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Variations in the geomagnetic dipole moment over the last 12 000 years

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SUMMARY

An analysis has been made of archaeointensity data for the past 12 000 years. There are 3243 results from different areas of the world covering the past 12 000 years. Of these, 2203 are from the European region and 1040 are from the rest of the world. The archaeointensity data set analysed in the present study is almost three times larger than that used by McElhinny & Senanayake (1982). Although there is no major difference between our global data and the earlier data, the data for the non-European region have been improved and we now have a data set for Asia.

Key words: archaeomagnetism, geomagnetism, palaeointensity, secular variation.

1 INTRODUCTION

To a first approximation, the magnetic field of the Earth is dipolar. The magnetic moment and orientation of the dipole are known to have changed with time from palaeomagnetic and archaeomagnetic measurements. An analysis of archaeointensity results (McElhinny & Senanayake 1982) has shown that the Earth's dipole moment was twice the present-day value 2000 years ago, whilst between 5000 and 6000 years ago it was much weaker. Over the past 15 years, many new archaeointensity results have been published. The amount of data analysed in the present study is almost three times that used by McElhinny & Senanayake (1982). Although there is still a heavy concentration in the Northern Hemisphere, many recent archaeomagnetic data are from Asia and America and there is less concentration in the European region. Based on the virtual axial dipole model, comparisons of archaeointensity results have been used either to track non-dipole geomagnetic field anomalies (Yang *et al.* 1993a) or to analyse the secular variation of the geomagnetic field (Aitken *et al.* 1989). Well-defined global and regional field models help us to understand how the geomagnetic field has changed over archaeological time and provide a reference for archaeomagnetic dating (Barbetti 1976; Shaw 1979).

2 STATISTICAL ANALYSIS OF VADMS

Archaeointensity data determined before 1982 were analysed statistically by McElhinny & Senanayake (1982). These are referred to in the present study as 'old' data. We have collected recent data from archaeomagnetic investigations since 1982 (referred to as 'new' data) and have analysed them in the same way as McElhinny & Senanayake (1982), transforming the field intensity results to virtual axial dipole moment (VADM) values (Smith 1967) For our analysis we divided the data into two sets, representing the European region and the rest of the world. We calculated the average value of the VADM in the same time intervals for each set and then combined the new VADM with the old values for each time interval based on the following formulae:

$$B=(N_o B_o+N_n B_n)/(N_o+N_n)\,,$$

$$\sigma=\sqrt{\{[N_o(B_o-B)^2+N_n(B_n-B)^2+N_o\sigma_o^2+N_n\sigma_n^2]/(N_o+N_n)\}}\,,$$

$$N=N_o+N_n\,,$$

Table 1. Average VDMs (VADMs) for 500 years intervals (to 2000 BC) and 1000 years intervals (from 2000 to 10 000 BC) from archaeomagnetic intensity data for the European region and the rest of the world separately.

Time intervals (years AD or BC)	European Region			Rest of world		
	VDM	*N*	SD	VDM	*N*	SD
1995–1500 AD	8.69	374	1.26	9.917	99	1.68
1500–1000	9.73	264	1.25	10.75	209	2.19
1000–500	11.38	234	1.60	11.05	240	1.32
500–0	10.45	188	1.56	11.70	138	2.47
0–500 BC	11.51	188	1.97	10.43	66	2.79
500–1000	11.38	101	2.05	9.39	48	1.67
1000–1500	11.38	147	2.00	9.41	39	1.24
1500–2000	8.86	36	1.83	9.26	33	1.47
2000–3000	8.89	77	1.65	8.42	51	1.48
3000–4000	8.47	78	1.51	6.62	60	0.86
4000–5000	7.94	223	0.69	6.33	19	1.23
5000–6000	7.39	276	1.12	6.93	17	0.84
6000–7000	9.43	12	1.91	5.81	5	0.87
7000–8000	10.46	5	1.08	7.05	9	1.95
8000–9000	–	–	–	6.76	5	1.34
9000–10000	–	–	–	8.36	2	0.06

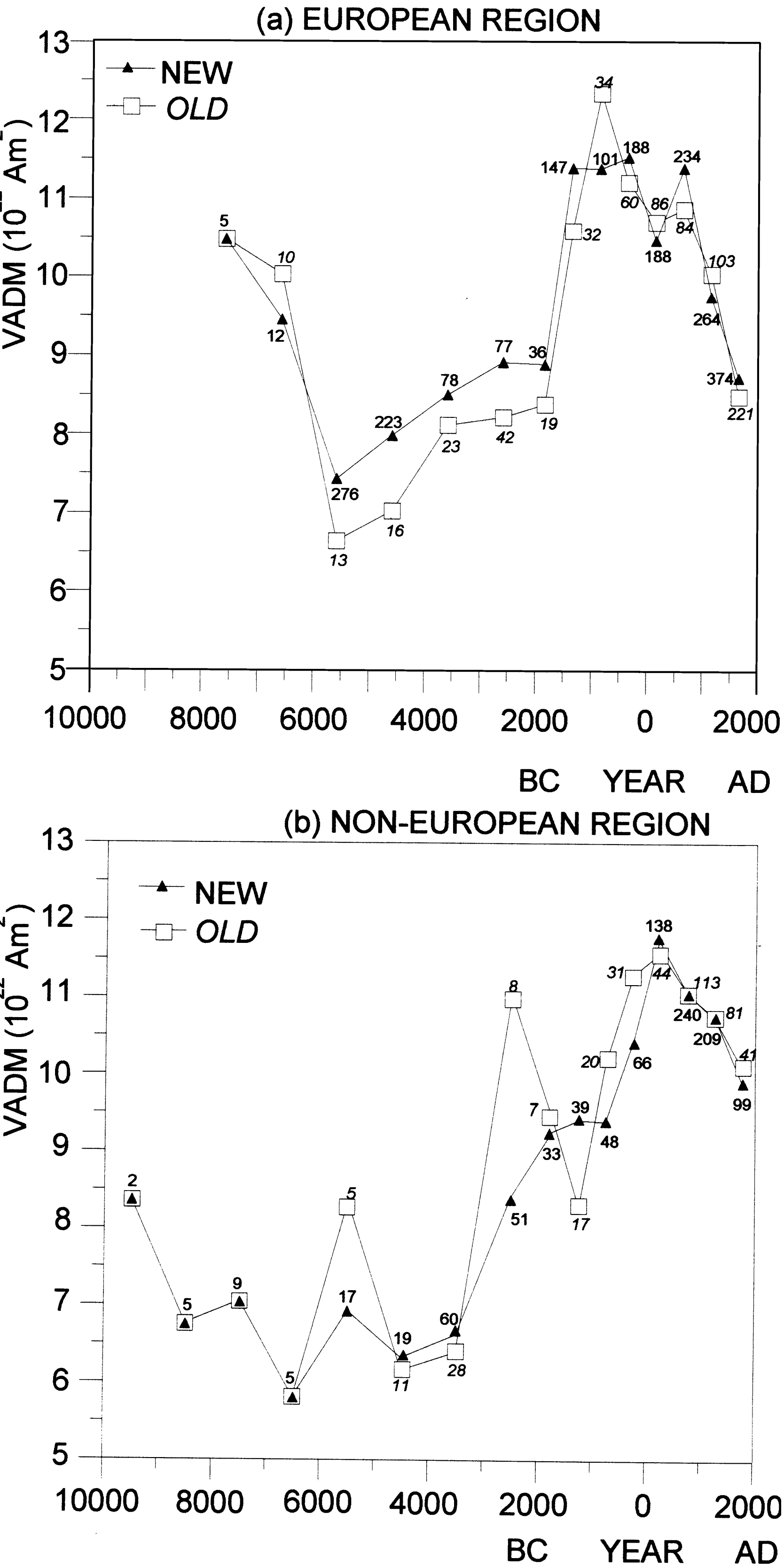

Figure 1. Comparison with previous results (McElhinny & Senanayake 1982) for the European region (a) and the rest of the world (b). The numbers are the number of data averaged in each 500 year interval (from 2000 BC) or 1000 year interval (prior to 2000 BC). The new data are given in Table 1.

Table 2. Global average VADMs using all the data in Table 1.

Time intervals	VADM	*N*	SD	95% limits
1995–1500 AD	8.95	473	1.45	0.123
1500–1000	10.18	473	1.80	0.157
1000–500	11.21	474	1.47	0.125
500–0	10.98	326	2.09	0.215
0–500 BC	11.23	254	2.26	0.270
500–1000	10.74	149	2.15	0.326
1000–1500	10.96	186	2.03	0.276
1500–2000	9.05	69	1.68	0.375
2000–3000	8.70	128	1.60	0.262
3000–4000	7.67	138	1.56	0.247
4000–5000	7.81	242	0.86	0.103
5000–6000	7.36	293	1.23	0.133
6000–7000	8.36	17	2.35	1.050
7000–8000	8.27	14	2.35	1.164
8000–9000	6.76	5	1.34	1.17
9000–10000	8.36	2	0.06	0.079

where N is the number of data, B is the field strength and σ is the standard deviation. N_o, B_o, σ_o and N_n, B_n, σ_n represent the old and new data (before and after 1982), respectively; B, σ and N are the combined data.

For the European region, the new data (after 1982) come from Bulgaria and Yugoslavia (Kovacheva & Kanarchev 1986; Kovacheva *et al.* (1995, personal communication, 1997), Greece (Odah *et al.* 1995; Hussain 1983, 1987) and other parts of Europe (summarized in Aitken *et al.* 1988, 1989). From the rest of the world the data are from Japan (Sakai & Hirooka 1986), China (Wei *et al.* 1982, 1986, 1987; Tang *et al.* 1991; Yang *et al.* 1993a,b), Peru (Gunn & Murray 1980; Yang *et al.* 1993c; Shaw *et al.* 1996) and North America (Sternberg 1989).

Periods shorter than 1000 years are usually associated with changes of the non-dipole field. Periods of about 10 000 years are associated with changes in the global geomagnetic dipole field (Cox & Doell 1964). To remove the short-period changes from the data, we averaged over 500 or 1000 years. The data for the European region and the rest of the world have been averaged and are summarized in Table 1. Comparisons of the present results with the previous results of McElhinny and Senanayake for the European region and the rest of the world are shown in Figs 1(a) and (b), respectively.

For the European region over the last 2000 years, there is no major difference between the new and the old data (Fig. 1a). The most noticeable difference is that the peak-to-peak amplitude variation is smaller for the new results. For the non-European region the old and new data are almost identical but the new data set is almost three times the old data set and provides us with a smoother curve.

The two data sets are combined in Table 2 and plotted in Fig. 2. Overall, the new data are very similar to the old data of McElhinny & Senanayake (1982) but with different features around 6000 to 1000 BC. The dipole field increased from its minimum at around 5500 BC, reached its maximum at around 1000 BC and remained at this maximum for almost 2000 years before starting to decrease to its present value. Comparing the data in Table 1 and Fig. 3, there are significant differences between the European region and the rest of the world, particularly over the period 2000–7000 BC.

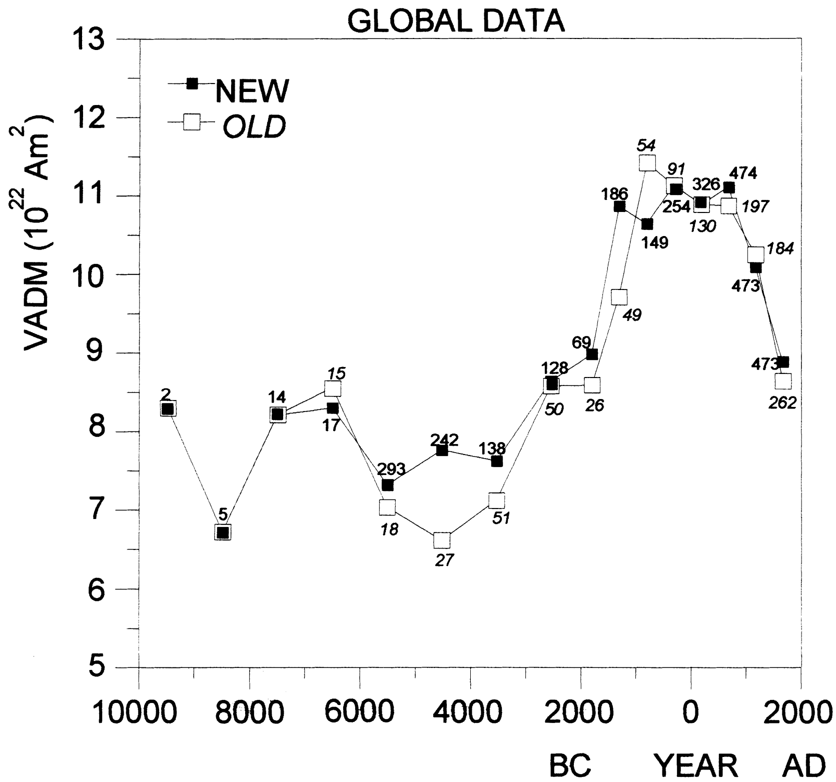

Figure 2. Comparison of mean VADMs from the present study with those from the previous study (McElhinny & Senanayake 1982). The numbers are the number of data averaged in each 500 year interval (to 2000 BC) or 1000 year interval (prior to 2000 BC). The new data are given in Table 2.

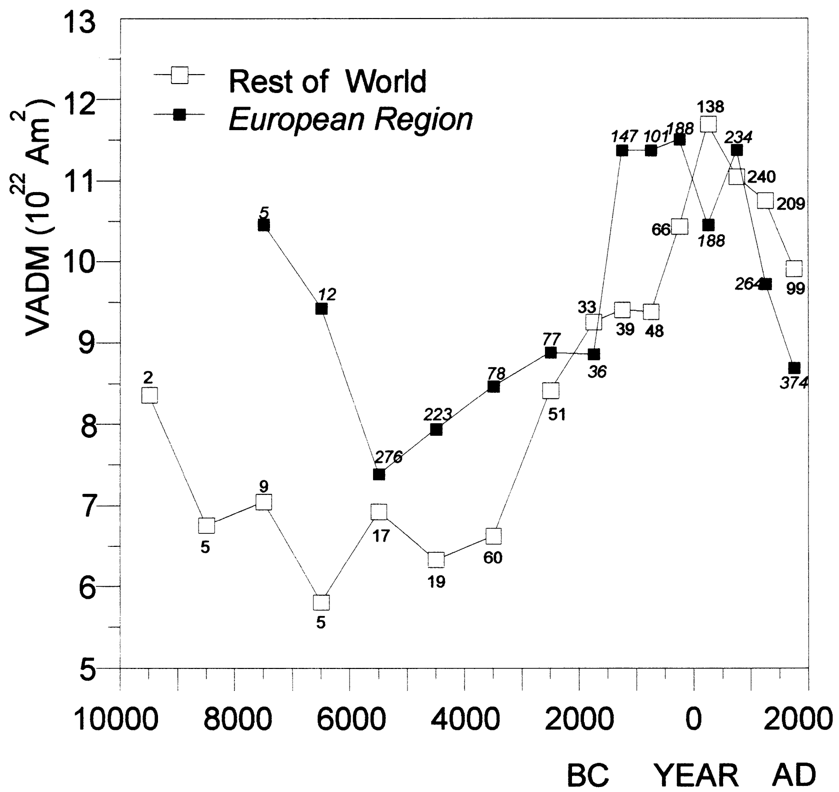

Figure 3. Comparison of average VADMs from the European region and the rest of the world. The numbers are the number of data averaged in each 500 year interval (from 2000 BC) or 1000 year interval (prior to 2000 BC). Data are listed in Table 1.

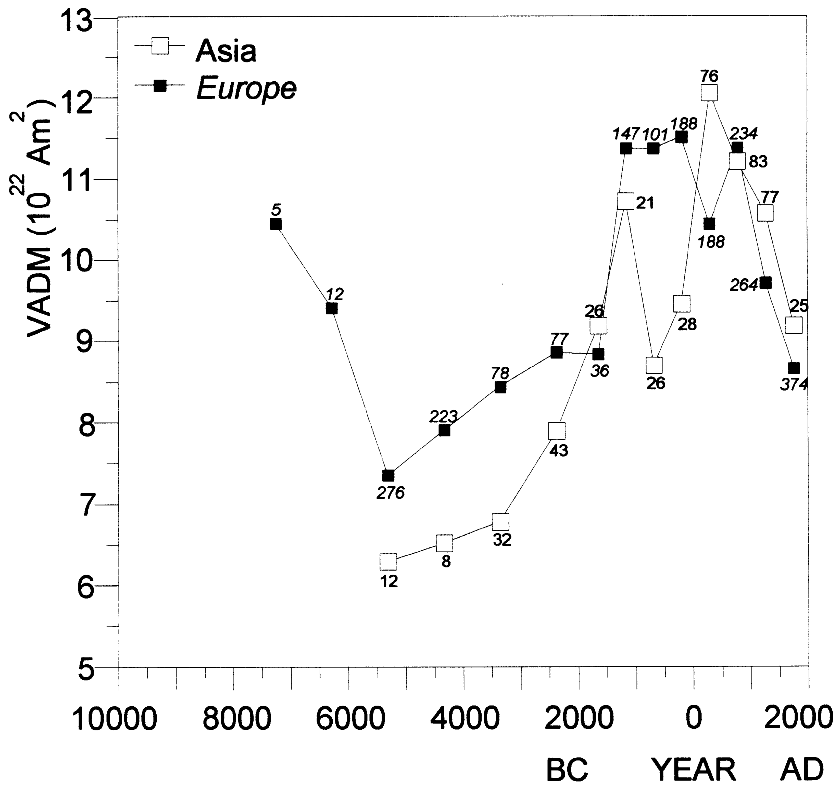

Figure 4. Comparison of mean VADMs for the European and Asian regions. The numbers are the number of data averaged in each 500 year interval (from 2000 BC) or 1000 year interval (prior to 2000 BC).

Many of the archaeointensity results come from China and Japan (Sakai & Hirooka 1986; Wei *et al.* 1986, 1987; Tang *et al.* 1991; Yang *et al.* 1993a,b); this has allowed the construction of an Asian data set, which is plotted, together with the European data, in Fig. 4. Again there are significant differences between the Asian data and the European data, particularly over the period 2000–5000 BC.

3 DISCUSSION

Archaeointensities are often determined from broken pieces of ceramic and there is therefore no orientation of the magnetization and no measurement of declination or inclination. In our analysis we have assumed that the field is an axial dipole field because we do not have directional data (D and I). Some of the differences between the data sets may be due to the dipole field axis being non-parallel to the spin axis. Alternatively, as pointed out by an anonymous referee, averaging field intensities will not average the non-dipole field, because the non-dipole field is usually not in the same direction as the dipole field. Only the component of the non-dipole field that is parallel to the dipole field is averaged. Any component that is orthogonal to the dipole field adds to the total field magnitude. In any area where there are large non-dipole field anomalies (positive or negative), the average field strength will be higher than in an area with fewer or smaller non-dipole anomalies. The strong VADM in Europe over the period 7000–2000 BC may be indicative of large local non-dipole field anomalies during this period.

4 CONCLUSIONS

We have analysed 3243 results from different areas of the world covering the past 12 000 years. Although there is no major difference between the new global model and the old data (McElhinny & Senanayake 1982), the data set for the non-European region has been improved and we now have a large data set for Asia. Differences between the data sets may be due to strong non-dipole field anomalies in Europe.

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