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Palaeomagnetism of Upper Jurassic Limestones from Southern Germany*

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Abstract. Flat-bedded, shallow water, marine limestones interlayered with marls are well exposed in Franconia and Swabia, Southern Germany. The Upper Jurassic sediments sampled have been dated in detail palaeontologically, and cover the interval from middle Lower Oxfordian to middle Lower Kimmeridgian. Bed by bed sampling of sections at 11 localities throughout a thickness of more than 130 m yielded about 400 samples (1100 specimens) for palaeomagnetic analysis. The NRM intensities appear to correlate with the clay content and averaged 2×10^{-7} Gauss. Progressive alternating field demagnetization of each specimen was used to isolate the direction of the characteristic remanence, whose mean intensity averaged 5×10^{-8} Gauss. Only normally magnetized rocks are found in the lower part of the section, but distinct zones of normal and reversed polarity are found in the upper part (middle Lower Kimmeridgian) in both regions of investigation. The polarity sequence is tentatively correlated with the ocean floor Mesozoic magnetic anomaly sequence. The data yield a reliable estimate of a Late Jurassic palaeomagnetic pole position for stable Europe.

Key words: Palaeomagnetism – Marine magnetic anomaly sequence – Mesozoic limestones – Southern Germany.

1. Introduction

At present the palaeomagnetic record of the Mesozoic and especially of the Jurassic in stable Europe is still very poorly established. Four years ago, when Hicken et al. (1972) published their catalogue of palaeomagnetic directions and poles, not a single reliable palaeomagnetic pole position of Jurassic age could be cited for Europe. This lack of data results in a large degree of uncertainty in establishing the Mesozoic apparent polar wander curve. Reconstructions such as that of Van der Voo and French (1974) suffer from this paucity of

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palaeomagnetic information in certain geological periods, especially in the Jurassic.

Interpretation of the Mesozoic magnetic polarity reversal sequence inferred from the oceanic magnetic surveys has recently undergone revision. The original Mesozoic reversal time scale of Larson and Pitman (1972) was criticized and refined in some respects. Larson and Hilde (1975) derived an improved scheme which comprised 18 new intervals of reversed polarity during the time span associated with anomalies M25–M17 covering part of the Late Jurassic. Since the marine magnetic anomaly sequence in itself provides only an undated record of relative polarity inversions, it is of great importance to calibrate the sequence by establishing its radiometric or biostratigraphic age by means of well-dated land-based sections. Lowrie and Alvarez (1977) succeeded in correlating in detail the Late Cretaceous marine anomalies (anomalies 34–29) with a contemporaneous land section in Italy. For the Late Jurassic, Steiner and Helsley (1975) tried to correlate the sedimentary record of two sections in Colorado with the oldest sea floor anomalies (M25–M23). Their correlation seems to be less positive than that of Lowrie and Alvarez.

The purpose of this paper is firstly to establish a reliable Late Jurassic palaeopole position for Europe and, secondly, to find out if a reversal stratigraphy on land can be correlated with the corresponding marine magnetic lineation pattern. The main reason for the lack of palaeomagnetic information for the Jurassic (and the rest of the Mesozoic) is that to a great extent only very weakly magnetized rocks were formed in Europe during this period. The development of extremely sensitive magnetometers (e.g. cryogenic magnetometers) permits the investigation of the natural remanent magnetization (NRM) of those rocks which are preferentially of sedimentary origin. The Upper Jurassic limestones exposed throughout Southern Germany are a suitable rock type to answer the two above problems, because they are unaltered, tectonically undisturbed and distributed over large geographical areas.

2. Geology

Rocks of Jurassic age are very well exposed in Southern Germany along a broad girdle which extends from Franconia (Northern Bavaria) in the north to the Danube river in the south and then continues southwestwards to Swabia (Württemberg) as shown in Figure 1. The uppermost part (Malm) contains the stages Oxfordian to Portlandian and is developed in carbonate facies, whereas the middle and lower Jurassic sections (Dogger, Lias) consist mainly of sandstones and shales.

Three facies types of carbonates can be distinguished in the Upper Jurassic sequence: well bedded, mainly chemical limestones and layered (biostromes) and unlayered moundlike (bioherms) biogenetic limestones. During the present study we have concentrated on the layered limestones. We have sampled sections from the beginning of Middle Oxfordian up to the end of middle Lower Kimmeridgian (Malm α–δ, Table 1). Thus according to the London Geological Society time scale (Howarth, 1964) the sampled profile covers the time interval from 156 my–147 my approximately.

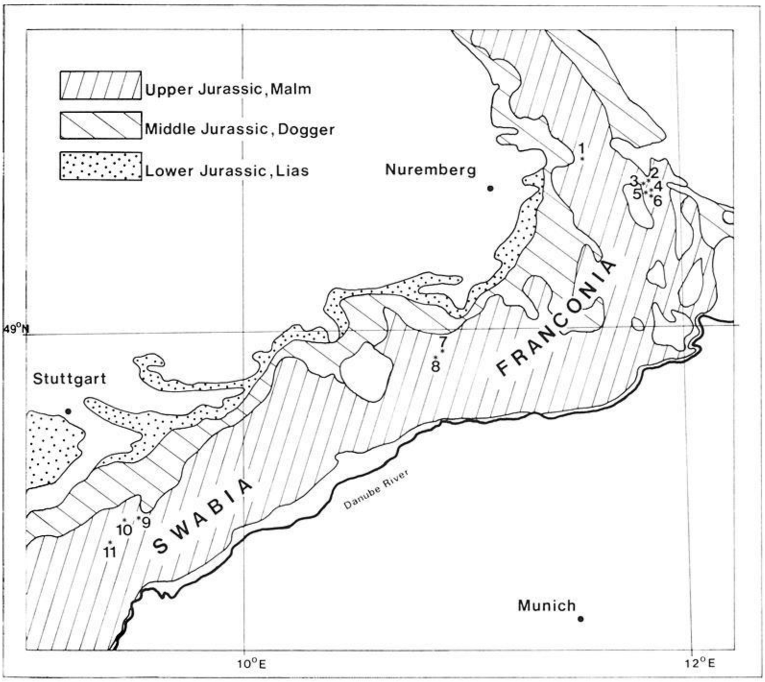


Fig. 1. Geological sketch map of the Jurassic in Southern Germany. Numbers indicate sampling localities 1–11

Table 1. Stratigraphic zonation of the Upper Jurassic section sampled

Stratigraphic stages		Zonation fossils (ammonites)	Regional sub-divisions	Absolute age (10^6 yrs)
Malm	Kimmeridgian			
	Upper			
				146?
		Virgataxioceras setatum Sutneria subeumela	Malm ε (25 m)	
	Lower	Aulacostephanus eudoxus Aulacostephanus eulepidus	Malm δ (60 m)	
		Crussoliceras divisum Ataxioceras hypselocyclum	Malm γ (30 m)	
				151
	Oxfordian			
	Upper	Sutneria galar Idoceras planula	Malm β (16 m)	
	Middle	Epipeltoceras bimammatum Epipeltoceras berrense Divisosphinctes bifurcatus Arisphinctes plicatilis	Malm α (32 m)	
	Lower	Cardioceras cordatum Quenstedtoceras mariae		
				157

The limestone sequence is flat-bedded throughout the whole region of investigation without any signs of major tectonic deformation. The limestones have been formed under marine shallow water conditions. In the lower part of the profile (Malm α–γ), fine-grained, fairly pure micrites with varying clay content (up to 10% by volume) are interlayered with marls, whereas in the upper part (Malm δ) biostrome facies predominate (especially in Franconia) which in the highest parts of the sections sampled show signs of beginning dolomitization. For most of the profile continuous sedimentation has been established. Minor sedimentation breaks are mooted for the Oxfordian/Kimmeridgian boundary (A. Zeiss, personal communication). The mean sedimentation rate is of the order of 1–2 cm/1000 y, and seems to increase as the age decreases.

The stratigraphy of the limestones has been studied in great detail (Schmidt-Kaler, 1962; v. Freyberg, 1966; Ziegler, 1959) and due to palaeontological bed by bed sampling well defined biostratigraphic zones have been delineated using ammonites as zone markers (Table 1). Thus even if facies changes took place between different regions, accurate correlation is still possible over lateral distances of several hundred kilometres (Zeiss, 1964).

For the present palaeomagnetic study about 400 cores which gave more than 1100 single specimens, were drilled bed by bed at 11 localities. They are spaced with a mean stratigraphic separation of 0.5 m throughout the entire profile of about 130 m thickness. Most sites are situated in Franconia (nrs. 1–8, Fig. 1) covering the lower three quarters (Malm α–γ) of the profile and generally overlap stratigraphically with one another. Three other localities (nrs. 9–11, Fig. 1) were chosen in Swabia to compare with the Malm δ data of Franconia and to extend the section up to the Malm δ/ε boundary.

3. Laboratory Procedures

The analysis of extremely weakly magnetic samples presents special problems not normally encountered in a palaeomagnetic study. To ensure as objectively as possible that the data obtained were reliable a set of laboratory procedures was used that enabled rejection criteria to be uniformly applied to all specimen measurements.

3.1. The Measurement and Reliability of Weak Remanences

The measurements of natural remanent magnetization (NRM) were carried out using a three-axis cryogenic magnetometer in which the components of magnetization along three orthogonal directions were simultaneously, and almost instantaneously, determined. The magnetometer was interfaced with an output terminal, and from there the data was transferred by cassette tape and telephone directly to the university's central computer.

Replicate observations were obtained by measuring each specimen twice, in an upright and in an inverted position. Initially, and between each pair of sample measurements, the signal of the empty sample holder was recorded.

Each of the 6 magnetization component readings was treated as an independent observation and was combined with two appropriate orthogonal components, thus giving eight estimates of the remanent magnetization vector. The internal dispersion of the directions about their mean, and the standard deviation of the intensity estimates, were used as control parameters for judging the reliability of each remanence measurement.

3.2. Selection of the Optimally Cleaned Direction

Each specimen was progressively demagnetized in alternating magnetic fields at 50 Oe increments to a peak field of 200 Oe. Some selected specimens were demagnetized to 3000 Oe. The directional stability of each specimen was judged objectively using a numerical index as follows. The direction cosines (l,m,n) were calculated at each demagnetization step. The change of direction (on a great circle) from the previous demagnetization step with direction cosines (l',m',n') is given by

$$\vartheta = \cos^{-1}(ll' + mm' + nn').$$

On dividing by the increment in field, a parameter $(\Delta\vartheta/\Delta H)$ was described which has minimum value in the most stable region of the demagnetization and whose average value over the entire demagnetization curve allows an objective estimate of the quality of the remanence stability.

3.3. Rejection Criteria

Individual remanence measurements were discarded if the sample signal was weaker than the signal of the quartz-made sample holder, equivalent to a magnetization of around 5×10^{-9} Gauss. Large values of the internal dispersion parameter (angular standard deviation $> 50°$) or of the scatter of magnetization components (standard deviation $> 50\%$ of mean) were used as indicators of unreliable measurements. Such large scatter could indicate the presence of very unstable components that remagnetize between each measurement in the weak fields in the laboratory, or it could indicate extreme inhomogeneity of the magnetization, or it could result merely from a faulty procedure (e.g. wrongly oriented sample in either measurement position). If the angular variation $\Delta\vartheta/\Delta H$ during stepwise AF demagnetization of a specimen always exceeded 0.5°/Oe, the specimen was rejected. Between 2 and 3 specimens were obtained from each bed by bed cored sample. As a final check on the data reliability the individual specimen directions were combined to give a sample mean. Again, if this mean were poorly defined, all data for the sample were rejected.

As a result of the cumulative application of these objective tests, about 15% of the collection of limestone samples was rejected. The remainder are considered to possess the characteristics for a reliable palaeomagnetic study.

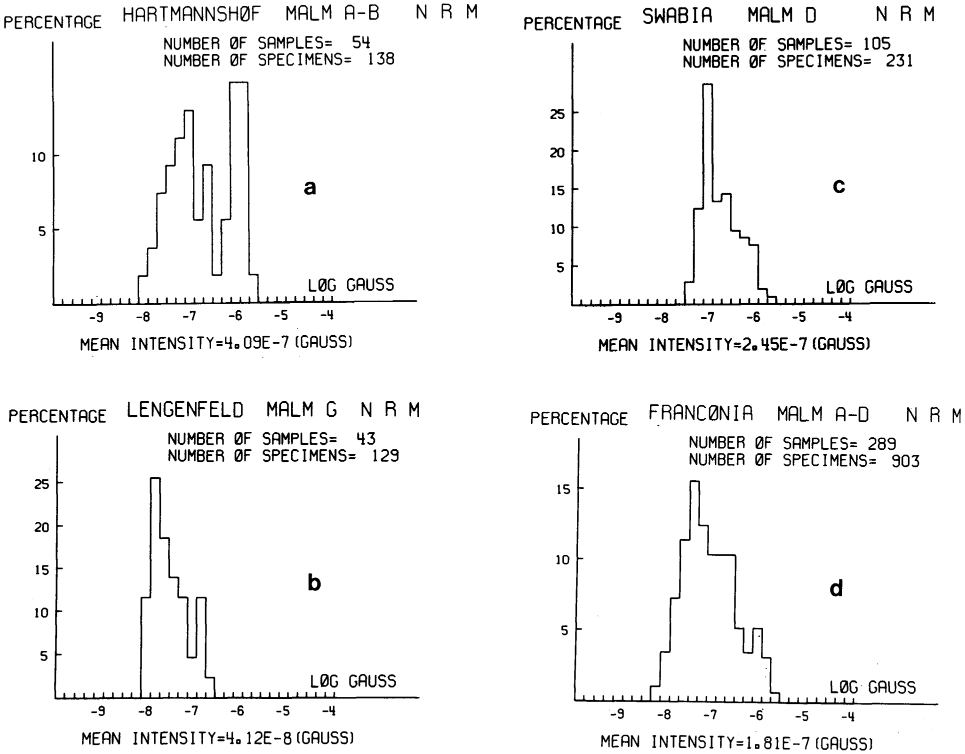


Fig. 2a–d. Histograms of NRM intensities before AF-cleaning. **a** Malm $\alpha+\beta$, site Hartmannshof (site no. 1, Fig. 1). **b** Malm γ, site Lengenfeld (site no. 2, Fig. 1). **c** Malm δ, all Swabian limestones (site nos. 9–11, Fig. 1). **d** Malm $\alpha-\delta$, all Franconian limestones (site nos. 1–8)

4. Palaeomagnetic Results

The initial NRM intensities average around 2×10^{-7} Gauss for all of the Franconian limestones (Fig. 2d), and appear to depend mainly on the clay content of the limestones. A higher intensity (peaking around 1×10^{-6} Gauss) was measured in 40% of the samples from the Hartmannshof site (Fig. 2a). These correspond to the marl-rich Malm α limestones, whereas the lower intensities belong to the very pure Malm β limestones.

AC demagnetization fields of 100–120 Oe lowered the remanent intensity drastically in many cases (for example, the Hartmannshof site, Fig. 3a), and on average to less than 50% of the initial value. Median destructive fields vary between 40 and 80 Oe. On the other hand not all samples were so unstable. Mainly samples in the biostrome limestones of Malm δ displayed extremely stable directions and intensities during AF demagnetization up to 3000 Oe peak field. The effect on these stable samples is seen by comparing the intensity histograms of the Swabian Malm δ rocks in Figures 2c and 3c, where almost all samples with higher initial NRM intensity retain the initial value after demagnetization.

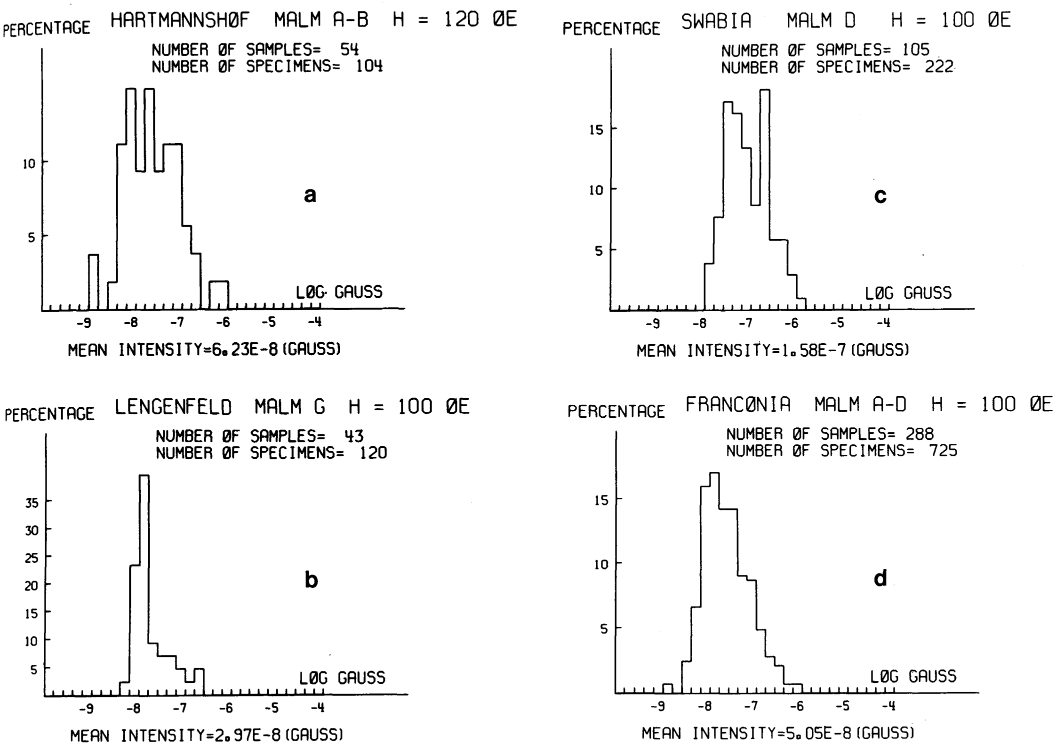


Fig. 3. Histograms of NRM intensities after AF-cleaning with peak fields of 100 Oe, respectively 120 Oe. Figures 3a–d refer to the same localities as shown in Figures 2a–d

Detailed studies of the rockmagnetic properties of the limestones have been initiated and will be published at a later date when complete. Preliminary indications are that in most cases magnetite is the remanent magnetization carrier. A second, high-coercivity mineral, not yet positively identified, is present in some samples. In most cases, the magnetite dominates, except in the Malm δ biostrome limestones where the roles often are reversed. Where both minerals are present the NRM direction associated with the high-coercivity mineral are close to those associated with the magnetite. The majority of samples probably carry a primary magnetization, but as no fold test were possible in these tectonically undisturbed flat lying beds, the effect of secondary magnetization can not be well estimated. All interpretation is made on the assumption that the age of the NRM is the same as the palaeontological age of the sediment.

Before AF cleaning the NRM directions are widely scattered (Fig. 4) with normal directions dominant. After using optimum cleaning fields ranging between 100 Oe and 200 Oe the scatter is reduced, but still appreciable. Areas with high density both of normal and reversed directions can be recognized. The reversed directions occur only in the higher part of the composite profile (cf. Swabian Malm δ data, Fig. 4). Mean directions for each geological subdivision and for the combined data from Franconia, and the resulting virtual palaeomagnetic pole position are listed in Table 2.

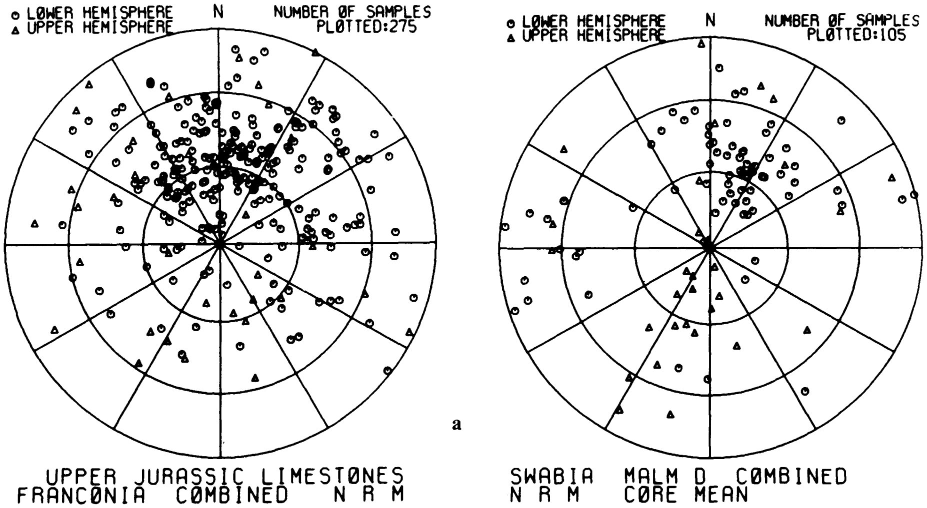


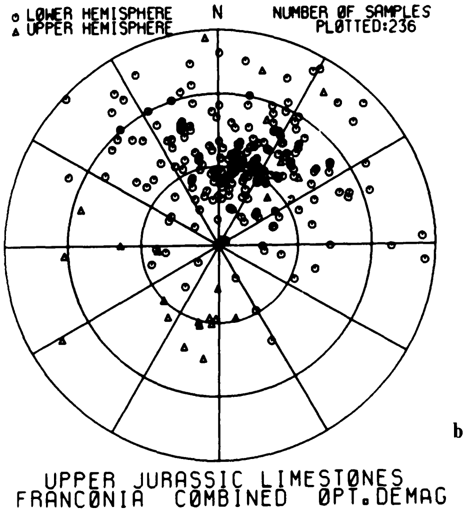
Fig. 4a and b. Equal area stereogram of Franconian and Swabian NRM directions **a** before AF-cleaning and **b** after optimum demagnetization

The declination and inclination data (Fig. 5) plotted against stratigraphic position after optimum AF cleaning do not show evidence for polarity reversals until the Malm γ/δ boundary. Although there is a lot of directional scatter, it is apparent that the whole Oxfordian and the lower part of the Lower Kimmeridgian are normally magnetized. Above the Malm γ/δ boundary several reversed intervals are observed in Franconia as well as in the partly overlapping section of Swabia. Correlation between Franconia and Swabia is fairly good, although the stratigraphic duration of normal and reversed zones seems to differ slightly, e.g. the normal interval between reversed intervals b and c (cf. the corresponding letters in Fig. 5). We think that these differences are due to varying sedimentation rates and sedimentation conditions between the two regions. (The clay content of the limestones in Swabia is generally higher than in the regions sampled in Franconia.)

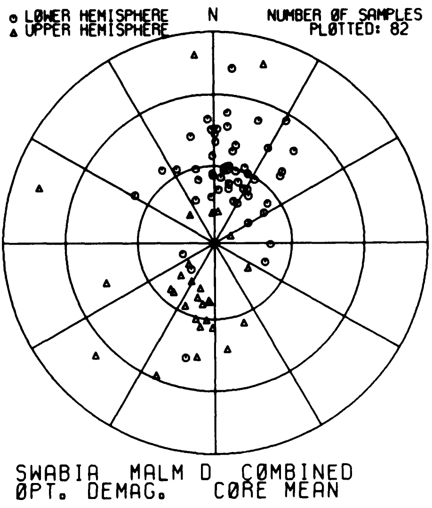
The consistency of the occurrence of normal and reversed rocks within the same limestone beds was checked by comparing the results from two quarries

Table 2. Mean directions of AF-cleaned NRM and virtual geomagnetic pole positions (VGP)

Malm sub-division	Region	Number of samples	Site nos. (cf. Fig. 1)	Direction of magnetization			VGP position	
				D	I	α_{95}	Lat. N	Long. E
α–δ	Franconia	172	1–8	22	55	4	69	128
δ	Swabia	80	9, 10, 11	16	64	5	79	107
δ	Franconia	45	3, 7, 8	11	59	5	79	142
γ	Franconia	48	2, 3, 5	31	51	8	62	122
$\alpha+\beta$	Franconia	79	1, 4, 6	23	53	5	68	130



b



(localities 7 and 8 in Fig. 1) situated close together and representing the lowermost Malm δ. Their limestone layering is equally developed and both sections have nearly the same thickness (Fig. 6). The distribution of truly reversed and normal samples is very similar and the thickness of polarity zones varies from less than a metre to several metres, the corresponding time intervals ranging between 10,000 and about 100,000 years. In at least some cases documented, transitions occur within a few centimetres which would imply within a few thousand years. The polarity zones frequently contain samples with intermediate direction which sometimes even have the "wrong" polarity. The polarity profile (Fig. 6) shows an increase of the reversal frequency towards the bottom of the section.

5. Discussion

The Larson and Hilde (1975) model of the Mesozoic reversal sequence is bounded at both ends by prolonged periods of constant normal polarity (the so-called "magnetic quiet zones"). In particular a normal interval has been proposed for the Middle and Late Jurassic which corresponds to the quiet zone found for example in the North-Atlantic ocean between the Keathley lineations and the continental margin.

On the basis of our data (Fig. 7) we can confirm this period of normal magnetic polarity during the Oxfordian and the beginning of the Lower Kimmeridgian, thus spanning a time interval with minimum duration of about 6 my. The lower end of this normal period was not found in our profile. The upper end of the normal period is assigned a younger age than that suggested by Larson and Hilde. This discrepancy is rather negligible compared with the

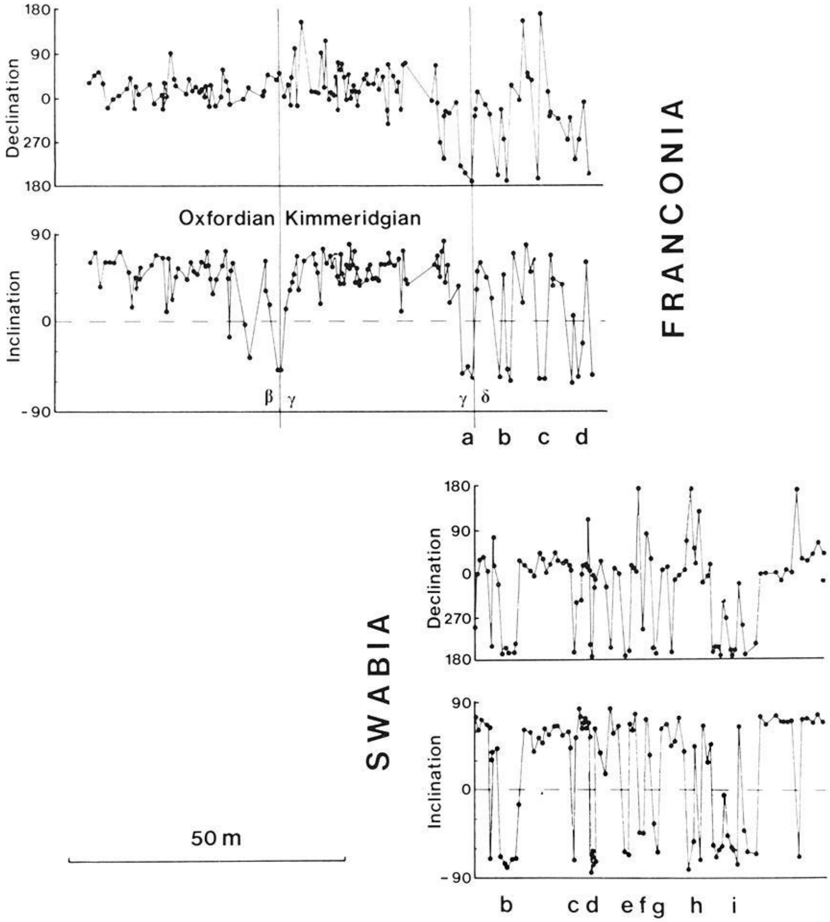


Fig. 5. Variation of declination and inclination of optimally AF-cleaned NRM across a composite profile of the Franconian limestones (above) and a composite profile from Swabia which extends the Franconian profile towards the Malm δ/ε boundary. Geological stage boundaries as well as boundaries of the regional Malm subdivisions (Malm β/γ, Malm γ/δ) are indicated. The sections constituting both profiles are taken from localities 1, 2, 7, 9, 10, 11 of Figure 1

probable errors arising from differences between micro- and macropalaeontological zonation and uncertainties in radiometric dating. However, if the ages of magnetic polarity zones are to be referred to stages of the geological time scale, then the onset of reversals is more safely dated from our profile than from the oceanic anomalies, as the ammonites which define the original Jurassic stage divisions control the stratigraphy of our profile.

5.1 Frequency of Reversals

If we compare the beginning of the Mesozoic sea-floor magnetic anomaly sequence (Fig. 7) with our land-based reversal pattern, a higher frequency of

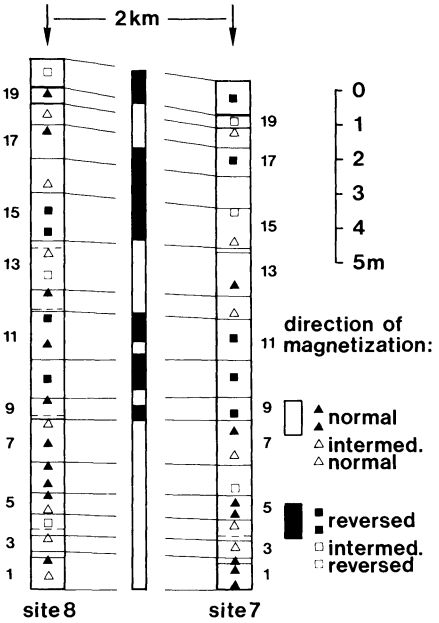


Fig. 6. Comparison of polarity distribution between two sites (nos. 7 and 8, Fig. 1) situated close together. The 2 sections cover the same stratigraphic horizons and the thickness of the layers is nearly equally developed. Small numbers along both sections according to the layer numbers introduced by Streim (1960). Full squares and full triangles indicate the position of samples with reversed, respectively normal NRM directions which are close to the overall mean of Malm δ rocks. The corresponding open symbols refer to intermediate directions with flat negative, respectively positive inclination. The symbols have been plotted exactly at the stratigraphic position where the cores had been drilled mostly ± parallel to the bedding plane. The combined polarity profile which results from the polarity distribution of the samples of both profiles has been drawn in between the 2 limestone sections

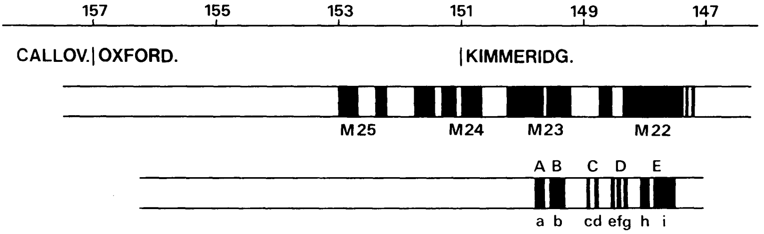


Fig. 7. Early Mesozoic sea-floor anomaly pattern (above) according to Larson and Hilde (1975) compared to the polarity profile (below) which has been observed in the land-based limestone sequence of Southern Germany. White zones within the profiles indicate record of normal polarity, black zones correspond to reversed polarity

reversals is recognized in the limestone section. Part of the higher frequency may be attributable to samples with intermediate directions possibly representing short magnetic field excursions; part may also be due to single samples with inverted directions possibly indicating a polarity event. Neither of these contributions has been filtered out of our reversal pattern in Figure 5 and both possibilities must therefore be taken into consideration. We think that two possible explanations for the correlation of the land-based profile with the marine anomaly sequence are at hand.

There is a tendency in the Mesozoic marine anomaly model for the reversal frequency to increase appreciably towards the lower end (M25) of the anomalies. Also the amplitude of the anomalies appears to decrease uniformly from about M21 to M25. Larson and Hilde (1975) suggested that this decrease was due to a corresponding variation of the geomagnetic field intensity at, and since, the end of the Jurassic quiet period. The remanence intensities of the limestones are too scattered and their magnetic properties too variable to be able to sustain or disprove this idea. The palaeointensity variation of the geomagnetic field can only be estimated in sediments when the remanence intensity can be normalized for variation in lithology. Extensive rockmagnetic studies on these limestones will be needed before a description of variation of the geomagnetic field intensity can be attempted.

The high reversal frequency in our data (Figs. 5, 6, 7) was also observed by Steiner and Helsley (1975, Fig. 1), but is not present in the reversal sequence inferred from analysis of oceanic magnetic anomalies. The apparent decrease of the oceanic anomaly amplitudes towards the Jurassic quiet zone may indicate the presence of a high frequency of reversals that cannot be resolved at the oceanic surface. This interpretation would be compatible with our data. The reversed zones of the Southern German land-based composite section (identified by A to E in Fig. 7) may correspond to the pattern of reversals between anomalies M25 and M24.

It is conceivable that the reversal sequence we have identified does not correspond to any of the Mesozoic zones of mixed polarity derived from oceanic anomalies. Low amplitude fluctuations do exist within the Jurassic quiet zone and it may be that these represent earlier reversals. Larson and Hilde (1975) terminate the Jurassic quiet zone earlier than our dating suggests, thus if our reversal sequence is associated with quiet zone fluctuations, the discrepancy in dating the onset of the Mesozoic mixed polarity sequence is increased.

Such a large error in dating of oceanic anomalies is unlikely, and our best estimate at present is to associate our reversed zones A–E with the M25–M24 reversal pattern.

5.2. Comparison with Apparent Polar Wander Path

The polar wander path for Europe is very poorly defined in the Cretaceous and Jurassic. The need to fill this gap was one of our prime motivations in undertaking the present investigation. Van der Voo and French (1974) attempted to reconstruct the polar wander path for each of the Atlantic-bordering continents by combining plate motion reconstructions with the best acceptable palaeomagnetic data for all the continents. The Jurassic-Cretaceous part of their European polar wander path is determined by data that is largely non-European and especially the Jurassic pole positions are poorly defined.

The virtual geomagnetic pole positions (VGP) for each of the Malm subdivisions have been plotted in Figure 8 and the European polar wander path of Van der Voo and French has been added excluding their very poorly defined Jurassic pole positions. The Malm $\alpha+\beta$ and γ VGP's are very near to the Late Triassic pole position. This implies that only minor apparent polar wander or, neglecting true polar wander, continental movement took place. On the other hand the Malm δ positions of the Franconian and Swabian locations are slightly different from one another and are situated closer to the rotation axis than the VGP's of the older limestones. The discrepancy between Van der Voo and French's (1974) Early Cretaceous pole and our Late Jurassic

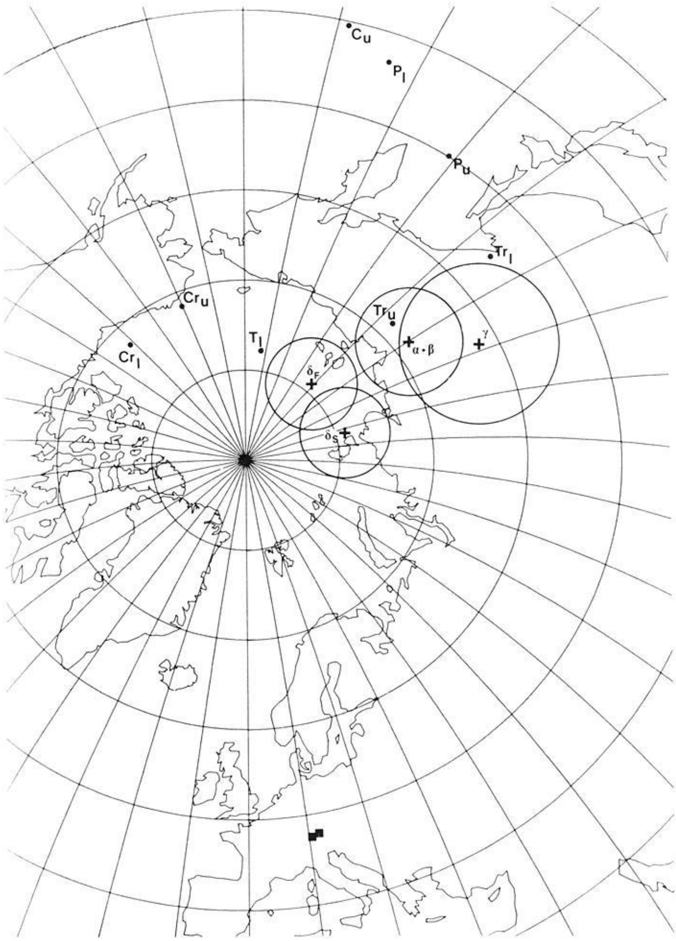


Fig. 8. Late Jurassic VGP positions from Southern German Malm subdivisions $\alpha+\beta$, γ and δ (δ_F = Franconian data, δ_S = Swabian data) and Van der Voo and French's (1974) reconstructed polar wander path for Europe (C_u: Late Carboniferous, P_1 and P_u: Early and Late Permian, Tr_1 and Tr_u: Early and Late Triassic, Cr_1 and Cr_u: Early and Late Cretaceous, T_1: Early Tertiary)

pole position requires a fairly rapid motion of the pole at a rate of 10 cm/yr between the Oxfordian and the Early Cretaceous, assuming the simplest path of movement. This sudden movement is in close agreement with the data of Steiner and Helsley (1972) who found very similar palaeomagnetic evidence in the Jurassic of North America. The steeper inclinations and westerly declinations of the Malm δ rocks (Table 2) suggest northward movement and anticlockwise rotation of the whole continental mass, beginning in the middle Lower Kimmeridgian.

6. Conclusions

Although the Upper Jurassic limestones of Southern Germany are extremely weakly magnetized, they seem to be reliable recorders of palaeomagnetic information. They yield a consistent estimate of a Late Jurassic pole position: Lat.N: $=69°$, Long.E: $=128°$, $A_{95}:=4°$. As this pole position is very close to the Late Triassic VGP of Van der Voo and French (1974), major movement of Europe with respect to the pole did not occur between Late Triassic and Late Jurassic. Probably commencing in the Lower Kimmeridgian major apparent polar wander or continental movement of about 30° of arc took place to reach the Lower Cretaceous pole position of Van der Voo and French. Although the rockmagnetic properties of the limestones are not yet completely worked out, we believe that the relatively close correlation of polarity distribution between our land profile and the marine magnetic anomaly pattern suggests a primary magnetization in the rocks investigated. The existence of a Jurassic normal quiet zone can be confirmed during at least the Oxfordian and the lower part of Early Kimmeridgian. The onset of the Mesozoic reversal sequence takes place during the middle Early Kimmeridgian.

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