (Type 4), vector diagrams (e.g., Fig. 6) were plotted for each individual sample in order to pick the direction of the low coercivity magnetization component. The higher coercivity components in these samples were considered to be not representative of the Upper Cretaceous geomagnetic field.

Some low coercivity magnetization components were shown to be unstable when applying a directional stability index (Heller 1977; Lowrie and Alvarez 1977) and had to be rejected. The data selection criteria together with the test on the accuracy of each individual measurement forced us to discard about one third of the demagnetized sample collection. The remaining samples which are considered to carry characteristic Upper Cretaceous NRM directions uncontaminated by later magnetization components, have been used for the calculation of the eleven site mean directions (Table 1).

Table 1. Palaeomagnetic data from the Münster Basin

Site (Location in Fig. 1)	Number of samples measured	Number of stable samples	Polarity %		Site mean direction after tectonic correction			Pole position			Stratigraphic position
			+	−	D	I	α_{95}	Lat. N	Long. E	α_{95}	
Neubeckum (1)	42	11	91	9	358.2	53.6	6.9	71.6	193.8	8.1	Upper Campanian
Enniger (2)	39	10	40	60	4.1	61.3	8.3	79.5	172.3	11.2	Upper Campanian
Erwitte (3)	23	14	100	–	8.3	61.3	6.5	78.5	156.8	9.2	Upper Turonian
Gesecke (4)	36	10	100	–	1.8	52.7	7.0	70.7	184.4	8.8	Upper Turonian
Paderborn (5)	17	14	100	–	3.3	59.3	5.6	77.4	177.3	6.7	Upper Turonian
Lengerich (6) (Fold I)	28	28	100	–	9.9	57.9	2.7	74.4	158.9	3.3	Middle Turonian
Lengerich (7)	21	21	100	–	355.7	57.1	3.9	74.9	202.2	5.2	Upper (?) Cenomanian
Lengerich (8) (Railway)	40	35	100	–	0.3	60.9	2.5	79.4	187.7	3.5	Middle Turonian
Lengerich (9) (Fold II)	26	26	100	–	8.2	52.6	3.5	69.7	168.7	4.0	Lower Turonian
Rheine (10)	25	24	100	–	0.2	63.1	3.2	82.1	188.0	4.7	Upper Cenomanian
Wettringen (11)	19	19	100	–	354.8	53.9	2.7	71.6	202.6	3.3	Upper Cenomanian
Mean (N=9)			100	–	2.5	57.8	3.1	75.8	181.1	3.8	Cenomanian-Turonian

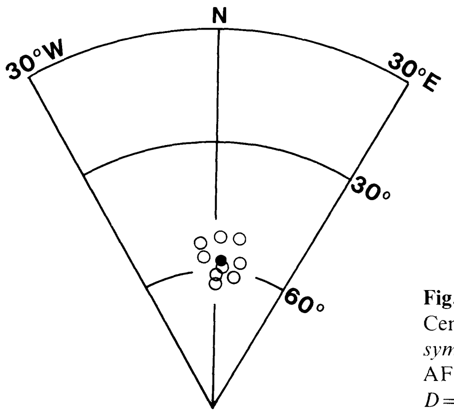

Fig. 8. Stereographic plot of the nine Cenomanian-Turonian site mean directions (*open symbols*; Table 1) after tectonic correction and AF-cleaning. The mean direction (*full circle*; $D=2.5°$, $I=57.8°$) has α_{95} of 3.1°

5. Palaeomagnetic Results and Conclusions

Table 1 shows that all the limestone samples of Cenomanian and Turonian age from the Münster Basin without exception carry NRM directions of normal polarity. The sections which we have sampled, certainly do not cover the entire time interval between 100 m.y. and 86 m.y., since our sections are spread across one quarter of the sediment pile at most. However, the normal polarity is consistent with our knowledge of the geomagnetic field during the Late Cretaceous. The Cenomanian and Turonian belongs to the Cretaceous quiet zone of normal polarity lasting from Early Aptian to the Santonian-Campanian (Lowrie and Alvarez 1977; Channell et al. 1979).

The Upper Campanian limestones from the Münster Basin are extremely weakly magnetized (initial NRM mean intensity: $2.7 \cdot 10^{-8}$ G) and only a small percentage of samples carried a characteristic low coercivity NRM (Table 1). Extremely stable, secondary magnetization components usually dominate the NRM of these limestones. The frequent negative polarity of the NRM indicates that this magnetization component significantly post-dates deposition because it has been established (Lowrie and Alvarez 1977) that the polarity of the geomagnetic field was normal during the Late Campanian when these limestones were deposited.

Therefore, the evaluation of an Upper Cretaceous mean direction for the Münster Basin is confined to the Cenomanian and Turonian limestones (Table 1, Fig. 8) which always carry a well-defined low coercivity magnetization component. The site mean directions (Fig. 8) cluster very closely ($\alpha_{95}=3.1°$) around a mean direction of $D=2.5°$ E and $I=57.8°$. This provides a reliable, well dated Upper Cretaceous pole for stable Europe (Long. = 181° E, Lat. = 76° N, $\alpha_{95}=3.8°$, $N=9$). The site pole positions and their mean have been plotted in Fig. 9.

Irving's (1977) polar wander curve for Eurasia shows an apparent minor loop during the Cretaceous (Fig. 9). Since Irving's Cretaceous pole positions have 95% confidence circles with radii of at least 5°, one might argue about

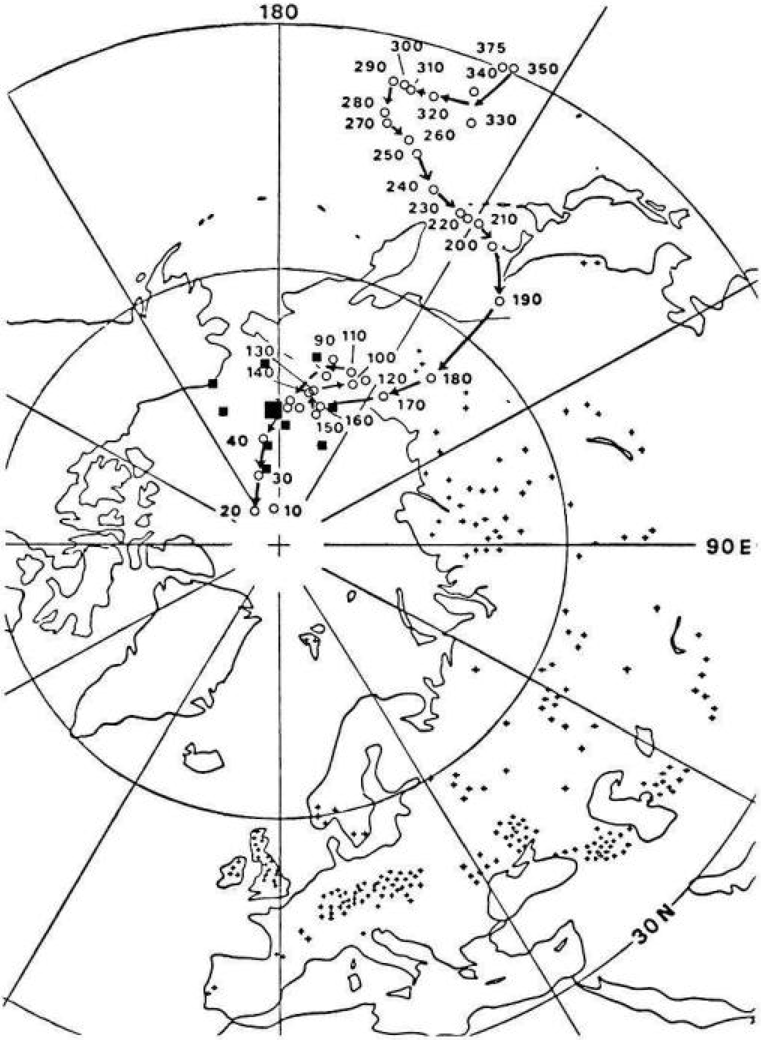

Fig. 9. The nine Upper Cretaceous pole positions from the Münster Basin (*small squares*) give a mean pole (*large square*) which does not coincide with the Upper Cretaceous portion of Irving's (1977) time-averaged polar wander path for Eurasia (*open circles*). The numbers give the age (m.y.) of the Eurasian poles

the significance of the loop. However, it produces a significant separation of our mean pole from Irving's time-averaging contemporaneous poles. The Münster Basin palaeopole indicates a simpler polar wander path for Europe than that derived by Irving. As mentioned above, Mesozoic palaeomagnetic data from Europe are almost non-existent and Irving's European APW curve relies heavily on Siberian poles and may be biased by data taken from orogenic belts (Caucasus).

The Upper Cretaceous Münster Basin palaeopole allows two tectonic conclusions to be drawn. The Upper Cretaceous Sintra granite in Spain (Van der Voo 1969) yields the same palaeopole position. Thus, Van der Voo's suggestion can now be confirmed that the anticlockwise rotation of the Iberian peninsula was complete in the Late Cretaceous. The Southern Alps have been interpreted by Channell and Tarling (1975) and VandenBerg and Wonders (1976), on the basis of palaeomagnetic measurements, to belong to an extension of the African plate. Cenomanian and Turonian sediments from this area carry an 'African' mean NRM direction $D=340.8°$ and $I=38.8°$. When comparing this value with the Münster Basin result, the minimum amount of rotation between Europe and Africa can be established to be about 20° since the Late Cretaceous. Also the former latitude of the Southern Alps can be estimated. Since the former latitude position of the Southern Alps is derived to be 9.5° ($\pm 3.8°$) more southerly than at present, the minimum shortening of the Tethys and its margins since the Late Cretaceous was of the order of 1,000 km.

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