Available online at www.sciencedirect.com
ScienceDirect
EPSL
Earth and Planetary Science Letters xx (2007) xxx–xxx
www.elsevier.com/locate/epsl

Jurassic–Early Cretaceous intermediate virtual geomagnetic poles and Pangaean subduction zones

Haroldo Vizán *, María Andrea Van Zele

Consejo Nacional de Investigaciones Científicas y Técnicas, in Facultad de Ciencias Exactas y Naturales (U.B.A.). Pabellón 2, Ciudad Universitaria, C1428EHA, Buenos Aires, Argentina

Received 18 April 2007; received in revised form 19 September 2007; accepted 29 September 2007

Editor: R.D. van der Hilst

Abstract

The objective of this paper is to show that the distribution of Jurassic–Early Cretaceous intermediate virtual geomagnetic poles (VGPs) seems to be conditioned by Pangaean subducted slabs. Palaeomagnetic data from between ~ 200Ma and 125Ma were compiled from reliable studies and their VGPs repositioned in their Jurassic–Early Cretaceous geographic location considering a "zero-longitude" motion of Africa over the last 200m.y. and the corresponding palaeomagnetic poles from each sequence. Those repositioned VGPs lying between latitudes of ± 60° were considered to be intermediate. To avoid bias as a function of simple sampling numbers for those sequences with more data, each VGP was weighted by Love's methodology. A colour-scale map of density of the weighted intermediate VGPs was obtained and compared with the Pangaean subduction zones. There is a good visual correlation between the distribution of these VGPs and the location of the subduction zones during the Jurassic, suggesting that there is a relationship between the Jurassic–Early Cretaceous geomagnetic reversals and the plate tectonic setting at that time. Minima of intermediate VGPs correlate well with the absence of VGPs predicted with a tomographic model and the intermediate VGP distribution is also well correlated with zones of faster seismic wave propagation in the lower mantle (just above of the core–mantle boundary), which suggests that the Jurassic geomagnetic polarity transitions could have been controlled by a structure of the core–mantle boundary similar to that at the Present time. We suspect that the subducted lithospheric slabs refrigerated the deepest mantle causing more heat than average flowing out from the core and controlling the geometry of the Jurassic–Early Cretaceous polarity transitions. The Earth's lithospheric plate motion history could have played a controlling role in the geometry of the geomagnetic reversals.

Keywords: Pangaea; geomagnetic reversals; subduction; lower mantle

1. Introduction

The Earth's Magnetic Field (EMF) has the property to invert its polarity (the sense of its dipolar field) from time to time. The physical phenomenon that is involved in polarity transitions is not yet well understood and the records are discontinuous and partially obscured by superimposition of multiple magnetizations in rocks and sediments dispersed around the world. However, there are several studies analyzing polarity transitions at different geological times based on primary magnetic directions recorded by rocks and sediments. There are

* Corresponding author. Tel.: +54 11 45763329; fax: +54 11 47883439.
E-mail addresses: haroldo@gl.fcen.uba.ar (H. Vizán), avanzele@gl.fcen.uba.ar (M.A. Van Zele).

0012-821X/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2007.09.044

different methodologies to recover these primary magnetic directions and from them it is possible to calculate the geographic position of their corresponding virtual geomagnetic poles (VGPs). The locus of the VGP is readily calculated knowing the measured direction sampling location and assuming a dipolar field. The unique method that allows a comparison of polarity transitions recorded at different localities of the Earth is to plot the VGPs calculated from directions recorded in different stratigraphic sequences. Based on this methodology, Clement (1991), Laj et al. (1991) and Glen et al. (1994, 1999) analyzed the VGPs of Late Cainozoic polarity transitions and observed that their VGPs were preferentially distributed along longitudinal bands. Laj et al. (1991) recognized two "transitional VGP paths" that coincide with regions of high velocity seismic wave propagation anomalies in the lower mantle (the American and Australia–Asian transitional paths).

The analysis and suggestions proposed by Laj et al. (1991) have been discussed by several authors. For example, Langereis et al. (1992), pointed out that the preferred distribution of transitional VGPs could be an artefact of the recording mechanism in a sedimentary sequence. A compilation of transitional VGPs from 0 to 16Ma lava flows (mainly from Iceland) failed to show any "preferred path" (Prévot and Camps, 1993). In contrast, analysis of volcanic sequences for the last 20m.y. showed similar "VGP transitional paths" (Love, 1998).

A recent model of the EMF (Coe et al., 2000) patterned on tomographic studies of the lower mantle supports the distribution of transitional VGPs on preferred longitudinal bands. According to them regions of high velocity seismic wave propagation anomalies in the lower mantle indicate lower than average temperature regions where more heat than average flows out from the core–mantle boundary (CMB). Simulated geomagnetic reversals with this model yield clusters of transitional VGPs that exhibit a crude correlation with these areas, offering some support for the hypotheses of preferred "transitional paths" (Coe et al., 2000).

On the other hand, these regions of high velocity seismic wave propagation anomalies in the lower mantle coincide geographically with the regions of subduction zones from the Jurassic until now (i.e. Chase and Sprowl, 1983; Richards and Engebretson, 1992; Kývalová et al., 1995; Wen and Anderson, 1995; Burke and Torsvik, 2004; Garnero et al., in review). Burke and Torsvik (2004) have also agued that the seismic wave propagation anomalies in the lower mantle have been relatively stable with respect to the spin axis of the Earth and the core for the last 200m.y.

Vizán and Van Zele (2001) suggested a correlation between Pangaean subduction zones and the preferred geographic distribution of intermediate Early Jurassic VGPs recorded at Breggia gorge. Intriguingly, the VGPs of the reversal recorded in Lesotho Basalts showed a transitional rebound path along the boundary of the Eurasia and Pacific plates (Prévot et al., 2003), which could be related to a subduction zone.

In this paper we show that Jurassic–Early Cretaceous intermediate VGPs (here defined as poles between ± 60° latitude) are related to Pangaean subducted slabs and hence not evenly distributed on the Earth surface.

2. Criteria to select the analyzed palaeomagnetic data

As pointed out by Prévot et al. (2003) with the exception of data from the Lesotho Basalts, there are no other studies of Jurassic–Early Cretaceous volcanic sequences with polarity transitions that can be used to test for preferred geographic distributions of transitional VGPs. There are however, several magnetostratigraphic studies in different Jurassic–Early Cretaceous sections of the world that are well constrained biostratigraphically. A typical magnetostratigraphic study sampling will include a number of stratigraphic levels distributed throughout a sequence and will record normal, reverse and intermediate polarities. Obviously, as the objective of a magnetostratigraphic study is different from one of a polarity transition, the compiled data of these papers must be considered with caution in further analysis. In particular objective reliability criteria were applied to the directions (or their VGPs) compiled from all localities considered to be original records of the Jurassic–Early Cretaceous EMF. Palaeomagnetic poles in tectonic or geodynamic studies are often selected according to the reliability criteria of Van der Voo (1993) and magnetostratigraphic studies intended for global correlation are selected according to the criteria proposed by Opdyke and Channell (1996). In both cases the data need not pass all the criteria to be incorporated rather it is ranked qualitatively; in this case as the purpose of the study is to focus on the spatial distribution of VGPs, criteria of exclusion were imposed on the compiled data in order to ensure only the most reliable data were incorporated. In other words, if the data fail only one criterion they were excluded from further analysis. The criteria adopted are described as follows.

1) Stratigraphic age must be defined at the Stage level according to accurate palaeontological or radiometric

Please cite this article as: Vizán, H., Van Zele, M.A., Jurassic–Early Cretaceous intermediate virtual geomagnetic poles and Pangaean subduction zones, Earth Planet. Sci. Lett. (2007), doi:10.1016/j.epsl.2007.09.044

data. This criterion was required because all the palaeomagnetic data were transferred to the geographic coordinates that they had when they were recorded. This restoration was done to South Africa present geographic coordinates using reconstruction parameters (Table 1) according to the age of the stratigraphic sequences and then to the spin axis of the Earth using the palaeomagnetic pole of each sequence.

2) Samples must have multi-step demagnetization and component analysis using orthogonal diagrams (Zijderveld, 1967) and/or typically principal component analysis (Kirschvink, 1980) to isolate palaeomagnetic directions. In some cases isolation of a primary component is not possible using this methodology because of overlapping coercivity forces or blocking temperatures related to remagnetizations. In such cases, the supposed primary directions can be estimated using the remagnetization circle method (i.e. McFadden and McElhinny, 1988). For this analysis it was considered that this approach was insufficiently robust to resolve an accurate intermediate direction (numbers of samples are typically too small) and hence such studies were not considered further (e.g. Iglesia Llanos and Riccardi, 2000).
3) Suspicious of inclination shallowing of the isolated directions (see Anson and Kodama, 1987). This effect occurs in sedimentary records and yields a spurious lower palaeolatitude of the sampling locality or an erroneous location of palaeopoles. Directions of magnetostratigraphic studies with suspicions of this problem were not considered.
4) Indications that intermediate directions could belong to a process different from that of the stable directions (Channell et al., 1990). In this case, all the directions of the study were excluded.
5) Undetectable geological structures. For example Galbrun et al. (1990) consider the spread of the directions obtained in Toarcian limestones from Iznalloz (Spain) are probably due to unresolved geological structures.
6) "Antipodal polarity test". Theoretically if the demagnetization of the samples was complete and all remagnetizations have been removed and the number of data is sufficient to average palaeosecular variation of the ancient EMF, the mean directions of both (normal and reverse) stable polarities should be antipodes. This is normally tested for using the reversal test for "Fisherian" distributed groups of stable directions (McFadden and McElhinny, 1990). In this analysis the methodology described in Vizán and Van Zele (2001) was used to separate groups of axially symmetrical directions from all directions from each study, considering normal and reverse polarities independently; subsequently mean stable (positive and negative) directions with their statistical parameters were calculated according to Fisher (1953) and the reversal test mentioned above applied. Not one study which passed all of exclusion criteria 1 to 5 got a positive "antipodal polarity test"; including those that with all original directions passed such a test in the original papers (i.e. Juárez et al., 1994; Kosterov and Perrin, 1996). Such a result would tend to suggest that the Jurassic EMF may not have been axially symmetric. To evaluate a reliability criteria for the data considered in this study, the directions recorded by the Lesotho Basalts were considered as reliable records of the Jurassic EMF, igneous rock generally being considered more faithful recorders of the EMF (i.e. Hoffman, 1992).To analyze the stable polarity directions recorded in Lesotho Basalts (Kosterov and Perrin, 1996; Prévot et al., 2003) groups with normal and reverse polarity were determined and the angle between their mean directions was calculated (inverting one direction to the polarity of the other). The value of this angle (12.5°) was considered as the maximum acceptable limit and

Table 1
Reconstruction parameters used in this paper

Age (Ma)	Lat. (°)	Long. (°)	Angle (°)	Reference
Europe vs. North America				
200–125	79.5	151.9	− 25.6	1
North America vs. Northwest Africa				
119.7	66.09	− 20.17	56.63	2
125.8	65.97	− 19.43	56.63	2
133.1	66.14	− 18.72	58.03	2
139.2	66.24	− 18.33	59.71	2
148.5	66.24	− 18.33	62.14	2
154.2	66.7	− 15.85	64.9	2
175–200	66.95	− 12.02	75.55	3
Northwest Africa vs. South Africa				
200–125	16.5	6.7	− 1.15	4
South America Craton vs. South Africa				
131.7	50	− 32.5	55.08	4
Paraná vs. South Africa				
131.7	47.5	326.7	56	4

References: 1 = Srivastava and Tapscott (1986); 2 = Roest et al. (1992); 3 = Klitgord and Schouten (1986); 4 = Nürnberg and Müller (1991). Q1 applied to the other studies such that if the difference between polarity group directions exceeded this angle all the data were rejected from further analysis. One example that was rejected using this criterion was the well known magnetostratigraphic study in Umbria (Lowrie and Channell, 1983).

3. Characteristics of the selected palaeomagnetic data

Palaeomagnetic poles (PPs) were calculated for each selected group of directions. Each PP was obtained with the averaged direction of both stable mean directions of each group, avoiding that one polarity with more data than the other biased the calculation. The interval of confidence of the averaged direction representative of every sequence was not considered because it was obtained averaging only two directions then the corresponding PPs did not have, also, intervals of confidence. We have tested the calculated PPs with others with similar or close ages that are listed by Torsvik et al. (2007) with some small modifications that are indicated in the text. The comparison was done considering the PPs selected by Torsvik et al. (2007) with their intervals of confidence (A_{95}). The overlapping of the calculated PPs by the A_{95} of the selected poles implies that they are indistinguishable at 95% of confidence. Similarities in the geographic locations between the calculated and selected PPs would indicate that the structural corrections performed to the directions compiled from magnetostratigraphic studies were probably good enough for the purpose of our analysis.

The main characteristics of the selected data are described in chronological order as follows (see also Table 2):

1) Hettangian and Sinemurian data from Paris Basin (Yang et al., 1996). These directions were obtained from drill cores in Montcornet (NW of Paris Basin) where the stratigraphic sequence spans the period c. 205Ma and 195Ma (according to the time scale of Gradstein et al., 1994). The directions considered as characteristic remanent magnetizations (ChRMs) were compiled from the published figures of Yang et al. (1996) and corrected by rotating the mean direction of the low blocking temperature component (< 300°C) to the present dipolar field direction. The calculated PP is in agreement with that of the 208Ma PP of Rhaetian Sediments (see Fig. 1a).
2) Pliensbachian–Aalenian data from Breggia gorge (Horner and Heller, 1983). These data belong to a stratigraphic sequence that is located in the Alps of Ticino (Switzerland) and spans the period c. 196Ma and 176Ma. The palaeomagnetic data of this sequence were previously used in the EMF analysis for the Early Jurassic (Vizán and Van Zele, 2001). The calculated PP agrees with the PP of Scania Basalts dated at 179Ma and with the PP of Alsace Bajocian Sediments with an age of 178Ma (Fig. 1a).
3) Toarcian data from Thouars and Airvault (Galbrun et al., 1988) from the type strata at Deux-Sèvres (France) that spans the period c. 188Ma and 180Ma. Rock magnetic analysis indicates that magnetite is the main magnetic carrier in the limestones from

Table 2
Characteristics of analyzed data

Sampling locality	Stratigraphic age[a]	Age[a] (Ma)	N°	*N*	*R*	Ang. (°)	Plat. (°N)	Plong. (°E)	Int. VGPs
Paris Basin, France	Sinemurian–Hettangian	205–195	453	270	169	4.9	54.2	104.6	59
Breggia gorge, Switzerland	Pliensbachian–Aalenian	196–176	445	118	174	10.8	69	123.6	142
Thouars and Airvault, France	Toarcian	188–180	97	32	33	9.3	76.7	121.3	15
Lesotho Basalts, South Africa	Toarcian	183±1 Ma	84	25	38	12.5	69.4	278.8	17
Aguilón and Tosos, Spain	Middle to Late Oxfordian	158–154	249	120	74	6.8	51.7	252.6	44
Brodno, Slovakia[b]	Tithonian–Berriasian	148–142	217	99	34	9.1	63.4	178.8	70
Arcevia, Italy[b]	Berriasian	144–137	130	43	69	9.4	44.5	259.3	17
Djebel Oust, Tunisia[b]	Kimeridgian–Early Valanginian	154–136	144	48	64	9.6	46.7	259.3	33
Kuqa Depression, NW China	Early Berriasian–Late Barremian	144–124	64	26	6	3.8	62.9	237.5	20

N°: number of directions compiled from each study. *N*: number of normal directions. *R*: number of reverse directions. Ang.: angle between stable normal and reverse mean directions (see text for explanation). Plat.: latitude of the palaeomagnetic pole (PP). Plong.: longitude of the PP. Int. VGPs: number of intermediate VGPs arbitrary defined between ±60° latitude.

[a] Conversion of stratigraphic age to chronological age according to Gradstein et al. (1994).

[b] The PPs are shown with the corresponding rotations about vertical axis in their sampling sites (see text for further explanations).

Please cite this article as: Vizán, H., Van Zele, M.A., Jurassic–Early Cretaceous intermediate virtual geomagnetic poles and Pangaean subduction zones, Earth Planet. Sci. Lett. (2007), doi:10.1016/j.epsl.2007.09.044

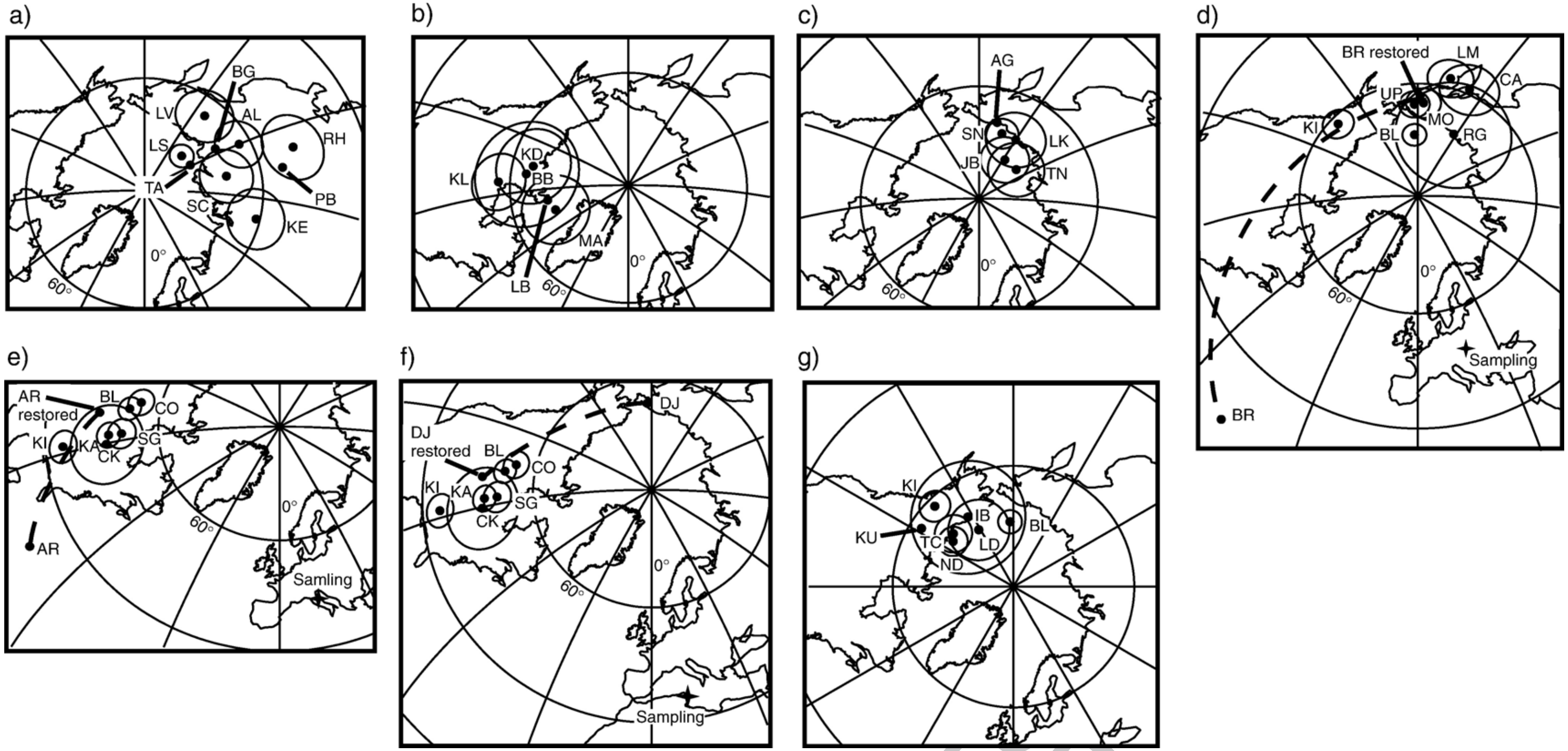

Fig. 1. Comparison between the palaeomagnetic poles (PPs) of the analyzed sequences and other reliable PPs of similar ages. a) PB (Paris Basin PP, 205–195Ma), RH (Rhaetian sediments PP, 208Ma), BG (Breggia gorge PP, 196–176Ma), SC (Scania Basalts PP, 179Ma), AL (Alsace Bajocian Sediments PP, 178Ma), TA (Thouars–Airvault PP, 188–180Ma), LS (Liassic Sediments PP 192Ma), KE (Kerforne dykes PP, 198Ma) and LV (Liassic Volcanics PP, 198Ma). The poles are referred to Europe geographic coordinates. b) LB (Lesotho Basalts PP, 183Ma), MA (Marandgudzi Hill Complex PP, 186Ma), BB (Batoka Basalts PP, 180Ma), KD (Karroo Dolerites PP, 180Ma), KL (Karroo Lavas PP, 180Ma). The poles are referred to South Africa geographic coordinates. c) AG (Aguilón and Tosos PP, 158–154Ma), SN (Subtatric Nappe PP, 159Ma), LK (Limestones, Krakow–Czestochowa Upland PP, 159Ma), TN (Terres Noires PP, 158Ma) and JB (Jura Blue Limestone, 156.5Ma). The poles are referred to Europe geographic coordinates. d) BR (Brodno PP, 148–142Ma), MO (Morrison Fm., Bushy Basin Mb. PP, 148Ma), UP (Upper Morrison Fm. PP, 147Ma), RG (Dykes Río Grande do Norte PP, 146Ma), KI (Kimberlite Dikes Ithaca PP, 143Ma), LM (Lower Morrison Fm. PP, 149Ma), CA (Canelo Hills Volcanics PP, 151Ma) and BL (Berriasian Limestones PP, 140Ma). The poles are referred to Europe geographic coordinates. e) AR (Arcevia PP, 144–137Ma), CK (Cretaceous Kimberlites PP, 129Ma), BL (Berriasian Limestones PP, 140Ma), KI (Kimberlite Dikes Ithaca PP, 143Ma), KA (Kaoko Lavas PP, 132Ma), SG (Serra Geral Basalts PP, 130Ma) and CO (Sierra Chica de Córdoba PP, 130Ma). The poles are referred to northwest Africa geographic coordinates. f) DJB (Djebel Oust PP, 154–136Ma) and the same PPs of Fig.1e in northwest Africa geographic coordinates. g) KQ (Kuqa Basin PP, 144–124Ma), IB (Intrusives of Beni Mellal PP 120Ma), KI (Kimberlite Dikes Ithaca PP, 143Ma), ND (Notre Dame PP, 128Ma), TC (Tatnic Complex PP, 122Ma), LD (Lebanon Dykes PP, 125Ma), BE (Berriasin Limestones PP, 140Ma). The poles are referred to Europe–Asia geographic coordinates. See text for further information.

Please cite this article as: Vizán, H., Van Zele, M.A., Jurassic–Early Cretaceous intermediate virtual geomagnetic poles and Pangaean subduction zones, Earth Planet. Sci. Lett. (2007), doi:10.1016/j.epsl.2007.09.044

Thouars and Airvault (Galbrun et al., 1988) and the ChRM is probably of detritical origin. The PP agrees with a PP of 192Ma from Liassic Sediments and is close to the PP of Scania Basalts with an age of 179Ma (Fig. 1a).

4) The Lesotho Basalts. Data from Prévot et al. (2003) sampled at Maserau (Bushmen's Pass) and Kosterov and Perrin (1996) were combined. There are several radiometric data for Lesotho Basalts; one of the most recently published is the mean age $^{39}Ar/^{40}Ar$ of 183 ± 1Ma (Duncan et al., 1997). The data from both palaeomagnetic studies belong to records in lava flows, such that each direction is regarded as an individual, independent measure of the EMF. In contrast the palaeomagnetic record in sediments could be open over a period of time such that the ChRM incorporate some palaeosecular variation. For that reason, in this paper, data that belong to cooling units (that involve discrete palaeomagnetic directions generally recorded in more than one lava flow, see Prévot et al., 2003) are considered together with data that belong to sedimentary rocks. The calculated PP is in agreement with that from Marandgudzi Hill Complex of 186Ma, the Batoka Basalts PP of 180Ma and the Karroo Dolerites PP of 180Ma (Fig. 1b).

5) Middle to Late Oxfordian data from Aguilón and Tosos in the Iberian Range (Spain) (Juárez et al., 1994). This stratigraphic sequence spans the period of c. 158Ma and 154Ma. There is another older magnetostratigraphic study of the same sequence (Steiner et al., 1985), which identified several magnetic chrons however this study is superseded by that of Juárez et al. (1994) as the demagnetization is more detailed and removed a possible Cretaceous age overprint and the primary Jurassic ChRM magnetization was better determined. After "closing" the Gulf of Biscay using the Euler pole of Rosenbaum et al. (2002) for 154Ma, the PP of Aguilón and Tosos (Fig. 1c) agrees with the Subtratic Nappe Sediments PP of 159Ma and the PP of the Limestones of Krakow–Czestochowa Upland of 159Ma.

6) Tithonian–Berriasian data from Brodno locality (Houša et al., 1999). This study offers magnetostratigraphic and micropalaeontological results from limestones of a sequence that crops out in the west of Slovakia and spans the period of c. 148Ma and 142Ma. In a previous paper, Houša et al. (1996) pointed out that the sampling locality was tectonically rotated more than 100° in a counter-clockwise sense about a vertical axis. The calculated PP is located at Lat. = 11.7° N, Long. = 311.5° E and was compared with other PPs with similar ages. There is only one reliable PP for Europe for the Tithonian–Berriasian time span (the Berriasian Limestones PP of 140Ma). For that reason five PPs from North America and one from South America craton were transferred to European coordinates. 4 PPs of North America belong to the Colorado plateau and were previously corrected for a counter-clockwise rotation of 5.4° (see Van der Voo, 1993). The 5 PPs from North America were transferred to European coordinates according to Srivastava and Tapscott (1986). The PP from South America craton belong to dykes of Rio Grande do Norte (NE Brazil) of 146Ma and was transferred first to northwest African coordinates according to Nürnberg and Müller (1991), then to North American coordinates using the Euler pole for 148.5Ma of Roest et al. (1992) and finally to European coordinates according to Srivastava and Tapscott (1986). The PP calculated with the data from Brodno does not agree with any of the others (Fig. 1d). The misfit is due to an anomaly in the magnetic declination of Brodno data. The mean of the 7 PPs compared with Brodno pole was considered as a reference pole and using Beck's method (Beck 1989), a counter-clockwise rotation of 109.3° about a vertical axis in the sampling locality (Table 3) was calculated. After applying a

Table 3
Tectonic motions calculated for Brodno, Arcevia and Djebel Oust stratigraphic sequences

Stratigraphic sequence	Pole Lat. (°N)	Pole Long. (°E)	Reference pole Lat. (°N)	Reference pole Long. (°N)	Reference pole A_{95} (°)	Apparent rotation ($R \pm \Delta R$)	Apparent poleward displacement ($P \pm \Delta P$)
Brodno	11.7	311.5	66.7	176.75	9	109.3±7.3	−3.3±6.5
Arcevia	18.2	287.9	48.7	263.9	7	37±5.4	−4.9±5
Djebel Oust	67.1	182.6	48.7	263.9	7	44.5±5.3	−3.8±5

Reference pole for Brodno PP: mean of 7 poles: Morrison Fm., Bushy Basin Mb. PP (148 Ma), Upper Morrison Fm. PP (147 Ma), Dykes Río Grande do Norte PP (146 Ma), Kimberlite Dikes Ithaca PP (143 Ma), Lower Morrison Fm. PP (149 Ma), Canelo Hills Volcanics PP, (151 Ma) and Berriasian Limestones PP (140 Ma).

Reference pole for Arcevia y Djebel Oust PPs: mean of 6 poles: Cretaceous Kimberlites PP (129 Ma), Berriasian Limestones PP (140 Ma), Kimberlite Dikes Ithaca PP (143 Ma), Kaoko Lavas PP (132 Ma), Serra Geral Basalts PP (130 Ma) and Sierra Chica de Córdoba PP (130 Ma).

Please cite this article as: Vizán, H., Van Zele, M.A., Jurassic–Early Cretaceous intermediate virtual geomagnetic poles and Pangaean subduction zones, Earth Planet. Sci. Lett. (2007), doi:10.1016/j.epsl.2007.09.044

clockwise rotation of 109.3° through a vertical axis in the sampling area, the PP is located at Lat. = 63.4° N, Long. = 178.8° E, together with the other PPs.

7) Berriasian data from Arcevia (Speranza et al., 2005). This section spans the period of c. 144Ma and c. 137Ma and is cut by faults that probably produce tectonic duplications that were recognized by Speranza et al. (2005). Following this study, data that could be duplicated were not considered in the present analysis. According to them the ChRMs from the whole section pass the reversal test if only the thermally cleaned samples are taken into account. This test is negative when the ChRMs from Alternating Field cleaning are used; therefore only thermally cleaned directions were considered. After discarding the directions probably repeated by tectonic duplications, a total number of 130 data were analyzed and the PP calculated with the average of the mean directions is located at 18.2° N and 287.9° E (Fig. 1e). Considering that the Apennines form part of the Africa plate (i.e. Muttoni et al., 2001), the Arcevia PP was compared with other PPs in northwest African coordinates. There is not any PP from northwest Africa continental block with an age for the period that covers the section of Arcevia. For that reason 6 PPs were transferred to northwest Africa from different continental blocks. Two PPs were transferred from South Africa block according to Nürnberg and Müller (1991). The PP of Sierra Chica de Córdoba that supersedes three previous published PPs (Geuna and Vizan, 1998) dated at 130Ma (Cejudo Ruiz et al., 2006), and the PP of Serra Geral dated at 130Ma (i.e. Ernesto et al., 1999), were transferred from Parana–Salado block to northwest African coordinates according to Nürnberg and Müller (1991). The PP of Ithaka Kimberlites dated at 143Ma was transferred from North America using the Euler pole for 139.5Ma of Roest et al. (1992) and the PP of Berriasian Limestones (140Ma) from Europe was rotated first to North America coordinates (Srivastava and Tapscott 1986) and then to northwest African coordinates (Roest et al., 1992). The PP calculated with the data from Arcevia is not in agreement with the others. The misfit is due to an anomaly in the magnetic declination of the Arcevia data. A mean PP calculated with the 6 PPs that were used in the comparison, was used as a reference pole and with Beck's method (Beck 1989), a counter-clockwise rotation of 37° about a vertical axis in the sampling locality was calculated (Table 3). Fig. 1e shows the selected PPs and the PP of Arcevia before and after rotation. The anomaly is interpreted as a counter-clockwise tectonic rotation of the sampling area as has commonly occurred with other blocks of the Apennines (i.e. Channell, 1992). Other localities sampled by Speranza et al. (2005) were not considered because their ChRMs are biased by overprint components that were not removed during demagnetization processes.

8) Kimeridgian–Early Valanginian data from northern Tunisia (Nairn et al., 1981). The analyzed data belong to the stratigraphic sequence that crops out in the Djebel Oust route and spans the period of c. 154Ma and 136Ma. Nairn et al. (1981) pointed out that they could not isolate a primary direction without any overprint from the other Cretaceous sequence that they also analyzed. The calculated PP (Lat. = 67.1° N, Long. = 182.6° E) does not fit with other PPs of similar age in northwest African coordinates. Recently, Torsvik and Van der Voo (2002) have also observed the same discrepancy with the PP obtained by Nairn et al. (1981). The data from the Kimmeridgian–Early Valanginian have a declination anomaly; applying Beck's method and using the mean PP calculated previously to compare Arcevia PP, a rotation of 44.5° about a vertical axis at the sampling locality is therefore necessary (Fig. 1f). A clockwise tectonic rotation of the sampling site post Early Valanginian is consistent with the Late Aptian–Early Albian deformation suggested by Bouaziz et al. (2002) for Tunisia.

9) Early Berriasian–Late Barremian data from Kuqa Depression (Peng et al., 2006). The analyzed data are from the Qigu, Yageliemu, Shushanhe and Baxigai formations and belong to a time span between c. 144Ma and c. 124Ma. The directions were obtained in red beds, whose use in magnetostratigraphy and studies of the ancient EMF has been widely debated. The debate centres on timing of remanence acquisition (Larson and Walker, 1985). Four lines of evidence suggest that the ChRM of the stratigraphic sequence from Kuqa Depression provides a reliable record of the ancient EMF. According to Peng et al. (2006) the isolated ChRMs have a positive fold test and a positive reversal test. Besides, the magnetic age proposed for the sequence is consistent with its palaeontological age estimated from fossil assemblages and the sedimentation rate computed from magnetostratigraphic results is consistent with that computed from grain size data. The calculated PP is located at Lat. = 62.9° N and Long. = 237.5° E (Fig. 1g) overlapped by the interval of confidence of the 120Ma Intrusives of Beni Mellal PP from northwest Africa. It is also close to the 143Ma Ithaka Kimberlites PP, the 128Ma Notre Dame Bay

dikes PP and the 122Ma Tatnic Complex PP, after transferring them to European coordinates with the reconstruction parameters of Roest et al. (1992) and Srivastava and Tapscott (1986).

4. Palaeoreconstruction of the selected data

To analyze the VGPs, “absolute” (latitudinal and longitudinal) reconstructions were applied to the sampling localities. Data could have been reconstructed using hotpot models (i.e. Morgan 1983; Müller et al., 1993; O’Neill et al. 2005; Wen 2006), however they are not very reliable before 100Ma and fixed hotspot models back to 200Ma should not be used (Torsvik et al., in review). For that reason, the VGPs and the sampling localities were repositioned in their Jurassic–Early Cretaceous geographic locations considering a “zero-longitude” motion of Africa over the last 200m.y.

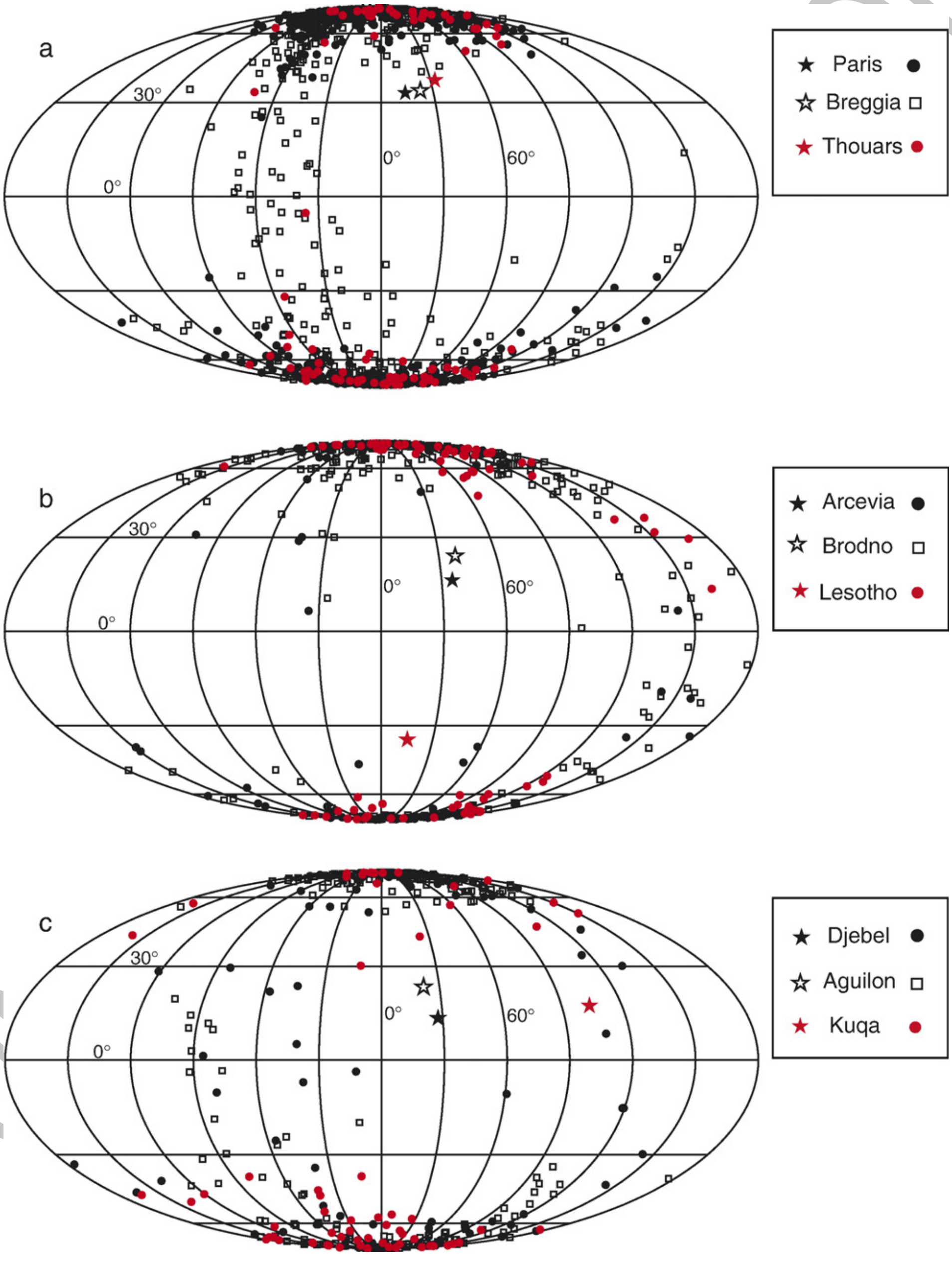

Fig. 2. VGPs of the 9 selected sequences and their sampling sites reconstructed for the geological time of their magnetic records. The geographic locations of the sampling sites are indicated with stars; the VGPs are represented with circles or squares.

Please cite this article as: Vizán, H., Van Zele, M.A., Jurassic–Early Cretaceous intermediate virtual geomagnetic poles and Pangaean subduction zones, Earth Planet. Sci. Lett. (2007), doi:10.1016/j.epsl.2007.09.044

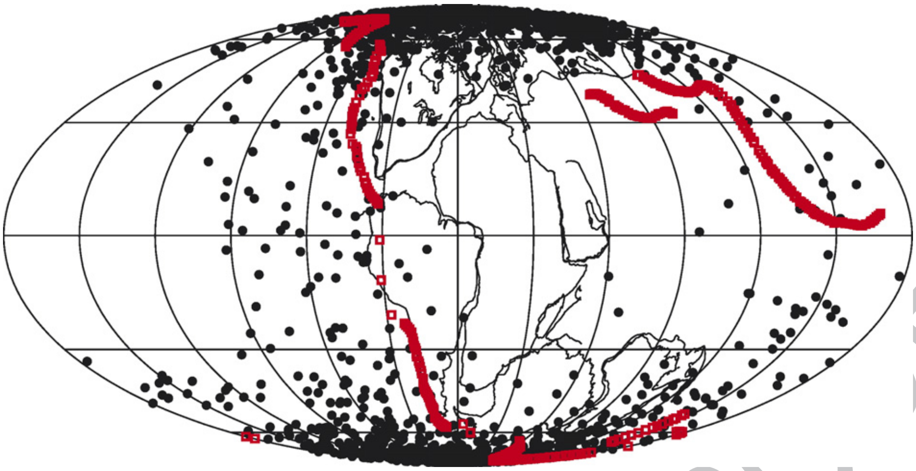

Fig. 3. Absolute reconstruction of a model of Pangaea for 180Ma, subduction zones of this supercontinent and all the VGPs of the 9 selected sequences. See text for further explanation.

(Burke and Torsvik 2004; Torsvik et al., in review). First, the plates and the poles of the selected sequences were rotated according to their ages to South African coordinates using the reconstruction parameters listed in Table 1 and then palaeomagnetically reconstructed (the plates were rotated about equatorial Euler poles to lead the PPs into coincidence with the Earth spin axis). In the cases that the sequences belonged to localities with tectonic rotations about vertical axis, the corresponding rotations were performed before the "absolute" reconstruction approaches.

Fig. 2 shows the geographic location of the sampling sites and the VGPs during Jurassic–Early Cretaceous time. Note that Kuqa Basin is located out of the longitudinal band between 0° and 30° as the other reconstructed sampling sites.

Fig. 3 shows the Jurassic–Early Cretaceous VGPs plotted on a model of Pangaea for 180Ma together with

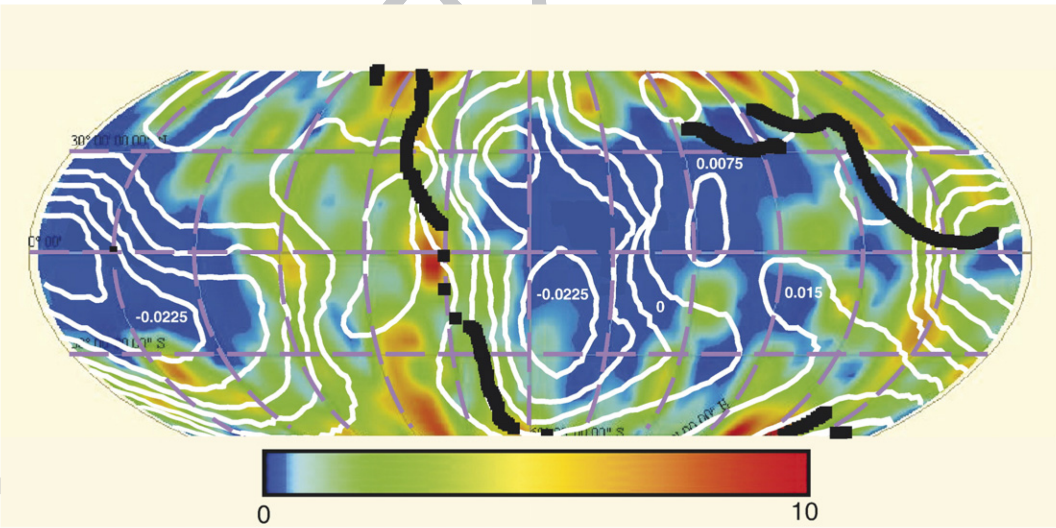

Fig. 4. VGP density map, 180–150Ma subduction zones and shear-velocity model of the lower mantle. The intermediate VGPs were previously weighted using Love's (1998) method (each VGP of every sequence was weighted by (cos λ) / N_I where λ is the latitude of every VGP and N_I is the number of the intermediate VGPs recorded in every sequence). The colour bar indicates the different density areas of these data. These results are compared with the 180–150Ma subduction zones of Pangaea (black squares) and a shear-velocity model of the lower mantle (white contours) from Masters et al. (1996) in the present day geographic coordinates (see Burke and Torsvik, 2004). The projection centre of this map is at the palaeoequator and the 0° meridian. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Please cite this article as: Vizán, H., Van Zele, M.A., Jurassic–Early Cretaceous intermediate virtual geomagnetic poles and Pangaean subduction zones, Earth Planet. Sci. Lett. (2007), doi:10.1016/j.epsl.2007.09.044

the known subduction zones for 180–150Ma (Richards and Engebretson 1992) first reconstructed to South Africa coordinates and then palaeomagnetically using a mean pole calculated with the PPs of Lesotho Basalts, Breggia Gorge and Thouars–Airvault in South Africa coordinates (N = 3, Lat. = 66.8° N, Long. = 265.6° E, A_{95} = 9.2°, K = 181.12).

5. Analysis of the selected data

In Figs. 2 and 3 VGPs from all the localities are plotted using standard palaeomagnetic conventions (Prévot and Camps 1993; Laj et al., 1991). Independently of the sampling site locations, there are zones of the Earth where the VGPs are very scarce. To further analyze this tendency intermediate VGPs, defined as lying between ± 60° of latitude (Love 1998) were selected. Differences in the absolute numbers of available intermediate VGPs from each record could introduce a sampling bias, hence we adopted Love's (1998) methodology such that each VGP was weighted by $(\cos \lambda) / N_I$ where λ is the latitude of the VGP and N_I is the number of intermediate VGPs recorded in each record. The available numbers of intermediate VGPs for each sequence is noted in Table 2.

Fig. 4 shows in Mollweide projection a colour-density map of the results together with the 180–150Ma subduction zones of Pangaea (black squares) and the shear-velocity model of the lower mantle (white contours) of Masters et al. (1996) at present geographic coordinates (see Burke and Torsvik, 2004). The projection centre of this map is at the palaeoequator and the 0° meridian. The histograms in Fig. 5 show quantitatively the longitudinal distribution of the selected intermediate VGPs without any weighting.

Fig. 4 shows that the highest density of intermediate VGPs occurs between ~ 300° E and 330° E longitude with a lesser concentration between ~ 120° E and 150° E longitude. A histogram of the (unweighted) longitudes of the VGPs (Figs. 5a) confirms these tendencies. In order to eliminate any bias from the Breggia gorge, both because of its high number of available data and its previous analysis (Vizán and Van Zele, 2001), these data were eliminated from the dataset in Fig. 5b, but a histogram of the VGP longitudes of the remaining data still yields peaks and deep minimums at the same longitudinal bands.

6. Discussion and conclusions

The data analyzed here do not belong to any particular polarity transition with the exception of that

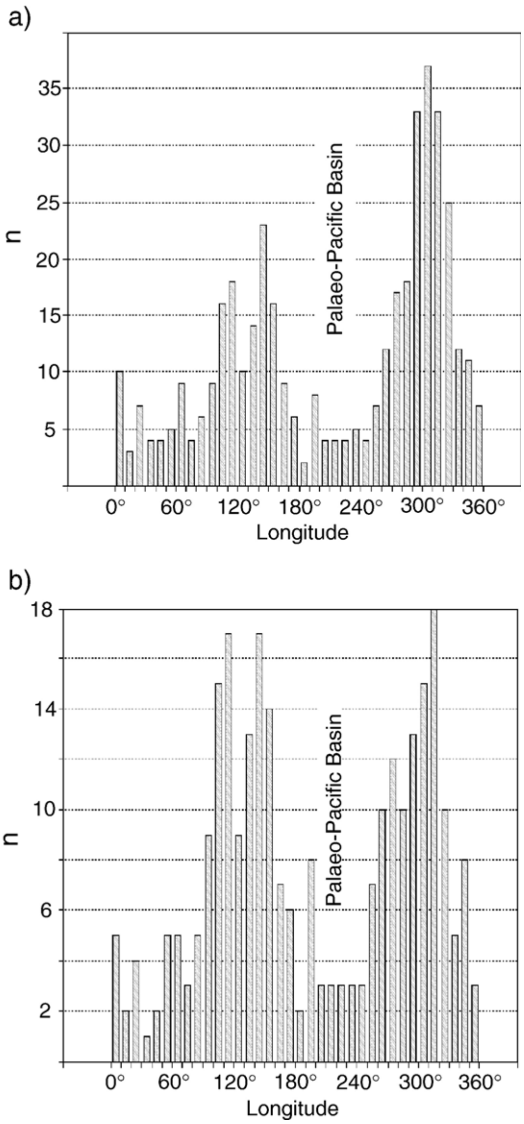

Fig. 5. Histograms showing quantitatively the concentration of the selected intermediate VGPs (without any weighting of them). a) All VGPs of the selected sequences. b) Without the data of Breggia gorge that could bias the whole database.

recorded in Lesotho Basalts. However, it is possible to make some suggestions according to the intermediate VGP distributions. Intermediate VGPs from different sampling sites have different distributions (compare data from Kuqa Depression or Lesotho Basalts with "European" data) in agreement with non-dipolar EMF models suggested for geomagnetic reversals (i.e. Gubbins, 1994). However, the minimum of intermediate VGPs between 180° and 240° E longitudes (Fig. 5) correlates fairly well with the conspicuous absence of VGPs in the Pacific Basin predicted with the

Please cite this article as: Vizán, H., Van Zele, M.A., Jurassic–Early Cretaceous intermediate virtual geomagnetic poles and Pangaean subduction zones, Earth Planet. Sci. Lett. (2007), doi:10.1016/j.epsl.2007.09.044

tomographic model of Coe et al. (2000). The lowest density areas of weighted intermediate VGPs are mainly located in present zones of low velocity anomalies of seismic wave propagation in the lower mantle (Fig. 4).

According to Coe et al. (2000) the regions of high velocity seismic wave propagation anomalies on the lower mantle indicates lower than average temperature regions where more heat than average flows out from the CMB. The correlation between these zones and the Jurassic–Early Cretaceous intermediate VGPs suggests a control of the CMB on the distribution of intermediate VGPs during this geological time span.

The 180–150Ma subduction zones are located roughly close to high density areas of the intermediate Jurassic–Early Cretaceous VGPs and the zones of high velocity seismic wave propagation anomalies. Indeed, the Jurassic subduction zone of the western border of Pangaea is clearly located to the west of one of these zones (Fig. 4). One hypothetical explanation for this location could be related with the fate of the subducted slabs in the lower mantle. For example, folding and westward spreading of the Farallon slab just above the CMB, offer viable explanation for seismic detections of this slab (Hutko et al., 2006). Then the spreading to the west in the lower mantle of the subducted material from the western border of Pangaea could also be the reason of the lower temperature (or higher seismic wave propagation) zone where there is a high density area of intermediate VGPs. We suspect that the Jurassic (or Triassic) subducted material spread over the lower mantle, refreshing the areas where more heat than average flows out from the CMB and controlled the distribution of intermediate VGPs. The subduction of the lithospheric slabs could be the reason of the preferred distributions of transitional or intermediate VGPs recognized by different authors at different geological times (i.e. Laj et al., 1991; Hoffman, 1992; Vizán and Van Zele, 2001). The intermediate VGP preponderance over the longitudes of America could be due to the historical continuity of the mainly north–south trend of the subducted zone in the western margin of this continent. We hypothesize that, in the end, the Earth's lithospheric plate motion history could have played a controlling role in the geometry of the geomagnetic reversals.

Acknowledgements

Analysis and diagrams were created with GMAP (Torsvik and Smethurst, 1999) and MAG88 (Oviedo, 1989). We thank Miriam Gabriela Nieto who digitalized most of the data used in this paper. We also thank Drs. V.A. Ramos, A.E. Rapalini, R. Somoza (Universidad de Buenos Aires) and G. Taylor (Plymouth University) for comments and suggestions. This work was supported by a grant of CONICET (Consejo Nacional de Investigaciones Científicas y Técnicas, Argentina): "PEI 6071/01". We are sincerely grateful to the reviewer, Trond H. Torsvik, for his useful recommendations.

References

Anson, G.L., Kodama, K.P., 1987. Compaction-induced inclination swallowing of post-depositional remanent magnetization in a synthetic sediment. Geophys. J. R. Astron. Soc. 88, 673–692.

Beck, M.E., 1989. Paleomagnetism of continental North America: implications for displacements of crustal blocks within the western cordillera, Baja California to British Columbia. In: Pakiser, L.C., Mooney, W.D. (Eds.), In Geophysical Framework of the Continental United States. Geol. Soc. Am., pp. 471–492. Memoir No. 72.

Bouaziz, S., Barrier, E., Soussi, M., Turki, M.M., Zouari, H., 2002. Tectonic evolution of northern African margin in Tunisia from paleostress data and sedimentary record. Tectonophysics 357, 227–253.

Burke, K., Torsvik, T.H., 2004. Derivation of large igneous provinces of the past 200 million years from long-term heterogeneities in deep mantle. Earth Planet. Sci. Lett. 227, 531–538.

Cejudo Ruiz, R., Goguitchaichvili, A., Geuna, S.A., Alva-Valdivia, L., Q2
Solé, J., Morales, J., 2006. Early Cretaceous absolute geomagnetic paleointensities from Córdoba province (Argentina). Special Issue: "Paleomagnetism and Tectonics in Latin America". Earth Planets Space, vol. 58(10), pp. 1333–1339.

Channell, J.E.T., 1992. Paleomagnetic data from Umbria (Italy): implications for the rotation of Adria and Mesozoic apparent polar wander paths. Tectonophysics 216, 365–378.

Channell, J.E.T., Massari, F., Benetti, A., Pezzoni, N., 1990. Magnetostratigraphy and biostratigraphy of Callovian–Oxfordian limestones from Trento Plateau (Monti Lessini, northern Italy). Palaeogeogr. Palaeoclimatol. Palaeoecol. 79, 289–303.

Chase, C.G., Sprowl, D.R., 1983. The modern geoid and ancient plate boundaries. Earth Planet. Sci. Lett. 62, 314–320.

Clement, B.M., 1991. Geographical distribution of transitional VGPs: evidence for non-zonal equatorial symmetry during the Matuyama–Brunhes geomagnetic reversal. Earth Planet. Sci. Lett. 104, 48–58.

Coe, R.S., Hongre, L., Glatzmaier, G.A., 2000. An examination of simulated geomagnetic reversals from a palaeomagnetic perspective. Phil. Trans. R. Soc. Lond. A 358, 1141–1170.

Duncan, R.A., Hooper, P.R., Rehacek, J., Marsh, J.S., Duncan, A.R., 1997. The timing and duration of the Karoo igneous event, southern Gondwana. J. Geophys. Res. 102, 18127–18138.

Ernesto, M., Raposo, M.I.B., Marques, L.S., Renne, P.R., Diogo, L.A., de Min, A., 1999. Paleomagnetism geochemistry and $^{40}Ar/^{39}Ar$ dating of the North-eastern Paraná Magmatic Province: tectonic implications. J. Geodyn. 28, 321–340.

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

Galbrun, B., Gabilly, J., Rasplus, L., 1988. Magnetostratigraphy of the Toarcian stratotype at Thouars and Airvault (Deux-Sèvres, France). Earth Planet. Sci. Lett. 87, 453–462.

Galbrun, B., Baudin, F., Fourcade, E., Rivas, P., 1990. Magnetostratigraphy of the Toarcian Ammonitico Rosso Limestones at Iznalloz, Spain. Geophys. Res. Lett. 17 (12), 2441–2444.

Please cite this article as: Vizán, H., Van Zele, M.A., Jurassic–Early Cretaceous intermediate virtual geomagnetic poles and Pangaean subduction zones, Earth Planet. Sci. Lett. (2007), doi:10.1016/j.epsl.2007.09.044

Garnero, E.J., Lay, T., McNamara, A., in review. Implications of lower mantle structural heterogeneity for existence and nature of whole mantle plumes. In: The Origin of Melting Anomalies: Plates, Plumes and Planetary Processes, Foulger, G.R. and D.M. Jurdy (eds.).

Geuna, S.E., Vizán, H., 1998. New Early Createaceous palaeomagnetic pole from Córdoba Province (Argentina): revision of previous studies and implications for the South American database. Geophy. J. Int. 135, 1085–1100.

Q4 Glen, J.M.G., Coe, R.S., Liddicoat, J.C., 1994. Persistent features of polarity transition records from western North America, 21, No.12, 1165–1168.

Glen, J.M.G., Coe, R.S., Liddicoat, J.C., 1999. A detailed record of paleomagnetic field change from Searles Lake, California 2. The Gauss/Matuyama polarity reversal. J. Geophy. Res. 104 (B6), 12,883–12,894.

Gradstein, F.M., Agterberg, F.P., Ogg, J.G., Hardenbol, J., van Veen, P., Thierry, J., Huang, Z., 1994. A Mesozoic time scale. J. Geophys. Res. 99, 24051–24074.

Gubbins, D., 1994. Geomagnetic polarity reversals: a connection with secular variation and core–mantle interaction? Rev. Geophys. 32 (1), 61–83.

Hoffman, K.A., 1992. Dipolar reversal states of the geomagnetic field and core–mantle dynamics. Nature 359, 789–794.

Horner, F., Heller, F., 1983. Lower Jurassic magnetostratigraphy at the Breggia Gorge (Ticino, Switzerland) and Alpe Turati (Como, Italy). Geophys. J. Int. 73, 705–718.

Houša, V., Krs, M., Krsová, M., Man, O., Pruner, P., 1996. Magnetostratigraphy of Jurassic–Cretaceous limestones in the Western Carpathians. In: Tarling, D.H., Morris, A. (Eds.), Palaeomagnetism and Tectonics of the Mediterranean Region. Geol. Soc. Spec. Pub., vol. 105, pp. 185–194.

Houša, V., Krs, M., Krsová, M., Man, O., Pruner, P., Venhodová, D., 1999. High-resolution magnetostratigraphy and micropalaeontology across the J/K boundary strata at Brodno near Žilina, western Slovakia: summary of results. Cretac. Res. 20, 699–717.

Hutko, A.R., Lay, T., Garnero, E.J., Revenaugh, J., 2006. Seismic detection of folded, subducted lithosphere at the core–mantle boundary. Nature 441, 333–336.

Iglesia Llanos, M.P., Riccardi, A.C., 2000. The Neuquén Basin composite section: magnetostratigraphy and biostratigraphy of the marine coger Jurassic from the Neuquén basin (Argentina). Earth Planet. Sci. Lett. 181, 443–457.

Juárez, M.T., Osete, M.L., Meléndez, G., Langereis, C.G., Zijderveld, J.D.A., 1994. Oxfordian magnetostratigraphy of the Aguilón and Tosos sections (Iberian Range, Spain) and evidence of a pre-Oligocene overprint. Phys. Earth Planet. Inter. 85, 195–211.

Kirschvink, J.L., 1980. The least-squares line and plane and the analysis of palaeomagnetic data. Geophys. J. R. Astron. Soc. 62, 699–718.

Klitgord, K.D., Schouten, H., 1986. Plate kinematics of the Central Atlantic. In: Vogt, P.R., Tucholke, B.E. (Eds.), The Geology of North America, vol. M, The Western North Atlantic Region. Geol. Soc. Am., pp. 351–378.

Kosterov, A.A., Perrin, M., 1996. Paleomagnetism of the Lesotho basalt, southern Africa. Earth Planet. Sci. Lett. 139, 63–78.

Kývalová, H., Čadek, O., Yuen, D.A., 1995. Correlation analysis between subduction in the last 180Myr and lateral seismic structure of the lower mantle: geodynamical implications. Geophys. Res. Lett. 22, 1281–1284.

Laj, C., Mazaud, A., Weeks, R., Fuller, M., Herrero-Bervera, E., 1991. Geomagnetic reversal paths. Nature 351, 447.

Langereis, C.G., van Hoof, A.A., Rochette, P., 1992. Longitudinal confinement of geomagnetic reversal paths as a possible sedimentary artefact. Nature 358, 226–229.

Larson, E.E., Walker, T.R., 1985. Comment on Paleomagnetism of a polarity transition in the lower(?) Triassic Chugwater Formation, Wyoming by Emilio Herrero-Bervera and Charles E. Helsley. J. Geophys. Res. 90, 2060–2062.

Love, J.J., 1998. Paleomagnetic volcanic data and geometric regularity of reversals and excursions. J. Geophys. Res. 103, 12.435–12.452.

Lowrie, W., Channell, J.E.T., 1983. Magnetostratigraphy of the Jurassic–Cretaceous boundary in the Maiolica limestone (Umbria, Italy). Geology 12, 44–47.

Masters, G., Johnson, S., Lake, G., Bolton, H., 1996. A shear-velocity model of the mantle. Phil. Trans. R. Soc. Lond., A 354, 1385–1411.

McFadden, P.L., McEhinny, M.W., 1988. The combined analysis of remagnetization circle and direct observation in paleomagnetism. Earth Planet. Sci. Lett. 87, 161–172.

McFadden, P.L., McElhinny, M.W., 1990. Classification of the reversal test in palaeomagnetism. Geophys. J. Int. 103, 725–729.

Morgan, W.J., 1983. Hotspot tracks and early rifting of the Atlantic. Tectonophysics 94, 123–139.

Müller, R.D., Royer, J.-Y., Lawver, L.A., 1993. Revised plate motions relative to the hotspots from combined Atlantic and Indian Ocean hotspot tracks. Geology 21, 275–278.

Muttoni, G., Garzanti, E., Alfonsi, L., Cirilli, S., Germani, D.Lowrie, W., 2001. Motion of Africa and Adria since the Permian: Paleomagnetic and paleoclimatic constraints from northern Libya. Earth Planet. Sci. Lett. 192, 159–174. Q3

Nairn, A.E., Schmitt, T.J., Smithwick, M.E., 1981. A palaeomagnetic study of the upper Mesozoic succession in Northern Tunisia. Geophys. J. R. Astron. Soc. 65, 1–18.

Nürnberg, D., Müller, R.D., 1991. The tectonic evolution of the South Atlantic from Late Jurassic to present. Tectonophysics 191, 27–53.

O' Neill, C., Müller, D., Steinberger, B., 2005. On the uncertainties in hot spot reconstructions and the significance of moving hot spot reference frames. Geochemistry, Geophysics and Geosystems 6 (4), 1–35.

Opdyke, N.D., Channell, J.E.T., 1996. Magnetic stratigraphy. In: Dmowska, R., Holton, J.R. (Eds.), Int. Geophys. Ser, p. 346.

Oviedo, E.S., 1989. MAG88: Un sistema de computación para análisis de datos paleomagnéticos. Tesis Doctoral, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires.

Peng, S., Li, Z., Huang, B., Liu, T., Wang, Q., 2006. Magnetostratigraphic study of Cretaceous depositional succession in the northern Kuqa Depression, Northwest China. Chin. Sci. Bull. 51 (51), 97–107.

Prévot, M., Camps, P., 1993. Absence of preferred longitudinal sectors for poles from volcanic records of geomagnetic reversals. Nature 366, 53–57.

Prévot, M., Roberts, N., Thompson, J., Faynot, L., Perrin, M., 2003. Revisiting the Jurassic geomagnetic reversal recorded in the Lesotho Basalt (Southern Africa). Geophys. J. Int. 155, 367–378.

Richards, M.A., Engebretson, D.C., 1992. Large-scale mantle convection and the history of subduction. Nature 355, 437–440.

Roest, W.R., Danobeitia, J.J., Verhoef, J., Collete, B.J., 1992. Magnetic anomalies in the Canary Basin and the Mesozoic evolution of the central North Atlantic. Mar. Geophys. Res. 14, 1–24.

Rosenbaum, G., Lister, G.S., Doboz, C., 2002. Relative motions of Africa, Iberia and Europe during Alpine orogeny. Tectonophysics 359, 117–129.

Speranza, F., Satolli, S., Mattioli, E., Calamita, F., 2005. Magnetic stratigraphy of Kimmeridgian–Aptian sections from Umbria–

Please cite this article as: Vizán, H., Van Zele, M.A., Jurassic–Early Cretaceous intermediate virtual geomagnetic poles and Pangaean subduction zones, Earth Planet. Sci. Lett. (2007), doi:10.1016/j.epsl.2007.09.044

Marche (Italy): new details on the M polarity sequence. J. Geophys. R. 110, B12109. doi:10.1029/2005JB003884.

Srivastava, S.P., Tapscott, C., 1986. Plate kinematics of the North Atlantic. In: Tucolke, B.E., Vogt, P.R. (Eds.), The Geology of North America, vol. M, The Western Atlantic Region. Geol. Soc. Am., pp. 379–404.

Steiner, M.B., Ogg, J.G., Melendez, G., Sequeiros, L., 1985. Jurassic magnetostratigraphy, 2. Middle–Late Oxfordian of Aguilon, Iberian Cordillera, northern Spain. Earth Planet. Sci. Lett. 76, 151–166.

Torsvik, T.H., Smethurst, M.A., 1999. Plate tectonic modelling: virtual reality with GMAP. Comput. Geosci. 25, 395–402.

Torsvik, T.H., Van der Voo, R., 2002. Refining Gondwana and Pangea palaeogeography: estimates of Phanerozoic non-dipole (octupole) fields. Geophys. J. Int. 151, 771–794.

Torsvik, T.H., Müller, R.D., Van der Voo, R., Steinberger, B., Gaina, C., in review. Global plate motion frames: toward a unified model. Reviews of Geophysics.

Van der Voo, R., 1993. Palaeomagnetism of the Atlantic, Tethys & Iapetus Oceans. Cambridge University Press, Cambridge, p. 411.

Vizán, H., Van Zele, M.A., 2001. Analysis of the early Jurassic geomagnetic data recorded at the Breggia Gorge (Ticino, Switzerland). Phys. Earth Planet. Inter. 125, 19–29.

Wen, L., 2006. A compositional anomaly at the Earth's core–mantle boundary. Earth Planet. Sci. Lett. 246, 138–148.

Wen, L., Anderson, D.L., 1995. The fate of slabs inferred from seismic tomography and 130million years of subduction. Earth Planet. Sci. Lett. 133, 185–198.

Yang, Z., Moreau, M.G., Bucher, H., Dommergues, J.L., Trouiller, A., 1996. Hettangian and Sinemurian magnetostratigraphy from Paris Basin. J. Geophys. Res. 101 (B4), 8025–8042.

Zijderveld, J.D.A., 1967. A.C. demagnetization of rocks: analysis of results. In: Collinson, D.W., Creer, K.M., Runcorn, S.K. (Eds.), Methods in Palaeomagnetism. Dev. Solid Earth Phys., vol. 3. Elsevier, Amsterdam, pp. 254–258.

Please cite this article as: Vizán, H., Van Zele, M.A., Jurassic–Early Cretaceous intermediate virtual geomagnetic poles and Pangaean subduction zones, Earth Planet. Sci. Lett. (2007), doi:10.1016/j.epsl.2007.09.044