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PERMIAN PALAEOSECULAR VARIATION AS RECORDED IN THE LODÈVE REDBEDS, SOUTHERN FRANCE

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Abstract: The initial goal of this study is to obtain a new insight into the Permian geomagnetic field during the Kiaman Interval (Permo - Carboniferous Reversed Superchron - PCR) through the palaeomagnetic study of a long redbed sequence in the Lodève Basin, southern France. A section of 1200 m of Upper Permian strata was sampled, representing some 10 Ma. The most definite geomagnetic result is the total absence of normal polarities indicating that the end of the PCR was not reached. It was shown that the VGP dispersion is reduced (~13°), although it is not as small as during the KN superchron (~7°).

Key words: palaeomagnetic secular variation, redbeds sediments, Permian sequences, southern France.

Introduction

Geomagnetists can now reach well beyond the short history of observatory data and can be provided with (palaeo-)secular variation (PSV) records covering several millennia and dating back millions of years. The resolution and accuracy of such PSV investigations decrease with increasing age of the formation studied. Consequently, most available PSV records concern only the last 5 million years, although McFadden et al. (1991) compile such data from lava flows as old as the Cretaceous, and a few studies involving older sedimentary rocks have been carried out (e.g. Baag & Helsley 1974).

The consequence of the difficulties inherent with older rocks is that very limited PSV information is available during the Paleozoic. However the end of this era is particularly interesting from a geomagnetic point of view because it corresponds to the Permo - Carboniferous Reversed Superchron (PCR), previously known as the Kiaman Interval. This superchron is one of two periods during the Phanerozoic (the other is the Cretaceous Normal, KN) when the geomagnetic field kept a nearly constant polarity for tens of millions of years. Clearly these periods are most important in the context of efforts to understand the mechanism of polarity reversals. It is therefore worth trying to obtain some information on the secular variation during the PCR, which is the longest documented interval of constant polarity. This is what motivated our study of a Permian sedimentary sequence with the initial prospect of recovering data from well over 1000 m of strata. Given an average sedimentation rate on the order of 0.1 mm/yr (Odin 1986), there could be in excess of 10 Ma of geomagnetic history available.

When trying to extract detailed palaeomagnetic data from sedimentary rocks one has to be very careful in assessing their true meaning. The issue of the magnetization origin was addressed in a previous paper (Maillol & Evans 1992). Our conclusion was that the magnetization was acquired shortly after deposition: it is a pDRM. The argument will be briefly summarized here, but the main purpose of this paper is the investigation and interpretation of directional variations of the geomagnetic field.

Field and laboratory procedures

The Lodève Basin is a subsidence zone at the southern margin of the French Massif Central and its present 350 km^2 are only the remnant of a much larger Permian Basin (Odin 1986). It contains approximately 3000 metres of continental, mostly detrital, deposits. The upper 1500 m of the sequence is uniformly red and of Thuringian age, and is the object of our study. The structure of the basin, a half graben with gently southerly dipping strata, provides easy access to the whole sequence along road cuts and river beds.

Sampling was carried out with the aim of recovering stratigraphically ordered data from the entire sedimentary column. Sandstone and siltstone could easily be drilled but these hard beds are abundant only in the lower 300 m of the Thuringian; in the rest of the sequence they are scarce or totally absent. It was therefore necessary to sample the mudstone, which proved to be almost impossible to drill. As a result it was decided to use a different technique. Plastic squares, 2 x 2 cm in size, were bonded onto the rock surface. Orientation was achieved by means of solar bearings and inclinometer readings. The advantage of this technique is that it permits one to collect small irregularly shaped samples, typically a few cubic cm in size. Such fragments could easily be extracted from the mudstone beds. Despite the use of this faster method, 3 months of intensive field work were needed to obtain the sample collection referred to here as the Basin Traverse. The final result is a collection of 201 samples representing 108 sites separated by 1 to 20 m of stratigraphic distance and spanning a total of 1220 m.

We also wanted to obtain information on the short scale variations of magnetization, and to this effect, cores typically 25 cm long, were drilled at four different sandstone and siltstone horizons. In one instance (site BLF), a 190 cm sequence was sampled continuously using several consecutive vertical cores. Finally, to allow horizontal variability of the magnetization to be investigated, several cores were taken from certain stratigraphic horizons at lateral distances ranging from 5 cm to 30 m. All cores were oriented using solar bearings. They were subsequently cut into disks, 7 mm thick on average, and yielded a total of 605 samples.

All remanence measurements were performed on a Molspin spinner magnetometer. Thermal demagnetizations were carried out in air, in a computer controlled furnace located in a magnetically shielded room.

Demagnetization results

The results of detailed demagnetization and rock magnetic experiments from closely sampled sequences are fully described in our previous paper (Maillol & Evans 1992). We will report here only new data relevant to the interpretation of the widely sampled Basin Traverse.

Twenty five samples representative of the three lithologies and of the different sampling methods used were selected for stepwise thermal demagnetization. This reveals the presence of two components of magnetization, one close to the direction of the present field, the other in the direction of the average Permian field. These results agree with those obtained in previous studies (Kruseman 1962; Evans & Maillol 1986; Merabet & Guillaume 1988). Orthogonal component plots (Fig. 1) indicate that end points in the demagnetization trajectories were reached between 400 and 500 °C. Consequently, a standard temperature of 510 °C was chosen for routine treatment of the remaining samples.

The magnitude of the recent overprint is variable and appears to be related to the lithology and degree of alteration. Sandstone and siltstone are generally less altered and less overprinted than mudstones. To assess the stability of the remanence directions of samples with larger overprint, a group of 22 of them (with angle between NRM and thermally cleaned directions greater than 50 °C), routinely treated to 510 °C, were further heated to 560 °C. The group mean direction at 510 °C is D = 199.9°, I = 10.8°, α_{95} = 5.7°, and at 560 °C it becomes D = 200.3 °C, I = 9.8°, α_{95} = 6.6°. These are not significantly different, which indicates that, even in the more heavily overprinted samples, a stable end point was reached at 510 °C.

Magnetization origin

In our previous paper (Maillol & Evans 1992) we report a detailed study of magnetic intensity variations in the small scale sections (7mm interval sampling). The interpretation of these variations has important consequences on the origin of the magnetization and the main results are therefore summarized here. Intensity fluctuations are found with amplitudes reaching an order of magnitude over a few centimetres. The observed peaks often exhibit asymmetric shapes with a gradual build up terminated by an abrupt decrease at the top ("saw tooth" pattern). Several of these profiles are shown in Fig. 2 in normalized form. Moreover, these abrupt decreases systematically coincide with sedimentation discontinuities. The significance of the presence of asymmetric shapes in the intensity profiles has been assessed using the statistical test set out in Fig. 3. For this purpose we use the longest profile available, site BLF, which spans 190 cm from which 265 disks were out.

The differences (Δ_i) were calculated, and the average positive and negative values compared, $R = \bar{\Delta}_+/\bar{\Delta}_-$. We find R = 1.17. To check the significance of this value the data set was randomly sampled 2500 times to obtain a distribution of R values. The

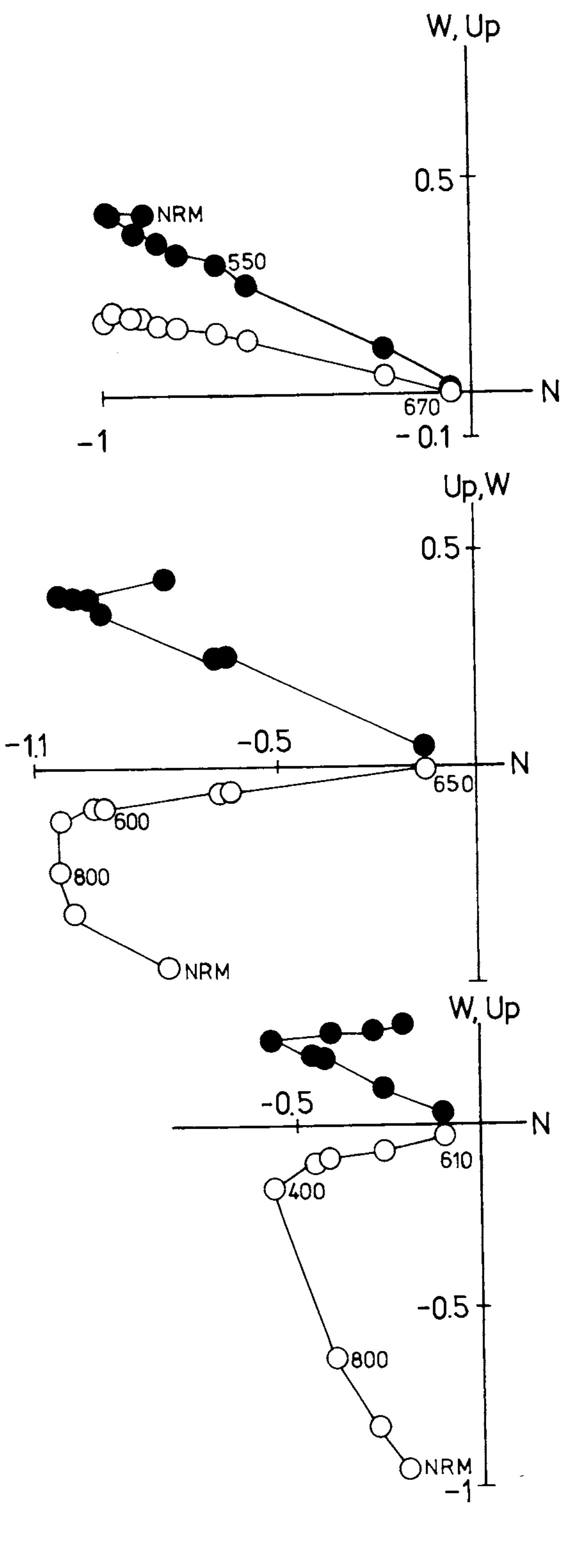

Fig. 1. Examples of orthogonal component plots during stepwise thermal demagnetization. Solid symbols are in the horizontal plane (axes N, W). Open symbols are in the N - S vertical plane. Intensities are normalized and temperatures are in degrees Celsius. Siltstone BLA12C (top), sandstone BL50 (middle), mudstone BL97A (bottom).

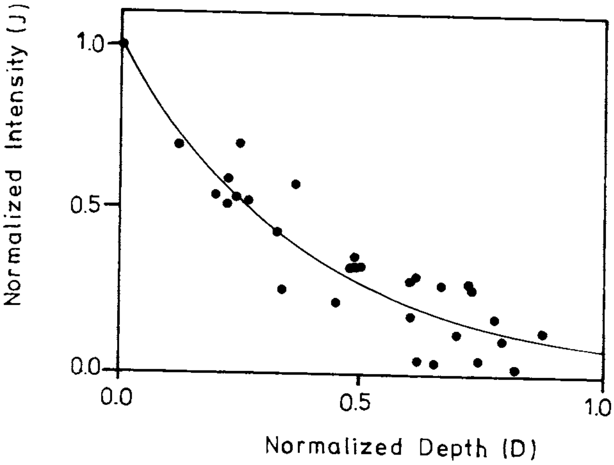

Fig. 2. Normalized, stacked, asymmetric intensity profiles for 11 different horizons. The curve shown is $J = \exp(-2.6D)$ and is forced to pass through $D = 0, J = 1$. Its purpose is simply to quide the eye. The actual intensity values range from 5 - 45x10^{-6} Am^{-2}/kg, the actual stratigraphic intervals represented range from 25 - 130 mm.

result is summarized as a histogram in Fig. 3, which shows that values exceeding 1.17 rarely occur by chance (the upper tail of the distribution actually amounts to 6 %). This effectively confirms that a saw tooth pattern with flat side facing upwards is indeed a feature of the observed intensity profile.

Bulk susceptibility and acquisition and destruction of isothermal remanence indicate that variations in amount and/or intrinsic properties of the magnetic carriers cannot explain the observed intensity variations. This, coupled with evidence that the remanence is carried by detrital hematite, suggests that the observed intensity patterns are due to the efficiency with which the magnetic grains were aligned, and that the magnetization is therefore early post-depositional.

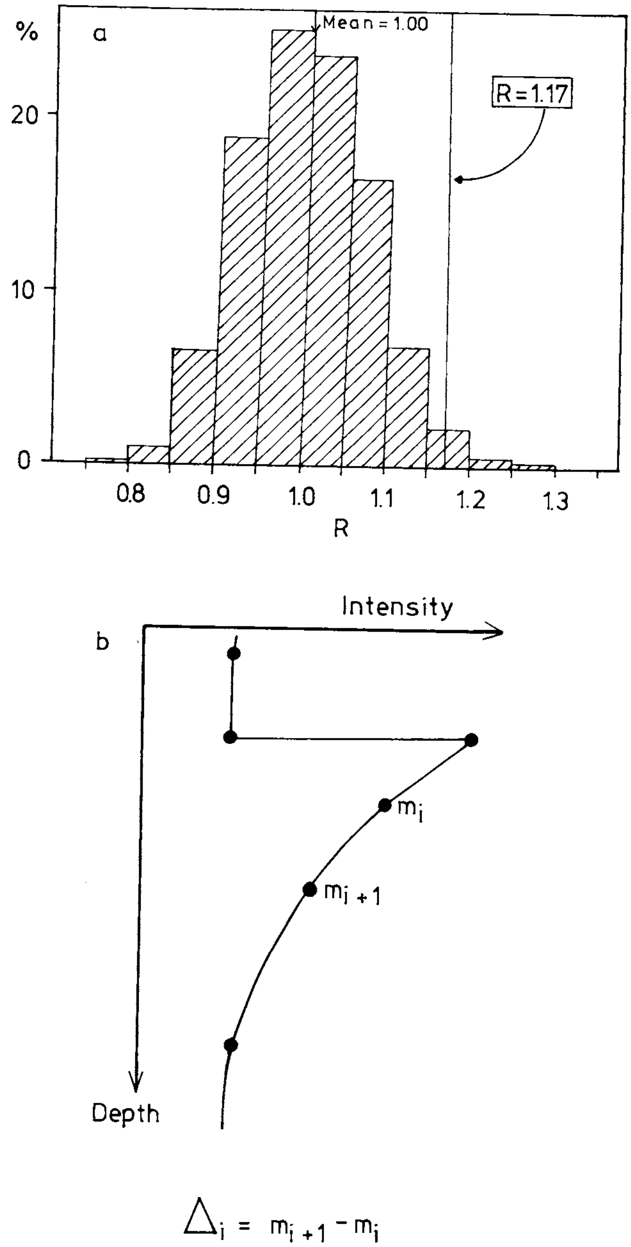

Fig. 3. a - statistical test on the intensity profile at site BLF (190 cm, 265 disks). "Saw tooth" patterns are characterized by R 1, symmetric or random patterns would tend to R = 1. The histogram summarizes the Monte Carlo sampling described in the text; **b** - the notation used.

Palaeomagnetic directions

Long time scale series

Directional results from the Basin Traverse are shown in Fig. 4. Represented are the mean declination and inclination of 108 sites after a bedding correction was applied. A smoothed curve was obtained by spline interpolation of the data to regular 5 m intervals followed by smoothing using a 20 m sliding window. Despite large intervals between some of the sampling sites, visual inspection reveals coherent oscillations in most parts of the record, with good serial correlation of the data points. The amplitude of these variations can reach 25° in both declination and inclination.

The 108 site means yield a mean declination = 200.3°, mean inclination = -3.8°, k = 35.4, α_{95} = 2.3°, which corresponds to a palaeopole at 154.1°E, 44.6°N, A_{95} = 1.6°. This is in good agreement with other European data (see e.g. van der Voo 1990). It is worth noting that recent investigations (Diego-Orozco & Henry 1992) indicate that other basins of southern France have undergone post-Permian regional rotations while the Lodève Basin remained stable. Thus the new pole, calculated from a substantial number of samples representing an extensive stratigraphic column, is a useful contribution to the Permian European APWP, and a significant datum for discussions of the tectonic evolution of SW Europe.

Short time scale series

The discovery of long period magnetic direction variations prompted the need to assess the reliability of the observations. Another point of interest was the resolution of the material, in other words, how small is the minimum distance over which clear variations of magnetic directions can be observed. This was achieved by studying continuous sequences, from 25 to 190 cm long, sampled at approximately 7 mm intervals. Results from a 190 cm sequence are shown in Fig. 5 and reveal that, even at this much smaller scale, coherent variations can be observed (mostly in declination in this case). Several laterally equivalent sections were also available and allowed correlations of the direction variations to be investigated. A good example is shown in Fig. 6.

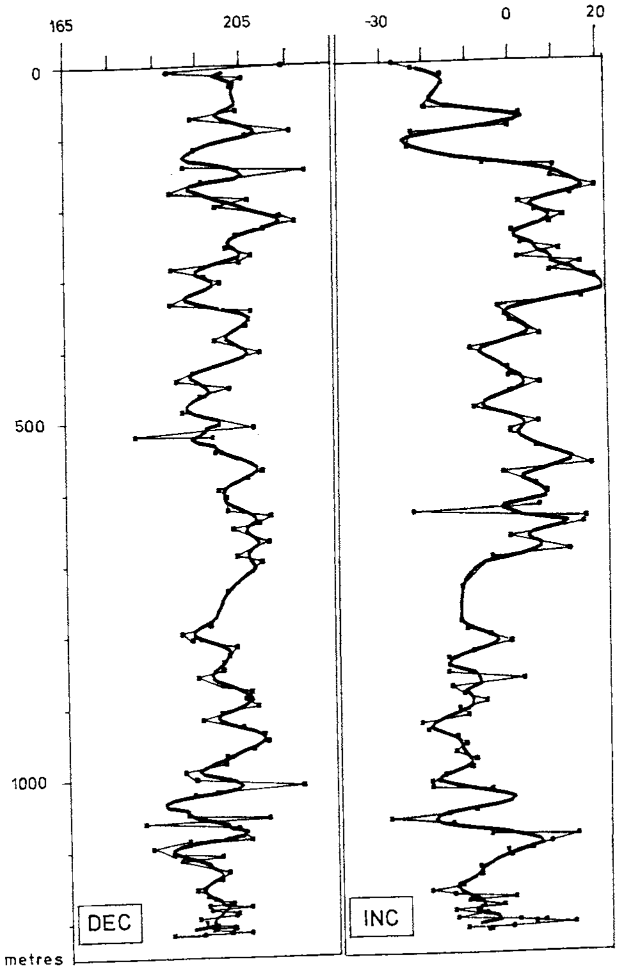

Fig. 4. Basin Traverse remanence directions shown on declination and inclination magnetograms for the 108 site means. The thick line was obtained by smoothing as described in the text.

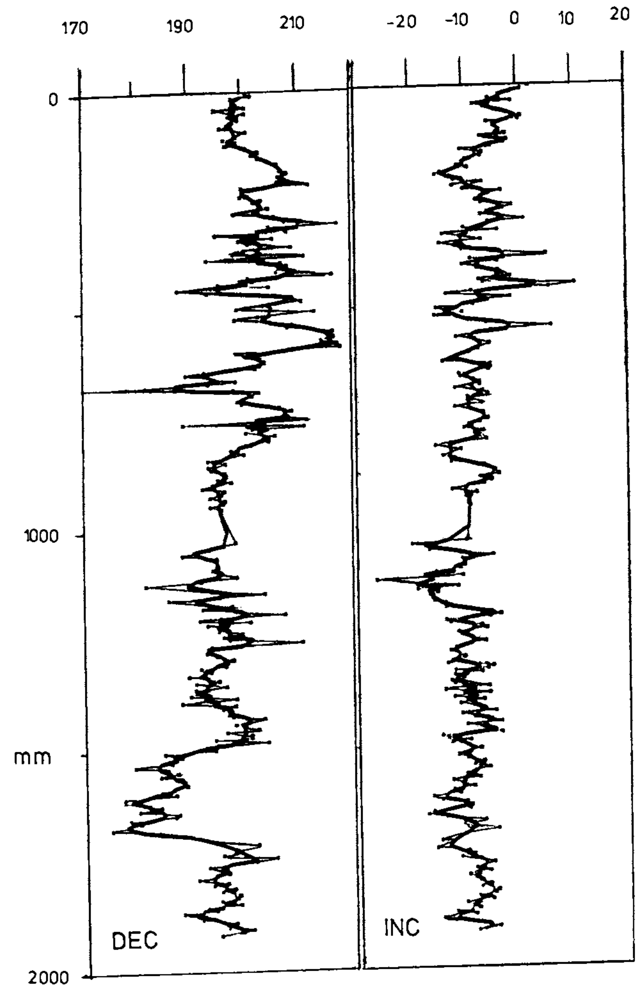

Fig. 5. Detailed remanence direction variations shown on magnetograms for site BLF (190 cm section, 265 disks). The thick line was obtained by smoothing using a 3 point moving average.

Discussion

Amplitude of PSV

Work pioneered by Cox (1968) has led to models of polarity reversals in which reversal rate depends on the amplitude of secular variation. One of these models (called M2) recently developed by Merrill & McFadden (1988) involves two distinct families of dynamo in the Earth's core (called primary and secondary families). An important prediction of this model is that low reversal rates would be accompanied by a reduced relative magnitude of the secondary family, and therefore by an overall reduction of the SV amplitude. This prediction seems to be confirmed by a study of palaeosecular variation from lavas dating back to 195 Ma (McFadden et al. 1991). In particular a very small contribution of the secondary family is found during the Cretaceous Long Normal Superchron (KN). In view of these considerations, the present study is interesting for several reasons. It involves rocks laid down during the Permo - Carboniferous Reversed Superchron (PCR), which is the longest known interval of constant polarity, and during which observations similar to those reported for the KN are expected, if model M2 is valid. Although our data come from sedimentary rocks, we have shown that there is evidence that the magnetization acquisition was an early diagenetic process which could provide an accurate recording of field variations. Our data set covers 1220 m of Thuringian sediments and, despite the difficulty of assessing magnetization rate, it is certain that this represents several million years. This is sufficient to insure a complete representation of PSV. Finally, our study, though it provides only one values of angular dispersion, is located at a site near the Permian equator (palaeomagnetic latitude = 2°), which is the only way to estimate the relative contribution of the secondary dynamo family without possessing dispersion values at distributed latitudes. Indeed it can be shown (McFadden et al. 1988) that at zero latitude the primary family does not contribute to the geomagnetic angular dispersion and consequently an estimate of the dispersion there is a direct estimate of the secondary family contribution.

A measurement of the PSV amplitude is given by the angular dispersion of the geomagnetic field over long periods of time,

$$S_T^2 = S_B^2 + S_W^2/N$$

where S_B and S_W are the between-site and within-site dispersions respectively, and N is the average number of samples per site. The within-site dispersion is due mainly to experimental causes while the between-site dispersion is due to geomagnetic field variations (McElhinny & Merrill 1975). In the present study it is

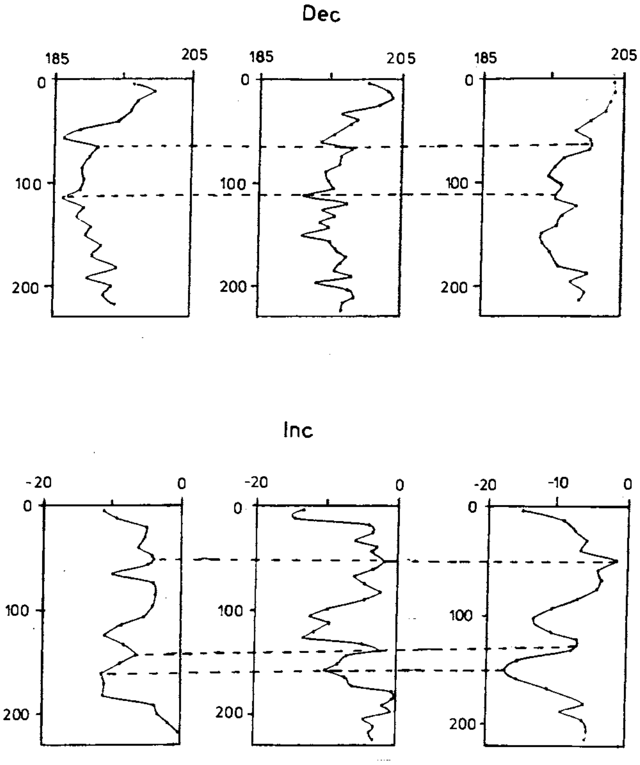

Fig. 6. Declination (top) and inclination (bottom) records for 3 cores collected from the same stratigraphic horizon (intercore distances are 40 and 50 cm). Dashed lines indicate correlations of certain features. Depths in mm.

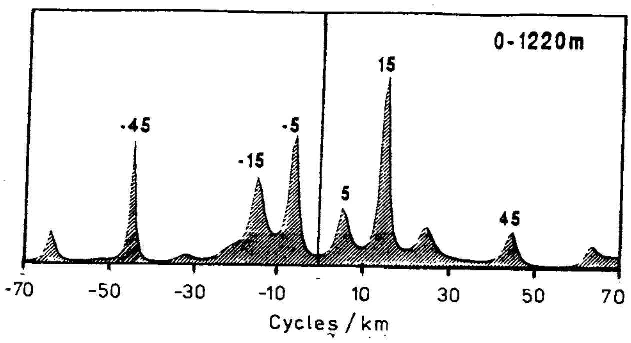

Fig. 7. Complex MEM spectrum for the Basin Traverse. Positive frequencies represent clockwise motion. Ordinate scale is arbitrary.

not possible to calculate Sw for each site of the Basin Traverse because for some of them only one sample is available and for the majority of the others the samples were not taken from exactly the same sedimentary units and cannot therefore be considered precisely contemporaneous. It would thus seen that the only accessible parameter would be S_T, which is an overestimate of the VGP dispersion since some scatter must be due to experimental causes. However, it is possible to estimate a likely value for S_W by examining the sources of error in the experimental procedure. One component that can be directly evaluated is instrumental error. This was done for 6 samples; each of them was measured 10 times over a period of 2 hours. In the VGP reference frame, the result is an average angular dispersion of 3°. Another source of error is the orientation of samples in the field which from mechanical considerations is generally thought not to exceed 2° (see e.g. Doell & Cox 1963; Butler 1992). Another 1° might be introduced by the preparation of the samples in the laboratory. If all these contributions are added, a total angular dispersion of 3.7° is obtained, which may be safely rounded off to 4°. This should provide a reasonable lower bound for S_W.

Because most of the samples at each site were collected at vertical distances of several tens of cm (which may represent thousands of years), it is preferable to calculate the total angular dispersion from individual VGPs rather than from site means. This is a conservative approach since the use of site means would yield an artificially low dispersion because of the averaging of directional variations due not only to experimental errors but also to real PSV. In other words, an unknown fraction of S_B would be wrongly attributed to S_W. The total dispersion for the 201 samples of the Basin Traverse is 10.7°. The estimate of 4° for S_W reduces this to 9.9°, but since the 4° was a lower bound this remains a slightly overestimated value of S_B.

So far we have considered causes that increase the angular dispersion and thus must be subtracted to obtain an estimate of the dispersion due to geomagnetic phenomena. However, in sedimentary palaeomagnetism, other causes can decrease the dispersion by their smoothing effect. Variations with quasi-periods on the order of the time constant of the remanence locking mechanism will be diminished, thus reducing the total angular dispersion. This effect can be important with CRM or DRM in very slowly deposited sediments. However, we have seen that there are reasons to believe that the remanence in the Lodève strata is a pDRM, and that it was acquired rapidly, in a high sedimentation rate environment. As a result it is reasonable to think that this effect is limited here.

After all these considerations, one is left with a value of VGP angular dispersion that is essentially equal to 10°, possibly a little smaller since Sw was underestimated. This value can be compared to those given by McFadden et al. (1991) for similar latitudes, keeping in mind that our data represent a period of zero reversal rate. For the past 5 Ma, corresponding to a relatively high reversal rate, they found a value of 12.9°. For the period 80 - 110 Ma, approximately corresponding to KN, they obtained a dispersion of 6.5°. The Lodève result indicates a somewhat reduced activity of the field during the PCR, and is therefore compatible with a link between reversal rates and PSV. However, the difference between the value obtained in the present study (~10°) and that for a high reversal rate period (~13°) is not large enough to be compelling.

Time series

Basin Traverse

Since the stratigraphic position of each sample is known, the present data set should in principle provide more information than the more overall statistical dispersion. But we face two difficulties. Firstly, in the absence of absolute time markers it is impossible to know the actual rate of magnetization acquisition. Secondly, in a continental environment the deposition is essentially discontinuous and rates can be expected to vary dramatically. Nevertheless, over a long section like the Basin Traverse we can assume that the average rate of remanence acquisition remained constant enough to allow some long period informa-

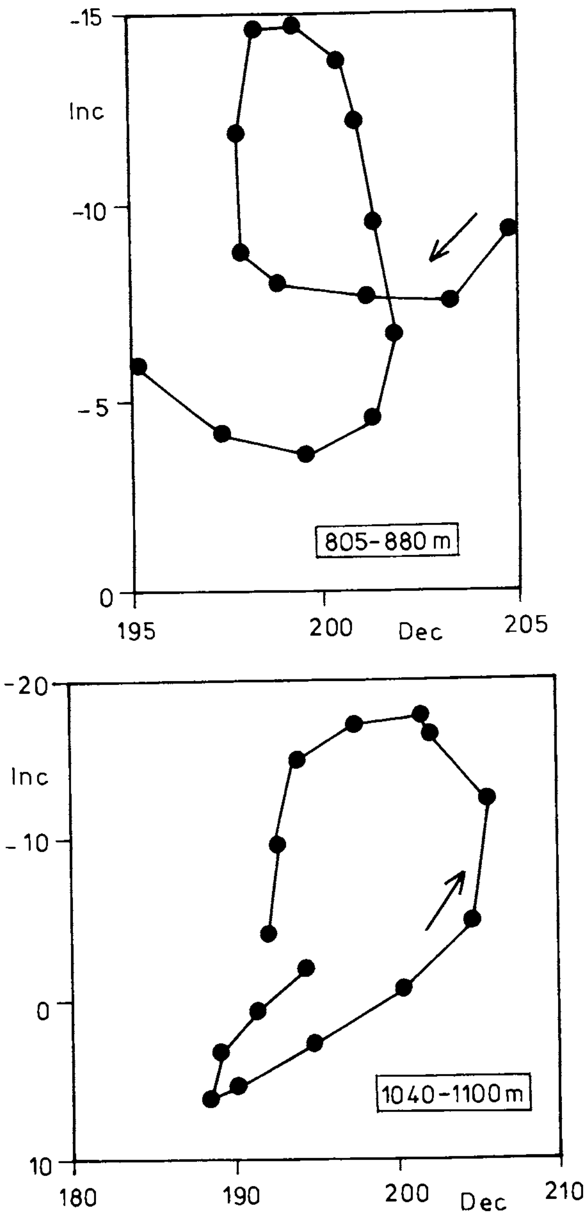

Fig. 8. Smoothed Bauer plots for two parts of the Basin Traverse showing clockwise (top) and counter-clockwise looping (bottom). Angles are in degrees (see Fig. 4).

tion to be recovered, and frequency analysis using the complex maximum entropy method (MEM) (Denham 1975) was therefore carried out.

In order to compensate for the widely variable sampling intervals, the data were interpolated and resampled at 5 m intervals by fitting a cubic spline through the experimental points. This was done on the X, Y, and Z components of the remanence vectors. The MEM spectrum is shown in Fig. 7. It is dominant by elliptic patterns, clockwise at 15 cycles/km and counter-clockwise at 5 cycles/km. A higher frequency (45 cycles/km) almost circular, counter-clockwise component also seems to be present.

The nature of the sediments makes it impossible to obtain really precise details about the frequency content of the secular variation recorded by them. Nevertheless, clear, coherent, patterns are detected - as illustrated by the examples shown in Fig.8 - and at least a crude estimate of their frequency can be made. Based on stratigraphic and sedimentologic considerations, Odin (1986) gives an average sedimentation rate of 0.12 mm/yr for the Thuringian. This leads to a plausible 10 Ma for the time span corresponding to the Basin Traverse. If we assume that on average the rate of magnetization acquisition is the same as the rate of accumulation this provides a basis for translating the MEM results into a time frame. Thus the 45, 15, and 5 cycles/km components correspond to periods of 0.19, 0.56, and 1.7 Ma, respectively. Such very long periods have not been much reported, but this simply reflects the paucity of relevant data hitherto. If dipole wobble can be regarded as a distinct phenomenon then one is predisposed to attribute these spectral peaks to it (McElhinny & Merrill 1975), but the confirmation of such a suggestion requires comparable data from sites with a wide geographic distribution.

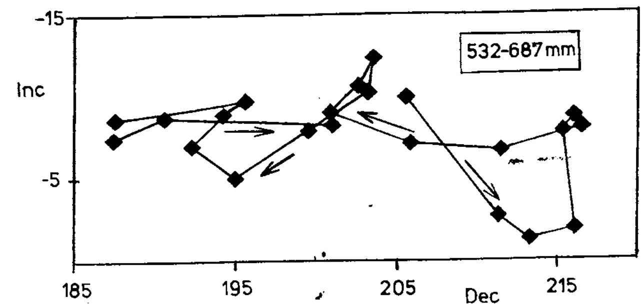

Fig. 9. Smoothed Bauer plot for part of the site BLF profile (see Figs. 5, 8).

Closely sampled sections

Visual inspection of the magnetograms of Figs. 5 and 6 reveals the presence of variations with pseudo-wavelengths of a few tens of cm and Fig. 9 shows a particular example, in this case a linear pattern on a Bauer plot. Here the passage from space domain to time domain is even more hazardous than for the Basin Traverse. In the latter, the large sampling interval and the length of the record made it legitimate to use an average deposition rate. However, on the small scale things are more complicated; deposition was certainly a discontinuous process, with numerous periods of no deposition alternating with periods of rapid accumulation. During active deposition the rate would have been higher than the average 0.12 mm/yr. An estimate of 1 mm/yr, possibly more, is reasonable for this kind of environment (Turner 1980). At this rate, periods of a few centuries are implied. If, on the other hand, the overall average of 0.12 mm/yr is used these values increase to a few millennia. The significance of these values is difficult to assess, but they are certainly within the range of typical secular variation of the field in the recent past (see e.g. Merrill & McElhinny 1983; Fig. 4.18).

Conclusions

The initial goal of this study was to obtain new insight into the Permian geomagnetic field during the Kiaman Interval (PCR) through the palaeomagnetic study of a long redbed sequence in the Lodève Basin, southern France. We have argued elsewhere that these redbeds carry a magnetization acquired early after deposition. A section of 1220 m of Upper Permian strata was sampled, representing some 10 Ma; this is one of the longest continuous palaeomagnetic records available to date.

The first and most definite geomagnetic result is the total absence of normal polarities indicating that the end of the PCR was not reached. This places the termination of this superchron in western Europe at the very end of the Upper Permian.

It was shown that the VGP dispersion is reduced (~ 10°) compared to periods of high reversal rates (~ 13°), although it is not as small as during the KN superchron (~ 7°). This result is compatible with models linking PSV and reversal rates but is certainly not yet decisive.

Directional variations are found on scales ranging from a few centimetres up to hundreds of metres. Despite the difficulties in assessing the rate of magnetization acquisition, it can be inferred that the longer period variations are on the order of hundreds of thousands of years, while the shorter period fluctuations are in the range of centuries to millennia. The more rapid changes can reasonably be attributed to secular variation of the kind seen over the last ten thousand years or so. Due to the paucity of appropriate data, the slower changes reported here have few counterparts in the published literature. Perhaps they represent some form of dipole wobble. Further work, representing a wide geographic distribution of sampling sites, is needed to assess their reality and permit more meaningful interpretation.

The palaeomagnetic pole obtained (154.1°E, 44.6°N, $A_{95} = 1.6°$) is concordant with other results from western Europe, and it is an improvement over previous results from the Lodève Basin because of the much better stratigraphic coverage. Since new results from contemporaneous sedimentary basins in France indicate that structural rotations have taken place (Diego-Orozco & Henry 1992), the Lodève result becomes an important reference pole in the ongoing task of unravelling the tectonic evolution of SW Europe.

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