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An updated and homogeneous world secular variation data base. 1. Smoothing of the archaeomagnetic results

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Abstract

The available original archaeomagnetic world data on intensity and direction have been compiled and sorted according to geographical region. Then, after correcting them to correspond to a single site associated with each region (called a world site), they have been processed using the Gaussian statistic for the intensity (F) data and bivariate statistic for the declination (D) and inclination (I) data, to obtain smoothed values at regular time intervals. We include a discussion of the statistical methods used. We have limited the data to the last 20 centuries because the archaeomagnetic data alone do not allow us to go back further in the past. We have also excluded archaeomagnetic studies at world sites where the number of data is not sufficient to perform a statistical analysis. We obtained results at nine world sites for which the values of at least two of the three above-quoted parameters have been calculated at 25 year intervals from the beginning of our era. The results for each world site with their associated errors are given and discussed. The potential of this new set of world data, for improving our knowledge of the global terrestrial magnetic field (TMF) during the past 20 centuries, is sketched. These results will be completed in a second paper by analysing in the same way the data supplied for volcanic rocks and lake sediments.

1. Introduction

The study of the terrestrial magnetic field (TMF) secular variation at a large number of sites distributed over the surface of the Earth is of interest for the understanding of the terrestrial dynamo. Whereas a study of the long-term evolution of the intensity F alone, even limited to a single site, already permits us to know the rough temporal behaviour of this dynamo, a more complete and spatial picture can be obtained if the evolution of the directional elements (declination D and inclination I) is also known on a global scale.

The historical direct measurements of the usual TMF elements (horizontal X and Y and vertical Z) have already allowed spherical harmonic anal-

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ysis up to order eight for the last three centuries (Bloxham and Jackson, 1992). This analysis showed that the axial dipole field changes relatively little during this interval, and that the non-dipole field and possibly the equatorial dipole field change very quickly at this scale. Nevertheless, the existence of a stationary component suggested by the analysis of these historical data (Bloxham et al., 1989) is controversial (Hulot and Le Mouel, 1994). It is easy therefore to appreciate the usefulness of extending this analysis for older periods; up to the beginning of our era, for example. It seems possible to obtain such an extension with the world archaeomagnetic data. Although the actual number of sites is limited and often only the declination D and the inclina-

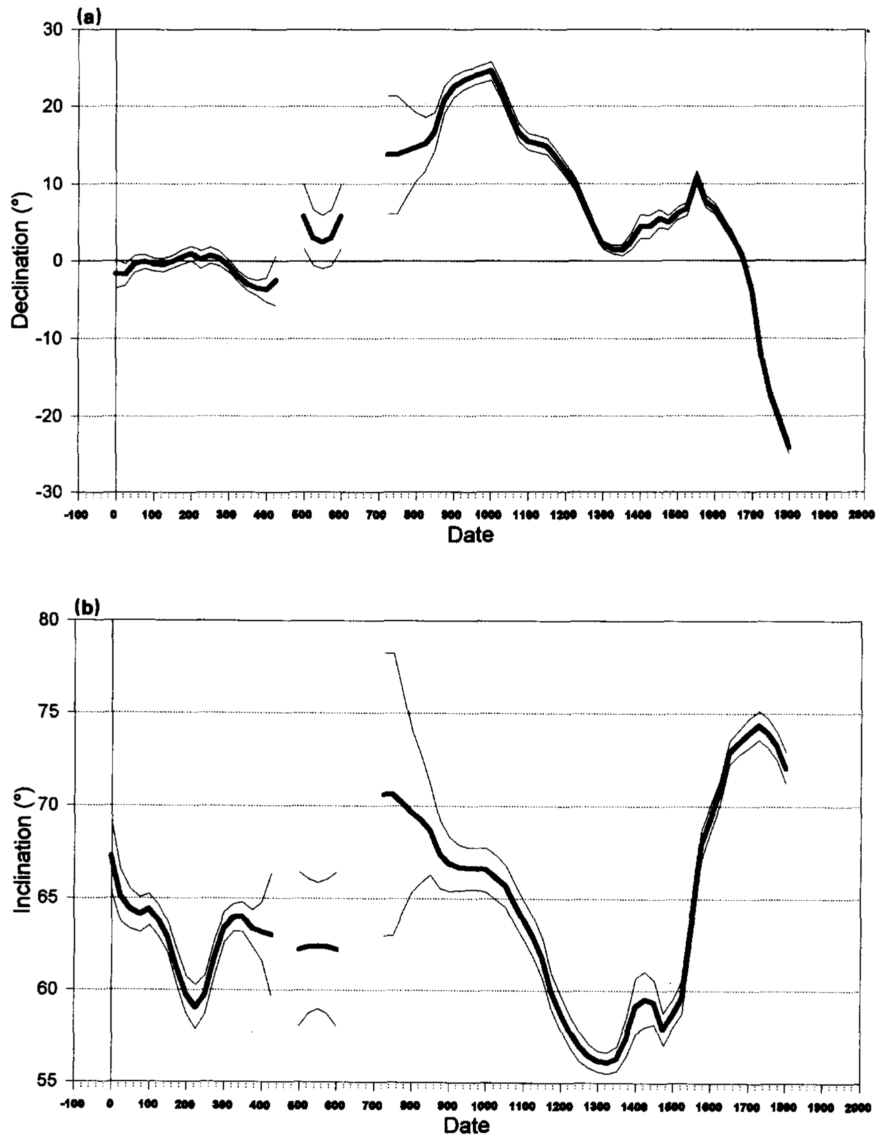


Fig. 1. Curves of (a) $D = f(t)$ and (b) $I = f(t)$ with 95% confidence band at Meriden in England; 80 year window.

Table 1
Data for England (Meriden: 52.4° N, 1.6° W)

Date	N_{si}	W_{si}	W_{sa}	I	D	α_{95}	α_x	α_y	Ω
0	3	1.7	25.9	67.3	−1.7	1.9	1.8	2.0	26.1
25	10	5.7	80.3	65.1	−1.8	1.4	1.4	1.5	8.5
50	11	9.5	145.5	64.4	−0.4	1.1	1.1	1.1	15.0
75	18	12.2	180.5	64.1	−0.1	0.9	1.0	1.0	50.8
100	19	13.5	200.3	64.4	−0.5	0.8	0.8	0.9	64.2
125	20	12.4	160.0	63.6	−0.6	0.9	0.9	1.0	51.3
150	16	12.7	161.1	62.9	−0.1	0.8	0.9	0.9	24.3
175	20	11.0	147.1	61.2	0.5	1.0	0.9	1.0	174.9
200	16	11.2	183.4	59.8	1.0	1.0	0.9	1.0	163.4
225	16	10.2	150.3	59.1	0.2	1.2	1.0	1.1	24.4
250	16	12.2	168.8	59.8	0.7	1.1	0.9	1.0	18.6
275	26	13.7	171.5	61.8	0.3	1.0	0.8	1.0	15.6
300	24	15.3	185.1	63.4	−0.7	0.8	0.7	0.8	13.8
325	24	15.7	187.5	64.0	−2.0	0.7	0.7	0.7	2.6
350	17	12.8	147.4	64.0	−3.1	0.8	0.7	0.8	166.5
375	13	7.7	83.4	63.4	−3.6	1.0	0.9	1.0	170.9
400	10	3.4	37.4	63.2	−3.8	1.6	1.3	1.5	173.8
425	7	1.0	11.4	63.0	−2.6	3.3	2.7	2.8	93.7
450	1	0.2							
475	1	0.3							
500	2	0.7	8.7	62.3	5.8	4.2	4.0	4.6	82.1
525	2	1.2	13.2	62.4	3.0	3.6	3.6	3.9	84.5
550	2	1.4	15.0	62.4	2.5	3.4	3.4	3.7	85.0
575	2	1.2	13.2	62.4	3.0	3.6	3.6	3.9	84.5
600	2	0.7	8.7	62.3	5.8	4.2	4.0	4.6	82.1
625	1	0.3							
650	2	0.3							
675	2	0.3							
700	1	0.4							
725	1	0.5	7.7	70.6	13.7	7.6	7.4	7.4	180.0
750	1	0.5	7.7	70.6	13.7	7.6	7.4	7.4	180.0
775	2	0.7	10.0	70.2	14.2	5.9	5.8	5.9	20.0
800	2	0.9	13.3	69.7	14.7	4.4	4.3	4.4	19.5
825	2	1.0	14.6	69.3	15.2	3.4	3.4	3.4	19.1
850	3	1.1	16.8	68.7	16.7	2.5	2.4	2.5	52.3
875	11	1.8	31.4	67.4	20.8	1.8	1.6	1.8	46.4
900	11	3.1	56.0	68.9	22.5	1.5	1.3	1.4	25.1
925	12	4.5	85.2	68.7	23.4	1.3	1.1	1.2	0.4
950	11	5.5	103.2	66.6	23.6	1.1	1.0	1.1	157.6
975	12	5.4	102.8	66.6	24.2	1.2	1.1	1.1	157.6
1000	12	5.1	99.6	66.5	24.6	1.2	1.1	1.2	149.8
1025	17	5.5	105.2	66.1	22.2	1.2	1.1	1.3	106.3
1050	14	6.7	119.6	65.7	19.2	1.1	1.1	1.2	97.3
1075	21	9.1	153.0	64.7	16.6	1.1	1.1	1.2	138.9
1100	21	10.8	177.0	63.8	15.4	1.1	1.0	1.2	158.9
1125	23	9.9	160.3	63.0	15.2	1.1	1.0	1.2	163.0
1150	15	8.9	134.5	61.8	14.8	1.1	1.0	1.3	165.1
1175	18	8.2	116.6	60.0	13.4	1.0	1.0	1.2	158.6
1200	16	9.0	126.6	58.9	11.8	0.9	1.1	1.2	152.8
1225	22	10.9	150.5	57.8	9.9	0.9	1.0	1.1	131.0
1250	22	12.1	180.8	57.0	7.2	0.6	0.6	1.0	111.6
1275	29	15.9	265.5	56.5	4.4	0.6	0.6	0.6	109.3
1300	26	17.7	323.8	56.2	2.1	0.6	0.6	0.6	102.4

Table 1 (continued)

Date	N_{si}	W_{si}	W_{sa}	I	D	α_{95}	α_x	α_y	Ω
1325	25	16.5	305.5	56.1	1.5	0.6	0.6	0.6	90.6
1350	21	11.2	199.4	56.3	1.4	0.7	0.7	0.5	94.1
1375	19	6.2	96.6	57.4	2.5	1.0	1.0	1.2	157.1
1400	8	4.0	54.0	59.2	4.4	1.5	1.2	1.9	159.0
1425	9	3.8	57.4	59.6	4.4	1.5	1.2	1.9	156.4
1450	9	4.5	78.8	59.4	5.5	1.2	1.1	1.5	154.7
1475	12	8.5	141.6	57.9	4.9	0.9	0.9	1.2	158.9
1500	12	9.9	174.2	58.8	6.2	0.8	0.7	1.1	155.8
1525	15	9.4	159.4	59.7	6.7	0.9	0.8	1.2	160.0
1550	11	5.5	111.1	63.9	10.8	0.9	0.7	1.1	177.1
1575	13	8.4	126.5	67.9	7.7	0.8	0.8	1.0	5.8
1600	11	9.4	145.0	69.3	6.8	0.7	0.7	0.9	178.8
1625	14	11.3	161.1	70.8	4.8	0.7	0.6	0.9	179.0
1650	9	7.5	113.6	72.9	3.0	0.6	0.6	0.7	32.9
1675	9	6.3	88.0	73.5	0.2	0.7	0.6	0.8	35.8
1700	5	4.0	56.7	73.9	−4.1	0.8	0.7	1.0	46.7
1725	5	4.2	60.6	74.4	−12.4	0.8	0.8	0.9	87.2
1750	4	4.0	60.0	74.0	−17.5	0.8	0.7	0.9	119.0
1775	4	4.0	60.0	73.3	−20.9	0.8	0.7	0.8	129.5
1800	3	3.0	45.0	72.1	−24.1	0.8	0.8	0.9	165.1

Columns (left to right): date AD; N_{si}, number of sites in the 80 year window; W_{si}, weight relative to sites; W_{sa}, weight relative to samples of the sites; I, inclination; D, declination; α_{95}, 95% dispersion angle of the circle of the classical Fisher statistic; α_x,α_y, 95% dispersion angles of the ellipse of the bivariate statistic; Ω, angle between the elongation direction of the confidence ellipse and the mean direction meridian.

tion I are known, spherical harmonic analyses extended over 2000 years are of some interest, even if they are only performed at low degrees and even if the Gauss coefficients can only be determined relative to the first one (Creer et al., 1973). In particular, it would be possible to study accurately, and independently of the concept of virtual geomagnetic pole (VGP), the dipole field, which remains poorly characterized for time constants of the order of a million years.

The first studies of the TMF D and I secular variation were made in France by Thellier (1937, 1938) using baked earth structures dated by archaeologists. Since that time, unfortunately, archaeomagnetism has been developed only in a few countries, the data obtained being, moreover, sometimes insufficient or badly distributed in time. The aim of this paper is to collect the world archaeomagnetic data which allow at the present time the determination at some world sites of a continuous secular evolution. As will be seen, there are fewer than ten sites where this is possible. This is why an attempt will subsequently be made (Daly and Le Goff, 1995) to use volcanic rocks and lake sediments, which recently have also given some secular variation data.

2. Treatment of the data

A description of the methods used in archaeomagnetism for the collection of samples and measurement of their magnetization in the laboratory has been given by Thellier (1981) and Bucur (1994). These measurements generally give the declination D, the inclination I and sometimes the intensity F of the TMF at a localized site, which we will term a regional site, where an archaeological structure has been studied. To this direction and intensity are generally respectively associated the parameter of the Fisher statistic and the standard error, defining the accuracy with which the mean value is obtained with the number N of analysed samples. These data are associated with a dating bracket given by the archaeologists. We thus have for a given territory (of area about that of France, for example), a number of data distributed more or less regularly in time and space. Two types of problems thus arise in determining, at a single site called a world site (Paris for France, for example), of latitude λ and of longitude φ, the regular evolution during time of some or all of the three TMF parameters. The first problem is to obtain, from the regional data (D, I, F), values corrected to

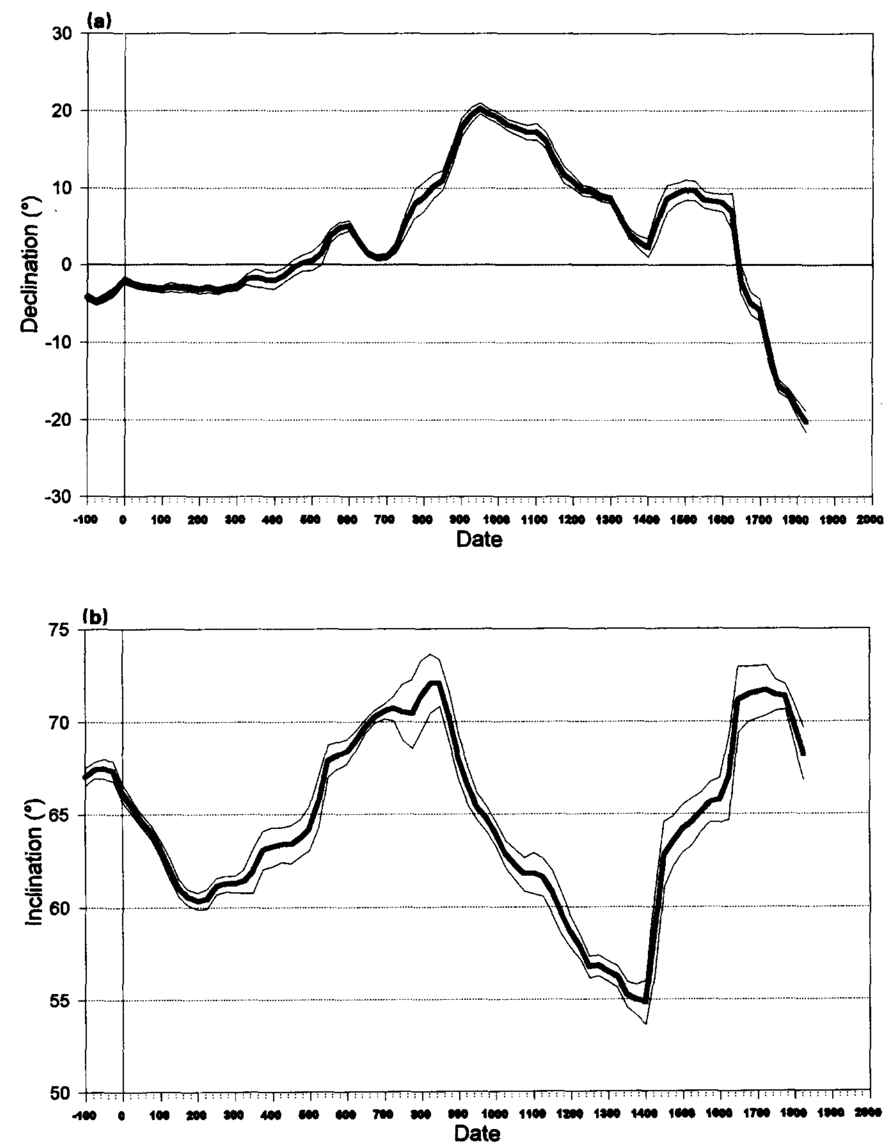


Fig. 2. Curves of (a) $D = f(t)$ and (b) $I = f(t)$ with 95% confidence band at Paris in France; 80 year window.

Table 2
Data for France (Paris 48.9° N, 2.3° E)

Date	N_{si}	W_{si}	W_{sa}	I	D	α_{95}	α_x	α_y	Ω
−100	4	3.3	71.0	67.05	−4.14	0.45	0.45	0.54	45.11
−75	5	4.9	82.4	67.42	−4.79	0.44	0.42	0.52	37.39
−50	8	4.7	67.4	67.48	−4.27	0.53	0.52	0.62	45.46
−25	7	4.4	67.4	67.35	−3.37	0.54	0.54	0.64	39.56
0	8	7.2	124.2	66.19	−1.97	0.46	0.43	0.48	166.40
25	17	14.3	213.6	65.44	−2.52	0.39	0.34	0.41	160.72
50	23	17.8	249.7	64.72	−2.86	0.35	0.31	0.38	165.14
75	22	16.4	203.7	64.05	−3.02	0.38	0.33	0.42	169.67
100	14	10.8	121.2	63.17	−3.18	0.45	0.41	0.50	178.69
125	18	9.4	94.5	62.11	−2.91	0.58	0.51	0.64	7.96
150	20	13.1	151.3	60.99	−3.11	0.46	0.43	0.52	10.74
175	19	14.3	185.3	60.52	−3.05	0.43	0.40	0.45	18.10
200	15	12.6	180.9	60.32	−3.28	0.44	0.41	0.45	22.54
225	18	8.0	131.3	60.43	−3.09	0.53	0.49	0.55	37.09
250	16	9.6	140.3	61.12	−3.36	0.45	0.42	0.51	43.77
275	12	10.3	136.9	61.24	−3.02	0.42	0.40	0.52	45.22
300	11	9.2	117.6	61.23	−2.91	0.43	0.42	0.54	45.99
325	10	4.6	58.2	61.42	−1.90	0.54	0.65	0.76	37.21
350	5	2.1	25.4	61.94	−1.72	1.17	1.10	1.14	171.17
375	6	3.6	39.2	63.08	−1.94	1.03	0.91	0.96	130.19
400	5	3.6	39.1	63.23	−2.05	1.06	0.89	0.97	121.25
425	7	4.6	43.2	63.35	−1.39	0.95	0.80	0.86	137.26
450	6	3.7	30.7	63.37	−0.39	1.03	0.85	1.00	166.23
475	5	3.2	23.9	63.73	0.24	1.01	0.77	1.19	173.39
500	4	2.4	18.8	64.23	0.46	1.20	0.79	1.48	173.21
525	6	1.6	18.6	65.71	1.43	1.41	0.77	1.64	167.86
550	3	1.2	26.0	67.89	3.74	0.87	0.64	0.90	170.44
575	5	1.6	39.9	68.18	4.70	0.73	0.57	0.56	177.16
600	4	2.0	50.6	68.39	5.10	0.67	0.54	0.83	0.57
625	7	2.8	81.8	69.00	3.17	0.52	0.51	0.64	25.04
650	9	4.6	136.0	69.76	1.44	0.38	0.42	0.48	36.69
675	9	5.7	156.0	70.27	0.93	0.35	0.42	0.44	38.03
700	7	5.2	127.6	70.56	1.03	0.40	0.49	0.49	56.77
725	8	3.4	64.3	70.73	2.26	0.66	0.73	0.78	40.89
750	5	1.6	19.5	70.52	5.20	1.51	1.35	1.61	30.61
775	4	1.1	14.6	70.41	7.89	1.84	1.58	1.91	177.34
800	4	1.1	15.2	71.40	8.90	1.89	1.58	1.99	0.71
825	6	1.5	19.0	72.06	10.22	1.57	1.34	1.68	17.10
850	4	2.1	25.4	72.08	10.97	1.24	1.04	1.38	26.91
875	6	3.0	34.7	70.24	14.22	1.40	0.82	1.72	28.51
900	8	4.1	47.3	68.09	17.78	1.20	0.65	1.51	26.67
925	8	4.0	47.0	66.54	19.38	1.01	0.52	1.28	22.31
950	7	4.2	51.2	65.41	20.27	0.70	0.56	0.86	14.41
975	7	3.5	43.7	64.80	19.50	0.70	0.50	0.96	15.37
1000	9	3.9	47.4	63.95	18.98	0.69	0.55	0.90	1.33
1025	8	4.3	50.1	62.84	18.06	0.72	0.56	0.89	166.04
1050	6	3.4	36.9	62.27	17.65	0.84	0.67	1.00	162.67
1075	5	2.7	27.9	61.76	17.14	0.90	0.77	1.03	153.16
1100	3	1.4	14.1	61.79	17.24	1.10	0.92	1.23	123.39
1125	3	1.5	13.7	61.59	16.21	1.03	0.98	1.14	125.11
1150	3	2.3	19.5	60.77	13.69	1.19	0.95	1.39	116.36
1175	5	2.9	26.8	59.62	11.66	1.11	0.94	1.29	128.04
1200	4	3.4	35.1	58.65	10.85	0.85	0.84	0.99	135.55

Table 2 (continued)

Date	N_{si}	W_{si}	W_{sa}	I	D	α_{95}	α_x	α_y	Ω
1225	8	4.1	45.0	57.84	9.67	0.67	0.73	0.77	50.34
1250	9	6.0	63.3	56.76	9.49	0.59	0.57	0.76	21.48
1275	11	7.5	86.5	56.84	8.77	0.54	0.47	0.68	27.58
1300	10	7.7	97.5	56.53	8.55	0.53	0.44	0.66	25.73
1325	11	7.8	103.8	56.25	6.29	0.57	0.61	0.63	71.31
1350	11	8.4	97.5	55.29	4.04	0.70	0.70	0.80	162.27
1375	10	6.9	72.7	55.00	2.98	0.62	0.78	0.94	172.68
1400	6	4.0	38.4	54.83	2.20	1.21	0.99	1.48	172.99
1425	5	1.6	13.4	58.52	5.54	2.19	1.35	2.76	160.53
1450	4	2.6	23.7	62.82	8.61	1.77	0.85	2.35	171.17
1475	5	3.7	33.1	63.53	9.26	1.36	0.71	1.81	173.76
1500	5	3.4	30.9	64.22	9.72	1.29	0.72	1.70	179.34
1525	6	2.8	24.2	54.57	9.67	1.29	0.78	1.67	9.01
1550	6	4.7	47.1	65.13	8.48	1.08	0.69	1.36	179.11
1575	5	4.3	44.3	65.67	8.23	1.10	0.72	1.35	175.94
1600	5	3.9	40.6	65.75	8.07	1.19	0.76	1.47	175.82
1625	3	0.8	6.2	67.04	7.03	2.33	1.61	2.83	29.89
1650	3	1.6	10.1	71.17	−1.83	1.76	1.55	1.95	61.43
1675	3	2.1	13.7	71.46	−4.95	1.47	1.22	1.71	75.06
1700	3	2.1	13.9	71.57	−5.79	1.40	1.19	1.64	80.14
1725	1	0.9	6.1	71.68	−11.54	1.33	1.33	1.33	0.00
1750	2	1.2	8.8	71.43	−15.52	0.82	0.74	0.91	103.29
1775	1	1.0	7.0	71.35	−16.49	0.68	0.68	0.68	0.00
1800	2	2.0	13.0	69.81	−18.52	1.10	0.77	1.38	157.36

Columns (left to right): date AD; N_{si}, number of sites in the 80 year window; W_{si}, weight relative to sites; W_{sa}, weight relative to samples of the sites; I, inclination; D, declination; α_{95}, 95% dispersion angle of the circle of the classical Fisher statistic; α_x,α_y, 95% dispersion angles of the ellipse of the bivariate statistic; Ω, angle between the elongation direction of the confidence ellipse and the mean direction meridian.

this world site. The second one is to perform a temporal smoothing of the reduced data by an adequate statistical treatment, after an analysis of the reasons for the dispersions and of the errors on individual measurements.

2.1. Reduction of region data

2.1.1. Direction of the TMF

The best solution would be of course to use only the regional sites sufficiently close to a world site. This occurs with lake sediments or volcanic rocks, for which the uniqueness of the place is evident. Unfortunately, dated archaeological materials are much more dispersed, and so scarce for some periods that it would not be reasonable to eliminate even one, for a simple reason of distance. In France, for instance, the regional sites are roughly distributed in a circle of 1000 km diameter (Bucur, 1994). How can the reductions be done? This question has already been fully discussed. Thellier (1981) simply reduced the French data under the hypothesis of a centred axial dipole. Irving (1964) introduced the reduction through the VGP (virtual geomagnetic pole). Neither of these methods can be really well justified theoretically, so we tried to compare with samplings of theoretical TMF values obtained from the IGRF (International Geomagnetic Reference Field). Bucur (1994) has examined again that discussion and the comparison for a geographical surface including the French territory. She showed, as did Shuey et al. (1970), that the method using the VGP gives the best concentration, i.e. a 95% confidence cone of about 2.5° of opening around the true value, even for regions where the declinations are important. Thus, we have systematically used that method.

Table 3
Data for Bulgaria (Sofia: 42.7° N, 23.3° E)

Date	N_{si}	W_{si}	W_{sa}	D	α_{95}	N_{si}	W_{si}	W_{sa}	I	α_{95}	F	σ
0	2	0.8	3.8	1.52	16.76	2	0.8	3.6	63.50	16.39		
25	2	0.8	3.6	1.52	16.76	6	1.5	8.4	62.90	7.17		
50	2	0.8	3.6	1.52	16.76	7	3.6	19.4	63.15	3.43	64.98	10.53
75	2	0.7	3.3	2.25	17.65	16	7.2	57.7	61.85	1.50	67.85	7.95
100	3	0.7	10.2	0.67	6.21	18	11.1	100.7	61.46	1.07	66.24	7.24
125	4	0.8	19.7	−2.53	3.61	21	12.3	144.0	60.76	0.83	64.85	7.18
150	4	1.2	30.8	−4.35	2.71	25	14.8	197.1	59.55	0.67	62.27	7.82
175	3	1.6	36.7	−4.97	2.47	24	13.0	193.1	58.47	0.68	61.64	6.04
200	3	1.9	38.8	−4.32	2.46	20	12.5	188.8	57.45	0.69	61.48	8.09
225	3	1.8	32.2	−3.75	2.74	22	8.8	115.0	56.03	1.00	62.97	7.87
250	5	2.2	27.9	−1.89	3.05	18	9.3	100.8	54.65	1.10	63.03	6.90
275	7	2.5	22.6	−0.59	3.45	22	10.5	102.5	53.90	1.07	62.71	7.01
300	5	2.7	20.1	0.19	3.50	18	10.7	104.3	53.24	1.07	62.06	7.40
325	6	2.8	21.5	−0.02	3.56	21	9.5	93.1	52.57	1.19	60.85	8.35
350	7	4.7	42.4	0.38	2.69	14	9.9	92.0	52.39	1.47	57.64	7.93
375	9	5.6	54.6	0.38	2.23	24	10.5	100.5	53.25	1.41	56.91	7.70
400	9	5.6	62.0	0.43	1.93	20	11.0	110.9	53.83	1.27	56.56	7.27
425	8	3.8	45.2	0.34	1.91	19	9.2	103.1	54.75	1.11	57.24	7.58
450	3	2.2	30.5	−0.07	2.03	13	8.2	96.7	55.13	1.05	58.22	7.93
475	5	1.9	19.5	1.24	2.94	23	8.5	94.7	56.77	1.04	61.69	8.43
500	4	1.8	12.5	4.17	4.76	23	10.5	102.8	58.92	0.99	62.86	7.30
525	4	1.9	10.4	6.68	4.64	25	13.5	119.6	60.06	0.87	63.55	6.64
550	4	2.8	19.0	6.11	3.15	22	15.1	133.0	60.14	0.81	64.66	7.63
575	7	3.4	31.0	4.54	2.62	24	13.5	126.5	59.95	0.85	86.98	8.76
600	6	4.0	52.5	2.33	2.12	19	9.5	112.7	59.79	1.03	69.12	8.21
625	6	3.6	54.3	0.78	2.20	18	6.1	84.8	60.31	1.33	71.04	7.11
650	3	2.6	42.2	−0.45	2.67	4	3.2	50.8	61.18	1.69	69.54	4.48
675	3	1.6	19.2	1.80	4.71	4	1.6	22.4	60.46	3.17	68.84	4.76
700	2	0.8	5.6	4.14	11.33	2	0.8	5.6	59.55	8.23		
725	2	0.3				2	0.3					
750	0	0.0				0	0.0					
775	0	0.0				1	0.2					
800	0	0.0				1	0.4					
825	0	0.0				1	0.6	7.2	65.80	2.78		
850	2	0.6	8.1	15.68	7.76	3	1.5	15.9	64.88	3.83	60.82	3.32
875	4	2.8	31.2	15.72	3.48	6	3.8	39.5	64.75	2.76	67.03	7.76
900	4	3.8	37.6	13.99	3.11	6	5.0	46.0	64.25	2.58	68.26	8.05
925	5	3.8	33.9	12.70	3.17	7	4.9	40.8	64.29	2.71	69.35	8.05
950	8	4.0	33.5	7.26	2.42	9	4.8	37.5	64.48	2.14	69.85	6.62
975	6	5.2	42.3	7.63	1.99	7	5.5	43.8	64.45	1.78	67.58	5.30
1000	5	4.9	41.4	8.14	2.02	5	4.9	41.4	64.69	1.84	66.90	4.74
1025	5	3.5	27.8	8.85	2.72	5	3.5	27.8	64.14	2.44	66.13	4.76
1050	3	1.5	8.9	16.30	5.96	3	1.5	8.9	63.21	5.47	64.78	4.78
1075	2	1.2	8.0	4.15	5.46	5	1.9	17.1	60.05	3.02	59.29	9.41
1100	2	1.4	9.8	5.90	4.94	6	3.7	36.5	59.18	1.81	55.59	8.53
1125	2	1.5	10.4	7.51	4.73	7	5.2	58.8	59.25	1.43	54.27	7.84
1150	1	0.8	5.6	12.58	4.38	9	6.6	80.3	58.47	1.17	54.15	7.70
1175	2	1.5	10.4	9.21	5.63	12	8.0	99.8	57.06	1.17	57.10	7.45
1200	2	1.4	9.8	8.31	6.22	10	7.3	89.2	56.47	1.25	58.65	6.99
1225	2	1.2	8.0	7.41	7.35	7	4.6	60.0	54.87	1.46	58.83	4.48
1250	1	0.3				6	2.7	33.3	54.66	1.93	53.49	5.05
1275	0	0.0				5	3.0	37.8	52.87	1.39	51.62	3.97
1300	0	0.0				6	3.9	48.6	52.67	1.27	52.57	5.10

Table 3 (continued)

Date	N_{si}	W_{si}	W_{sa}	D	α_{95}	N_{si}	W_{si}	W_{sa}	I	α_{95}	F	σ
1325	1	0.3				8	4.2	47.4	52.62	1.24	53.32	5.83
1350	1	0.8	8.0	15.87	2.03	7	5.0	45.2	53.39	1.24	55.14	6.62
1375	2	2.0	18.0	13.01	2.02	7	5.4	38.3	54.19	1.24	56.04	6.64
1400	2	1.8	16.0	12.68	2.20	7	5.5	38.2	54.04	1.26	55.71	7.21
1425	2	1.3	11.0	11.40	2.93	7	3.5	29.0	53.77	1.56	53.49	8.70
1450	0	0.0				3	2.3	24.8	53.64	1.77	43.15	6.26
1475	0	0.0				5	2.1	31.4	59.09	2.06	45.53	6.58
1500	0	0.0				5	3.2	44.8	62.00	1.70	49.45	6.54
1525	0	0.0				6	4.0	54.3	65.18	1.35	53.97	6.47
1550	0	0.0				4	3.6	46.2	65.97	1.17	55.13	5.20
1575	0	0.0				5	4.0	39.9	70.76	1.38	61.64	9.00
1600	0	0.0				3	2.4	17.8	72.43	2.20	63.12	10.42
1625	0	0.0				5	2.8	20.8	70.07	3.09	64.27	9.51
1650	0	0.0				3	2.6	22.0	64.57	3.29	68.33	6.51
1675	0	0.0				4	3.5	32.0	60.85	1.77	58.98	6.23
1700	0	0.0				4	3.6	33.0	61.24	1.76	57.69	6.61
1725	2	1.3	5.5	−7.98	5.26	6	3.9	28.5	62.11	1.93	55.12	5.47
1750	2	1.8	8.0	−10.18	5.05	4	3.5	21.7	59.13	2.57	52.08	4.54
1775	2	2.0	9.0	−10.70	4.86	4	4.0	19.0	59.32	2.68	52.20	4.77
1800						3	2.8	14.0	58.18	3.10	51.03	5.61

Different values of N_{si}, W_{si} and W_{sa} are associated with separate smoothing of D and I, F intensity of the field; σ, standard error. α_x, α_y and Ω are not indicated (see text).

2.1.2. Intensity of the TMF

The spatial variation of F is relatively less important than that of the TMF direction. Nevertheless, knowing the intensity F_1 at the regional site of latitude λ_1, we have determined the intensity F_2 at the latitude of reduction λ_2 using the Gauss dipole formula:

$$F_2 = F_1\left(\frac{3\sin^2\lambda_2 + 1}{3\sin^2\lambda_1 + 1}\right)^{1/2}$$

2.2. Causes of error

2.2.1. Quality of each regional site

This is practically never mentioned in the tables of results. The question is principally to know, with certainty, that the archaeological structure has not been displaced during the centuries when it lay buried. A rotation of a few degrees is difficult to appreciate but is not negligible, bearing in mind that the secular variation is entirely 'contained' within a cone of 15° of opening.

2.2.2. Effect of the reduction

As was mentioned above, the reduction produces another cause of additional error, principally in the declination. As Thellier (1981) observed, it is not without risk to try to correct it using the actual magnetic map because the equal value curves change with time, and it is precisely this which we are trying to find.

2.2.3. Dispersion of the measurements

The scattering of the individual sample magnetization directions is not the same for all the studied sites. There are many reasons for this: intrinsic quality of the TMF record in the baked earth; further movement of the structure for directional data; precision of the magnetic analysis and of the measurements themselves. For many sites the directional data are often obtained with an uncertainty smaller than 3°. Therefore, each time it was possible to appreciate the accuracy of the measurements, we have alway eliminated those having α_{95} greater than 5°. Similarly, we generally eliminated intensity data with a standard error greater than 10%.

2.2.4. Uncertainty on the age

The age is among the most difficult information to be confirmed, even for the most efficient archaeologist. The risk in calculating a mean value with anachronistic data is therefore always present. For original data, we only eliminated those having an uncertainty in age of more than 200 years.

2.3. Statistical analysis and smoothing of the TMF directional data

For a statistical treatment of the directional data, the methods developed for fitting the polar wander paths may be used. Two types of method have been used up to the present. The first, described by Irving (1964), applies the Fischer

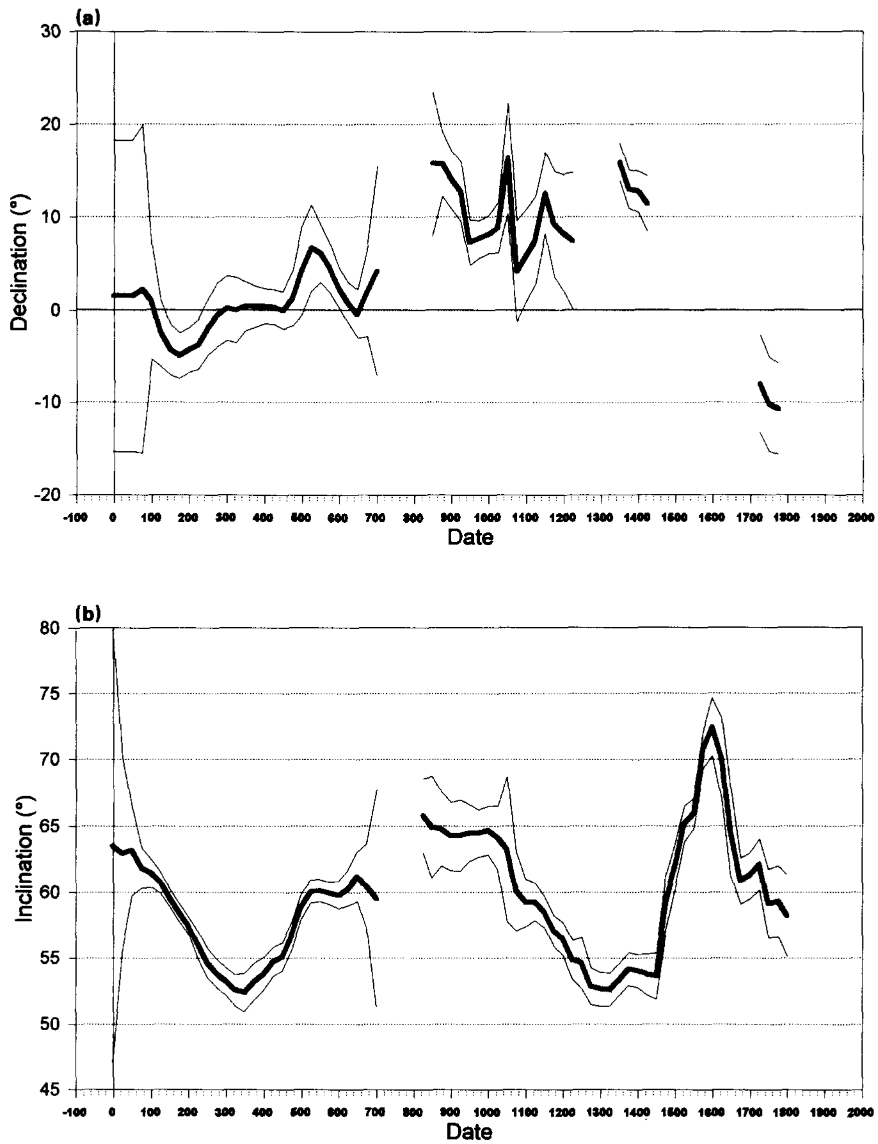


Fig. 3. Curves of (a) $D = f(t)$ and (b) $I = f(t)$ with 95% confidence band, and (c) $F = f(t)$ with standard deviation band at Sofia in Bulgaria; 80 year window.

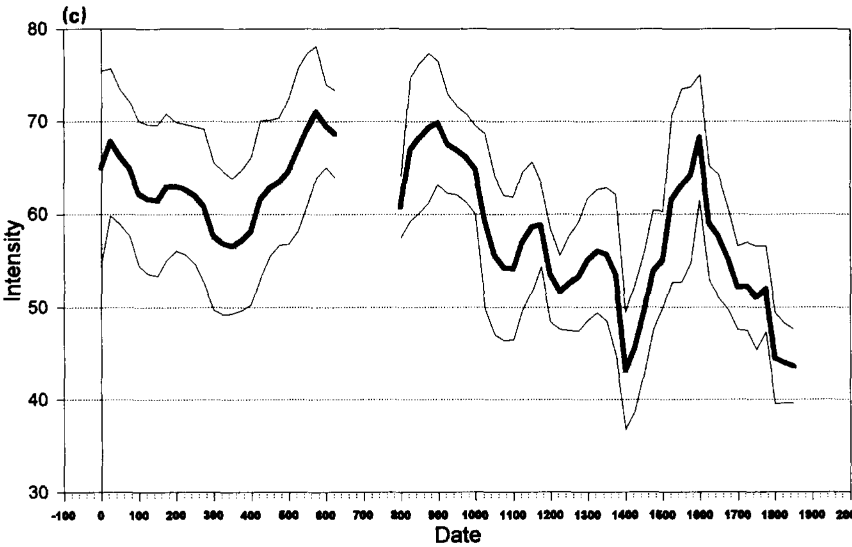


Fig. 3 (continued).

statistic to data contained in a given age window (McElhinny, 1973; Irving, 1977). The second method applies two independent regressions to the angles D and I using cubic splines. This method as been optimized by Thompson and Clark (1981), who introduced an objective research of the best smoothing degree, that is to say of the optimal age window bandwidth for the spline functions, using the cross-validation method (Stone, 1974). Nevertheless, one cannot be certain that it is right to consider D and I as two independent functions of time, whose respective smoothing is not necessarily performed with the same number of interpolation knots (Thompson and Clark, 1981). Moreover, it is always assumed that the sub-populations cut off by the age windows are Fisherian. Furthermore, the cones of confidence relative to the regional sties are ignored.

The hypothesis of a Fisherian distribution is often erroneous, as can be seen from the ellipse parameter values given in tables of results. The most obvious reason is the effect of spreading out of the data by the age uncertainties. This is the reason why we prefer to use the bivariate statistic (Le Goff, 1990; Le Goff et al., 1992), which is an extension of the Fisherian statistic (Fisher, 1953) but taking into account the elongation of the distributions, and giving the parameters of a confidence ellipse. The direction and the amount of elongation of the successive ellipses provide valuable information for the analysis: for example, an elongation in the direction of the secular variation curve is a favourable indication; on the other hand, a perpendicular elongation indicates an abnormal dispersion and should cause the re-examination of some data.

Briefly, it can be stated that the parameters of the bivariate statistic are all contained in the inertia tensor I (obtained from the matrix of the covariances in the orthonormal reference frame Ox, Oy, Oz) of the whole set of individual directions considered. These parameters are the number N of initial values (or samples), the mean direction (I_m, D_m), the perpendicular concentration parameters kx and ky and the angle Ω, which defines the elongation direction of the ellipse with respect to the mean direction meridian. This statistic conforms strictly to that of Fisher with $k = k_x = k_y$ (and Ω undetermined).

Table 4
Data for Ukraine (Kiev: 50.4° N, 30.5° E)

Date	N_{si}	W_{si}	W_{sa}	I	D	α_{95}	α_x	α_y	Ω	F	σ
−100										73.93	3.77
−75										73.93	3.77
−50										73.93	3.77
−25										73.35	4.11
−0	8	3.0	38.8	72.93	7.66	1.26	1.13	1.50	128.28	72.05	4.53
25	8	2.9	45.0	71.96	8.76	1.13	1.00	1.37	106.00	70.06	4.41
50	4	2.8	48.8	71.34	9.44	1.04	0.81	1.33	99.43	68.28	3.42
75	6	2.6	49.5	70.59	8.23	1.26	1.06	1.44	111.57	63.90	5.05
100	6	2.4	50.8	69.11	6.10	1.46	1.34	1.57	127.54	61.47	4.07
125	6	2.1	52.1	67.24	3.84	1.48	1.49	1.55	85.26	60.48	3.05
150	3	2.0	52.8	65.87	2.42	1.42	1.26	1.65	63.99	60.15	2.50
175	12	3.0	73.3	64.39	0.93	1.07	1.03	1.12	66.22	61.34	3.94
200	12	4.6	107.6	63.32	−0.04	0.74	0.70	0.72	124.61	63.54	5.04
225	13	7.2	145.9	62.56	−0.75	0.54	0.46	0.50	139.97	66.24	4.98
250	11	8.7	167.4	62.50	−0.29	0.46	0.38	0.46	118.82	68.31	3.75
275	17	8.8	147.6	62.36	0.04	0.52	0.43	0.57	118.56	67.24	4.67
300	16	7.0	108.8	62.08	0.00	0.69	0.60	0.80	120.68	64.99	5.58
325	16	6.0	73.5	61.41	−0.81	0.95	0.82	1.09	122.06	62.11	5.31
350	6	4.8	51.2	60.49	−2.65	1.16	1.12	1.27	117.31	59.32	3.27
375	9	4.3	51.1	61.37	−3.17	1.41	1.22	1.44	9.86	60.22	4.07
400	9	3.6	50.8	63.35	−4.47	1.51	1.13	1.78	15.83	61.87	4.81
425	9	2.8	50.5	58.35	−6.83	1.25	0.96	1.70	18.56	63.75	4.91
450	3	2.4	50.4	68.97	−9.46	0.80	0.80	0.82	163.09	65.00	4.55
475	12	3.3	61.3	70.47	−11.50	0.79	0.66	0.94	18.10	65.38	4.90
500	12	4.8	79.6	71.71	−13.45	0.65	0.51	0.76	13.83	65.36	5.30
525	12	6.3	97.8	72.34	−14.57	0.51	0.40	0.60	3.72	66.26	5.59
550	9	7.2	106.8	72.59	−15.04	0.43	0.34	0.52	175.11	66.45	5.72
575	19	7.4	118.0	72.62	−15.72	0.52	0.46	0.55	1.19	86.30	5.29
600	20	7.7	133.7	72.58	−16.85	0.59	0.55	0.60	21.39	66.12	4.61
625	20	8.1	149.3	72.56	−17.89	0.62	0.59	0.64	49.12	65.98	3.97
650	11	8.3	158.7	72.55	−18.46	0.63	0.60	0.65	56.13	65.90	3.58
675	31	9.5	191.7	73.10	−14.78	0.58	0.56	0.74	93.60	68.45	5.94
700	31	11.7	246.7	73.67	−10.12	0.49	0.48	0.73	57.62	71.42	6.72
725	31	13.8	301.7	73.99	−6.70	0.41	0.41	0.68	80.74	73.46	6.45
750	21	15.1	334.7	74.12	−5.08	0.37	0.37	0.65	76.74	74.41	6.10
775	26	13.3	292.8	74.02	−4.71	0.40	0.40	0.68	75.94	75.26	6.56
800	26	10.3	223.1	73.75	−3.84	0.47	0.47	0.75	74.11	77.02	7.11
825	26	7.3	153.3	73.25	−2.33	0.58	0.57	0.82	71.60	79.37	7.13
850	9	5.5	111.5	72.69	−0.73	0.58	0.67	0.82	72.59	81.20	6.59
875	17	5.6	111.7	72.95	1.61	0.71	0.71	0.85	70.49	81.37	6.56
900	17	5.7	112.1	73.32	5.48	0.72	0.73	0.85	48.43	81.85	6.46
925	16	5.9	112.3	73.61	9.55	0.67	0.50	0.88	23.09	83.17	5.96
950	5	6.0	112.8	73.72	11.46	0.62	0.50	0.90	17.41	81.52	9.04
975	20	6.6	122.9	73.26	12.75	0.63	0.54	0.87	18.37	76.79	6.04
1000	20	7.6	139.8	72.65	14.34	0.63	0.56	0.81	12.65	73.80	7.03
1025	20	8.6	156.7	72.17	15.49	0.60	0.56	0.75	6.37	73.24	5.95
1050	13	9.2	166.8	71.93	16.03	0.58	0.55	0.71	1.04	72.87	5.75
1075	27	9.7	170.8	70.82	15.79	0.66	0.60	0.85	4.28	71.86	6.03
1100	27	10.6	177.6	69.21	15.49	0.72	0.65	0.94	3.92	70.50	5.98
1125	27	11.5	184.3	67.83	15.26	0.70	0.67	0.94	15.87	68.02	5.84
1150	16	12.0	188.4	67.10	15.15	0.67	0.67	0.92	22.22	66.51	4.98
1175	23	11.0	163.3	67.28	15.19	0.71	0.70	0.97	22.96	56.38	5.01
1200	23	9.2	121.4	57.66	15.27	0.79	0.76	1.07	25.10	65.96	5.33

Table 4 (continued)

Date	N_{si}	W_{si}	W_{sa}	I	D	α_{95}	α_x	α_y	Ω	F	σ
1225	23	7.2	78.9	67.99	15.57	0.88	0.83	1.20	31.31	65.98	5.80
1250	7	5.6	52.8	67.99	16.14	0.56	0.83	1.28	43.31	65.54	6.16
1275	24	6.8	70.8	66.40	14.61	0.76	0.84	0.93	40.87	64.26	7.20
1300	23	9.2	102.0	65.19	13.01	0.59	0.63	0.64	131.90	60.25	6.83
1325	24	13.0	136.7	64.82	12.02	0.47	0.46	0.51	10.20	58.57	6.13
1350	18	14.6	155.8	64.62	11.70	0.42	0.40	0.48	15.16	57.26	5.08
1375	22	12.7	136.0	54.61	11.51	0.49	0.45	0.51	17.02	57.42	5.36
1400	21	8.4	100.0	64.37	11.05	0.68	0.63	0.67	31.09	57.48	5.45
1425	21	5.1	67.0	64.15	9.90	1.03	0.93	0.99	55.13	57.40	5.29
1450	4	3.2	47.2	63.78	8.10	1.44	1.31	1.45	56.02	54.97	5.81
1475	8	3.2	45.2	64.50	7.90	1.48	1.29	1.54	17.45	55.71	6.38
1500	8	3.2	42.0	66.51	7.53	1.46	1.11	1.60	8.54	60.47	8.92
1525	8	3.2	38.8	68.20	7.11	1.22	0.84	1.39	5.23	61.59	8.34
1550	4	3.2	36.8	69.21	6.83	0.81	0.58	1.04	0.69	62.84	7.37
1575	6	2.9	33.8	69.59	6.07	0.91	0.67	1.16	10.92	63.18	6.46
1600	6	2.4	28.8	70.41	4.28	1.06	0.76	1.36	22.81	61.24	6.28
1625	6	1.9	23.8	71.64	1.26	1.07	0.31	1.36	30.03	59.06	7.20
1650	2	1.6	20.8	72.69	−1.80	0.79	0.72	0.85	153.76	56.40	6.39
1675	3	1.4	21.1	73.08	−2.30	1.01	0.78	1.03	9.36	55.64	6.76
1700	3	1.2	21.6	73.95	−3.49	1.10	0.78	1.27	18.32	54.47	6.74
1725	3	0.9	22.1	75.26	−5.58	0.97	0.77	1.24	22.22	53.22	7.87
1750	1	0.8	22.4	76.41	−7.79	0.78	0.77	0.77	90.00	52.18	6.91
1775										51.27	5.69
1800										51.13	5.37

Inversely, knowing the previous parameters for the ith site of a population of M sites, one also knows immediately the tensor $\boldsymbol{I}_i$. To obtain the weighted mean of these M sites, one first calculates the following tensorial sum, where w_i is the weight attributed to each site:

$$\boldsymbol{I}_m = \sum_{i=1}^{M} w_i \boldsymbol{I}_i / \sum w_i$$

from which one can extract the previous parameters representative of the population mean. The confidence ellipse around this last mean direction may then be calculated by considering that it has been obtained with the weighted total of the samples of each site:

$$N_m = \sum_{i=1}^{M} w_i N_i$$

Let us now examine the archaeomagnetic data. From tables of rough results, one can characterize each element of data by the declination D_i, the inclination I_i and the Fisher concentration parameter k_i obtained with N_i samples, and the age bracket A_i given by the archaeologists. The declination is sometimes unknown and, instead of k_i, one may employ the variance σ_i^2, in which case a different treatment is necessary.

A window of given opening W centred on a given age permits us first to select the M data which will be introduced in the calculus of the mean direction and of the confidence ellipse for that age. A weighting coefficient p_i may be applied as a function of the percentage of A_i contained in W.

The statistical problem is the following: is it right to simply add these M data, or is it necessary to apply a weighting proportional to the size or the concentration of each of them (Fisher et al., 1987)? The examination of the original data allows us to see relatively important differences between N and k, with, on average, about ten samples per site. Some weighting attempts showed some differences between the secular variation curves, but according to the sources of error previously examined, one cannot eliminate the possibility that a high-quality archaeomagnetic result (high values of N and k) may be more polluted by 'non-statistical' errors than a less good one. Therefore, we preferred to eliminate the results of too great uncertainty (generally having α_{95} greater than 5°) and we kept a weighting only in age ($w_i = p_i$).

The choice of the age window width was made after successive attempts, for all the world sites, to find the value which gives the best overall

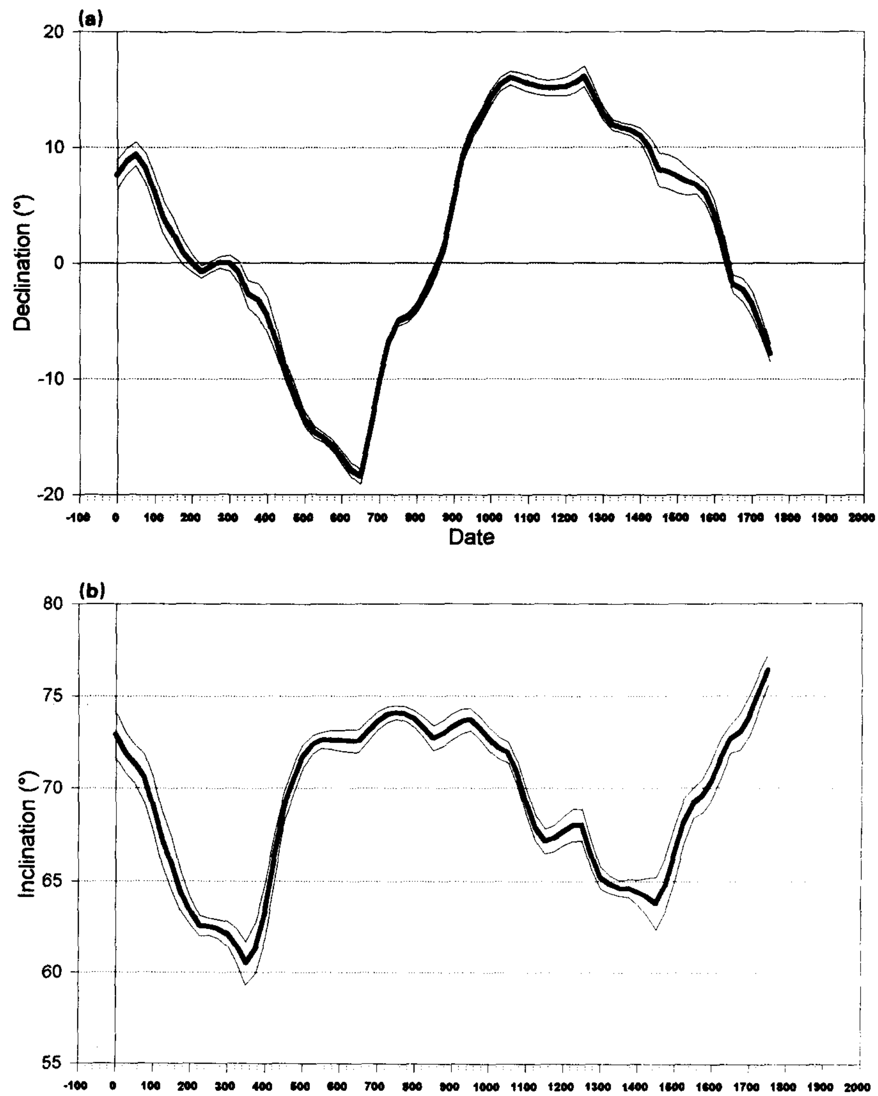


Fig. 4. Curves of (a) $D = f(t)$ and (b) $I = f(t)$ with 95% confidence band, and (c) $F = f(t)$ with standard deviation band at Kiev in Ukraine; 80 year window.

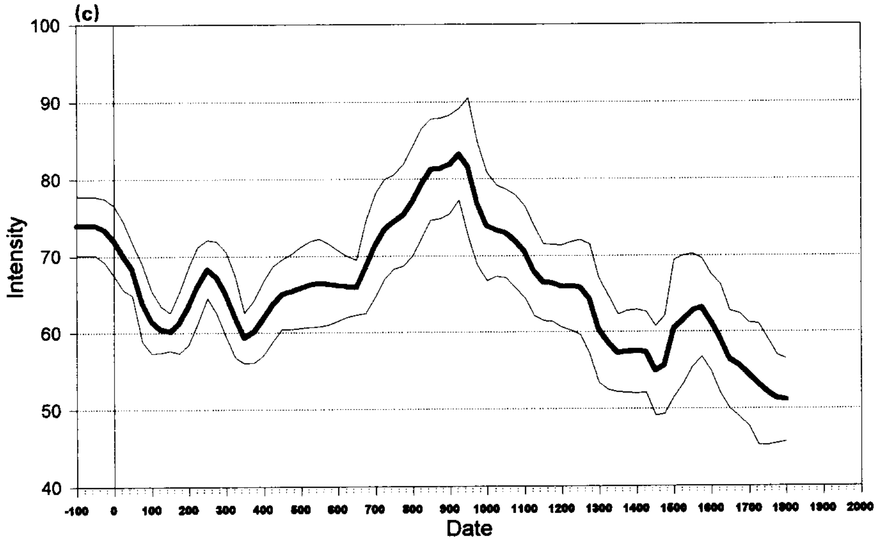


Fig. 4 (continued).

homogeneity. We selected an 80 year window, with steps of 25 years.

Let us note that this method can be used if the inclination alone is known. In this case, the declination is supposed to be constant and equal to zero. With the standard error on I, one can recalculate the equivalent k value and the 95% dispersion angle of the classical Fisher statistic which remain the only significant parameters. However, we lose here the advantages of the confidence ellipse of the bivariate analysis. Such a process was used to analyse the incomplete sets of D and I data relative to Bulgaria and Caucasus.

2.4. Statistical analysis and smoothing of the intensity data

The intensity results have been treated more or less successfully in the past. The computations of Bulgarian data (Kovacheva and Kanarchev, 1986), performed using a polynomial of second order, introduce some oscillations of abnormally high frequency. We favoured the more simple treatment previously used by Kovacheva (1980).

We remade these computations using a very similar formula. Knowing the strength $(N_1 \ldots N_n)$, the mean $(\bar{x}_1 \ldots \bar{x}_n)$ and the standard error $(\sigma_1 \ldots \sigma_n)$ of n populations, one can deduce the mean and the standard error weighted by p_i ($\bar{x}$ and σ) of the whole population formed by their union:

$$\bar{x} \sum_{i=1}^{n} p_i N_i = \sum_{i=1}^{n} p_i N_i \bar{x}_i,$$

$$\sigma^2 \sum_{i=1}^{n} p_i N_i = \sum_{i=1}^{n} p_i N_i \left[\sigma_i^2 + (\bar{x}_i - \bar{x})^2\right]$$

As previously for the directions, and in all the problems of statistics, the only restriction to such a calculus of mean is that one is never sure that the different populations, especially when few in number, may be statistically associated. Nevertheless, the measurements of the TMF intensity are, a priori, less sensitive to the mechanical state of the structure, and to the accuracy of the sampling. It seems then more normal here to take into account the size and the dispersion of the measurements, which justifies the use of the given formula.

Table 5
Data for Caucasus (Gori, 42.0°N, 44.1°E)

Date	N_{si}	w_{si}	w_{sa}	D	α_{95}	N_{si}	w_{si}	w_{sa}	I	α_{95}	E	σ
−100	1	0.4	0.0			3	0.7	2.7	51.79	13.72	62.91	2.00
−75	1	0.6	8.4	4.72	1.26	3	0.8	3.2	50.74	11.81	53.27	6.77
−50	1	0.5	10.4	4.72	1.13	3	0.9	3.5	50.26	10.9	52.92	6.62
−25	1	0.6	8.4	4.72	1.26	4	0.9	3.7	51.01	9.9	53.47	7.33
0	2	0.5	5.9	5.16	4.89	5	1.2	4.8	52.05	7.27	67.91	3.99
25	2	0.4				3	1.3	5.3	52.62	5.72	69.35	3.17
50	1	0.3				3	1.5	6.1	53.08	5.15	69.95	2.52
75	1	0.3				3	1.2	5.2	53.04	5.56	64.54	9.42
100	1	0.3				3	0.9	3.7	52.94	6.49	59.17	10.61
125	1	0.3				3	0.5	2.2	52.68	7.89	55.97	9.97
150	1	0.3				1	0.3				54.65	8.91
175	3	0.6	2.8	4.50	6.50	3	0.6	2.8	55.56	6.31	55.02	7.19
200	3	1.1	5.3	3.84	4.26	4	1.2	5.9	57.66	4.13	55.23	6.13
225	3	1.6	7.8	3.59	3.30	4	1.8	8.7	58.17	3.19	55.34	5.61
250	3	1.9	9.3	3.50	2.94	4	2.1	10.4	58.34	2.86	55.38	5.46
275	3	1.5	7.6	3.50	3.30	5	1.9	9.1	57.68	3.31	54.81	5.77
300	4	1.1	4.9	2.30	4.41	6	1.7	7.2	56.82	4.34	53.99	6.24
325	5	1.4	4.6	−0.82	3.94	8	2.3	7.7	57.31	4.4	52.77	6.43
350	4	2.7	7.7	−1.29	2.77	6	3.7	11.2	58.04	3.38	52.21	6.94
375	4	3.3	9.5	−1.16	2.46	7	4.3	13.2	58.67	2.86	52.91	6.84
400	4	2.7	7.7	−1.29	2.77	8	3.9	12.1	59	2.85	54.39	6.35
425	4	1.2	3.2	−2.16	4.77	8	2.4	8.2	59.26	3.52	55.82	4.84
450	1	0.3				4	1.6	5.9	59.64	4.25	57.01	3.46
475	1	0.3				7	1.7	6.1	58.69	4.66	60.26	5.39
500	1	0.3				7	1.9	6.5	57.32	4.94	61.72	5.09
525	1	0.3				6	2	6.8	56	4.95	62.40	4.89
550	1	0.3				5	2.1	7.2	55.57	4.84	61.28	4.35
575	2	0.4				6	2.1	7.2	54.48	5.04	61.85	3.99
600	2	0.5	1.9	0.28	12.67	7	2.1	7.9	52.54	4.83	62.03	3.69
625	1	0.6	2.6	2.00	6.26	6	2.1	8.2	50.32	4.48	65.24	7.83
650	1	0.8	3.2	2.00	5.49	5	2.1	8.5	49.51	4.28	71.35	10.71
675	6	1.1	4.2	−0.70	10.64	14	2.7	10.4	53.71	5.27	70.72	10.19
700	6	1.6	6.0	−4.17	8.30	15	3.7	13.9	58.35	4.82	70.44	9.91
725	6	2.1	7.7	−6.56	5.50	14	4.7	17.1	60.93	4.13	68.20	8.90
750	5	2.4	8.8	−7.65	3.94	11	5.3	19.3	61.93	3.69	64.96	4.16
775	9	2.9	15.1	−5.45	3.06	17	6.6	30.6	63.67	2.64	69.22	9.03
800	9	3.6	25.6	−2.85	2.07	18	7.1	39.9	65.24	2.06	73.72	10.50
825	9	4.4	36.1	−0.58	1.58	18	7.5	49	66.62	1.61	76.56	10.36
850	8	4.8	42.4	0.41	1.40	14	6.8	48.4	67.59	1.49	77.50	10.06
875	11	4.4	38.4	−0.84	1.50	16	6.3	44.2	67.3	1.58	72.59	11.65
900	11	3.6	31.6	−3.51	1.73	19	5.6	37.7	66.6	1.78	66.64	10.32
925	11	2.8	24.8	−7.31	2.07	18	4.7	30.8	65.56	2	63.78	6.57
950	3	2.4	20.8	−10.44	2.36	8	4.3	26.9	65.04	2.2	63.58	4.50
975	6	2.2	17.9	−7.17	3.05	11	3.8	23.3	64.24	2.61	64.34	5.04
1000	6	1.8	13.2	−0.77	4.56	11	3	17.2	62.28	3.54	63.81	5.51
1025	6	1.4	8.5	6.71	6.50	10	2.1	10.9	58.62	4.86	62.45	5.97
1050	3	1.2	5.6	11.46	4.33	5	1.7	7.5	55.15	3.96	59.60	5.52
1075	5	1.5	6.6	10.81	4.04	11	2.2	9.4	55.87	3.6	61.96	7.36
1100	5	2.0	8.4	10.14	3.62	14	5.3	21	55.72	2.42	61.96	7.25
1125	5	2.5	10.2	9.72	3.30	13	6.2	24.3	56.05	2.25	52.07	7.20
1150	5	2.8	11.2	9.54	3.13	13	6.9	26.5	55.25	2.16	59.78	5.18
1175	5	2.3	9.1	9.54	3.49	11	4.3	16.4	57.3	2.74	59.62	5.01
1200	5	1.4	5.6	9.54	4.59	11	3.5	12.9	57.86	3.13	59.31	4.63

Table 5 (continued)

Date	N_{si}	w_{si}	w_{sa}	D	α_{95}	N_{si}	w_{si}	w_{sa}	I	α_{95}	E	σ
1225	5	0.5	2.1	9.54	5.39	11	2.6	9.4	58.78	3.69	58.78	3.84
1250	0	0.0				6	2.1	7.3	59.71	4.12	58.55	3.46
1275	3	0.4	2.6	4.18	10.15	12	2.7	10.6	60.98	3.77	58.72	3.67
1300	3	1.2	6.8	4.18	5.64	13	3.9	16.4	62.01	3.16	58.84	3.91
1325	3	2.0	11.0	4.18	4.33	12	4.7	20.8	62.24	2.83	59.02	4.03
1350	3	2.4	13.6	4.18	3.87	8	4.9	22.3	61.91	2.67	59.02	4.15
1375	5	2.4	12.9	−0.03	4.72	12	4.3	19.5	60.11	2.92	59.02	4.88
1400	6	2.4	11.6	−6.09	5.54	11	3.9	16.9	57.5	3.29	59.02	6.05
1425	6	2.4	10.3	−10.94	5.12	10	3.8	15.4	55.36	3.68	59.01	7.36
1450	3	2.4	9.6	−13.30	3.02	6	3.8	14.6	54.1	3.84	59.02	7.94
1475	5	2.2	9.0	−13.69	3.35	13	4	15.4	55.17	3.84	58.51	7.53
1500	5	2.0	8.0	−14.49	3.80	14	4.5	17.5	56.91	3.64	57.58	6.62
1525	5	1.8	7.0	−15.61	3.96	14	5	19.3	58.24	3.39	56.56	5.26
1550	2	1.6	6.4	−16.51	3.69	9	5.3	20.3	58.92	3.23	55.89	3.99
1575	3	1.4	5.8	−14.87	4.71	14	5.2	20.6	59.72	3.15	56.06	3.76
1600	3	1.2	4.8	−10.97	6.31	14	5.1	21.1	61.09	2.91	56.35	3.34
1625	3	1.0	3.8	−4.38	7.18	15	5.9	25.6	63.96	2.49	56.63	2.85
1650	1	0.8	3.2	2.00	5.49	14	9.9	47.9	63.76	1.86	56.21	2.64
1675	2	0.8	3.2	3.96	6.74	21	12.2	56.9	63.4	1.64	55.19	2.79
1700	2	0.8	3.2	7.70	7.43	20	11.3	52.6	62.71	1.68	54.68	2.67
1725	2	0.8	3.2	12.06	6.74	17	9.3	43.3	62.43	1.43	51.07	2.88
1750	1	0.8	3.2	15.00	5.49	9	6.6	31.5	61.97	1.86	49.99	1.92
1775						16	8.9	43.9	59.94	2.21	47.70	3.99
1800						15	7.3	34.3	58.77	2.79	43.05	4.44

An alternative solution might be to use the method of Thompson and Clark (1981) which, although it may be criticized for its independent computation of directional data, could also be used to smooth the scalar intensity results.

3. Results

3.1. The curves for England and France

Most of the original data for England, with their complete set of precision parameters, have been given by Aitken and Weaver (1962), Aitken et al. (1963) and Aitken and Hawley (1966, 1967). We add to them 29 data ('good dating points') given by Clark et al. (1988), excluding the others and information from lake sediments. For these last data, where only the 95% confidence angle was mentioned, giving to N the value of 15, which is the mean of samples used in other studies. The 150 data have been reduced at Meriden (52.4°N, 1.6°W), then analysed by the bivariate statistic. The results are given in Table 1, for intervals of 25 years, and illustrated in Fig. 1. As they are obtained from archaeomagnetic data (eight historical values have been introduced only to complete the analysis up to 1800 AD), they can be compared with those obtained by Clark et al. (1988) or Tarling (1989), who also used lake sediment information. In some time intervals the mean values cannot be defined, but elsewhere, they are given with an estimation of the error. This is important complementary information needed to solve correctly inversion problems on the global field (Gubbins, 1983).

The French data initially given by Thellier (1981) have been revised and increased by Bucur (1994), who gave the curves of variation of D and I as a function of time and the corresponding vectorial equal area diagram. The 120 data have been reduced at Paris (48.9°N, 2.3°E), then analysed by the bivariate statistic. As for England, we list in Table 2 the D and I mean values obtained every 25 years, with the results on their precision. Fig. 2 shows some significant differences as compared with the inclination and declination curves at Meriden, in spite of the relatively small distance between these two world sites.

3.2. The curves for Bulgaria

The original data selected for Bulgaria are those published by Kovacheva (1992), from which those dated by archaeomagnetism have been eliminated. Seven archaeomagnetic results from Greece (Belshe et al., 1963) were added, owing to

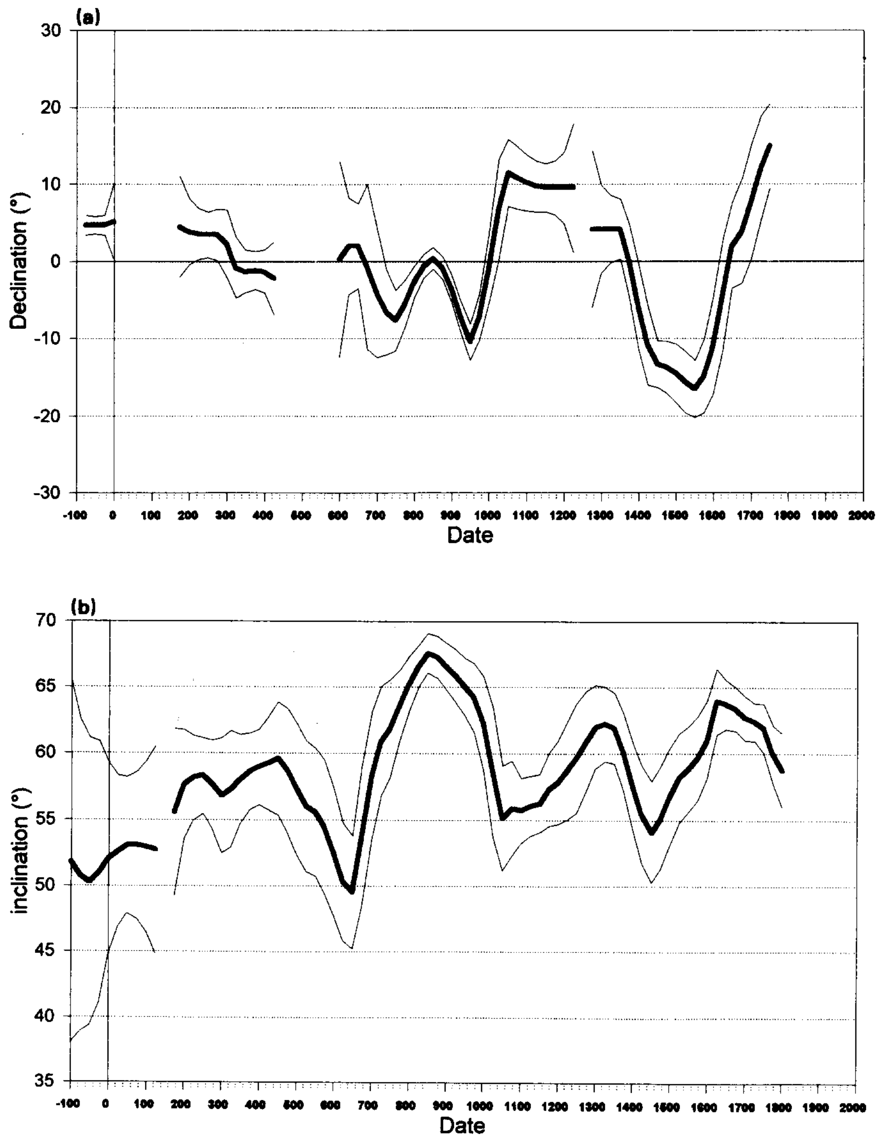


Fig. 5. Curves of (a) $D = f(t)$ and (b) $I = f(t)$ with 95% confidence band, and (c) $F = f(t)$ with standard deviation band at Gori in Caucasus; 80 year window.

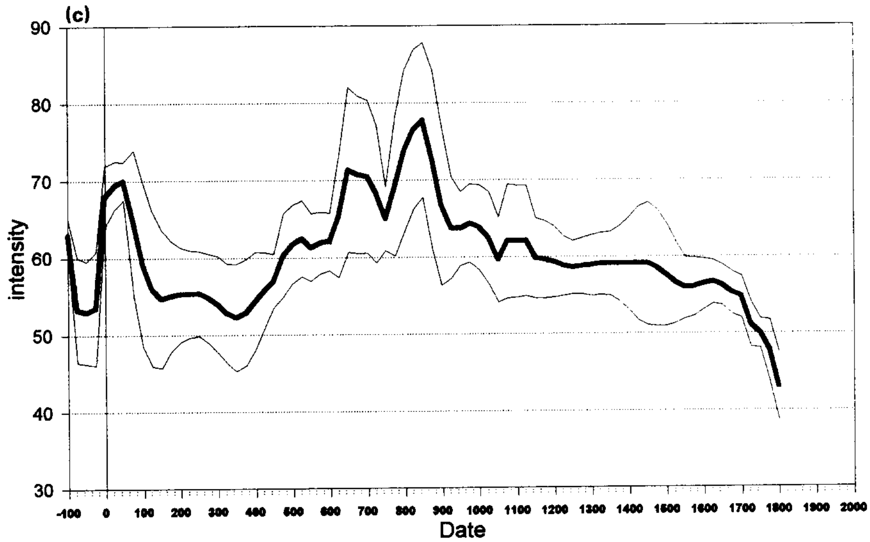


Fig. 5 (continued).

the geographical proximity. These data have been reduced at Sofia (42.7°N, 23.3°E). The inclinations were selected at 135 sites, the intensities at 128 and the declinations at 38 only. The bivariate statistic was thus first applied to these 38 sets (D,I). The results allow us to obtain a curve of variation of D, the precision of which is poor. The statistic was then applied to the whole inclination data set, considering the associated declinations to be zero. We obtain a curve of variation of the inclination, the precision of which is better. Finally, the classical statistic was applied to intensity data. The complete results are given in Table 3 and are illustrated in Fig. 3. As has been indicated previously, only the parameters (here the 95% dispersion angles) of the Fisher statistic obtained by the two different determinations of D and I are given in the table.

3.3. *The curves for Ukraine and Caucasus*

The data from the USSR were first taken from the world compilation published by the Russian Academy of Sciences (Burlatskaya, 1986). Some results from Rusakov and Zagniy, not mentioned in that data base but previously published elsewhere (Petrova, 1977), were added. Similarly, the results given by Rusakov and Zagniy (1973), but not present in any of these data bases, were added.

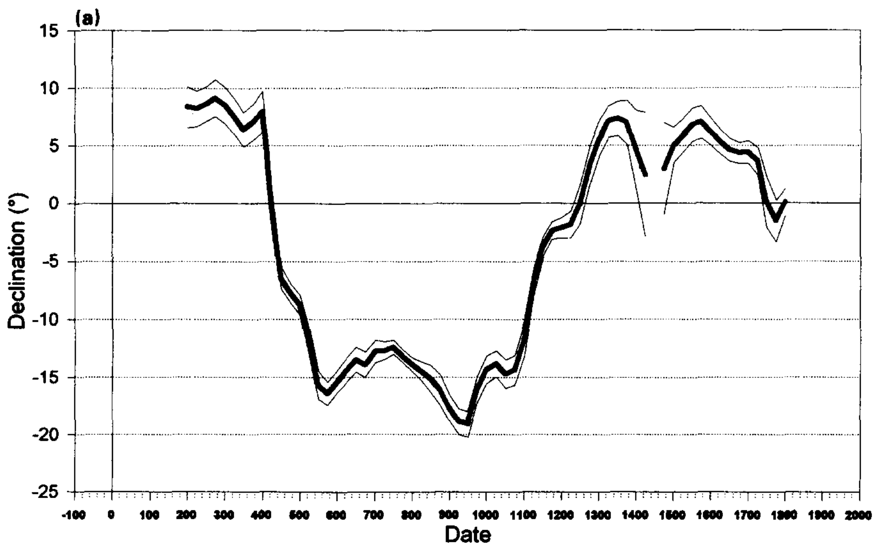
The corresponding sites are dispersed on a surface twice that of France (more than 25° of longitude), so we separated them in two sets on the basis of their distance from the two chosen world sites of reduction. The first reduction site is situated in Ukraine at Kiev (50.4°N, 30.5°E). At that site were associated 165 original directional data and 259 intensity data (14 from Poland), for which all the precision parameters were given. The results obtained after the statistical treatments appear in Table 4, and the corresponding D, I and F variation curves in Fig. 4.

The second reduction site is located in Georgia at Gori (42.0°N, 44.1°E). For that site, we found only 36 declination data relatively well distributed in time, but not all having their corresponding precision parameters. So as to continue the analysis, we associated with these last data precision parameters, the values of which were taken to be the mean of those of other samples. There is a greater number of inclination data alone. After grouping them with those having a

D value and filling up some missing precision parameters as described above, the 103 data were treated in a similar way to the Bulgarian inclination data, considering the declinations as zero. Finally, the 83 intensity data with their statistical parameters were treated by classical statistics. The results are given in Table 5 and are illustrated in Fig. 5.

3.4. The curves for Japan

There is a great number of data from Japan, but the sources are not the same for the different researchers. The data obtained from 1950 to 1970 were compiled by Kinoshita (1970). An examination of the original work permits a correction of some of these data (Kawai and al., 1965). The



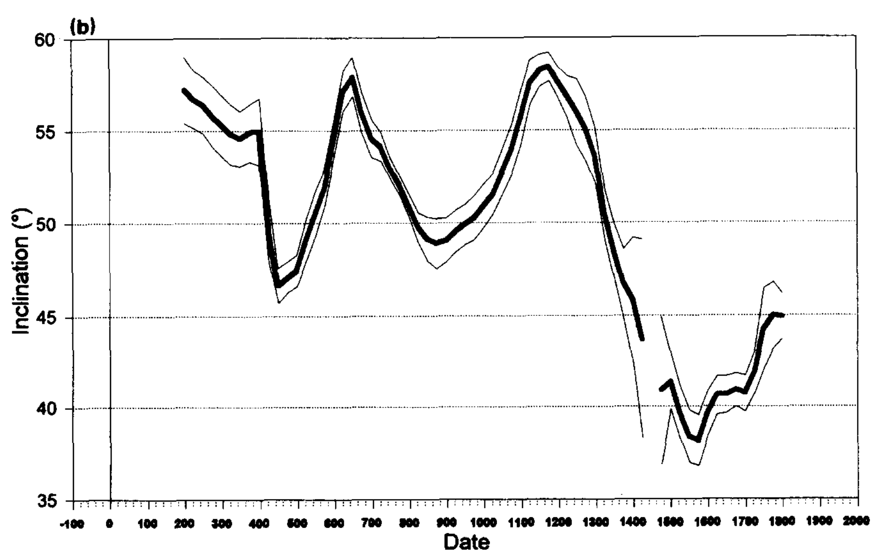


Fig. 6. Curves of (a) $D = f(t)$ and (b) $I = f(t)$ with 95% confidence band, and (c) $F = f(t)$ with standard deviation band at Kyoto in Japan; 80 year window.

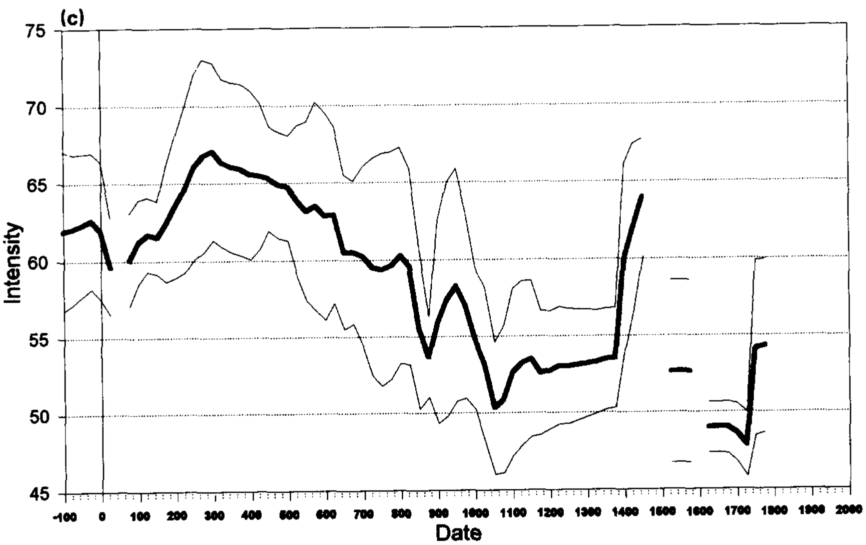


Fig. 6 (continued).

data obtained after 1970 were published by Shibuya and Nakajima (1979) and Hirooka (1983), who failed to give the references of the previous work. From the total D and I data set, we excluded those obtained on volcanic rocks. As the territory of Japan extends over about 15° both in latitude and in longitude, we tried to separate the local sites into two sets. However, as the greater part of these sites were situated in the central and western part of the archipelago, this separation has not been possible. After the elimination of 29 results having a confidence angle greater than 5°, the 287 selected data were reduced at Kyoto (35.0°N, 135.7°E).

The most recent intensity data have been published by Sakai and Hirooka (1986). Adding to them some older results of Nagata et al. (1963) and Sasajima and Maenaka (1966), we obtain 66 data. Fig. 6 shows the almost continuous evolution of D, I and F during the last two millennia. The corresponding values are given in Table 6.

3.5. The curves for Meso-America, Arizona and Arkansas

We used the American original data which can be found in the appendix of the book edited by Eighmy and Sternberg (1990). Because of the proximity of the corresponding sites, we have put together the results of the studies carried out by Sternberg and McGuire (1990) in New Mexico, Arizona and Colorado, and by Eighmy et al. (1990) in the Colorado Dolores region. The 155 data, selected on the basis of their precision parameter, were reduced at a point in Arizona at 35.0°N, 110.0°W. The results of the bivariate analysis are shown in Table 7 and allow continuous curves of the secular variation of D and I between 650 and 1500 AD to be drawn (Fig. 7).

From the studies done by Wolfman (1990a), 73 data have been selected, then reduced at Little Rock in Arkansas (34.7°N, 25.0°W). The analysis gives the results shown in Table 8 and continuous

Table 6
Data for Japan (Kyoto: 35.0°N, 135.7°E)

Date	N_{si}	W_{si}	W_{sa}	I	D	α_{95}	α_x	α_y	Ω	F	σ
−100										61.92	5.13
−75										62.05	4.84
−50										62.30	4.62
−25										62.59	4.39
0										61.96	4.46
25										59.63	3.15
50											
75										60.05	2.99
100										61.21	2.69
125										61.59	2.40
150										61.52	2.35
175										62.42	3.78
200	11	4.9	56.3	57.22	8.36	1.79	1.42	1.58	128.17	83.57	4.66
225	11	7.4	86.3	56.72	8.21	1.56	1.13	1.37	125.06	64.62	5.39
250	12	8.8	106.7	56.40	8.63	1.52	1.07	1.32	117.83	86.08	5.96
275	24	9.4	112.2	55.83	9.15	1.61	1.19	1.42	105.55	66.78	6.25
300	24	10.1	107.9	55.32	8.52	1.61	1.27	1.45	97.69	57.07	5.74
325	23	10.7	100.2	54.83	7.56	1.59	1.33	1.48	86.97	56.32	5.43
350	15	10.9	90.2	54.60	6.39	1.48	1.38	1.45	86.04	66.04	5.50
375	16	9.5	76.0	54.93	7.10	1.53	1.48	1.66	113.86	65.88	5.55
400	16	7.5	66.4	54.98	7.98	1.77	1.64	1.96	108.82	65.55	5.49
425	38	10.7	151.5	49.52	−0.68	1.58	1.31	2.00	138.64	65.45	4.74
450	30	22.6	377.8	46.64	−6.48	0.95	0.91	1.03	148.09	65.27	3.36
475	37	31.0	510.9	47.11	−7.78	0.84	0.77	0.91	15.56	54.56	3.43
500	40	31.2	494.9	47.46	−8.78	0.85	0.77	0.93	26.57	64.69	3.40
525	47	22.5	277.7	49.14	−12.04	1.15	1.01	1.26	34.07	63.83	4.89
550	30	18.5	191.7	50.57	−15.70	1.24	1.09	1.42	34.13	63.15	5.81
575	31	19.9	233.7	51.95	−15.43	1.02	0.92	1.24	23.38	63.48	6.73
600	31	20.2	322.3	54.58	−15.37	1.00	0.88	1.15	12.50	62.84	6.70
625	29	16.5	287.9	57.15	−14.37	1.09	0.96	1.25	13.46	62.89	5.71
650	29	19.2	306.3	57.90	−13.46	1.07	1.06	1.15	171.27	60.50	4.99
675	48	23.0	299.9	56.00	−13.90	1.09	1.11	1.12	92.06	60.46	4.62
700	41	26.2	306.4	54.58	−12.74	0.99	0.96	1.06	89.06	60.20	5.86
725	57	33.1	430.2	54.16	−12.67	0.75	0.74	0.81	60.74	59.49	7.06
750	61	44.4	677.3	53.01	−12.39	0.58	0.55	0.62	11.59	59.32	7.53
775	73	48.7	751.7	52.05	−13.16	0.55	0.51	0.60	4.75	59.62	7.34
800	66	42.6	658.9	50.95	−13.85	0.60	0.55	0.65	3.92	60.26	7.01
825	57	26.5	364.6	49.75	−14.45	0.81	0.71	0.83	5.61	59.52	6.29
850	25	14.3	187.0	49.14	−15.10	1.18	0.97	1.19	9.96	55.50	5.21
875	30	10.1	119.4	48.90	−16.12	1.36	1.14	1.42	10.21	53.70	2.66
900	25	10.1	112.3	49.08	−17.66	1.19	1.05	1.39	10.86	55.90	6.55
925	26	11.6	132.2	49.57	−18.88	1.14	1.01	1.37	10.64	57.42	7.59
950	18	12.3	141.6	49.92	−19.10	1.10	1.00	1.34	9.95	58.31	7.56
975	28	14.6	158.8	50.28	−16.14	1.19	1.26	1.28	27.42	57.02	6.05
1000	27	14.7	155.7	50.95	−14.31	1.21	1.23	1.37	97.89	54.79	4.57
1025	31	16.7	172.4	51.60	−13.82	1.12	1.15	1.30	100.14	53.21	5.03
1050	21	14.6	149.2	52.60	−14.70	1.23	1.27	1.41	113.37	50.34	4.28
1075	32	13.4	134.7	53.96	−14.35	1.30	1.31	1.47	135.62	50.91	4.75
1100	28	11.5	107.1	55.75	−11.64	1.50	1.51	1.63	140.58	52.70	5.40
1125	33	13.4	137.0	57.60	−6.79	1.19	1.16	1.32	152.16	53.28	5.33
1150	24	16.8	183.8	58.25	−3.76	0.85	0.86	0.95	171.40	53.53	5.05
1175	26	17.2	198.0	58.44	−2.36	0.76	0.78	0.84	6.44	52.61	4.03
1200	26	14.0	163.0	57.61	−2.13	0.84	0.88	0.90	62.82	52.77	3.83

Table 6 (continued)

Date	N_{si}	W_{si}	W_{sa}	I	D	α_{95}	α_x	α_y	Ω	F	σ
1225	25	9.5	105.4	56.81	−1.85	1.15	1.12	1.24	96.41	53.07	3.83
1250	13	6.9	66.1	56.00	−0.07	1.77	1.60	2.03	100.43	53.03	3.74
1275	19	8.7	96.5	55.05	3.36	1.69	1.64	1.76	70.66	53.12	3.61
1300	20	9.7	134.4	53.66	5.55	1.49	1.41	1.62	1.04	53.22	3.48
1325	21	10.9	172.3	50.44	7.10	1.35	1.15	1.62	177.37	53.31	3.36
1350	12	8.2	147.8	48.39	7.35	1.49	1.18	1.81	170.51	53.48	3.28
1375	9	5.6	100.8	46.69	7.00	1.91	1.49	2.27	169.55	53.56	3.23
1400	4	1.8	38.1	45.75	4.59	3.47	2.92	4.01	161.77	60.05	6.08
1425	3	0.8	17.1	43.70	2.49	5.39	4.55	5.86	169.87	62.01	5.42
1450	1	0.2								63.94	3.80
1475	3	0.4	7.6	40.92	3.02	4.00	3.10	4.95	134.14		
1500	5	2.5	46.9	41.40	5.07	1.54	1.41	1.72	143.01		
1525	6	3.6	70.9	39.73	5.89	1.43	1.53	1.66	26.09	52.68	5.93
1550	7	4.8	87.7	38.40	6.83	1.42	1.48	1.72	42.77	52.68	5.93
1575	16	6.2	111.6	38.19	7.05	1.36	1.34	1.59	48.02	52.68	5.93
1600	17	8.4	152.1	39.64	6.22	1.21	1.16	1.33	41.66		
1625	17	10.3	191.2	40.65	5.37	1.06	1.02	1.10	34.20	49.02	1.62
1650	16	10.9	207.9	40.68	4.68	1.01	0.96	1.03	19.13	49.02	1.52
1675	18	12.1	215.1	40.92	4.38	0.91	0.89	0.91	173.00	49.01	1.87
1700	17	9.6	168.3	40.74	4.46	0.99	0.96	0.99	30.66	48.65	1.87
1725	19	6.5	104.9	41.93	3.65	1.19	1.13	1.22	75.88	47.88	2.06
1750	7	2.1	35.0	44.25	0.10	2.19	1.91	2.39	53.74	54.16	5.68
1775	6	2.6	47.2	44.98	−1.53	1.78	1.64	1.81	54.09	54.31	5.83
1800	8	6.3	103.9	44.93	0.08	1.19	1.12	1.20	60.60		

curves of *D* and *I* from 400 to 1600 AD (Fig. 8).

Finally, the 73 data obtained by Wolfman (1990b) in Meso-America (Central and southern Mexico, Guatemala, Honduras and Salvador) were reduced at a point in the Sierra Madre situated at 16°N, 93°W. The analysis gives *D* and *I* continuous variation curves from 0 to 1250 AD (Fig. 9). The detailed results are shown in Table 9.

4. Conclusion

We observe that the secular variation is defined with good precision and continuously for the last two millennia at a very small number of world sites: in Bulgaria, England, France, Japan and Ukraine. The intensity results are lacking for two of these sites and it would be of great interest to establish them. The results for the other world sites require completion. Some of them — the data for Arizona, Arkansas and Meso-America — fail to cover the whole period of the two millennia. Some others are defined with poor precision — those for Caucasus, or Bulgaria in terms of declination. The data of the tables may be obtained from the authors by sending a $3\frac{1}{2}$ inch diskette.

Nevertheless, some new information on the global behaviour of the geomagnetic field may be obtained. As a preliminary illustration, VGP analysis, begun by Champion (1980) and extended by Merrill and McElhinny (1983), has been performed. Fig. 10 shows the evolution of the mean VGPs of all sites (three to nine according to time intervals). At less than 2°, the mean of all VGPs is centred on the axis of the Earth ($\lambda_{PGV} = 88.6°$, $\varphi_{PGV} = 89°$). It is, of course, possible to define by spherical harmonic analysis the evolution of the geomagnetic dipole for the two millennia, using first only the four sites where the three components of the field are known and then all the directional data to define further relative Gauss coefficients (Creer et al., 1973). However, these methods do not take into account uncertainties in the data, and do not allow treatment of heterogeneous data. Therefore, these techniques are at present being compared with other methods of stochastic analysis (Hongre et al., 1995).

Otherwise, if we consider the dispersion, sometimes very important in the original data or the precision parameters given in the tables, it is easy to conclude that it is not possible to use isolated results or sets of results covering an insufficient period of time. This is the case in particular for Hungary (Marton, 1986) and Australia (Barton and Barbetti, 1982), where the number of archaeomagnetic data is not sufficient, and for China (Wei et al., 1981), where they are too widespread. An objective would then be to complete these archaeomagnetic results, but this would take a long time. This is why it seems more

Table 7
Data for Arizona (Navajo: 35.0°N; 110.0°W)

Date	N_{si}	W_{si}	W_{sa}	I	D	α_{95}	α_x	α_y	Ω
650	5	3.4	36.2	56.03	−1.74	1.98	1.57	2.31	26.12
675	6	4.6	49.0	54.03	0.36	1.64	1.25	1.97	26.23
700	11	5.6	59.8	51.39	1.68	1.37	1.07	1.68	14.22
725	18	7.2	78.0	49.54	2.15	1.20	0.90	1.47	179.23
750	24	14.3	158.6	49.25	2.18	0.97	0.69	1.19	178.70
775	30	23.0	255.0	48.46	1.81	0.88	0.60	1.09	178.18
800	31	24.7	274.0	48.44	1.94	0.91	0.58	1.14	179.76
825	45	22.1	242.8	48.88	1.92	1.00	0.63	1.25	0.27
850	66	37.8	425.2	50.81	3.75	0.58	0.46	0.70	8.10
875	61	53.7	609.0	51.01	3.91	0.43	0.38	0.50	21.02
900	58	51.2	580.5	51.04	3.88	0.43	0.38	0.49	27.67
925	54	30.8	345.0	51.16	3.46	0.58	0.50	0.68	28.59
950	10	4.2	39.3	55.19	−2.90	2.05	1.72	2.30	12.33
975	8	3.7	32.8	56.16	−3.53	2.55	2.16	2.71	14.99
1000	9	3.8	33.8	57.11	−5.12	2.91	2.38	3.20	30.22
1025	10	3.5	31.2	57.70	−6.42	3.41	2.70	3.86	35.67
1050	7	3.4	30.9	59.24	−9.38	3.72	2.77	4.30	38.97
1075	16	5.7	50.5	60.98	−13.28	2.48	2.02	2.78	43.05
1100	16	8.4	73.1	61.46	−14.53	1.85	1.67	2.01	42.58
1125	22	10.7	93.1	60.98	−14.35	1.50	1.46	1.59	34.86
1150	25	12.1	103.6	60.04	−12.95	1.34	1.35	1.42	22.10
1175	26	12.1	102.8	59.30	−11.77	1.20	1.23	1.27	165.45
1200	24	13.5	113.6	59.28	−11.09	0.99	1.02	1.08	145.69
1225	29	16.1	135.8	59.65	−9.92	0.91	0.93	1.01	11.68
1250	35	20.7	174.0	59.91	−9.15	0.83	0.80	0.94	19.58
1275	41	24.0	202.7	59.87	−8.44	0.79	0.74	0.91	20.14
1300	36	21.0	179.4	59.76	−7.74	0.85	0.80	0.97	19.57
1325	32	17.2	150.2	59.43	−6.82	0.93	0.92	1.02	17.29
1350	16	11.1	99.7	58.86	−5.05	1.19	1.20	1.26	150.41
1375	13	9.2	80.4	58.84	−4.47	1.30	1.27	1.39	122.87
1400	11	6.5	55.0	58.96	−3.45	1.51	1.44	1.65	122.76
1425	6	3.3	27.4	59.45	−1.49	1.97	1.87	2.11	126.25
1450	3	1.7	13.7	59.77	0.27	2.45	2.38	2.60	163.29
1475	3	0.6	5.1	59.77	0.27	4.21	3.89	4.24	163.29

appropriate to attempt to include, in the same way, (1) recent volcanic rocks which could be dated by the radioactive disequilibria method (Condomines et al., 1995), and (2) some selected well-dated lake sediment series. The results given in the present paper must then be considered as the first elements of a world data base of secular variation, which could be used for analysing more completely the global behaviour of the geomagnetic field.

Using combined archaeomagnetic, lake sediment and volcanic rock data, it seems possible to obtain the secular evolution at some 20 world sites. This number is sufficient to reach the order

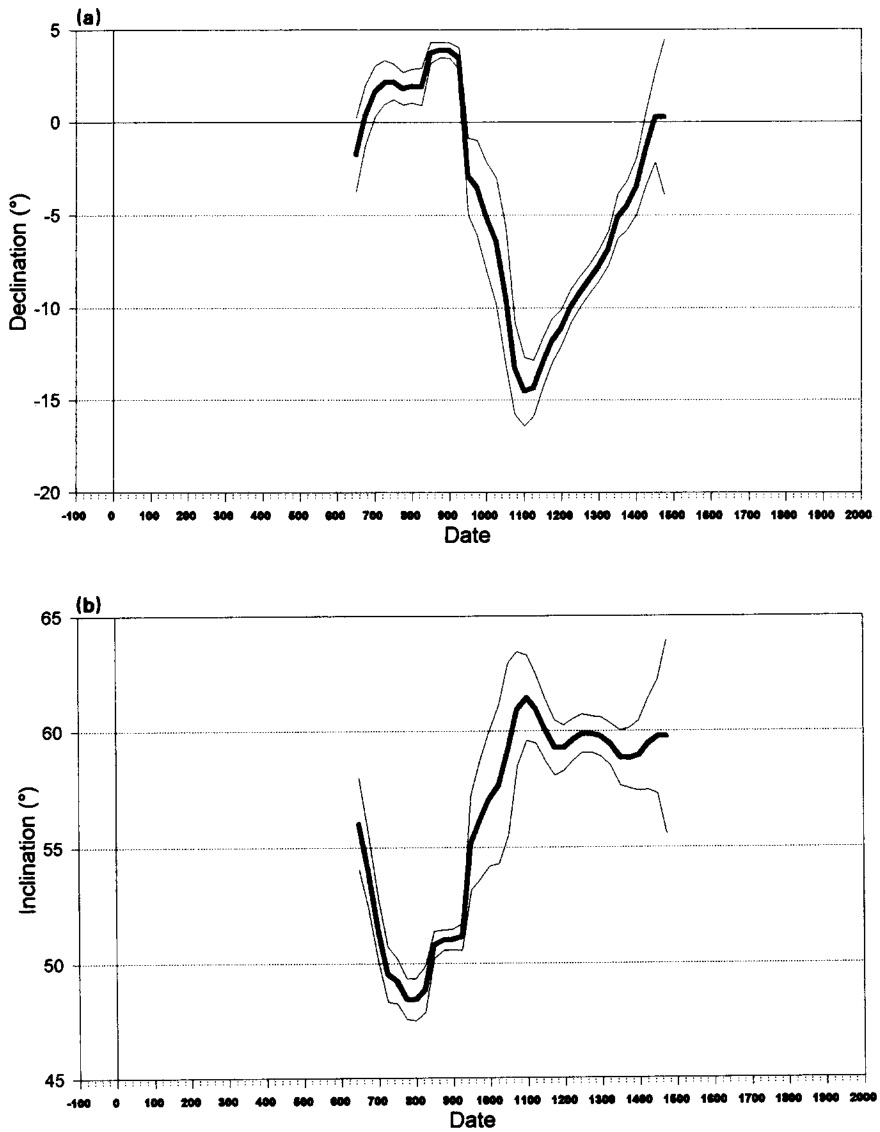


Fig. 7. Curves of (a) $D = f(t)$ and (b) $I = f(t)$ with 95% confidence band for Navajo region in Arizona; 80 year window.

Table 8
Data for Arkansas (Little Rock: 34.7°N, 92.2°W)

Date	N_{si}	W_{si}	W_{sa}	I	D	α_{95}	α_x	α_y	Ω
400	7	0.9	6.6	48.79	−6.33	7.77	6.98	7.86	149.13
425	6	1.3	9.8	47.86	−7.18	6.24	6.03	6.21	151.78
450	6	1.6	12.0	47.86	−7.18	5.59	5.43	5.60	151.78
475	6	1.6	12.0	47.86	−7.18	5.59	5.43	5.60	151.78
500	6	1.6	12.0	47.86	−7.18	5.59	5.43	5.60	151.78
525	6	1.6	12.0	47.86	−7.18	5.59	5.43	5.60	151.78
550	6	1.6	12.0	47.86	−7.18	5.59	5.43	5.60	151.78
575	6	1.6	12.0	47.86	−7.18	5.59	5.43	5.60	151.78
600	6	1.6	12.0	47.86	−7.18	5.59	5.43	5.60	151.78
625	7	1.7	12.7	48.59	−6.75	5.50	5.15	5.70	156.43
650	7	1.9	13.9	49.64	−6.10	5.31	4.73	5.72	156.84
675	10	2.0	14.7	50.56	−5.07	5.17	4.68	5.48	158.84
700	11	2.1	15.8	51.22	−5.03	4.92	4.76	4.90	49.11
725	5	1.7	13.6	51.97	−4.48	5.27	4.23	5.82	62.68
750	5	2.0	15.9	51.46	−4.83	4.87	3.78	5.54	63.41
775	6	2.0	15.7	51.36	−5.15	4.90	3.71	5.62	62.49
800	6	1.9	15.4	51.18	−5.70	4.93	3.57	5.77	61.15
825	6	1.9	15.1	50.99	−6.27	4.97	3.39	5.92	60.00
850	5	1.9	14.9	50.87	−6.62	4.99	3.27	6.02	59.39
875	5	1.6	13.1	51.35	−7.03	5.33	3.60	6.30	59.07
900	5	1.3	9.9	52.53	−8.05	5.99	4.38	6.74	58.98
925	5	0.9	6.8	54.63	−10.02	6.61	5.58	6.56	69.98
950	2	0.7	4.9	56.92	−12.39	5.68	2.48	6.98	134.14
975	3	0.6	4.5	57.11	−13.82	5.97	3.31	7.01	131.36
1000	3	0.5	3.9	57.48	−16.84	6.29	4.20	6.89	124.36
1025	3	0.5	3.4	57.34	−21.07	5.94	4.67	5.86	129.67
1050	2	0.6	4.4	55.51	−23.14	4.29	2.46	5.00	14.61
1075	10	1.2	9.4	54.66	−18.61	3.14	2.89	3.21	41.22
1100	16	2.8	21.3	54.49	−15.44	2.15	1.86	2.40	118.26
1125	17	4.3	32.5	54.32	−14.92	1.75	1.43	2.03	122.12
1150	17	5.4	40.4	54.17	−14.92	1.58	1.26	1.87	123.72
1175	31	7.4	55.4	54.02	−13.56	1.42	1.20	1.67	120.08
1200	32	10.5	78.6	53.96	−12.14	1.19	1.06	1.38	118.78
1225	34	13.4	100.3	54.04	−11.04	1.04	0.97	1.19	120.55
1250	33	15.1	112.7	54.19	−10.28	0.96	0.93	1.08	124.31
1275	39	14.6	109.0	54.74	−9.56	0.96	0.93	1.08	135.43
1300	38	14.0	105.4	55.55	−8.66	0.95	0.90	1.07	143.15
1325	44	12.7	96.5	56.17	−7.64	1.01	0.96	1.12	147.06
1350	36	11.5	86.8	56.45	−6.35	1.10	1.07	1.19	171.28
1375	43	10.4	76.9	56.09	−5.35	1.28	1.24	1.40	9.54
1400	31	9.4	68.8	55.71	−4.60	1.48	1.43	1.62	13.68
1425	34	9.1	66.4	55.55	−4.36	1.61	1.58	1.73	15.96
1450	28	9.1	65.9	55.50	−4.01	1.70	1.68	1.79	19.02
1475	26	8.6	62.8	55.74	−3.43	1.76	1.73	1.85	21.20
1500	24	7.9	58.0	56.13	−2.73	1.80	1.75	1.91	24.68
1525	20	6.5	47.2	56.57	−1.93	1.95	1.86	2.11	26.58
1550	17	5.4	38.8	56.85	−1.85	2.09	2.00	2.24	29.93
1575	17	4.0	28.8	56.79	−2.09	2.41	2.32	2.54	31.79

four in a classical harmonic analysis. As a comparison, one can note that it is also by taking the field elements from the IGRF (International Geomagnetic Reference Field) 1965.0 at only 21 sites (63 data) that Shure et al. (1982) achieved a downward continuation at the core–mantle boundary which seems very convincing. They introduced a priori conditions using the harmonic splines method. However, all these data, distributed in space at some 20 sites and in time for some two millennia, seem to be used more generally by spatio-temporal stochastic inversion

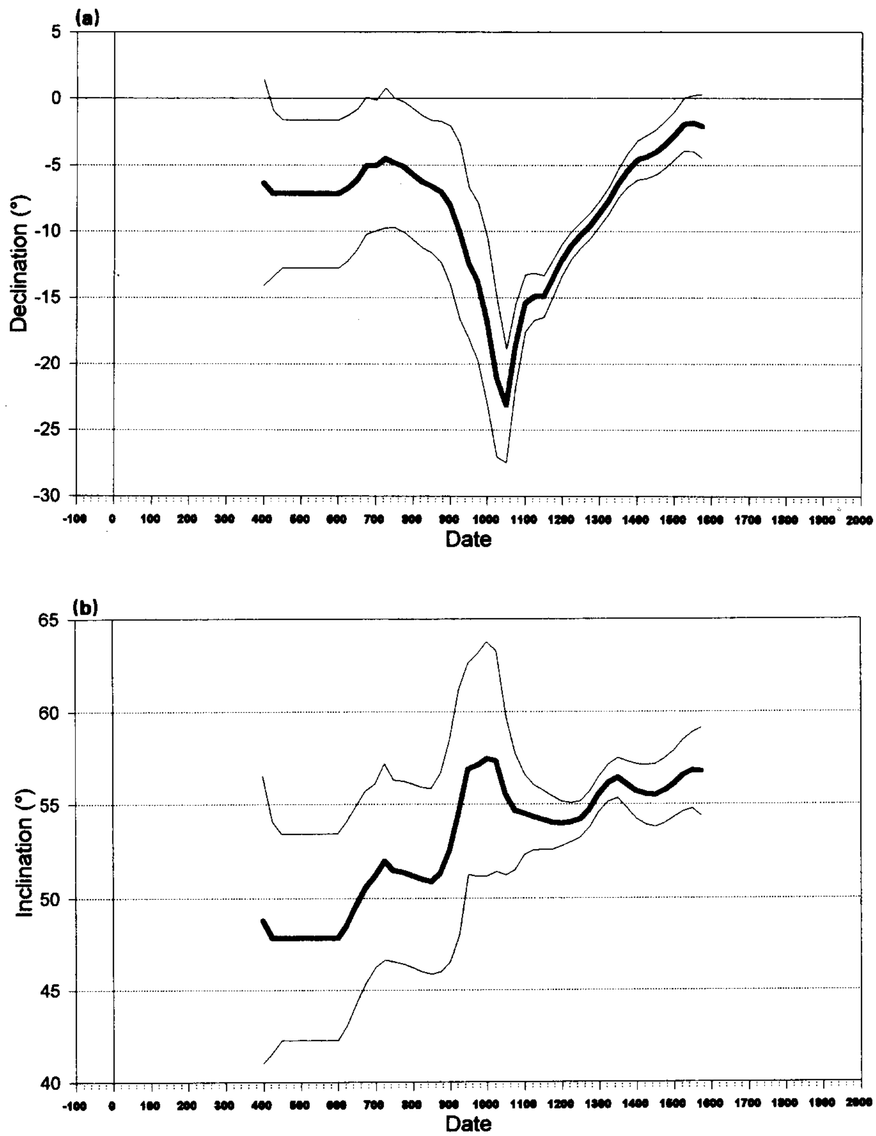


Fig. 8. Curves of (a) $D = f(t)$ and (b) $I = f(t)$ with 95% confidence for Little Rock in Arkansas; 80 year window.

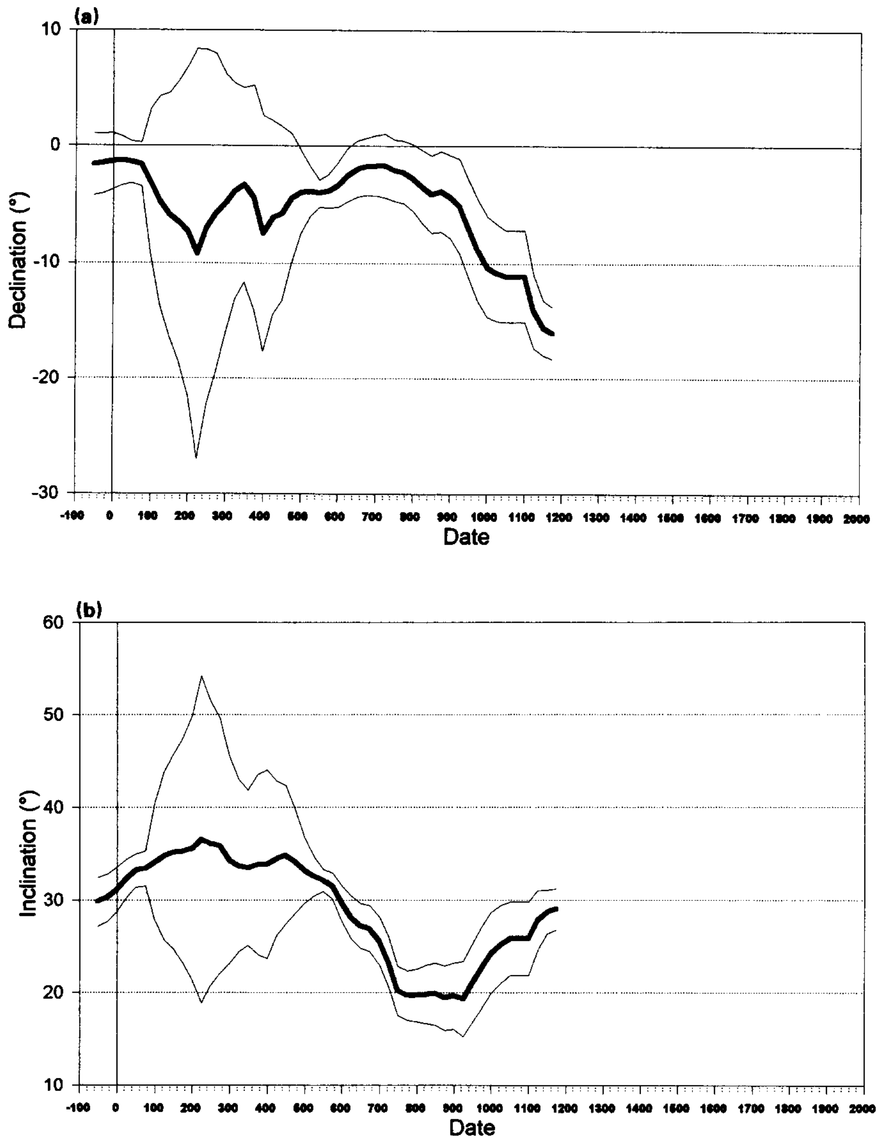


Fig. 9. Curves of (a) $D = f(t)$ and (b) $I = f(t)$ with 95% confidence for Sierra Madre region in Meso-America; 80 year window.

Table 9
Data for Meso-America (Sierra Madre: 16.0°N; 93.0°W)

Date	N_{si}	W_{si}	W_{sa}	I	D	α_{95}	α_x	α_y	Ω
−50	12	3.2	23.7	29.80	−1.57	2.64	1.24	3.63	169.24
−25	12	3.1	23.0	30.25	−1.48	2.57	1.28	3.53	169.01
0	12	2.9	21.8	31.13	−1.31	2.41	1.34	3.25	168.34
25	13	2.8	21.3	32.30	−1.26	2.10	1.43	2.67	168.48
50	12	2.9	21.6	33.20	−1.37	1.79	1.51	2.05	170.07
75	12	2.8	20.5	33.45	−1.58	1.90	1.61	2.15	175.14
100	14	2.7	19.4	34.11	−3.13	6.31	2.25	6.91	65.69
125	13	2.3	16.6	34.78	−4.69	9.04	2.59	10.17	67.06
150	10	2.1	15.5	35.20	−5.91	10.53	2.79	12.06	67.88
175	10	1.8	13.4	35.29	−6.48	12.10	3.06	14.07	68.32
200	11	1.5	11.3	35.61	−7.34	14.26	3.36	17.03	69.08
225	6	1.1	9.0	36.58	−9.25	17.66	3.62	22.49	70.72
250	6	1.3	10.6	36.13	−6.93	15.26	3.16	19.19	69.46
275	6	1.4	11.9	35.88	−5.71	13.71	2.88	17.16	68.80
300	8	1.7	14.8	34.31	−4.88	11.15	2.84	14.06	67.73
325	10	2.0	18.0	33.69	−3.86	9.29	2.57	11.54	67.06
350	10	2.3	20.0	33.47	−3.31	8.40	2.41	10.24	66.76
375	11	2.5	21.3	33.85	−4.46	9.74	2.30	11.20	69.74
400	14	2.9	25.0	33.87	−7.53	10.17	2.12	11.58	73.31
425	17	4.0	35.3	34.53	−6.16	8.36	1.84	9.18	74.72
450	17	5.0	43.6	34.90	−5.82	7.49	1.67	8.25	74.78
475	25	6.5	55.3	34.15	−4.46	5.55	1.51	5.77	74.65
500	27	8.6	70.4	33.22	−3.94	3.60	1.33	3.57	76.13
525	27	10.2	81.3	32.57	−3.88	2.16	1.22	2.10	84.68
550	24	10.5	83.3	32.13	−4.02	1.19	0.89	1.44	125.96
575	30	9.1	72.3	31.52	−3.83	1.45	1.28	1.62	139.33
600	36	8.7	69.0	29.60	−3.31	1.94	1.68	2.16	4.00
625	33	8.3	65.9	28.15	−2.48	2.26	1.80	2.61	8.83
650	27	8.2	65.2	27.21	−1.93	2.38	1.84	2.80	9.20
675	28	8.0	64.2	26.89	−1.72	2.44	1.85	2.89	9.15
700	30	7.7	61.3	25.55	−1.66	2.57	1.89	3.07	10.32
725	29	7.0	55.8	23.30	−1.65	2.70	1.97	3.22	15.12
750	21	6.2	49.2	20.23	−2.03	2.62	1.78	3.19	32.49
775	21	5.8	46.2	19.73	−2.20	2.67	1.82	3.23	36.37
800	21	5.2	41.5	19.75	−2.70	2.84	1.97	3.40	38.69
825	21	4.5	35.6	19.84	−3.48	3.12	2.20	3.71	41.25
850	15	4.0	32.1	19.90	−4.09	3.32	2.36	3.92	42.87
875	15	3.5	28.5	19.49	−3.86	3.46	2.49	4.07	41.77
900	18	3.2	25.6	19.68	−4.30	3.55	2.48	4.22	38.76
925	10	2.1	17.5	19.38	−5.13	4.04	2.50	4.99	30.58
950	10	2.2	18.1	21.06	−7.05	4.20	2.32	5.32	29.87
975	10	2.1	16.7	22.66	−8.86	4.39	2.19	5.61	27.94
1000	8	2.0	15.1	24.26	−10.34	4.36	2.07	5.57	25.64
1025	8	1.8	13.9	25.20	−10.84	4.19	2.19	5.34	25.99
1050	7	1.8	13.1	25.83	−11.16	3.95	2.27	5.08	26.29
1075	7	1.8	13.1	25.83	−11.16	3.95	2.27	5.08	26.29
1100	7	1.8	13.1	25.83	−11.16	3.95	2.27	5.08	26.29
1125	13	3.6	27.2	27.83	−14.19	3.18	1.74	4.26	40.31
1150	13	6.6	50.7	28.73	−15.61	2.37	1.26	3.23	43.03
1175	13	7.4	57.7	29.02	−16.09	2.23	1.17	3.05	43.73

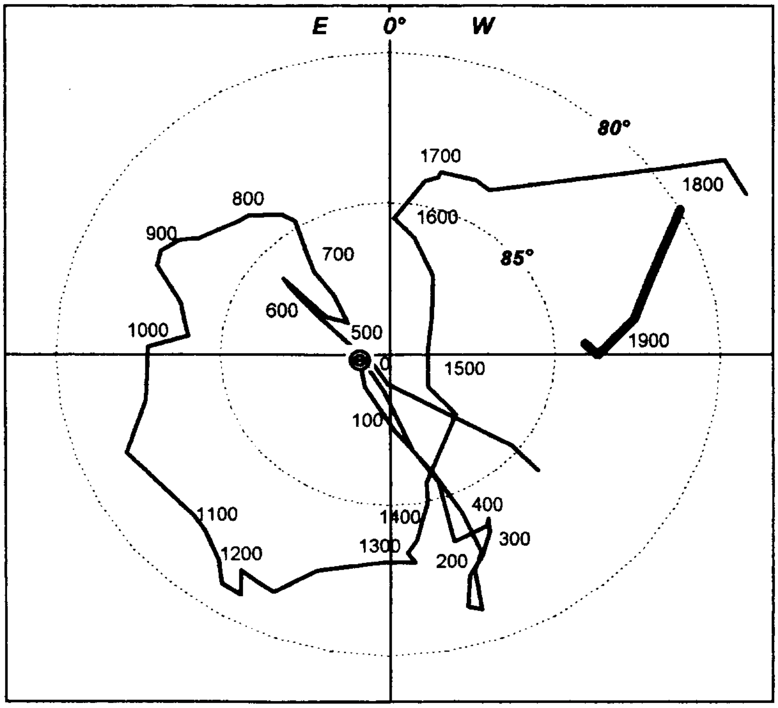


Fig. 10. Evolution of the mean VGPs relative to I and D values from the nine tables of results. The confidence circles (not shown) range from 2 to 6°, and the mean VGP (target) of the whole period is at 88.6°N, 89°E. The thick line represents the evolution from 1800 to 1950 obtained with the nine TMF directions taken from the IGRF.

(Bloxham and Jackson, 1992), with the introduction of a priori conditions for spatial data as well as for the temporal data.

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References

Aitken, M.J. and Hawley, H.N., 1966. Magnetic dating III: further archeomagnetic measurements in Britain. Archaeometry, 9: 187–197.

Aitken, M.J. and Hawley, H.N., 1967. Archeomagnetic measurements in Britain IV. Archaeometry, 10: 129–135.

Aitken, M.J. and Weaver, G.H., 1962. Magnetic dating: some archeomagnetic measurements in Britain. Archaeometry, 5: 4–24.

Aitken, M.J., Hawley, H.N. and Weaver, G.H., 1963. Magnetic Dating: further archeomagnetic measurements in Britain. Archaeometry, 6: 76–80.

Barton, C.E. and Barbetti, M., 1982. Geomagnetic secular variation from recent lake sediments, ancient fireplaces and historical measurements in Southeastern Australia. Earth Planet. Sci. Lett., 59: 375–387.

Belshe, J.C., Cook, K. and Cook, R.M., 1963. Some archaeomagnetic results from Greece. Ann. Br. School Archaeol. Athens, 58: 8–13.

Bloxham, J. and Jackson, A., 1992. Time dependent mapping of the magnetic field at the core-mantle boundary. J. Geophys. Res., 97(B13): 19537–19563.

Bloxham, J., Gubbins, D. and Jackson, A., 1989. Geomagnetic secular variation. Philos. Trans. R. Soc. London, 329(1606): 415–502.

Bucur, I., 1994. The direction of the terrestrial magnetic field in France during the last 21 centuries. Recent progress. Phys. Earth Planet. Inter., 87: 95–109.

Burlatskaya, S.P., 1986. Archaeomagnetic determinations of geomagnetic field elements, world data. Soviet Geophysical Committee of the USSR Academy of Sciences, Moscow.

Champion, D.E., 1980. Holocene geomagnetic secular variation in western United States: implications for the global geomagnetic field US Geol. Surv. Rep. Open File, 314: 80–824.

Clark, R.M., Tarling, D.H. and Noel, M., 1988. Developments in archaeomagnetic dating in Britain. J. Archaeol. Sci., 15: 645–667.

Condomines, M., Tanguy, J.C. and Michaud, V., 1995 Magma dynamics at Mt Etna: constraints from U–Th–Ra–Pb radioactive disequilibria and Sr isotopes in historical lavas. Earth Planet. Sci. Lett., 132: 25–41.

Creer K.M., Georgi, D.T. and Lowrie, W., 1973. On the representation of the Quaternary and late Tertiary geomagnetic fields in terms of dipoles and quadrupoles. Geophys. J.R. Astron. Soc., 33: 323–345.

Daly, L. and Le Goff, M., 1995. An updated and homogeneous world secular variation data base. 2 — Smoothing of the volcanic rocks and lake sediments results. In preparation.

Eighmy, J.L., Hattaway, J.H. and Kane, A.E., 1990. Archaeomagnetic secular variation in the American Southwest, A.D. 700–900: final results from the Dolores archaeological program. In: J.L. Eighmy and R.S. Sternberg (Editors), Archaeomagnetic Dating. University of Arizona Press, Tucson, AZ.

Eighmy, J.L. and Sternberg, R.S. (Editors), 1990. Archaeomagnetic Dating. University of Arizona Press, Tucson, AZ.

Fisher, N.I., Lewis, T. and Embleton, B.J.J., 1987. Statistical Analysis of Spherical Data. Cambridge University Press, Cambridge, 329 pp.

Fisher, R.A., 1953. Dispersion on a sphere. Proc. R. Soc. London, Ser. A, 217: 295–305.

Gubbins, D., 1983. Geomagnetic field analysis — I Stochastic inversion. Geophys. J.R. Astron. Soc., 73: 641–652.

Hirooka, K., 1983. Results from Japan. In: K.M. Creer, P. Tucholka and C.E. Barton (Editors), Geomagnetism of Baked Clays and Recent Sediments. Elsevier, Amsterdam, pp. 150–157.

Hongre, L., Khokhlov, A. and Hulot, G., 1995. What kind of information may we recover from spherical harmonic analysis of the archaeomagnetic data? (abstract) IUGG XXI General Assembly, Boulder, CO, 2–14 July 1995.

Hulot, G. and Le Mouel, J.L., 1994. A statistical approach to the Earth's main magnetic field. Phys. Earth Planet. Inter., 82: 167–183.

Irving, E., 1964. Paleomagnetism and its Application to Geological and Geophysical Problems. Wiley, New York.

Irving, E., 1977. Drift of the major continental blocks since the Devonian Nature, 270: 304–309.

Kawai, N., Hirooka, K., Sasajima, S., Yaskawa, K., Ito, H. and Kume, S., 1965. Archaeomagnetic studies in southwestern Japan. Ann. Géophys., 21(4): 574–578.

Kinoshita, H., 1970. Lists of archaeomagnetic and palaeomagnetic, results 1950–1970. J. Geomagn. Geoelectr., 22(4): 507–555.

Kovacheva, M., 1980. Summarized results of the archaeomagnetic investigation of the geomagnetic field variation for the last 8000 yr in south-eastern Europe. Geophys. J.R. Astron. Soc., 61: 57–64.

Kovacheva, M., 1992. Updated archaeomagnetic results from Bulgaria: the last 2000 years. Phys. Earth Planet. Inter., 70: 219–223.

Kovacheva, M. and Kanarchev, M., 1986. Revised archaeointensity data from Bulgaria. J. Geomagn. Geoelectr., 38: 1297–1310.

Le Goff, M., 1990. Lissage et limites d'incertitude des courbes de migration polaire: pondération des données et extension bivariante de la statistique de Fisher. C.R. Acad. Sci., Sér II, 311: 1191–1198.

Le Goff, M., Henry, B. and Daly, L., 1992. Practical method for drawing a VGP path. Phys. Earth Planet. Inter., 70: 201–204.

Marton, P., 1986. Archaeomagnetic directional results from Hungary. J.R. Astron. Soc., 86: 719–725.

McElhinny, M.W., 1973. Palaeomagnetism and Plate Tectonics. Cambridge University Press, London.

Merrill, R.T. and McElhinny, M.W., 1983. The Earth's Magnetic Field. Academic Press, New York.

Nagata, T., Arai, Y. and Momose, K., 1963. Secular variation of the geomagnetic total force during the last 5000 years. J. Geophys. Res., 68: 5277–5281.

Petrova, G.N., 1977. Archaeomagnetic determinations of geomagnetic field elements, World Data. Soviet Geophysical Commitee of the USSR Academy of Sciences, Moscow.

Rusakov, O.M. and Zagniy, G.F., 1973. Archaeomagnetic secular variation study in the Ukraine and Moldavia. Archaeometry, 15(1): 153–157.

Sakai, H. and Hirooka, K., 1986. Archaeointensity determinations from Western Japan. J. Geomagn. Geoelectr., 38: 1323–1329.

Sasajima, S. and Maenaka, K., 1966. Intensity studies of the archaeosecular variation in West Japan, with a special reference to the hypothesis of the dipole axis rotation. Mem. Coll. Sci. Univ. Kyoto, Ser. B, 33: 53–67.

Shibuya, H. and Nakajima, T., 1979. Archaeomagnetism of southwestern Japan measured and compiled in Osaka University. In: Rock Magnetism and Palaeogeophysics, Vol. 6, In Memory of the Late Professor N. Kawai, Rock Magnetism and Paleogeophysics Research Group, Tokyo, pp. 10–13.

Shuey, R.T., Cole, E.R. and Mikulich, 1970. Geographic correction of archaeomagnetic data. J. Geomagn. Geoelectr., 41: 485–489.

Shure, L., Parker, R.L. and Backus, G.E., 1982. Harmonic splines for geomagnetic modelling. Phys. Earth Planet. Inter., 28: 215–229.

Sternberg, R.S. and McGuire, R.H., 1990. Archaeomagnetic secular variation in the American Southwest, A.D. 700–1450. In: J.L. Eighmy and R.S. Sternberg (Editors), Archaeomagnetic dating. University of Arizona Press, Tucson, AZ.

Stone, M., 1974. Cross-validatory choice and assessment of statistical predictions. J.R. Stat. Soc., B., 36: 111–147.

Tarling, D.H., 1989. Geomagnetic secular variation in Britain during the last 2000 years. In: F.J. Lowes et al. (Editors), Geomagnetism and Paleomagnetism. Kluwer Academic, Dordrecht, pp. 55–62.

Thellier, E., 1937. Sur l'aimantation dite permanente des basaltes. C.R. Acad. Sci., 204: 876–879.

Thellier, E., 1938. Sur l'aimantation des terres cuites et ses applications géophysiques. Ann. Inst. Phys. Globe Univ. Paris, 16: 157–302.

Thellier, E., 1981. Sur la direction du champ magnétique terrestre, en France, durant les deux derniers millénaires. Phys. Earth Planet. Inter., 24: 89–132.

Thompson, R. and Clark, R.M., 1981. Fitting polar wander paths. Phys. Earth Planet. Inter., 27: 1–7.

Wei, Q.Y., Li, T.C., Chao, G.Y., Chang, W.S. and Wang, S.P., 1981. Secular variation of the direction of the ancient geomagnetic field for Loyang Region, China. Phys. Earth Planet. Inter., 25: 107–112.

Wolfman, D., 1990a. Archaeomagnetic dating in Arkansas and the border areas of adjacent states — II. In: J.L. Eighmy and R.S. Sternberg (Editors), Archaeomagnetic Dating. University of Arizona Press, Tucson, AZ.

Wolfman, D., 1990b. Mesoamerican chronology and archaeomagnetic dating, A.D. 1–1200. In: J.L. Eighmy and R.S. Sternberg (Editors), Archaeomagnetic Dating. University of Arizona Press, Tucson, AZ.