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First archaeomagnetic secular variation curve for the Iberian Peninsula: Comparison with other data from western Europe and with global geomagnetic field models

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[1] A first secular variation (SV) curve for the Iberian Peninsula was computed by hierarchical Bayesian method using a total of 134 archaeomagnetic directions with ages ranging from -775 to 1959 A.D. A general agreement is observed between the Iberian curve and the French and German SV curves, although some interesting differences were found, such as the occurrence of lower inclinations between the 11th and 14th centuries in the Iberian curve. The analysis of these three reference curves indicates that SV in western Europe is characterized by three major directional changes at -125 , 200, and 1350 A.D. It is suggested that these cusps are regional features of the geomagnetic field. The Iberian curve has been compared with the predictions of the Jackson, CALSK7K.2, and Hongre global models. Despite large differences recognized between these models, even for the dipolar terms, they predict reasonably well the Iberian archaeomagnetic SV.

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1. Introduction

[2] The variation of the geomagnetic field in the archaeological past can be obtained from paleomagnetic directions determined from heated and well dated archaeological structures. Archaeomagnetic data are presently the most precise high-resolution paleomagnetic data for the last millennia (data from lakes and sediments may be smoothed and/or offset due to the magnetization acquisition process and to sedimentation gaps). These data are used to build secular variation (SV) reference curves that provide knowledge of geomagnetic field variations at regional and global scales for periods covering the last few millennia. Along with historical data, detailed SV curves can also be used for dating purposes. Several SV curves are now available for Europe, including Great Britain [Batt, 1997], Bulgaria [Kovacheva et al., 1998], France [Gallet et al., 2002], Hungary [Márton, 2003], Germany [Schnepf and Lanos, 2005] and Austria [Schnepf and Lanos, 2006]. Despite the high number of archaeological excavations carried out in Spain only limited data are available for this region. In a recent work, Gómez-Paccard et al. [2006] provide a compilation of 5 previous results and present 58 new archaeomagnetic directions. In the present study this data set is used, along with data from southern France and northern Morocco, to propose a first SV curve for the Iberian Peninsula. The French and Moroccan data can be used in constructing the SV curve due to their geographical proximity to the Iberian Peninsula. The hierarchical bivariate method by moving average technique [Le Goff, 1990; Le Goff et al., 1992; Daly and Le Goff, 1996; Lanos et al., 2005] and the hierarchical Bayesian modeling [Lanos, 2004] are implemented in order to determine the best way to calculate the Iberian curve. To determine the characteristics of the geomagnetic SV in western Europe over the last two millennia, the Iberian curve has been compared with the French and German archaeomagnetic reference curves. Finally, a comparison between available geomagnetic field global models [Hongre et al., 1998; Jackson et al., 2000; Korte and Constable, 2005] has

been conducted in order to test the reliability of their predictions.

2. Available Data From Spain, France, and Morocco

2.1. Spanish Data

[3] Gómez-Paccard et al. [2006] compiled the available data for Spain and presented 58 new archaeomagnetic directions, carefully describing the sampling, experimental procedures and dating constraints of the new directions. Samples were taken as oriented blocks or drilled directly from the archaeological heated structures. Classical thermal, alternating field demagnetization or Thellier method were applied in order to determine the characteristic directions for each structure. In most cases, high-quality, single-component remanence vectors were obtained. For some structures, which were heated to relatively low temperatures, more than 1 component could be recognized and great circle analysis was required. The characteristic directions and their statistical parameters were calculated using principal component [Kirschvink, 1980] or great circle [McFadden and McElhinny, 1988] analysis and Fisher [1953] statistics. As proposed by Lanos et al. [2005], a hierarchical structure was followed in the calculation of the 58 new directions. Together with 5 previous data from Spain, a total of 63 archaeomagnetic directions are available from Spain (see Table 1 and Figure 1).

2.2. French and Moroccan Data

[4] Archaeomagnetic research started in France with the work of E. Thellier [Thellier, 1938], who later published the first SV curve for France for the last two millennia [Thellier, 1981]. This curve has been revised, completed and extended by Bucur [1994]. Since then, new archaeomagnetic directional results have been collected by Moutmir [1995], Chauvin et al. [2000], and Gallet et al. [2002], who presented a new SV curve for France. Together they provide a high-quality collection of archaeomagnetic data. In this study, only the data from sites with a geographical proximity to the Iberian Peninsula (within a 900 km radius of

Table 1. Archaeomagnetic Directions From Spanish, French, and Moroccan Sites^a

Name	t_{\min}	t_{\max}	t_{mean}	t_{bayesian}	I_s , deg	D_s , deg	N	α_{95}	k	Lat., °N	Long., °E	Stratigraphic Constraints	Source
Plaza de Moros (PLM)	-150	-50	-100	-98.7	58.2	-4.0	8	4.1	182	39.50	-4.00		
Ampurias (AMP)	-200	100	-50	-98.7	63.5	-8.5	4	1.5	2592	42.12	3.13		Thellier [1981]
El Monastil (MON)	-50	35	-7.5	-5.6	57.3	0.3	9	2.2	546	38.47	-0.79		
El Gallinero (GA)	40	50	45	45.0	53.4	3.8	7	4.9	150	36.53	-6.19		
Villa del Pañuelo I (VILLI)	0	100	50	51.4	57.1	-5.5	25	2.6	116	40.30	-3.40		Oyamburu et al. [1996]
Calahorra, La Maja (LMA)	0	100	50	54.9	58.4	-0.8	29	2.1	128	42.27	-2.02		Parés et al. [1992]
Costalita (COS)	0	100	50	46.8	54.3	3.7	14	6.0	46	36.42	-5.15		
Venta del Carmen (VC)	80	90	85	85.3	46.7	2.1	27	2.3	146	36.18	-5.49		
Villares Andujar (VIA)	50	150	100	109.2	50.5	1.4	9	3.2	259	38.06	-4.04		
Cartuja I (CAR-HI)	50	150	100	86.3	55.3	-1.7	7	3.5	293	37.18	-3.10		
Cartuja II (CAR-HII)	50	150	100	100.1	52.2	-3.1	7	5.4	125	37.18	-3.10		
Cartuja III (CAR-HIII)	50	150	100	96.5	52.3	2.9	5	3.9	392	37.18	-3.10		
Patio Cardenal I (PARI)	90	130	110	109.0	53.0	-2.4	10	2.2	484	37.38	-5.98		
Patio Cardenal III (PAR3)	90	130	110	108.6	54.1	-4.1	6	3.7	324	37.38	-5.98		
Patio Cardenal IV (PAR4)	90	130	110	109.1	53.3	-2.7	7	1.9	1026	37.38	-5.98		
Patio Cardenal V (PAR5)	90	130	110	109.0	53.5	-4.3	17	2.6	193	37.38	-5.98		
Baelo Claudia (BC)	100	150	125	128.2	46.7	-2.2	14	3.6	145	36.03	-5.62		
Gallineras (GAL)	100	220	160	140.5	55.8	-0.1	7	4.6	176	36.47	-6.18		Evans, private communication
Arva (ARV)	150	250	200	199.1	51.8	-3.7	17	1.3	682	37.60	-5.50		
Setla Miratorsa Mirafior (DENA)	220	250	235	234.9	52.6	-4.5	10	1.9	669	38.86	0.02		
Hypolytus (HIP)	225	325	275	274.4	52.6	-4.0	18	3.4	104	40.48	-3.32		
Villa del Pañuelo II (VIL2)	250	350	300	296.6	51.7	-2.7	31	2.2	131	40.30	-3.40		Oyamburu et al. [1996]
Valeria (VAL)	270	330	300	299.7	48.0	-5.4	7	9.7	58	39.77	-2.13		
Puente Grande I (PG1)	400	410	405	404.9	46.4	-14.1	13	7.3	33	36.18	-5.49		
Puente Grande II (PG2)	400	410	405	405.0	52.5	0.3	15	3.4	129	36.18	-5.49		
Ramon Ortega II (RO2)	1000	1050	1025	1027.7	50.9	17.3	14	4.0	100	38.86	0.12		
Murcia c/Sagasti (MURG)	1000	1100	1050	1033.2	51.3	21.7	8	1.5	1437	37.98	-1.12		
Ramon Ortega I (RO1)	1050	1100	1075	1079.0	47.9	15.8	16	1.9	380	38.86	0.12		
Cabrera d'Anoia (CDAP)	1010	1220	1115	1174.4	50.6	3.6	8	3.6	236	41.50	1.50		
Cabrera d'Anoia (CDAU)	1029	1203	1116	1119.6	44.7	13.6	6	3.8	308	37.98	-1.12	before MURN	
Murcia c/Puxmarina (MURO)	1100	1200	1150	1135.8	45.1	14.0	6	2.1	1038	37.98	-1.12	after MURO and before MURN	
Murcia c/Puxmarina (MURN)	1100	1200	1150	1151.7	45.5	14.9	7	2.1	811	37.98	-1.12	after MURN and before MURL	
Murcia c/Puxmarina (MURM)	1100	1200	1150	1170.8	44.2	16.2	9	1.2	1842	37.98	-1.12	after MURN	
Murcia c/Puxmarina (MURL)	1100	1200	1150	1157.4	41.7	15.2	7	4.1	215	37.98	-1.12		
Murcia c/Puxmarina (MURI)	1100	1200	1150	1146.4	45.2	14.1	9	2.2	547	37.98	-1.12		
Murcia c/Puxmarina (MURK)	1100	1200	1150	1134.3	46.4	17.3	10	2.7	330	37.98	-1.12		
Murcia c/Puxmarina (MURH)	1100	1200	1150	1217.0	45.2	9.0	8	2.7	416	41.50	1.50		
Cabrera d'Anoia (CDAJ)	1056	1262	1159	1215.1	46.4	10.7	5	1.3	3461	41.50	1.50		
Cabrera d'Anoia (CDAH)	1043	1281	1162	1270.6	42.6	11.5	5	4.8	500	40.63	-3.16		
Magisterio I (MAGI)	1250	1300	1275	1275.9	47.3	4.1	6	6.1	179	40.63	-3.16		
Magisterio II (MAGII)	1250	1300	1275	1286.6	44.9	11.4	8	2.9	356	39.02	-3.82		
Calatrava la Vieja (CALA)	1275	1300	1287.5	1286.6	44.9	11.4	8	2.9	356	39.02	-3.82		

Table 1. (continued)

Name	t_{\min}	t_{\max}	t_{mean}	t_{bayesian}	I_s , deg	D_s , deg	N	α_{95}	k	Lat., °N	Long., °E	Stratigraphic Constraints	Source
Calatrava la Vieja (CALB)	1275	1300	1287.5	1287.4	44.4	7.1	10	2.9	284	39.02	-3.82		
Valencia Velluters (VALN)	1238	1350	1294	1310.6	46.6	2.1	9	1.2	1859	39.47	-0.37		
Guadalajara (GUA1)	1275	1325	1300	not used	57.8	14.3	4	2.8	1104	40.60	-3.20		
Castillo de San Romualdo (CSR)	1100	1500	1300	1334.0	46.0	8.1	3	7.2	298	36.30	-6.10		
Valencia Velluters (VALJ)	1238	1400	1319	1329.6	46.4	4.4	11	1.7	725	39.47	-0.37		
Av. Blas de Infante (BI)	1369	1369	1369	1369.0	41.9	0.4	10	3.4	206	36.13	-5.45		
Valencia Velluters (VALM)	1300	1450	1375	1342.8	47.0	7.2	9	1.0	2733	39.47	-0.37	before VALK	
Valencia Velluters (VALK)	1300	1450	1375	1383.5	44.2	3.0	9	1.3	1606	39.47	-0.37	after VALM	
Llano las Damas (LLD)	1400	1415	1407.5	1407.2	37.0	9.6	14	4.0	98	35.89	-5.30		
Huerta Rufino (HR)	1400	1415	1407.5	1407.0	35.9	7.8	7	3.1	417	35.89	-5.30		
Calatrava la Vieja (CALC)	1400	1420	1410	1410.3	47.0	3.0	8	2.0	790	39.02	-3.82		
Paterna c/Huertos (PATA)	1450	1500	1475	1487.6	56.4	3.6	10	1.7	792	39.50	-0.43	before PATB	
Paterna Testar del Moli (TMO)	1490	1540	1515	1520.1	55.7	7.5	16	2.0	343	39.50	-0.43		
Paterna Testar del Moli (PATJ)	1429	1611	1520	1593.6	62.2	6.6	16	1.1	1201	39.50	-0.43		
Paterna Testar del Moli (PATH)	1450	1600	1525	1515.7	53.5	7.3	10	1.7	831	39.50	-0.43		
Paterna c/Huertos (PATB)	1525	1650	1587.5	1625.6	64.1	5.8	11	1.6	827	39.50	-0.43	after PATA	
Valencia Velluters (VALL)	1575	1625	1600	1591.5	56.6	9.1	11	1.9	557	39.47	-0.37		
Monastery at Yuste (YUS1)	1784	1814	1799	1835.2	55.5	-14.3	7	4.6	173	40.10	-5.70		
Huertas del Carmen (GUA2)	1825	1845	1835	1800.4	61.5	-21.1	13	2.7	238	40.60	-3.20		
Palacio de Perales (AL)	1830	1910	1870	1865.5	63.0	-14.2	6	5.3	159	40.10	-3.10		
Monastery at Yuste (YUS2)	1959	1959	1959	1959.0	58.2	-11.1	5	6.5	138	40.10	-5.70		
<i>Sites r < 600 km (France and Morocco)</i>													
Saint Florence	-325	-275	-300.0	-299.4	66.4	-2.8	11	2.2	386	44.8	0.0		Bucur [1994]
Dchar Jdid, the citadel	-300	-100	-200.0	-186.9	53.0	1.8	10	5.1	75	35.5	-6.0		Kovacheva [1984]
Aiguillon F1+2+3	-120	-80	-100.0	-99.5	62.4	-2.4	45	1.1	1825	44.3	0.3		Bucur [1994]
Aiguillon F4	-120	-80	-100.0	-99.7	64.1	2.6	19	0.8	1607	44.3	0.3		Bucur [1994]
Montans 4	-100	-80	-90.0	-90.0	63.5	-2.6	11	1.0	1696	43.9	1.8		Bucur [1994]
Lagrene	-80	-40	-60.0	-59.9	62.9	-3.7	14	0.9	1797	44.4	0.2		Bucur [1994]
Limoux II (four II)	-20	-5	-12.5	-12.6	62.0	-0.3	7	2.1	625	43.1	2.3		Bucur [1994]
Montans 6	20	30	25.0	24.9	62.3	-1.2	7	1.2	2054	43.9	1.8		Bucur [1994]
Al Kouass (Chkakra)	-100	0	-50.0	-49.3	54.3	-6.1	5	3.3	360	35.5	-6.0		Kovacheva [1984]
Montans I	140	160	150.0	150.1	56.0	-0.1	12	1.6	673	43.9	1.8		Bucur [1994]
Abrens (Laure Minervois)	175	225	200.0	200.0	56.8	-0.3	16	1.1	1031	43.3	2.5		Bucur [1994]
Barat de Vin	400	400	400.0	400.5	59.6	-1.0	8	1.5	1079	43.5	-1.0		Bucur [1994]
Lectoure	375	425	400.0	397.9	57.5	-4.3	20	1.7	311	43.9	0.6		Bucur [1994]
Toulouse Place St. Etienne	450	550	500.0	508.7	63.4	1.0	9	0.6	5769	43.6	1.4		Bucur [1994]
Sadirac SB4	1350	1400	1375.0	1373.6	51.0	1.9	10	0.8	2865	44.8	-0.5		Bucur [1994]
Sadirac SB3	1500	1525	1512.5	1512.2	57.9	10.0	8	1.0	2331	44.8	-0.5		Bucur [1994]
<i>Sites r < 900 km (France and Morocco)</i>													
Gannat	-850	-700	-775.0	-744.2	65.1	14.0	10	2.9	237	46.2	3.3		Moutmir [1995]
Lignat	-850	-700	-775.0	-762.9	67.7	29.4	24	2.4	146	45.8	3.3		Moutmir [1995]
St. Blaise	-575	-550	-562.5	-561.6	65.6	0.5	11	0.9	2355	43.5	5.0		Bucur [1994]
Issoire 1	-750	-250	-500.0	-662.7	69.1	21.6	21	1.4	961	45.5	3.3		Moutmir [1995]

Table 1. (continued)

Name	t_{\min}	t_{\max}	t_{mean}	t_{bayesian}	I_{sr} deg	D_{sr} deg	N	α_{95}	k	Lat., °N	Long., °E	Stratigraphic Constraints	Source
Aspiran. AFR 6186	-525	-475	-500.0	-501.1	69.5	9.9	17	1.8	398	43.6	3.6		Gallet et al. [2002]
Aspiran. AFR 6416	-525	-475	-500.0	-501.4	69.4	9.6	13	1.5	728	43.6	3.6		Gallet et al. [2002]
Issoire 2	-700	-600	-650.0	-648.0	73.0	22.0	8	1.6	483	45.5	3.3		Moutmir [1995]
Loupjac. Loup-01	-850	-700	-775.0	-777.6	64.5	27.0	14	1.3	889	44.9	1.5		Gallet et al. [2002]
Loupjac. Loup-03	-850	-700	-775.0	-814.6	62.4	36.2	14	2.6	242	44.9	1.5		Gallet et al. [2002]
Loupjac. Loup-12	-850	-700	-775.0	-742.0	66.7	19.7	9	3.4	236	44.9	1.5		Gallet et al. [2002]
Loupjac. Loup-16	-850	-700	-775.0	-794.2	62.4	27.4	17	3.2	123	44.9	1.5		Gallet et al. [2002]
Petit et grand Lezat	-100	-50	-75.0	-75.9	65.7	-7.9	10	1.5	931	46.0	3.3		Bucur [1994]
Sallèles d'Aude F10	-30	30	0.0	-1.3	62.5	0.2	8	1.8	756	43.2	3.0		Chauvin et al. [2000]
Marseille	-30	40	5.0	-2.3	63.7	-2.4	46	0.6	1215	43.3	5.4		Bucur [1994]
Lezoux F3	-25	50	12.5	6.8	64.5	-2.4	14	1.1	1243	45.8	3.4		Bucur [1994]
Lezoux LAS65	15	20	17.5	17.5	63.5	-1.3	22	1.3	684	45.8	3.4		Bucur [1994]
Gievres II sol brûlé	40	40	40.0	40.5	64.1	-0.5	6	0.8	5047	47.3	1.7		Bucur [1994]
Mougou II	40	60	50.0	50.9	61.4	-3.3	20	1.1	1698	47.1	0.5		Bucur [1994]
Sallèles d'Aude F12	50	90	70.0	71.6	57.8	-1.6	18	1.2	756	43.2	3.0		Chauvin et al. [2000]
Yseure (Le Pavillon)	79	80	80.0	80.0	61.0	-1.5	17	0.7	2265	46.6	3.4		Bucur [1994]
Amboise	75	125	100.0	103.0	60.2	-5.5	14	1.7	474	47.4	1.0		Bucur [1994]
Pouillé les Bordes (four 5)	75	150	112.5	101.4	64.6	-6.3	8	1.8	771	47.3	1.3		Bucur [1994]
Pouillé les Bordes (four 6)	75	150	112.5	116.2	60.4	-1.1	7	1.5	1248	47.3	1.3		Bucur [1994]
Sallèles d'Aude F13	100	160	130.0	130.4	56.7	-5.1	8	1.0	2450	43.2	3.0		Chauvin et al. [2000]
Sallèles d'Aude F15	120	180	150.0	150.9	55.9	-5.6	10	1.7	678	43.2	3.0		Chauvin et al. [2000]
La Croiselle/Briance	150	200	175.0	176.1	56.9	1.1	10	2.3	372	45.6	1.6		Bucur [1994]
Varennes/Allier	150	210	180.0	180.6	58.8	-1.5	8	1.8	749	46.3	3.4		Bucur [1994]
Lezoux (Hôpital)	160	200	180.0	181.3	53.7	-2.5	11	1.7	548	45.8	3.4		Bucur [1994]
Toulon/Allier	180	180	180.0	180.5	57.9	-2.5	17	1.0	4012	46.6	3.3		Bucur [1994]
Lezoux 85	175	190	182.5	182.5	58.2	-5.3	15	0.6	3206	45.8	3.4		Bucur [1994]
Sallèles d'Aude F3	190	230	210.0	210.2	56.1	0.2	20	1.7	339	43.2	3.0		Chauvin et al. [2000]
Sallèles d'Aude F9	195	235	215.0	215.2	56.9	0.3	16	2.0	306	43.2	3.0		Chauvin et al. [2000]
Volubilis, the big furnace	200	300	250.0	252.6	50.3	-7.8	10	3.6	151	34.0	-5.5		Kovacheva [1984]
Sallèles d'Aude F7	235	295	265.0	264.5	58.8	1.2	15	2.3	907	43.2	3.0		Chauvin et al. [2000]
Volubilis, NE	200	390	295.0	283.2	44.7	0.1	3	1.8	2016	34.1	-5.5		Najid [1986]
Volubilis, palais Justice	200	390	295.0	295.7	47.2	-8.4	4	8.5	68	34.1	-5.5		Najid [1986]
Sallèles d'Aude F8	280	340	310.0	309.9	56.5	-2.8	10	2.8	250	43.2	3.0		Chauvin et al. [2000]
Sallèles d'Aude F14	280	340	310.0	310.0	56.5	-3.3	9	2.1	494	43.2	3.0		Chauvin et al. [2000]
Volubilis, S thermal bath	250	390	320.0	320.0	47.5	-1.8	9	3.1	227	34.1	-5.5		Najid [1986]
Lezoux III Jardin de l'Hospice	385	450	417.5	418.8	61.1	2.0	7	1.3	1622	45.8	3.4		Bucur [1994]
Le Thoronet (Abbaye)	400	500	450.0	443.9	58.5	2.0	7	1.5	1333	43.5	6.3		Bucur [1994]
Volubilis, the furnace in the S of the site	400	500	450.0	447.7	51.7	-6.7	5	2.5	627	34.0	-5.5		Kovacheva [1984]
Masmolène I	500	600	550.0	547.1	62.9	4.4	11	0.6	4360	44.0	4.5		Bucur [1994]
El Basra	600	1000	800.0	864.8	51.9	22.5	28	2.3	132	34.8	-5.9		Najid [1986]
El Basra	600	1000	800.0	858.2	51.5	18.1	8	3.4	212	34.8	-5.9		Najid [1986]
Peran en Pledran	910	930	920.0	919.8	65.6	23.3	12	1.0	1776	48.5	-2.8		Bucur [1994]

Table 1. (continued)

Name	t_{\min}	t_{\max}	t_{mean}	t_{bayesian}	I_s , deg	D_s , deg	N	α_{95}	k	Lat., °N	Long., °E	Stratigraphic Constraints	Source
Douè la Fontaine (cellule II)	900	1000	950.0	949.7	63.1	20.3	10	1.8	607	47.2	-0.3		Bucur [1994]
Moulins/Cephons	1032	1068	1050.0	1050.5	59.3	15.7	15	1.1	1138	47.0	1.6		Bucur [1994]
Cabasse	1100	1150	1125.0	1115.4	58.5	15.8	10	1.1	1608	43.4	6.2		Bucur [1994]
Planier	1250	1300	1275.0	1277.2	53.7	6.9	14	1.0	1372	43.2	5.9		Bucur [1994]
Sainte Barbe (Marseille)	1280	1320	1300.0	1301.7	49.2	4.6	15	1.7	460	43.3	5.4		Bucur [1994]
Cadrix	1365	1385	1375.0	1374.7	48.9	7.2	14	1.3	841	43.5	5.9		Bucur [1994]
Tintaine (four à chaux)	1550	1590	1570.0	1568.9	60.5	9.0	7	1.8	985	43.1	3.1		Bucur [1994]
Blois	1578	1578	1578.0	1578.5	60.4	6.7	15	0.7	2562	47.6	1.3		Bucur [1994]
La Madrague (St. Cyr/Mer)	1680	1720	1700.0	1702.8	67.1	-11.5	7	1.3	1796	43.2	5.6		Bucur [1994]
Thoronet Four de l'âne	1829	1831	1830.0	1830.0	62.9	-18.3	6	1.4	1626	43.5	6.3		Bucur [1994]

^aThe first set includes Spanish archaeomagnetic sites, the second includes sites from Morocco and France inside a circle around Madrid of 600 km, and the third includes sites from Morocco and France between the circles described by two circles of 600 and 900 km. Columns are, from left to right: Name, name of the structure; t_{\min} , minimum age of the abandon of the structure; t_{\max} , maximum age of the abandon of the structure; t_{mean} , mean age of the interval proposed for the abandon of the structures in years A.D.; t_{bayesian} , time at which the maximum of probability is obtained (using Bayesian modeling); I_s and D_s , inclination and declination of the mean site direction in situ; N, number of samples used for the calculation of the archaeomagnetic mean direction; α_{95} and k, 95% confidence limit and precision parameter from Fisher statistics; Lat. and Long., site latitude and longitude; Stratigraphic Constraints, stratigraphic constraints between the structures; Source, source for each archaeomagnetic direction (for the Spanish data, blank entry indicates Gómez-Paccard *et al.* [2006]).

Madrid) have been considered (see Figure 1). This includes data from Gallet *et al.* [2002] (which itself includes a selection of well-dated results (called PC) from Bucur [1994], data from Moutmir [1995], and some new archaeomagnetic directions), together with the directional results of Chauvin *et al.* [2000]. A total of 63 archaeomagnetic directions from France have been compiled (see Table 1).

[5] In contrast, very few archaeomagnetic studies have been performed in Morocco. The first concerned the study of six structures coming from three localities [Kovacheva, 1984], in which four reliable archaeomagnetic directions were given. Five directions from Najid [1986] are also available in the archaeomagnetic database of Korte *et al.* [2005], giving a total of 9 archaeomagnetic directions from Morocco (Figure 1). They correspond to sites within a 900 km radius of Madrid (see Table 1).

3. Reference Curve Data Set

[6] The reference curves have been established assuming that within a restricted region the SV curves can be represented by a single curve assigned to a fixed reference site. Madrid is close to the geographic centre of the Iberian Peninsula (40.4°N, 3.7°W) and has been chosen as the reference point. A total of 63 Spanish archaeomagnetic directions are available from within the 600 km radius, with a further 16 from Morocco and southern France. One of the Spanish directions (GUA1 in Table 1) is offset from the general trend displayed by the other data. Recent results of radiocarbon dating cast doubt on the age assigned to the structure and so the direction has not been used in calculating SV curves.

[7] The data set (called the 600 km data set) contains 78 directions, which are shown in Figure 2, after relocation to Madrid via the virtual geomagnetic pole (VGP) method. They are generally very well defined. Around 60% have α_{95} values less than 3°, and only 5 have values bigger than 5°. Uncertainties related to the ages of the structures can differ depending on the archaeological information available, but for the Spanish data set it is generally around 50 years. The compiled data span approximately 2000 years, from -100 to 1959 A.D. Throughout most of the record several directions per century are available, although there is a gap in the data between the 6th and 10th centuries.

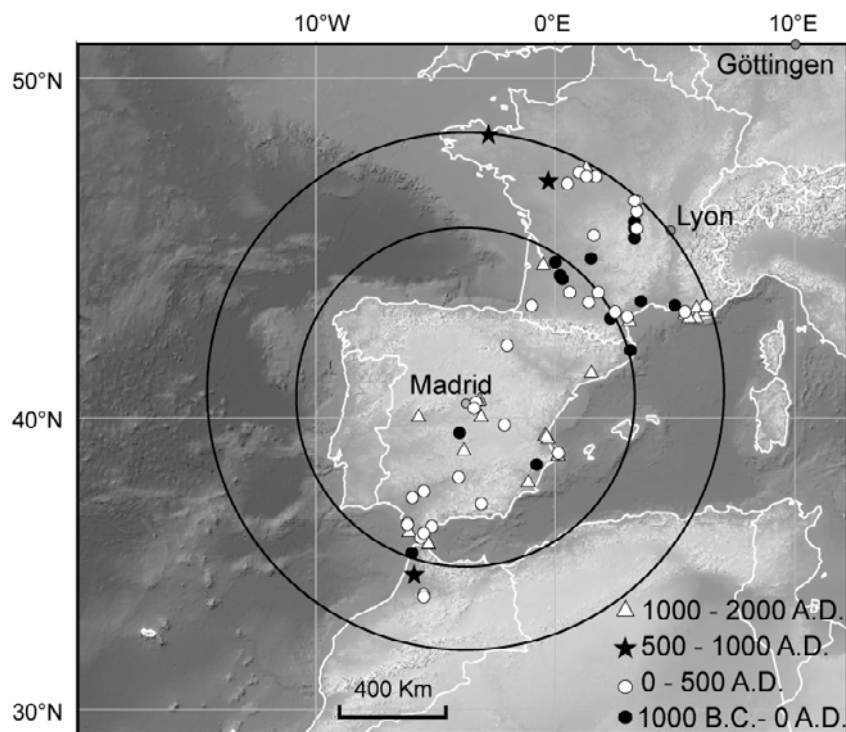


Figure 1. Map showing locations of archaeomagnetic sites (plotted with different symbols for the different age ranges) compiled for the construction of the secular variation curve for the Iberian Peninsula. Madrid (40.4°N, 3.7°W) has been chosen as the reference site. Two circles with radii of 600 km and 900 km are shown.

[8] In southern France or northern Morocco several data can help to cover this gap, but they are from localities more than 600 km from Madrid (see Figure 1). Using data from such distal sources may introduce systematic errors due to the process of relocation to the central reference point. To investigate this question the angular errors introduced during the relocation process via the VGP method have been estimated in the same way as by *Noel and Batt* [1990]. The IGRF values have been calculated for an area described by 30°N, 50°N and 15°W, 10°E, relocated to Madrid, and the results are compared with the Madrid IGRF values. For an area of radius 900 km, inclination errors are less than 2° and declination errors are less than 3° (see Figure 3). Assuming that the harmonic content of the field has been similar throughout archaeological time, then similar error values can be expected in the past. Angular relocation errors of 2°–3° are of the same order as the typical α_{95} values of the Spanish archaeomagnetic directions, and if the error margins of the estimated SV curve are bigger, then these errors would not be significant. The assumption of almost constant harmonic content of the field during archaeological times has been tested

using the global model CALSK3.2 of *Korte and Constable* [2005]. The results indicate that the ratio of the magnetic energy of the nondipole (from degree 2 up to degree 10) to the energy of the dipole, at the Earth surface, has remained almost constant during the last 3 millennia with a mean value of 0.02 ± 0.005 .

[9] Two archaeomagnetic directional data sets have been compiled. The first one includes archaeomagnetic directions corresponding to sites which fall within a 600 km radius circle centered on Madrid, and the second includes an additional 56 (“foreign”) archaeomagnetic directions corresponding to sites situated between 600 and 900 km from Madrid, giving a total of 134 data (see Table 1). It can be seen (Figure 2) that the relocated directions from the two data sets are similar over the same time periods, and that there is no observable systematic error associated with the data between 600 and 900 km from Madrid.

[10] As the accuracy of any calculated SV curve depends principally on the number of reference points and on their associated dating errors, the use of the 900 km data set should increase the reliabil-

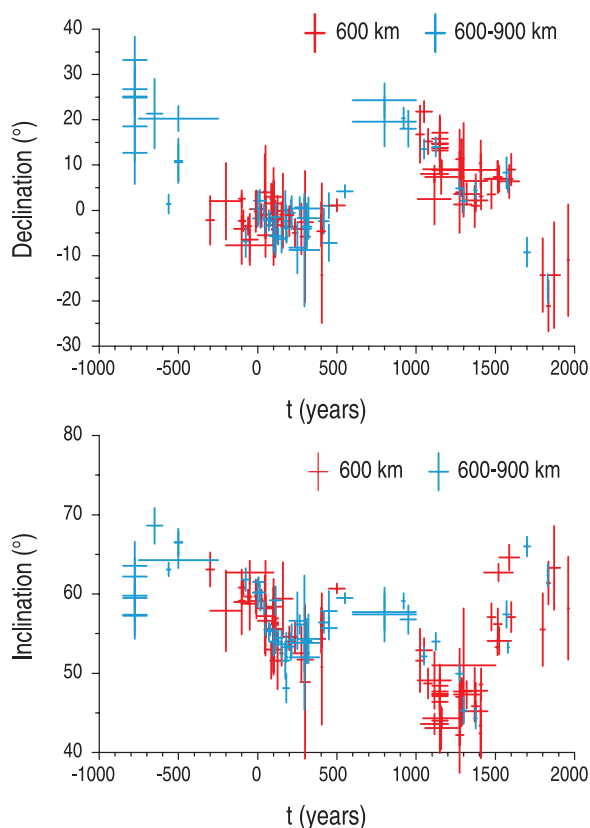


Figure 2. Declination and inclination of the archaeological directions available for the two reference areas, relocated to Madrid. Data coming from localities less than 600 km from Madrid are plotted in red, and data coming from localities between 600 and 900 km are plotted in blue.

ity of a curve obtained for the Iberian Peninsula. Furthermore, the 900 km data set includes data that partially fill the gap between the 6th and 10th centuries A.D. in the 600 km data set. It also includes data from the -6th to -8th centuries, which are not represented in the 600 km data set, thus extending coverage over a longer time period.

4. First SV Curve for Iberia

[11] In order to determine the best SV curve for Iberia the two compiled data sets (600 and 900 km) were treated using the hierarchical bivariate [Lanos *et al.*, 2005] and the hierarchical Bayesian modeling based on roughness penalty [Lanos, 2004]. A comparison between the classical stratified bivariate [Le Goff, 1990; Le Goff *et al.*, 1992; Daly and Le Goff, 1996] and the hierarchical bivariate approaches has been presented by Lanos *et al.*

[2005]. The principal difference found was in the estimation of the error margins. In the stratified approach these errors are divided by the total number of samples contributing to the window, while in the hierarchical approach these errors are divided by the number of sites contributing to the window. As demonstrated by Lanos *et al.* [2005], a hierarchical approach should be used in archaeological curve estimation. Therefore this approach has been retained here.

[12] In order to determine the best window widths to use with hierarchical bivariate statistics several values were tested (50, 80, 100 and 120 years). No significant differences were found, therefore it was decided to use a window width of 80 years, plotted in 25 year steps, with at least four reference points per window.

[13] Bayesian modeling [Lanos, 2004] puts some prior knowledge on the global nature of the curve to be estimated, i.e., it is assumed that the studied physical phenomena vary in a smooth way, and it allows the window width to be automatically adapted to the density of points along the time axis, making the points movable within their respective dating error ranges. This approach allows the fitting of a spherical spline function based on roughness penalty to the data in three dimensions (declination, inclination and time), calculating the weight on the construction of the SV curve of all of the possible three-dimensional data. The results are expressed as a mean curve and an envelope (error) at a 95% confidence level. The “real” curve will lie somewhere inside the error band. In addition, this method takes into account stratigraphic constraints provided by archaeological investigations, some of which are known for the Spanish data (Table 1) [Gómez-Paccard *et al.*, 2006].

[14] Figures 4a and 4b show the curves obtained for the 600 and 900 km data sets calculated using Bayesian methods and the comparison between the hierarchical bivariate and Bayesian modeling for the 900 km data set. The hierarchical bivariate curves are not continuous because some time windows contain less than four reference points (Figure 4b). It is noticeable that the mean values obtained with the two methods are very similar, although the hierarchical bivariate mean curve and corresponding errors seem a little choppy.

[15] The archaeological data sets are unevenly distributed in time. For this reason, Bayesian modeling has been retained in order to calculate

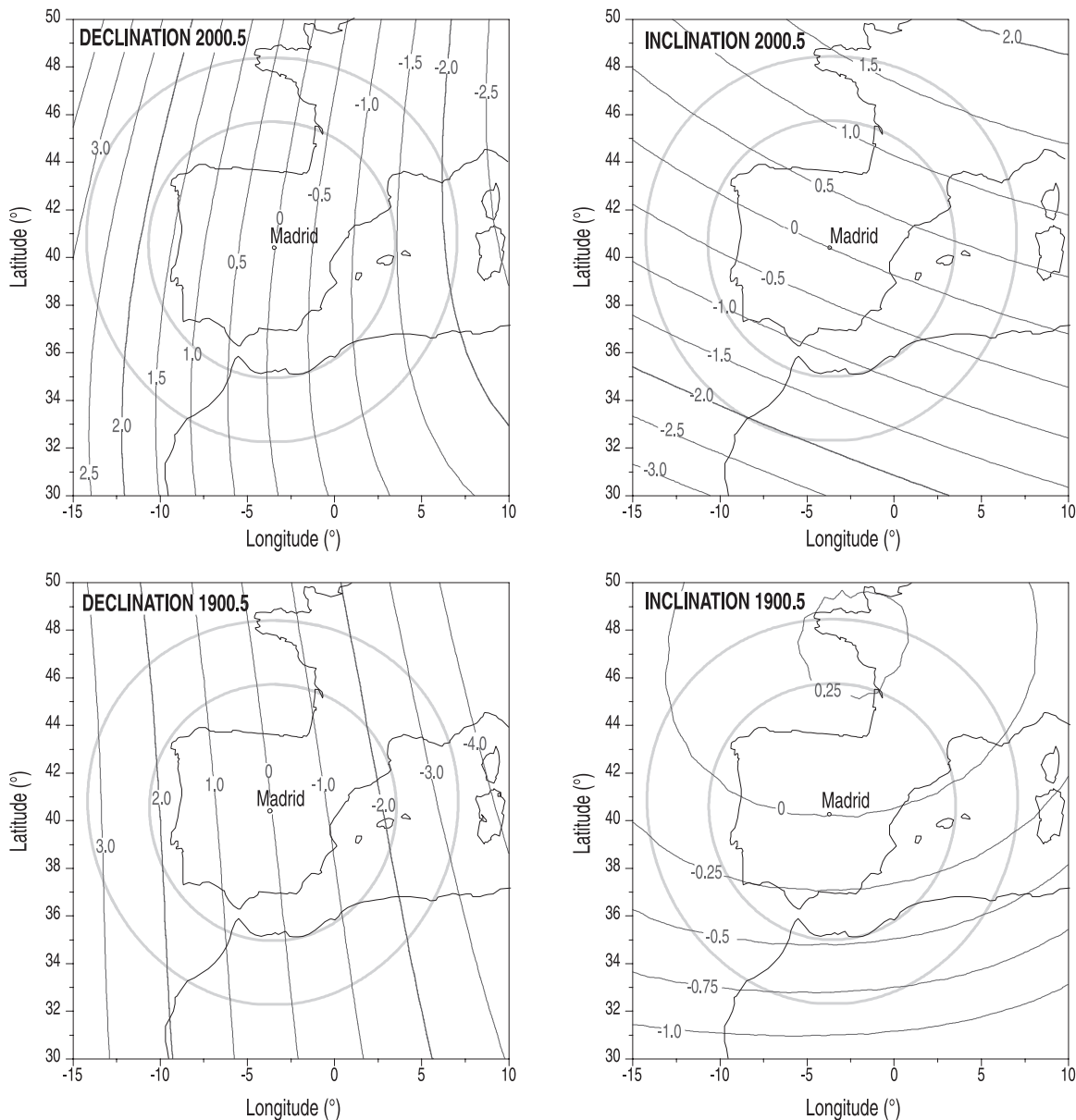


Figure 3. Isolines of the errors in declination and inclination introduced during the VGP relocation between any point on the plot and Madrid. The errors have been calculated using the IGRF 1900 and IGRF 2000 models. Two circles centered at Madrid with 600 and 900 km radii are shown.

the best SV curve for Iberia. The Bayesian curves, and their error envelopes, calculated with the 600 and 900 km data sets are very similar between -350 and 2000 A.D. (Figure 4a). As previously discussed, the maximum error due to the VGP relocation process from any point inside a reference area of 900 km (Figure 3) to Madrid is approximately 3° . This error is lower than the errors of declination and inclination at the 95% confidence level obtained for the Bayesian curve (of about 5° , Figure 4a). Therefore it is considered

that the error introduced during relocation is included in the error inherent to the archaeomagnetic data.

[16] Taking into account all of the previous discussions, Bayesian modeling of the 900 km data set has been used to calculate the curve most representative of the SV for the Iberian Peninsula. It is shown in Figure 5. Table 2 gives the results obtained for inclination and declination (in steps of approximately 25 years), together with their 95%

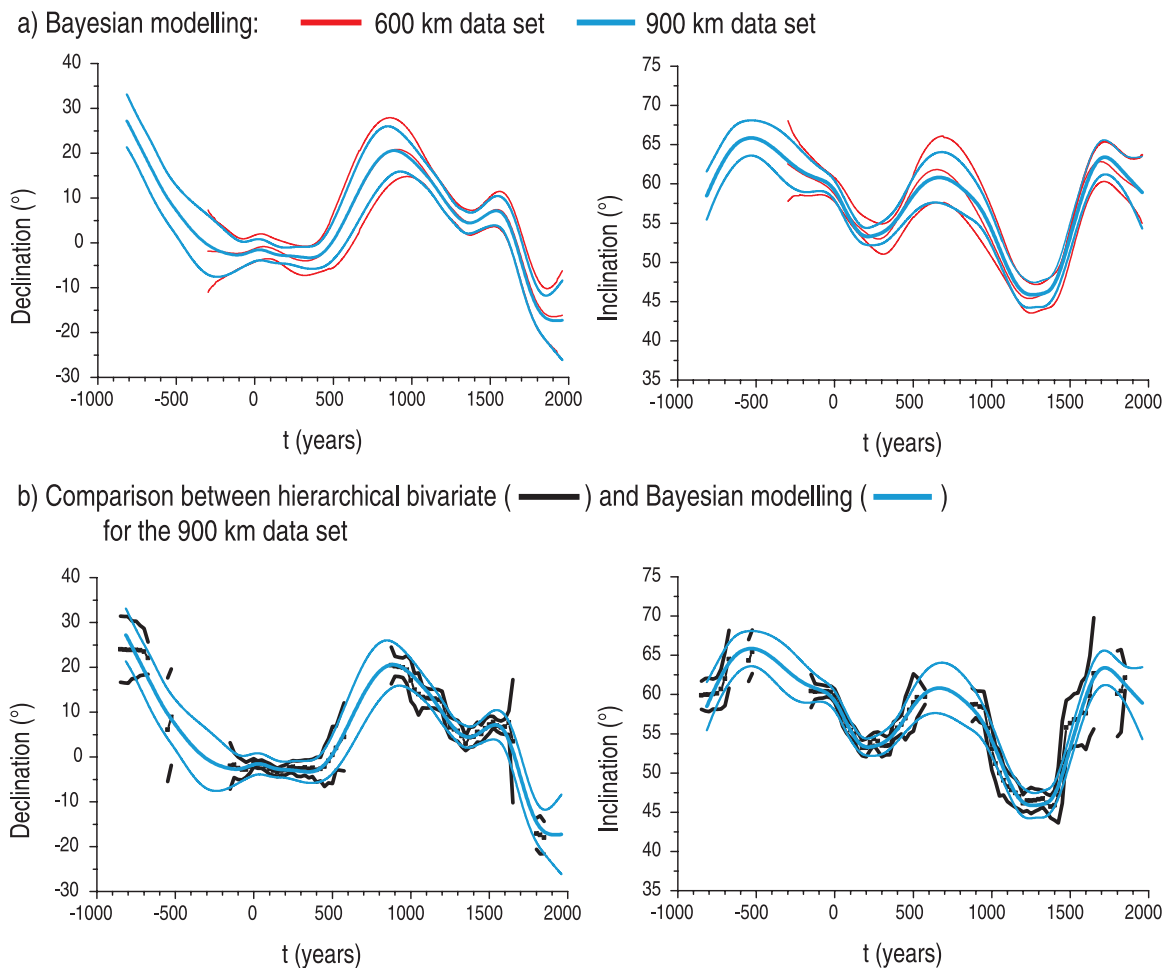


Figure 4. Comparison between the hierarchical bivariate and the Bayesian modeling: (a) the results from Bayesian modeling for the 600 and 900 km data set and (b) a comparison between the results obtained by hierarchical bivariate (calculated using 25 year steps with a least four reference points per window) and Bayesian modeling for the 900 km data set. All curves have been calculated at Madrid and are plotted with their 95% confidence level error bands.

error envelopes. In Table 1, t_{bayesian} indicates the most probable ages (at the 95% confidence level) obtained by Bayesian modeling for each structure. In order to check the influence of data with larger errors on the construction of the SV curve, the Iberian curve has also been calculated rejecting data with dating errors ≥ 75 years or $\alpha_{95} \geq 3.5$. A total of 106 points has been considered. The results obtained are very similar to those obtained using the complete 900 km data set (134 points).

[17] The age of the reference archaeomagnetic data used (134 points) ranges from -775 to 1959 A.D. Throughout most of the record several directions per century are available, although there is a need to extend the data, especially between the 6th and 10th centuries A.D. and prior to 0 A.D., where the

majority of the data come from neighboring countries.

5. Comparison With French and German Secular Variation Curves

[18] In order to compare the Iberian SV curve with the French and German curves, the Bayesian curves for these two countries have been computed. The German archaeomagnetic curve was published by *Schnepf and Lanos* [2005], relocated to Göttingen. It includes a total of 166 archaeomagnetic directions. The French SV curve was calculated at Paris, by Bayesian modeling, the reference data set used is the same as that of *Gallet et al.* [2002], together with the 12 archaeomagnetic directions determined by *Chauvin et al.*

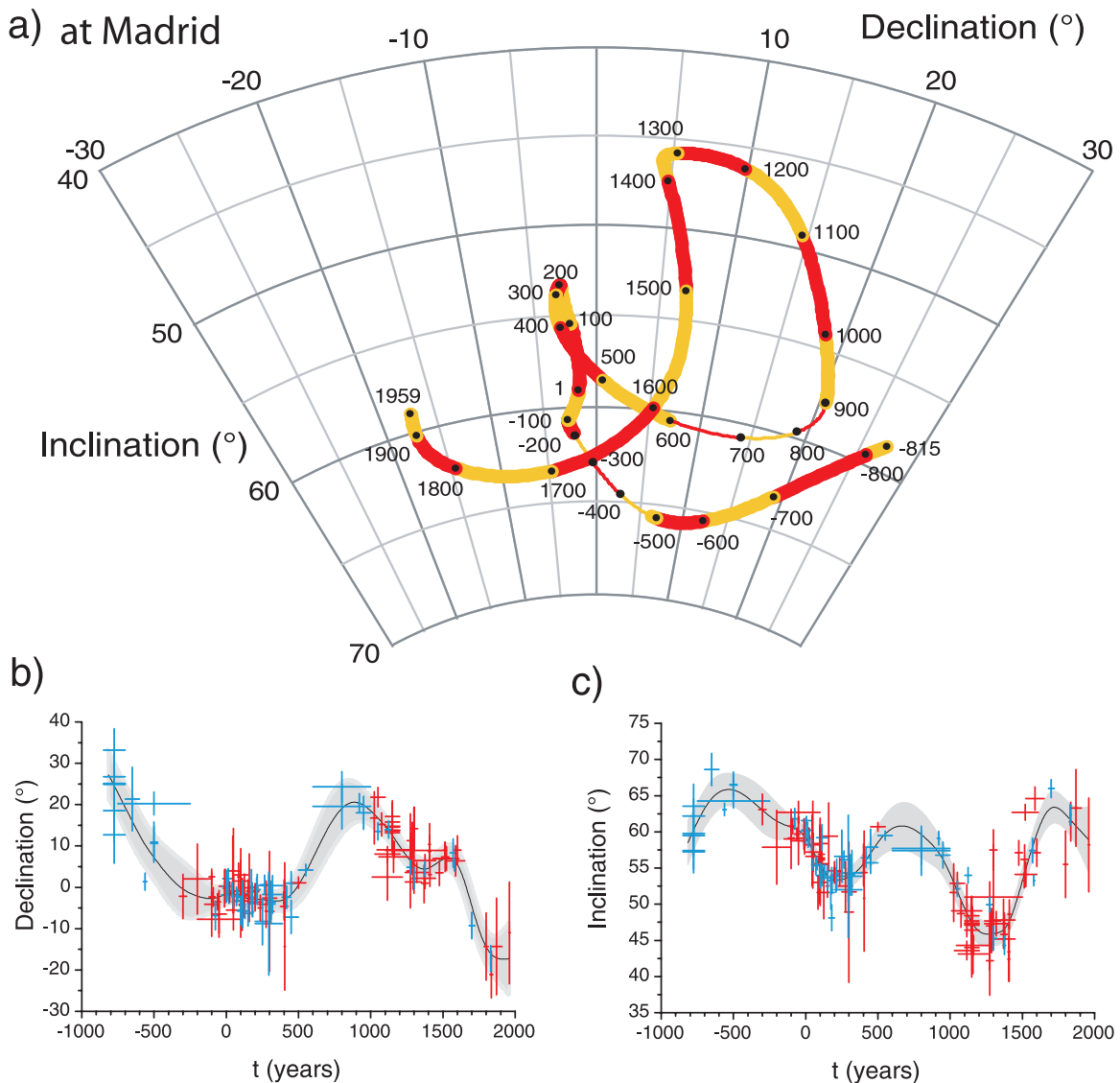


Figure 5. First SV curve for Iberia obtained by Bayesian modeling of the 900 km data set. (a) Stereoplot of declination and inclination, where orange and red indicate century timescales (thin line indicates where the curve is based on a small number of data), (b) declination versus time, and (c) inclination versus time. In Figures 5b and 5c, data coming from localities less than 600 km from Madrid are plotted in red, and data located between 600 and 900 km from Madrid are plotted in blue.

[2000]. The three curves were recalculated at Lyon (45.46°N, 4.50°E, Figure 1), chosen because of its central location between Madrid and Göttingen (Figure 6 and 7). No systematic relocation effect was observed related to this process. However, and in order to avoid relocation errors, the velocities and changes in curvatures of the curves have been calculated directly from the spherical splines obtained for Madrid (Iberian curve), Paris (French curve) and Göttingen (German curve). It is worth pointing out that the Iberian and French curves have 61 archaeomagnetic directions in common, while the French and German curves

have 25 common data. In contrast, the Iberian and the German curves have no points in common.

[19] The three SV curves look similar during most of the past three millennia, especially the French and Iberian curves. However, closer inspection reveals some significant differences in the details of the curves. The observed differences cannot be explained by the effect of relocation processes alone. Lower inclinations are seen in the Iberian curve between the 11th and 14th century and between the 16th and 19th century (Figures 6 and 7). These two differences are constrained by

Table 2. (continued)

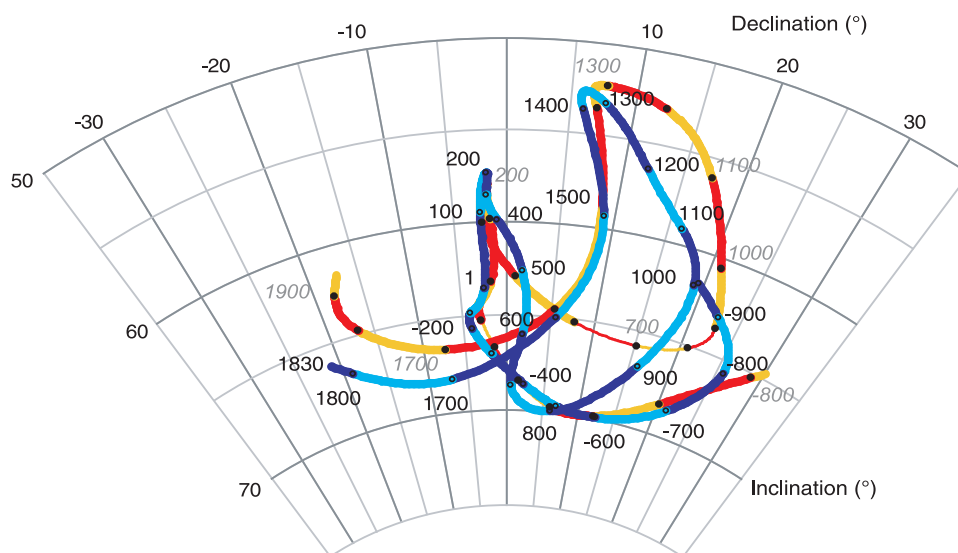
t, years	I, deg	I _{min} , deg	I _{max} , deg	D, deg	D _{min} , deg	D _{max} , deg
1959	59.0	54.5	63.5	-17.3	-26.0	-8.5

^aHere t, age in years A.D.; I (D), inclination (declination); I_{min} – I_{max} (D_{min} – D_{max}), error margins for inclination (declination).

a relatively large number of Spanish data and may be related to features of the local geomagnetic field. If the Iberian and German SV curves are

characterized by a period of two centuries (from 1200 to 1400 A.D.) with low inclinations, this period of low inclinations seems shorter in the French SV curve. The trend of the Iberian SV curve between the 10th and 15th centuries is very similar to that obtained for Italy recorded in historical lava flows [Tanguy *et al.*, 1999; Arrighi *et al.*, 2004]. It is noticeable that the lowest inclinations observed for France and Iberia do not have exactly the same values as for Germany. The differences between the three curves observed

a) Iberian (—) and French (—) SV curves, at Lyon



b) Iberian (—) and German (—) SV curves, at Lyon

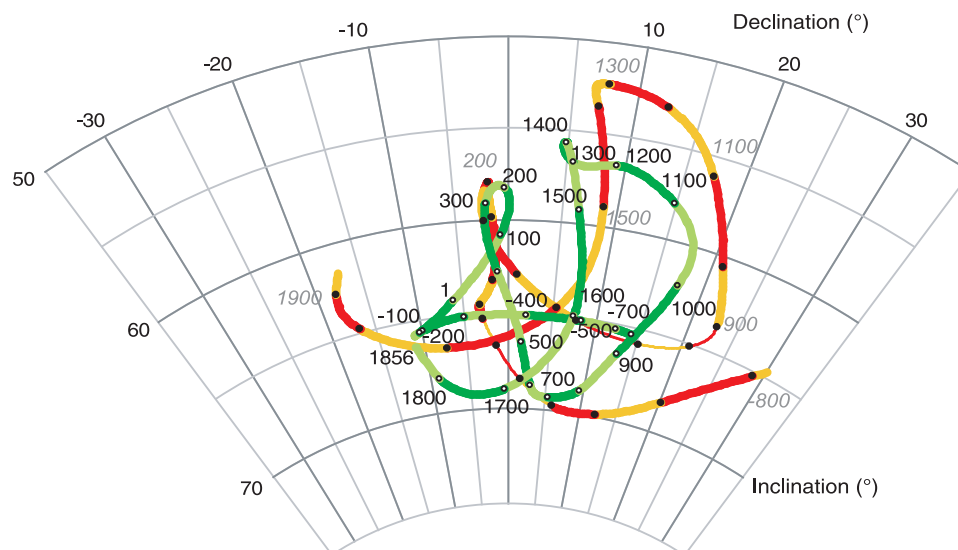


Figure 6. SV curves for (a) Iberia and France and (b) Iberia and Germany at Lyon (45.46°N, 4.50°E). All have been calculated by Bayesian modeling. Ages are plotted in black for the French and Germany SV curves and in gray for the Iberian SV curve. Thin lines indicates where the Iberian curve is based on a small number of data.

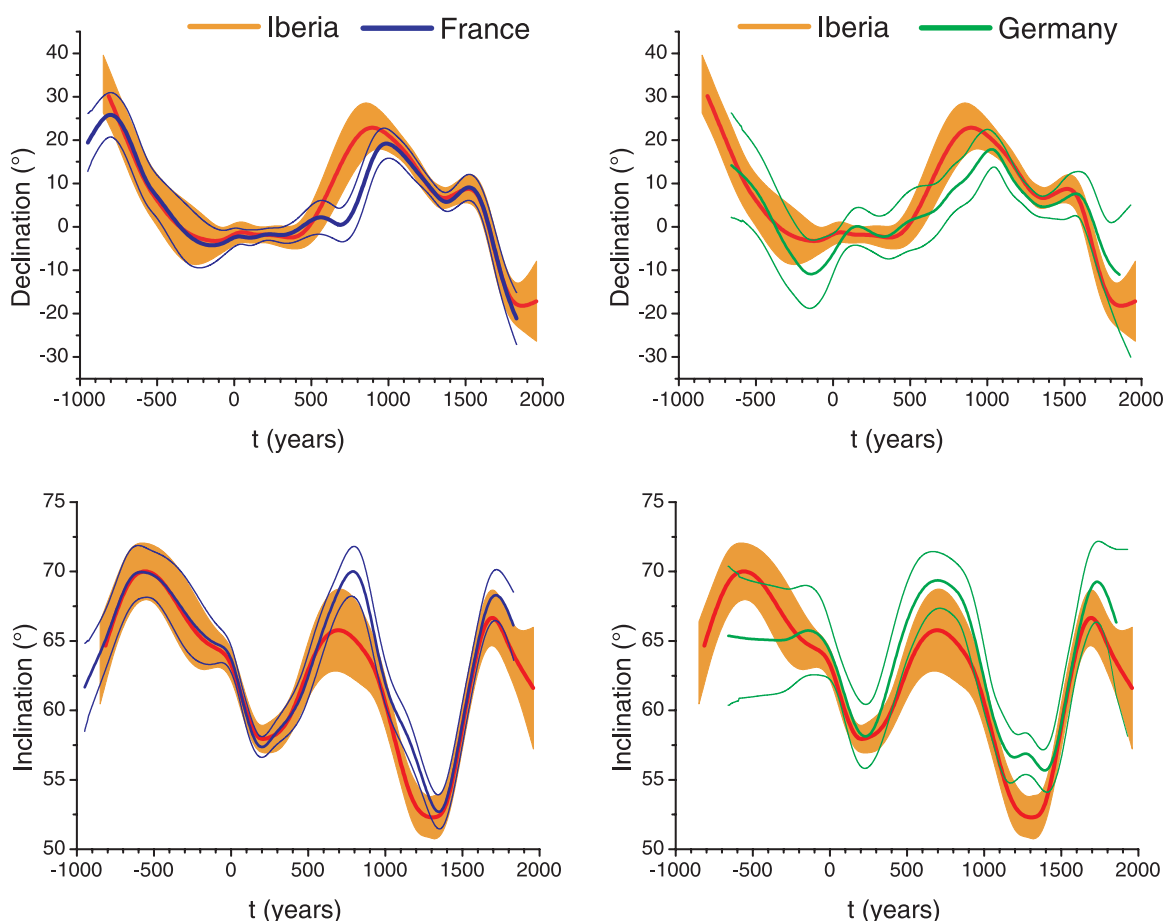


Figure 7. Declination and inclination reference curves together with their 95% error envelope versus time for the Iberian, French, and German SV curves at Lyon. All results are obtained by Bayesian modeling.

during the 6th–9th centuries can be explained by the small number of data available for this period in the Iberian curve. It is important to notice that the French and German curves are also less well constrained during this period (6th–9th) because of a sparse number of data.

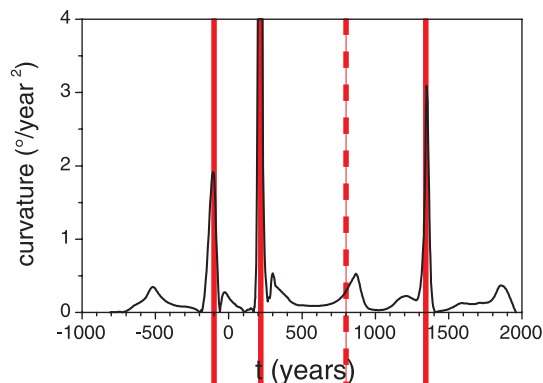
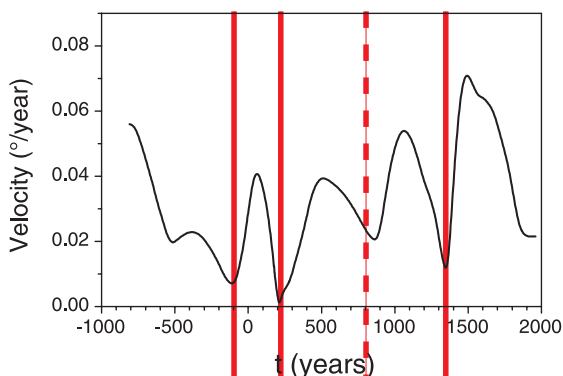
[20] The same analysis can be done taking into account the error estimates of the curves (Figure 7). They are generally lower for the French SV curve than for the Iberian or German curves, due to the larger number of archaeomagnetic data available for France. However, the error margins of the Iberian curve for the period between the 10th and 17th centuries are small and the differences discussed before are well constrained for this region.

[21] Figure 8 shows the rate of the secular variation (velocity) and curvature values computed using Iberian, French and German Bayesian curves. The general trend of the obtained values of velocity and curvature is very similar. Three major directional cusps, related with velocity minima, are

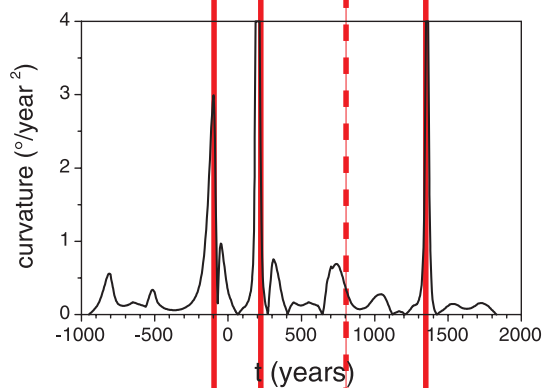
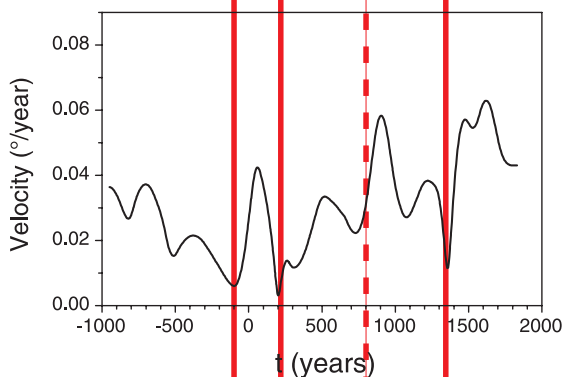
observed in each of the curves, the first around –125 A.D., the second around 200 A.D. and the third around 1350 A.D. Two of these major directional changes (at 200 and 1350 A.D.) are in agreement with those found by *Gallet et al.* [2003] (200 and 1400 A.D.) and seem to occur a little later in the German curve. A further change in curvature is seen at around 600–700 A.D. for the German curve, which is suggested in the French curve but poorly expressed in the Iberian curve (Figure 8). This last directional cusp could be related to the one derived by *Gallet et al.* [2003] and identified at around 800 A.D. The weak temporal resolution of this last directional change could be explained by the lack of data in the European records between the 5th and the 10th centuries (the so-called Dark Ages).

[22] It is concluded that the SV for western Europe over the last three millennia is characterized by 3 major directional changes associated with low secular variation rates. In order to see if these characteristics have a regional or a global signifi-

Iberian Peninsula



France



Germany

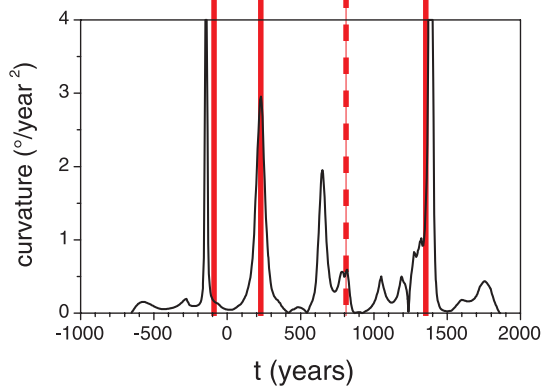
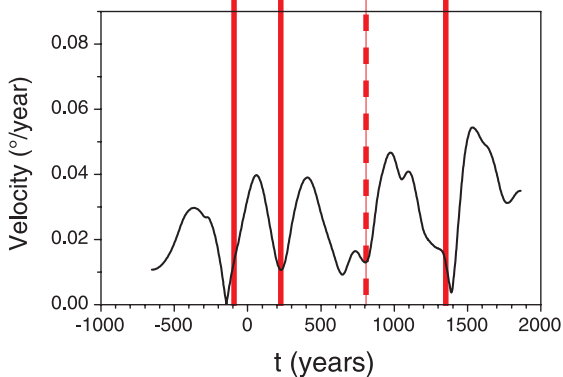


Figure 8. Comparison of the velocity and changes in curvature of the Iberian, French, and German SV curves, calculated by Bayesian modeling.

cance, archaeomagnetic data from other regions have been analyzed. In the global archaeomagnetic data set built by *Korte et al.* [2005] the records from Japan and southwest United States are the most continuous (outside Europe), both in declination and inclination, and are also the less scattered over the last 1500 years. After relocation of the data to a common point (35.3°N, 136.8°E for Japan and 39.5°N, 250.7°E for southwest United States), SV curves for these two regions have been calculated using Bayesian modeling (Figure 9a). The

only difference with the previous analysis is that the number of samples per site used to calculate the mean directional data is not taken into account, because this information is not reported in the data set published by *Korte et al.* [2005].

[23] The secular variation rates and changes in curvature obtained are shown in Figure 9b. Three (for southwest United States) and four (for Japan) major directional changes can be observed, occurring at different time periods. Moreover, the ages of

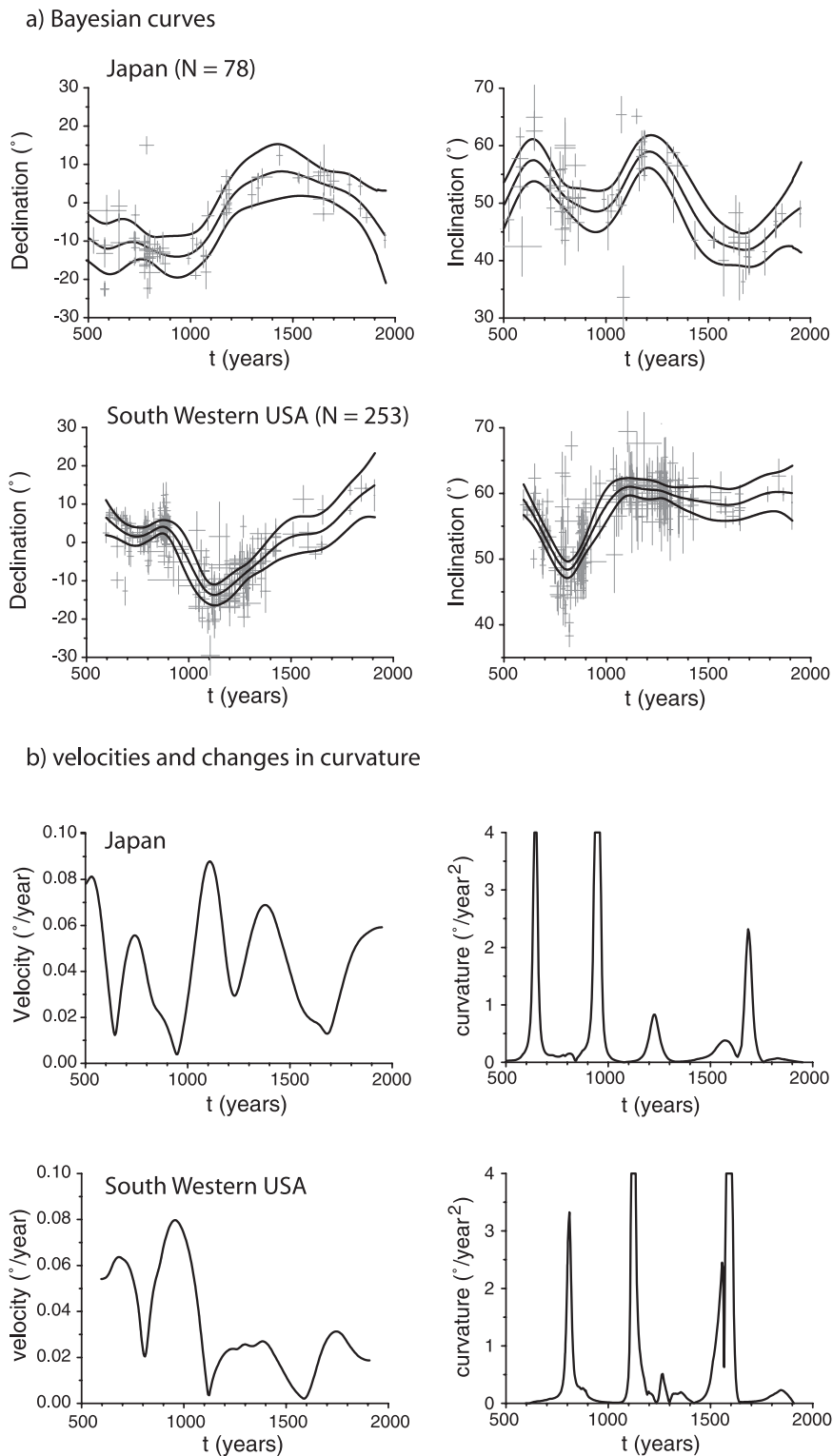


Figure 9. (a) Declination and inclination values together with the error margins versus time for Japan and southwest United States and (b) corresponding velocities and changes in curvature. All results are obtained by Bayesian modeling. N indicates the number of archaeomagnetic directions used to obtain the Bayesian curves.

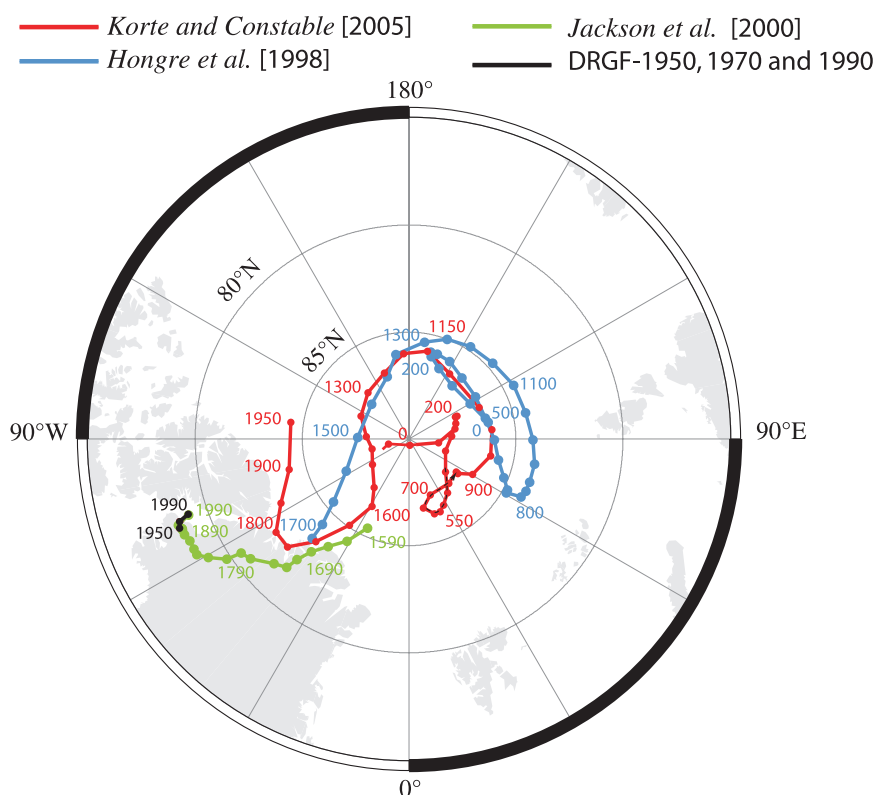


Figure 10. Location of the north geomagnetic pole as computed from CALS3K.2 [Korte and Constable, 2005], from Hongre et al. [1998] global models, and from the model of Jackson et al. [2000]. The results obtained from DRGF-1950, DRGF-1970, and DRGF-1990 are also given.

these cusps are not in agreement with those observed in Europe, except perhaps the one present for the period 650–800 A.D. This seems to indicate that major directional changes are a regional feature of the geomagnetic field, even though more detailed and longer records are clearly needed.

6. Comparison With Global Models

[24] The Iberian SV curve presented here has been compared with the CALS3K.2 and CALS7K.2 global models of Korte and Constable [2005], the geomagnetic model of Jackson et al. [2000] and the model of Hongre et al. [1998]. The Hongre et al. [1998] model is derived with Gauss coefficients up to degree 2 plus degree 3 order 3. The models of Korte and Constable [2005] are derived with Gauss coefficients up to order 10. This is a significant difference between these models. As a smoothing constraint is used by Korte and Constable [2005], their resolution is probably in the order of degree 4 or 5. For the last two millennia there is little difference between the CALS3K.2 and CALS7K.2 models, so the CALS3K.2 model has been used here. The Jackson et al.'s model, based

on massive 400 years historical records, is derived with Gauss coefficients up to degree 14.

[25] Differences between the available global models can be seen in Figure 10. This gives the corresponding positions of the north geomagnetic pole. It was expected that the dipole terms would be the most robust and should be similar for the three models, but this is clearly not the case. It can be noticed that DRGF and Jackson models are in close agreement over the past five decades.

[26] Model predictions of declination and inclination at Madrid have been calculated. The results are displayed in Figure 11, together with the Iberian SV curve. The directional changes expected at Madrid when only dipole terms are included (Figure 11a), when terms up to order 2 (Figure 11b) and 3 (Figure 11c) are used and when all Gauss coefficients are used (Figure 11d) are shown. It can be seen how the results for the dipole directional changes are quite different for both models, the curves obtained with Hongre et al.'s [1998] model being smoother. However, the dipole part predictions of declination and inclination show the same overall shape and features as the archaeomagnetic

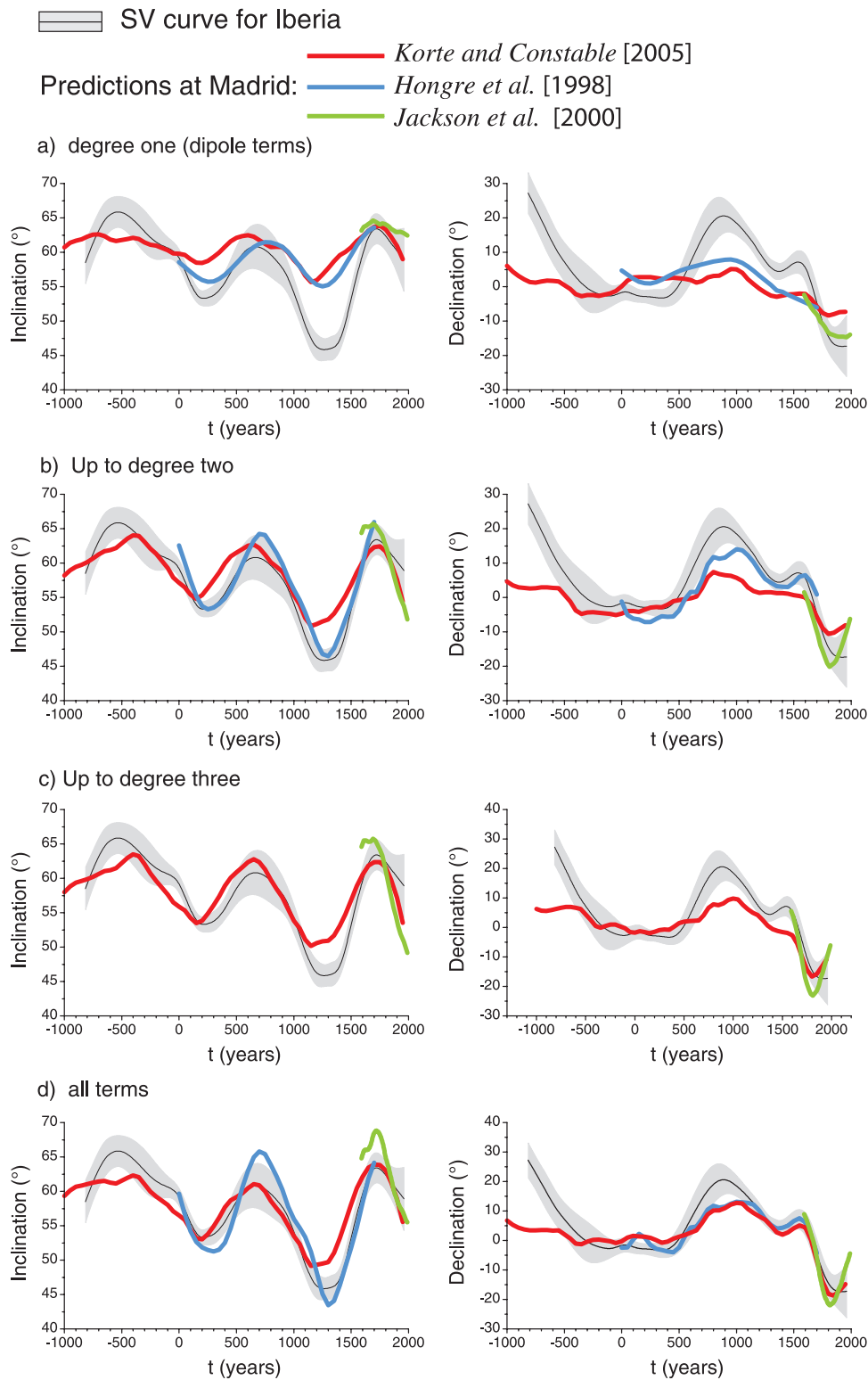


Figure 11. Comparison between the declination and inclination of the SV reference curve obtained for Iberia (in gray) and declination and inclination values predicted by *Korte and Constable* [2005] and *Hongre et al.* [1998] and from *Jackson et al.*'s [2000] models using the Gauss coefficients up to different degrees, calculated at Madrid: (a) degree 1, (b) degree 2, (c) degree 3, and (d) all Gauss coefficients provided by the models. Results from CALS7.K2 are very similar to those from CALSK3.2 and are not plotted.

SV curve for Iberia, although the amplitudes are very different. When non dipole terms are included, the amplitudes of the fluctuations of the predicted SV curves increase considerably and the models fit reasonably well the archaeomagnetic curve, showing the same fluctuations with time. However, there is a discrepancy between some of the amplitudes of these fluctuations (in both declination and inclination). The declination results obtained using the models from *Korte and Constable* [2005] agree very well with the results from *Hongre et al.* [1998], except before 600 A.D. where the declination values are generally more easterly for the CALS3K.2 model. In contrast, for inclination, the amplitudes are clearly more important for the *Hongre et al.* [1998] model when all the coefficients are used. The best fit is obtained with the *Hongre et al.* [1998] model, up to degree 2 (Figure 11b). As can be seen in Figure 11d, *Jackson et al.*'s [2000] results provide higher inclinations between 1590 and 1800 A.D. than *Korte and Constable*'s [2005] and *Hongre et al.*'s [1998] models and the Bayesian curve.

[27] In spite of their differences the *Korte and Constable* [2005] and *Hongre et al.* [1998] models predict the Iberian archaeomagnetic SV reasonably well for the last two millennia. This is not very surprising since the majority of the available archaeomagnetic data used to build these models (especially CALS3K.2 and *Hongre* models) comes from Europe. The good fit between the SV curve and the global model predictions is interpreted as an indicator of the good agreement between the new data and the previous European archaeomagnetic data. To improve knowledge of the evolution of the dipole, more data are clearly needed in order to increase the accuracy of global models. The Iberian data used in this article could be used for future global modeling and will increase their resolution.

7. Conclusions

[28] This study presents the first archaeomagnetic SV reference curve for Iberia. It has been calculated using Bayesian modeling. The age of the reference archaeomagnetic data used ranges from -775 to 1959 A.D. Throughout most of the record several directions per century are available, although there is a need to extend the data, especially before 0 A.D. and between the 6th and 10th centuries (where the majority of the data comes from neighboring countries). However, the first SV for Iberia is now available.

[29] Compared to French and German SV curves the same general patterns are found but significant differences can be observed between the 11th and 14th centuries A.D. and the last few centuries, where lower inclinations are found for the Iberian curve. Analysis of the Iberian, French and German reference curves indicates that SV in western Europe is characterized by three cusps or major directional changes associated with low SV rates (at -125 , 200, and 1350 A.D.). The SV curves and corresponding rates and changes in curvature for Japan and southwest United States have also been calculated using Bayesian modeling. The results suggest that the observed cusps are representing a regional feature of the geomagnetic field. Longer and more detailed records are clearly needed in order to test this idea.

[30] Differences between the available global models [*Korte and Constable*, 2005; *Hongre et al.*, 1998; *Jackson et al.*, 2000] are clearly observed. Even the lowest terms (i.e., the dipole) are quite different for these models. Despite these differences, all models predict reasonably well the Iberian archaeomagnetic SV curve.

[31] The SV curve obtained extends the archaeomagnetic dating technique to Spain and Portugal. This provides a valuable tool for archaeologists working in the region, which has a rich and increasingly studied archaeological past. Finally, the Iberian curve contributes to the increase in the knowledge of the Earth's magnetic field, and the data can be used for future modeling of geomagnetic field behavior.

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