A new 200 Ma paleomagnetic pole for Africa, and paleo-secular variation scatter from Central Atlantic Magmatic Province (CAMP) intrusives in Morocco (Ighrem and Foum Zguid dykes)

A. Palencia-Ortas,1 V. C. Ruiz-Martínez,1 J. J. Villalain,2 M. L. Osete,1 R. Vegas,3 A. Touil,4 A. Hafid,4 G. McIntosh,1 D. J. J. van Hinsbergen5 and T. H. Torsvik5,6,7

1Departamento de Física de la Tierra, Astronomía y Astrofísica I, Facultad de Física, Universidad Complutense de Madrid, Avda. Complutense s/n, 28040 Madrid, Spain. E-mail: vcarlos@fis.ucm.es
2Departamento de Física, Escuela Técnica Superior, Universidad de Burgos, Avda. Cantabria s/n, 09006 Burgos, Spain
3Departamento de Geodinámica, Facultad de Geología, Universidad Complutense de Madrid, Spain
4Département des Sciences de la Terre, Faculté des Sciences et Techniques, Guéliz BP 548 Marrakech, Morocco
5Physics of Geological Processes (PGP), University of Oslo, Sem Sæland s vei 24, NO-0316 Oslo, Norway
6Center for Geodynamics, Geological Survey of Norway (NGU), Leiv Eirikssons vei 39, 7491 Trondheim, Norway
7School of Geosciences, University of the Witwatersrand, WITS 2050 Johannesburg, South Africa

SUMMARY
Available apparent polar wander (APW) paths for the 200 Ma configuration of Pangea, just prior to the opening of the Central Atlantic Ocean, differ as much as 10° in arc length. Here, we add new data from northwest Africa for this time, obtained from the northeast-trending Foum-Zguid and Ighrem dykes (ca. 200 Ma). These dykes form part of the northern domain of the Central Atlantic Magmatic Province (CAMP), and crosscut the Anti-Atlas Ranges in Morocco, and compositionally correspond to quartz-normative tholeiites intruded in continental lithosphere shortly before the opening of the Central Atlantic Ocean. The Foum-Zguid dyke has been intensively studied, whereas the Ighrem dyke has received less scientific focus. We sampled both dykes for paleomagnetic investigation along 100 km of each dyke (12 sites for Foum-Zguid and 11 for Ighrem, 188 samples included in the final analyses). Rock magnetic experiments indicate a mixture of multidomain and single-domain magnetite and/or low-Ti titanomagnetite particles as the principal remanence carriers. In both dykes, the primary nature of the characteristic remanent magnetization is supported by positive contact tests, related to Fe-metasomatism or baked overprints of the corresponding sedimentary country rocks. The directions of the characteristic magnetization exhibit exclusively normal polarity. Site-mean virtual geomagnetic poles are differently grouped in each dyke, suggesting distinct geomagnetic secular variation records. The Foum-Zguid paleomagnetic pole ($N = 12$, $PLat = 67.9^\circ$N, $PLon = 247.9^\circ$E, $\kappa = 125$, $A_{95} = 3.9^\circ$) plots close to that of Ighrem ($N = 11$, $PLat = 78.4^\circ$N, $PLon = 238.2^\circ$E, $\kappa = 47$, $A_{95} = 6.7^\circ$), confirming those mineralogical and geochemical evidences supporting that they represent dissimilar magmatic stages. Virtual geomagnetic poles dispersion from both dykes ($S = 10.5^{13.0}_{8.1}$) is in line with those obtained from recent studies of a CAMP-related dyke in Iberia and results from CAMP lavas in the Argana basin. These three new estimates of paleosecular variation at low latitudes around the Triassic–Jurassic boundary are concordant with a recently proposed dispersion curve for the Jurassic but suggest a slightly lower geomagnetic scatter than considered so far. After combining results from both dykes, the resulting paleomagnetic pole ($PLat = 73.0^\circ$N, $PLon = 244.7^\circ$E, $N = 23$, $\kappa = 55$, $A_{95} = 4.1^\circ$) is statistically compared with existing and coeval African paleopoles, and with global synthetic 200 Ma running mean poles in northwest Africa coordinates.

Key words: Plate motions; Palaeomagnetic secular variation; Palaeomagnetism applied to tectonics; Rock and mineral magnetism; Cratons; Africa.
1 INTRODUCTION

Several paleomagnetic studies have been carried out in uppermost Triassic–lowermost Jurassic rocks from Africa, but in the most recent apparent polar wander (APW) paths (Besse & Courtillot 2002; Torsvik et al. 2008; hereafter referred as to BC2002 and T2008 APWPs, respectively) there are still few high quality ∼200 Ma paleopoles for the African Plate. A key to overcome this shortcoming is to obtain data from ‘stable’ Africa, as many of the poles come from ‘old’ studies that do not meet current experimental standards.

The dykes of Foum-Zguid (FZ; Leblanc 1973; Sebai et al. 1991) and Ighrem (IG; Touil et al. 2008) in Morocco (subsequently named FZ and IG dykes, respectively; Fig. 1) form part of the African expressions of the northern domain of the so-called Central Atlantic Magmatic Province (CAMP). The mafic dykes and sills, and the tholeiitic surface basalts of the ∼200 Ma CAMP are spread over at least 7 million km² across North and South America, West Africa and southwestern Europe, centred upon, but extending far beyond the initial Pangean rift zone that developed into the Central Atlantic Ocean (Marzoli et al. 1999). The northern domain of the CAMP is characterized by large, NE trending, extrabasinal dykes occurring in the Iberian Massif, the Anti-Atlas Ranges of Morocco and the coastal plain of the Canadian Maritime Provinces. They are quartz-normative tholeiites intruded into continental lithosphere prior to the opening of the Central Atlantic Ocean (May 1971) that started at around 195 Ma (Labails et al. 2010).

Some preliminary paleomagnetic work has been performed at the FZ dyke but no previous paleomagnetic information is available for the IG dyke. Hailwood & Mitchell (1971) carried out a pioneering paleomagnetic study of five sites from the FZ dyke, but the study does not meet today’s quality criteria. Recent paleomagnetic investigations of CAMP units have been performed in North America (Olsen et al. 2003), Brazil (De Min et al. 2003; Ernesto et al. 2003), Iberia (Palencia-Ortas et al. 2006) and Morocco (e.g. Palencia-Ortas 2004; Knight et al. 2004; Ruiz-Martinez et al. 2007). Knight et al. (2004) studied 66 lavas and sediments from the High Atlas, but they concluded that their pole did not represent an ‘African pole’ because it does not adequately average secular variation of the Earth’s magnetic field.

In this new paleomagnetic study, we present new data from the FZ dyke increasing the number of sites studied by Palencia-Ortas (2004) to 12 sites, all collected in its central part with respect to the margins. These data characterize the magnetic properties of these FZ dyke samples and resolve a high-quality FZ paleomagnetic pole. In addition, we present the first rock magnetic and paleomagnetic results from the IG dyke (11 sites), as well as from its sedimentary host rocks (of Precambrian age, Thomas et al. 2004). A positive baked contact test and a new IG palaeopole are presented. Then we compare FZ to IG paleopoles, as well as with (i) previous preliminary paleomagnetic FZ results; (ii) the 20 Ma window running mean pole centred at 200 Ma of the BC2002 and T2008 APWPs (which differ in the paleomagnetic data selection and the plate

Figure 1. Left-hand panel: simplified sketch showing the main tectonic units of Morocco and the location of the studied Ighrem (IG) and Foum Zguid (FZ) dykes. Right-hand panel: photographs of the IG dyke intruding Precambrian sediments (showing a dotted white-outline sketch of the dyke contact), and of the prominent FZ dyke (foreground) and the Paleozoic sediments (background).
circuits used), transferred to northwest African coordinates and (iii) those individual African paleomagnetic poles obtained from igneous and sedimentary rocks with ages ranging between 190 and 210 Ma which are included in the BC2002 or T2008 compilations. Finally, the results of these comparisons and the reliability of these poles are discussed.

2 GEOLOGICAL SETTING AND AGE OF THE STUDIED MOROCCAN INTRUSIONS

2.1 Foum-Zguid and Ighrem dykes

The FZ and IG dykes are subvertical, NE–SW trending, CAMP-related dolerite dykes located in southern Morocco (Figs 1 and 2). Contact metamorphism is observed at the intruded formations (Youbi et al. 2003). The dykes traverse the Hercynian-folded Precambrian and Paleozoic strata of the Anti-Atlas, an area that has remained tectonically stable since the end (ca. 300 Ma) of the Hercynian orogeny (e.g. Marcais & Choubert 1956; Burkhard et al. 2006), with some recent uplift partly ascribed to the occurrence of a high-temperature mantle anomaly in Neogene times (Frizon de Lamotte et al. 2009).

The exceptionally well exposed (Fig. 1) and intensively studied FZ dyke is one of the major dykes of the Anti-Atlas domain. It has an overall length of about 200 km (from the village of Foum Zguid to the FZ great dyke, extending over almost 200 km between Ait Abdellah and Taliwine villages, from east of the Kerrous inlier to the south to the Siroa Massif in the north. It crosscuts at high angle the different Precambrian and lower Paleozoic formations of the southwestern Anti-Atlas (Fig. 2). The dyke was intruded along vertical Hercynian fractures, and its width varies from 60 to 150 m (Youbi et al. 2003). Unlike the FZ dyke, the IG dyke is often covered by Neogene and Quaternary deposits and appears segmented and highly weathered, occupying the tahlwegs (valley ways) oriented along its trace. Good exposure is rare and situated to the northwest of the Ait Abdellah uplifted inlier, where the outcrops contain fresh rocks (Touil et al. 2008). The IG dyke has remained undated and is vaguely referred to as ‘Hercynian magmatism’ despite its orientation. However, the IG dyke is ascribed to the CAMP as it is petrologically and structurally similar to the FZ dyke (Touil et al. 2008), and further chronological studies are in progress to verify its radiometric age. The available mineralogical and geochemical analyses for the IG dyke (Touil et al. 2008) differ from those presented by the Foum Zguid (Bertrand et al. 1982; Bertrand 1991) and Messejana-Plasencia (Cebrián et al. 2003) dykes. The IG dyke analyses show a contrasted evolution of the compositions that is marked by the increase in Fe2O3, TiO2, P2O5, K2O, Ba, Nb and Ce contents and the decrease in Al2O3, MgO and CaO during crystallization (compared to the FZ and Messejana-Plasencia dykes). On the contrary, taking into account its constant and low MgO content, the IG rocks are thus comparatively richer in Fe2O3, TiO2, P2O5 and K2O and trace incompatible elements, and poorer in Al2O3, CaO (Figs 6 and 7 from Touil et al. 2008). This means that although all three dykes belong to the CAMP, the IG dyke is magmatically the most evolved (Touil et al. 2008).

2.2 Moroccan CAMP volcanism

The number of CAMP geochronological data has increased over recent years, although new Moroccan data come from basaltic flows, and not intrusives. Nomade et al. (2007) reviewed and selected available 40Ar/39Ar data, accepting 37 ages for African CAMP magmatism that ranged from 202.5 ± 3.0 to 190.5 ± 1.2 Ma (‘older’ data of Sebai et al. 1991 were not included because of calibration...
problems with the applied LP6 biotite monitor). In the Moroccan central High Atlas and Oujda basins, Verati et al. (2007) reported CAMP $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages ranging from 197.8 ± 0.7 to 201.7 ± 2.4 Ma (with a restricted peak at 199.1 ± 1 Ma) for the main tholeiitic basaltic event, followed by a younger, smaller volume episodic eruption of mafic magmas (mean age of 196.6 ± 0.6 Ma).

Using geochronological, magnetostratigraphic (the reversed polarity chron E23r) and geochemical correlations between CAMP subprovinces, Marzoli et al. (2004) and Knight et al. (2004) suggested a short duration for the peak CAMP activity of less than 1 Ma (with an $^{40}\text{Ar}/^{39}\text{Ar}$ age of 199.1 ± 1.0 Ma) and concluded that CAMP volcanism in Morocco erupted across the Triassic–Jurassic (T–J) boundary. Milankovitch cyclostratigraphy was used by Whiteside et al. (2007) to correlate the onset in Morocco (Argana basin and central High Atlas) with that in eastern North America (Newark and Fundy basins), where the total duration of the CAMP volcanic event is constrained to ~610 ky. Recently, high precision $^{206}\text{Pb}/^{238}\text{U}$ zircon CAMP data of 201.38 ± 0.31 Ma has been reported (Schoene et al. 2010) at the North Mountain Basalt (Fundy basin) correlating this volcanism and the end-Triassic mass extinction. According to the trans-Atlantic CAMP multidisciplinary basin correlating this volcanism and the end-Triassic mass extinction. According to the trans-Atlantic CAMP multidisciplinary correlation of Deenen et al. (2010), the onset of CAMP volcanism in Morocco (Argana basin) is proposed to occur ~20 ka after the chron E23r, prior to the T–J boundary. Only normal polarities were observed in lava flows from the Argana basin (Ruiz-Martinez et al. 2007).

Analytical resolution of the geochronological data is not yet precise enough for the timing of the T–J boundary, or even for estimating the relatively short CAMP volcanic activity duration. In contrast, and despite the absence of temporal correlations between Moroccan CAMP volcanism and intrusions, uncertainties on the order of 1 to few Ma are not problematic for our paleomagnetic purposes. IG and FZ CAMP dykes are reasonably ascribed to an age of ca. 200 Ma. In fact, their time span are quite precise as they will be compared with 20 Ma APWP running windows centred at 200 Ma and with individual paleopoles of latest Triassic–earliest Jurassic age.

3 FIELD SAMPLING AND LABORATORY MEASUREMENTS

A total of 23 sites from the central parts of the IG and FZ dykes (11 and 12 sites, respectively) spanning 100 km of each dyke have been sampled (Fig. 2). In addition, host sedimentary Precambrian rocks close to the IG dyke margins (site TZ5, Figs 1 and 2) were sampled to perform a baked contact test. Samples were cored (2.54 cm in diameter) with a portable gasoline-powered drill and oriented using an inclinometer and a magnetic compass. Cores were cut in the laboratory into standard specimens (2.2 cm length) for paleomagnetic measurements. Alternating field demagnetized specimens, core chips and core end pieces were used for rock magnetic experiments.

Measurements were made in the Paleomagnetic laboratory and the Physical Techniques Center of the Complutense University in Madrid and in the Paleomagnetic laboratory of the University of Burgos. Low-field magnetic susceptibility ($\chi$) was measured using an AGICO KLY-3 susceptibility meter. Remanence measurements (natural and isothermal, NRM and IRM, respectively) were made using an AGICO JR5-A spinner and 2G cryogenic (model 755 DC SQUID) magnetometers. IRM was imparted using an ASC Scientific IM10-30 impulse magnetizer. Magnetic hysteresis measurements were made using a coercivity meter (Jasonov et al. 1998). Low-temperature IRM curves were measured using a Quantum Design MPMS-XL squid magnetometer. Thermal (TH) and alternating field (AF) demagnetization of NRM and IRM were carried out using Schonsted Instruments THD-1, AFD-1 and ASC TD48-SC demagnetizers.

4 ROCK MAGNETIC RESULTS

Representative samples were subjected to stepwise IRM acquisition up to 2 T, applying at least 16 field steps. Subsequently, thermal demagnetization of orthogonal IRMs (Lowe 1990, applying fields of 2, 0.4 and 0.12 T) was carried out. All samples displayed a similar behaviour, approaching saturation below 0.3 T. The 0.12 T IRM component was completely demagnetized by 550–600 °C, suggesting magnetite, possibly partially oxidized, as the low coercivity mineral (Figs 3a and b and 4a and b). In some cases, a decrease in magnetization was observed around 350–400 °C (Fig. 3b), which may indicate the presence of maghemite. In only a few cases did the 0.4 and 2 T components contribute significantly to the IRM, with unblocking temperatures over 600 °C probably indicating haematite. There was no evidence for unblocking of the 0.4 and 2 T components below 150 °C, so that contribution of goethite to the remanence can be discounted.

Hysteresis parameters were obtained for selected samples in a maximum applied field of 0.5 T. Closed loops, saturation of the ferromagnetic grains and little or no paramagnetic/diamagnetic high-field contributions were observed. Both the induced ($M_i$) and remanent ($M_r$) magnetization curves were dominated by low coercivity ($<0.3$ T) minerals (Figs 3c and 4c), in agreement with the IRM results. The data fall within the upper left part of the pseudo-single-domain region of a Day plot (Figs 3d and 4d; Day et al. 1977), closely following the trends for single- and multidomain mixture of magnetite or low-Ti titanomagnetite (Duplon 2002).

Low-temperature IRM curves were measured for FZ representative samples. A 4 K IRM, acquired in a 5 T applied field, was measured during zero-field warming to room temperature. A large drop in remanence around 110 K was observed, due to the Verwey transition associated with magnetite (Fig. 3e).

In summary, rock magnetic experiments suggest a magnetic mineralogy dominated by a mixture of single-domain and multidomain grains of nearly pure magnetite or low-Ti titanomagnetite. This is in close agreement with the findings of Silva et al. (2004), who performed complementary rock magnetic investigations on FZ dyke margin sites (Curie curves, microscopic studies), and with the petrographic observations of Touli et al. (2008) at the IG dyke indicating the presence of titanomagnetite in the primary minerals assemblage.

5 PALEOMAGNETIC RESULTS

5.1 Foum-Zguid dyke

A large scatter in both initial NRM directions and intensities was observed. Intensity values typically ranged between 4 × 10$^{-2}$ and 3 Am$^{-1}$, with some specimens exhibiting anomalously high intensities (up to 342 Am$^{-1}$). Initial NRM intensities $NRM_i$ versus $\chi$ are plotted in Fig. 3(f), together with the Koenigsberger values (Stacey 1967; Dunlop et al. 1984), $Q_k$, which quantify the ratios between the remanent and induced magnetizations ($Q_k = NRM_i/(\chi H)$). $H$ is the geomagnetic field intensity ($= 39$ Am$^{-1}$). The values obtained were generally consistent with a thermoremanent (TRM) origin for
the NRM, but high ratios ($Q_n > 10$) and dispersed NRM directions also suggest the presence of IRMs acquired by lightning strikes. The predominantly high positive relief of the FZ dyke with respect to the country rock may explain the relative importance of lightning strikes.

Detailed stepwise thermal (TH) and alternating (AF) demagnetization techniques were applied to 2–4 pilot specimens per site. One or two magnetic components were observed, with different degrees of overlap. Specimens with high $Q_n$ ratios ($Q_n > 10$) were rejected from the paleomagnetic study because their NRMs were completely remagnetized (Fig. 5a) or their high NRM intensities might have disturbed the field sampling orientation when using the magnetic compass. From a total of 296 specimens, 120 independently oriented samples (12 sites) were selected for demagnetization and directional analyses.

In some cases, only one stable component was observed (Fig. 5b). In most cases, a low coercivity component with highly scattered directions overlapped with a second, higher coercivity component (Fig. 5c). This component always showed well grouped, normal polarity directions, and is interpreted as the ChRc. When two components were observed, AF demagnetization was usually more effective than TH demagnetization in isolating the ChRc. Therefore, AF demagnetization was used as the routine demagnetization technique, with at least eight steps up to a maximum of 80–100 mT. Median destructive fields ranged between 5 and 20 mT. Maximum unblocking temperatures ranged between 450 and 575–600 °C.

When the low coercivity phase exhibited anomalously high intensities we have interpreted this as a lightning-induced IRM. There have been few cases without anomalous initial NRM values in which it could be due to chemical alteration, hydrothermal and/or viscous magnetization effects. In the absence of petrographic or viscosity investigations, we are unable to distinguish between these possibilities. In spite of this, the magnetic behaviour during NRM demagnetization of the samples from the central part of the dyke stands out in contrast to the complexity of the remanence of the samples of the margin of the same dyke (Silva et al. 2006b), where several directional magnetic components were found. These authors did not find indication of lightning effects but described (i) a low-temperature component, probably a viscous remanent magnetization (VRM); (ii) an intermediate component (sometimes close to the recent field, sometimes not) that could correspond to a chemical remanent magnetization (CRM) related to the presence of maghemite; and (iii) a highest temperature component (above 500 °C) associated with the ChRc. The widespread CRM acquired since late Tertiary times in the Sahara region (Henry et al. 2004), that according to Silva et al. (2006b) could likely be responsible of these directions from the FZ.

Figure 3. Representative rock magnetic results from FZ dyke. (a) IRM acquisition curve and (b) thermal demagnetization of orthogonal IRM components. (c) Hysteresis curve: remanent ($M_r$) and induced ($M_i$) magnetizations. (d) Hysteresis parameters of all samples, along with theoretical curves for mixtures of single domain (SD), multidomain (MD) and superparamagnetic (SP) magnetite and 60 per cent Ti-titanomagnetite (TM60) grains (Dunlop 2002). (e) Saturation IRM acquired at 4 K monitored during zero field heating to room temperature. (f) Koenigsberger ratio, $Q_n$, of all FZ samples.
Paleomagnetism of CAMP intrusives in Morocco

Figure 4. Representative rock magnetic results from IG dyke. (a) IRM acquisition curve and (b) thermal demagnetization of orthogonal IRM components. (c) Hysteresis curve: remanent ($M_r$) and induced ($M_i$) magnetizations. (d) Hysteresis parameters of all samples, along with theoretical curves for mixtures of single domain (SD), multidomain (MD) and superparamagnetic (SP) magnetite and 60 per cent Ti-titanomagnetite (TM60) grains (Dunlop 2002). (e) Koenigsberger ratio, $Q_n$, of IG dyke and sedimentary country rock samples.

Margins close to the recent field, it is not observed in the samples of the central part of the FZ dyke (this study).

Where possible, paleomagnetic directions were calculated from stable endpoints (with at least five linear steps) using principal component analysis (Kirschvink 1980) and site-mean directions were calculated using Fisher (1953) statistics (Fig. 5d). In cases where a high degree of overlapping was detected, principal component analysis was applied to fit (with at least eight planar steps) the corresponding plane that comprises both overlapped directions, and site-mean directions were calculated using the combined analysis of linear segments and remagnetization circles (McFadden & McElhinny 1988). Although it was possible to determine stable endpoint directions for some of these specimens, remagnetization circles were better defined after detailed AF demagnetization (Fig. 5e), and their convergence favoured by the random nature of the lightning-induced remagnetization, giving better results. For each site-mean direction, quantile–quantile plots of declination (inclination) against an assumed uniform (exponential) distribution supported Fisher-distributed directions. Site-mean directions (Table 1) were well grouped, with tectonically useful 95 per cent confidence intervals ($1.8^\circ \leq \alpha_{95} \leq 8.4^\circ$, geometric mean = $4.4^\circ$) and precision parameters ($35 \leq k \leq 833$, geometric mean = 133). The ChRe exhibited exclusively normal polarities (Fig. 7a).

5.2 Ighrem dyke

Initial NRM intensities (ranging from 0.9 to 5.1 Am$^{-1}$ at dyke samples; 2 Am$^{-1}$ on average) led to moderate $Q_n$ ratios ($Q_n \approx 1$), consistent with TRM values in both the dyke and the nearest country rock samples, with susceptibility and intensity ranges typical of igneous and sedimentary rocks, respectively (Fig. 4e). Initial NRM site-mean directions were generally well grouped, with the exception of some sites with visible signs of alteration. Unlike the FZ dyke samples, no evidence of lightning strikes is present in those from the IG dyke.

Two magnetic phases were distinguished after applying detailed, stepwise AF and TH demagnetization in specimens from the same sample. First, low coercivity/unblocking temperature component is isolated between 2 and 15 mT or 75–125 and 350–500 °C. Secondly, not overlapping, high coercivity/unblocking temperature component is isolated between 25 and 100 mT or 375–500 and 600 °C (Fig. 6a). The former directions have been interpreted as remagne-

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Figure 5. Orthogonal vector diagrams, equal area projections and normalized magnetization decays during AF and TH demagnetization of typical FZ dyke samples. (a) Rejected specimens (from the same sample, FZ3.14) exhibiting anomalously strong NRM due to lightning strikes. (b) Accepted specimens (the same sample, FZ3.10) with one stable component. (c) Accepted specimen (BR2.3B) with two overlapping components. Equal area projection of specimen and site-mean directions for (d) single component (FZ) and (e) two overlapped components (BR2).

Directions because their inclinations/declinations are systematically higher/closer to the present-day field than those from the latter corresponding directions. The remaining dyke samples were fully demagnetized by both TH and AF techniques. Median destructive fields ranged between 5 and 20 mT, and maximum unblocking temperatures were observed around 550–600°C. Principal component analysis was applied to calculate IG ChRcs, using at least six linear steps of the high coercivity/unblocking temperature component and the origin, except in one of them where lines were combined with remagnetization planes. IG site-mean directions (Table 2) pass Fisherian distribution tests and show a slightly higher within-site dispersion (3.8° ≤ α95 ≤ 12.3°, geometric mean = 7.3°; 39 ≤ k ≤ 391, geometric mean = 128) than those observed at the FZ dyke. The IG dyke ChRcs are all observed to be of normal polarity (Fig. 7c).

At the TZ5 site, the IG dyke intrudes folded Precambrian limestones (Thomas et al. 2004). Both limbs of the metre-scaled fold are clearly in contact with the ca. 60 m wide IG dyke (Fig. 1). The country rock was sampled at different distances from the dyke (from few centimetres to tens of metres) to perform a paleomagnetic baked contact test. Those country rock samples that are closest to the IG dyke (only some centimetres distant) have a single, linear magnetic component that is isolated at temperatures up to 550 °C (TZ5.20A, Fig. 6c). The direction of the component carried by the
immediate host sediments, calculated without applying any correction for their paleohorizontal restitution, is identical to that of the ChRc direction of the IG dyke samples at TZ5 (Fig. 6b). This total thermal remagnetization becomes a partial TRM with decreasing overprint temperatures as samples are increasingly distant from the dyke (see country rocks normalized magnetization decays during thermal demagnetization, Fig. 6c). Country rock samples located 6 m from the dyke show a normal polarity, low unblocking temperature (∼350°C in TZ5.23A, Fig. 6c) directional component that is overlapped with a high unblocking temperature component of reversed polarity which is considered the ChRc of these sedimentary host rocks. After a detailed thermal demagnetization of these samples, the planes that contain the two directional unblocking temperature components describe remagnetization great circles in the equal-area demagnetization paths (TZ5.23A, Fig. 6c). A ChRc mean direction was calculated for the country rocks using the remagnetization great circles method, sometimes combining great circle and linear segment analysis as described by McFadden & McElhinny (1988). Reversed country rock ChRcs exhibited a higher grouping in their paleo-horizontal coordinates (n = 5; Dec = 157.0; Inc = −20.4; α95 = 11.8), suggesting a pre-folding magnetization. The baked contact test indicates that the closest intruded sedimentary rocks are completely remagnetized by the thermal process due to the dyke intrusion. Precambrian host rocks are gradually less thermally affected in metre-scale distances from the IG dyke, preserving a pre-folding reversed polarity magnetization. The positive baked contact test supports a primary ChRc direction of the IG dyke.

Table 1. ChRc site-mean directions and VGPs from Foum Zguid and Ighrem dykes. Site (D.T.): Site code name and (AF, alternating field; TH, thermal) demagnetization technique (D.T.); n: number of independently oriented samples included in the analysis; nL/p: number of lines/planes calculated by principal component analysis; SLat, SLon: site location in latitude and longitude; Dec, Inc: declination and inclination; k, α95: precision parameter and semi-angle of 95 per cent confidence of directions; PLat, PLon: pole latitude and longitude. (SLat, SLon, Dec, Inc; α95, PLat, PLon in degrees).

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<tr>
<th>Site (D.T.)</th>
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<th>n</th>
<th>nL/p</th>
<th>SLat</th>
<th>SLon</th>
<th>Dec</th>
<th>Inc</th>
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6 Foum-Zguid and Ighrem New Paleopoles and Reliability Criteria

Virtual geomagnetic poles (VGPs) for each site have been calculated for the FZ and IG dykes, together with their statistical parameters (Tables 1 and 2, Figs 7b and d). ‘Quantile–quantile’ plot tests were positive for each dyke, indicating that the VGPs were Fisher-distributed. Despite these results, which support that an incomplete resolution of ChRc can be excluded, an adequate averaging of geomagnetic secular variation in each dyke cannot be asserted.

The paleomagnetic pole obtained for the Foum Zguid dyke is: 
\[ PLat = 67.9°N, PLon = 247.9°E, N = 12, K = 125 and A95 = 3° \] (Tables 1 and 3). The paleopole obtained for the IG dyke is: 
\[ PLat = 78.4°N, PLon = 238.2°E, N = 11, K = 47 and A95 = 6° \] (Tables 2 and 3). FZ and IG paleopoles implies overlapping paleolatitudes at each site (22.4° ± 2.8° and 24.8° ± 5.0°, respectively).

Van der Voo (1990) proposed seven criteria by which to reliably determine a paleomagnetic pole, giving rise to a quality factor \( Q \) (0 ≤ \( Q \) ≤ 7) that can be assigned to the paleopole determination. A quality factor \( Q = 5 \) has been ascribed to the determination of IG and FZ individual paleopoles because each of them meets at least the following reliability criteria of Van der Voo (1990): (1) well-determined age (for paleomagnetic purposes) of the rock unit (CAMP-affinity intrusion), (2) tectonic coherence—it is younger than the last tectonic phase that affected northwest African craton area of the dyke emplacement, (3) positive contact test constraining the age of the magnetization, (4) adequate demagnetization and (5) no suspicion of remagnetization. The quality factor does not
reach the maximum value of seven due to the absence of (antipodal) reversals and (probably) to the insufficient quantity of entries and adequate statistical precision (i.e. not averaging out geomagnetic secular variation). Deenen et al. (2007) proposed additional statistical reliability envelope to test whether the obtained statistical parameters can be explained by paleosecular variation (PSV), defined by $A_{95\text{ min}}$ and $A_{95\text{ max}}$. Values within this envelope can be straightforwardly explained by PSV alone, whereas values below $A_{95\text{ min}}$ likely under-represent PSV, and values above $A_{95\text{ max}}$ contain an additional source of scatter aside from PSV.

Table 2. ChRc mean directions and paleomagnetic poles from Foum Zguid (FZ), Ighrem (IG) and combined dykes (FZ+IG), and corresponding statistical parameters. $N$: number of sites; $\text{Dec, Inc}$: declination and inclination; $\text{PLat, PLon}$: pole latitude and longitude; $k/\kappa$ and $\alpha_{95}/A_{95}$: precision parameters and semi-angles of 95 per cent confidence of mean directions/paleopoles. ($\text{Dec, Inc, } \alpha_{95}, \text{PLat, PLon, } A_{95}$ in degrees).

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<th>$\text{Inc}$</th>
<th>$\alpha_{95}$</th>
<th>$\text{PLat}$</th>
<th>$\text{PLon}$</th>
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<td>IG+FZ</td>
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<td>55</td>
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</table>

The corresponding paleolatitude is $23.7^\circ \pm 3.0^\circ$, and the $A_{95}$ value falls within the $N = 23$. $A_{95\text{ min/max}}$ envelope of 3.4/11.4 $sensu$ Deenen et al. (2007), suggesting proper representation of PSV.
Figure 7. (a) Site-mean directions and (b) VGPs and paleopole of the Foum Zguid dyke on equal area projection. (c) Site-mean directions and (D) VGPs and paleopole of the Ighrem dyke on equal area projection.

Table 3. Paleomagnetic poles from 210 to 190 Ma igneous and sedimentary rocks of northwest Africa. Code name: Reference, number and name (see Fig. 9b and Table 4); Age (code names 8, 9, 11, 12, 13): mean age assigned in T2008; Ref.: Reference; N: number of sites; PLat, PLon: Pole latitude and longitude; $A_{95}$, dm, dp: corresponding semi-angles of 95 per cent confidence. (PLat, PLon, $A_{95}$, dm, dp in degrees).

<table>
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<th>N</th>
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<th>PLon</th>
<th>$A_{95}$</th>
<th>Reference</th>
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<td>78.4</td>
<td>238.2</td>
<td>6.7</td>
<td>This study</td>
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<td>2 FZ</td>
<td>Foum Zguid dyke, Morocco, CAMP (200 Ma)</td>
<td>12</td>
<td>67.9</td>
<td>247.9</td>
<td>3.9</td>
<td>This study</td>
</tr>
<tr>
<td>3 IG+FZ</td>
<td>Ighrem and Foum Zguid dykes, Morocco, CAMP (200 Ma)</td>
<td>23</td>
<td>73</td>
<td>244.7</td>
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<td>This study</td>
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<td>Silva et al (2006)</td>
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<td>Hailwood &amp; Mitchell (1971)</td>
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<td>T2008 running mean (200 Ma, northwest Africa)</td>
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<td>69.9</td>
<td>236.9</td>
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<td>Bardon et al. (1973)</td>
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<td>73.0</td>
<td>241.3</td>
<td>$dm = 18.5$; $dp = 5.0$</td>
<td>Knight et al. (2004)</td>
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7 DISCUSSION

7.1 Paleosecular variation at the T–J boundary

Although the knowledge of the angular dispersion dependence with latitude in ancient geological times is still a work in progress (e.g. Biggin et al. 2008), IG+FZ paleosecular variation (PSV) has been evaluated in terms of the angular dispersion of the data set of 23 VGPs around their mean paleomagnetic pole (Fig. 8b). The total angular dispersion \( S_T \) of the IG+FZ VGPs, each being an angular distance \( \Delta \) away from the mean, was calculated (e.g. McElhinny & McFadden 1997) from \( S_T = \sum \Delta^2/(N - 1) \). \( S_T \) value must be corrected (Cox 1970) by the within-site scatter \( S_W \) (a function of the mean value of \( \alpha_{\text{avg}} \) for the data set \( \alpha_{\text{avg}} \), the latitude \( \lambda \) and the mean value of the number of samples per site, \( n_{\text{avg}} \)) produced by the experimental errors: \( (S_W/ \ n_{\text{avg}}) = (0.335\alpha_{\text{avg}}\lambda^2) \ (2 (1 + 3\sin^2\lambda) )/(5 + 3\sin^2\lambda) \). The geomagnetic dispersion \( S_T \) is then: \( S_T^2 = S_T^2 - (S_W/ \ n_{\text{avg}}) \).

None of the IG+FZ VGPs were rejected after applying the iterative process defined by Vandamme (1994) to obtain an optimum cut-off angle \( \Theta = 24.7^\circ \) (which directly depend on the angular dispersion of the VGP distribution; \( \Theta = 1.8 S + 5^\circ \)). The obtained cut-off angle is \( \Theta = 24.7^\circ \) and the maximum individual VGP distance to the mean 20.5°. The bootstrap method was used to evaluate upper and lower propagations of the geomagnetic dispersion uncertainty.

IG+FZ VGP dispersion (\( N = 23, S_T = 10.5^\circ \pm 13^\circ \), Fig. 8) is an excellent agreement with that observed at the CAMP-related Messejana–Plasencia dyke (MP, Fig. 8) that traverses Portugal and Spain (\( N = 44, S_T = 10.6^\circ \pm 12^\circ \); Palencia-Ortas et al. 2010) when the 46 paleomagnetic results available for this Iberian dyke (Schott et al. 1981; Perrin et al. 1991; Palencia-Ortas et al. 2006) are combined after rejecting 5 sites with less than 5 samples, and their PSV analysed in the same way using the Vandamme cut-off.

IG+FZ VGP dispersion is also concordant, at its corresponding paleolatitude and considering its uncertainty, with the best-fit Model G (McFadden et al. 1988) fitted to the high-quality PSV results from selected Jurassic data sets of Biggin et al. (2008) (applying a Vandamme cut-off, in which the dependence of \( S \) with latitude differs from that observed during the last 5 Ma, Fig. 8c). This high-quality data set of Biggin et al. (2008) compiles results from extrusive rocks and tuffs, including Moroccan CAMP results from the High Atlas (Knight et al. 2004; hereafter also referred as K2004, see Fig. 8). The K2004 data yields a much higher VGP dispersion (\( N = 40, S_T = 21.3^\circ \pm 18.3^\circ \)) than those obtained from the rest of the Jurassic inputs (Fig. 8c), as well as from our new results obtained at similar paleolatitudes from the IG+FZ dykes (\( N = 23, S_T = 10.5^\circ \pm 13^\circ \)). Biggin et al. (2008) noted that the K2004 data set is heavily affected by short duration bursts of volcanic activity, and Knight et al. (2004) hence binned their results into clustered ‘directional groups’ (numbered DG1–DG7, also based on stratigraphy and geochemistry). The K2004 input used by Biggin et al. (2008) is the combination of all the data from the five directional groups selected by Knight et al. (2004) to give a mean pole for Africa at 200 Ma (Tables 3 and 4). However, we agree that taking many data points clustered around essentially five unique, fairly separated directions will lead to an overestimation of VGP dispersion. Vandamme cut-off selection, depending on each scatter distribution, enhances these effects on the K2004 data set.

On the other hand, PSV estimates obtained from dykes may slightly underrepresent PSV, as dykes cool slower, and within each site some PSV may be averaged. We can check if the slower cooling rate of dykes than lavas may suppress the PSV scatter slightly in the dykes. Therefore, we have calculated VGP dispersion of the CAMP lava flows from the Argana basin in Morocco, preliminarily reported by Ruiz-Martinez et al. (2007). Resulting geomagnetic dispersion (\( N = 13, S_T = 11.4^\circ \pm 9.4^\circ \)) is in line (AR, Fig. 8) with the results obtained from the IG+FZ and MP CAMP dykes but lower than the High Atlas K2004 input included in Biggin et al. (2008).

We note that the scatter values obtained from the MP Iberian dyke (Palencia-Ortas et al. 2010) and IG+FZ dykes and AR lava flows are within the error bars suggested by Biggin et al. (2008), but are consistently lower than the average graph for the Jurassic. But given the small amount of reliable data sets for PSV in the Jurassic, and because of the shape parameters and 95 per cent bootstrap uncertainty limits of the best-fit Model G (McFadden et al. 1988), the curve based on the Jurassic data (Biggin et al. 2008) is strongly influenced by the K2004 input (Fig. 8), our new data points may suggest a generally lower Jurassic PSV scatter than thus far assumed. We suggest that the MP and (IG+FZ) dykes and AR lava flows estimates (Fig. 8) yields the most reliable representation.
Table 4. Testing indistinguishable directions ('MM90 tests', McFadden & McElhinny 1990) between pairs of paleopoles (see Code name) listed in Table 3. Marked column 3: IG+FZ (this study) paleopole tested against the rest (results showed in bold). Negative (−) and positive (+) results of the MM90 tests. (Ind.: indeterminate result, performed vs. K2004∗ using $A_{95} = dm$).

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*of PSV for late Triassic—early Jurassic ages at the corresponding paleolatitudes.

7.2 Comparison with the African APW 200 Ma paths and poles

The new IG and FZ paleopoles obtained in this study have been (individually and combined) compared (Table 3, Figs 9a and b) with (i) previous preliminary studies of the FZ dyke (Hailwood & Mitchell 1971; Silva et al. 2006b), (ii) the 200 Ma BC2002 and T2008 'synthetic' poles calculated for a 20 Ma sliding window in 10 Myr intervals, after transferring them to northwest African coordinates ($N = 19$, $PLat = 63.4^\circ$, $PLon = 250.1^\circ$, $A_{95} = 4.3^\circ$ and $N = 35$, $PLat = 69.9^\circ$, $PLon = 236.9^\circ$, $A_{95} = 3.2^\circ$, respectively) and (iii) the African entries of ‘similar’ ages (200 ± 10 Ma) included in the BC2002 and T2008 compilations. The T2008 APWP contains only five paleomagnetic poles, whereas the BC2002 APWP contains no African poles of this time window. The T2008 poles were obtained from igneous (Hargraves et al. 1999; Bardon et al. 1973; Knight et al. 2004) and sedimentary (Martin et al. 1978; Kies et al. 1995) rocks.

Africa has traditionally been divided into three main tectonic domains, S Africa, NE Africa and NW Africa. All individual, available analysed paleopoles of ‘similar’ ages (200 ± 10 Ma) come from the northwest Africa domain. In spite of the low value of the rotation angles involved ($\omega < 2^\circ$), finite rotation poles for Gondwana used to rotate BC2002 and T2008 APWPs for South Africa onto NW Africa coordinates were respectively those used in BC2002 (Müller et al. 1993) and in T2008 (Nürnberg & Müller 1991).

The statistics described by McFadden & Jones (1981) and McFadden & McElhinny (1990) (hereafter denoted the ‘MM90 test’) have been used to test the hypothesis that two Fisherian distributions of individual directions share a common true mean direction at the 95 per cent confidence level (by evaluating both the angle between the two mean directions, $\gamma_0$, and the critical angle, $\gamma_c$, at which the hypothesis would be rejected), and their ‘A’, ‘B’, ‘C’ or ‘indeterminate’ quality classification (decreasing with rising values of $\gamma_c$: $\gamma_c \leq 5^\circ$, $5^\circ < \gamma_c \leq 10^\circ$, $10^\circ \leq \gamma_c \leq 20^\circ$ and $\gamma_c > 20^\circ$, respectively).

Figure 9. (a) Equal area projection showing IG, FZ and combined IG+FZ paleopoles comparison with similar aged trends of the BC2002 and T2008 APWPs transferred to northwest Africa. (b) Northwest African paleopoles listed in Table 3. (1) IG (this study), (2) FZ (this study), (3) IG+FZ (this study), (4) Silva et al. (2006b), (5) Hailwood & Mitchell (1971), (6) T2008 (Torsvik et al. 2008), (7) BC2002 (Besse & Courtillot 2002), (8) Hargraves et al. (1999), (9) Bardon et al. (1973), (10) ‘all sites’, Knight et al. (2004), (11) Martin et al. (1978), (12) Kies et al. (1995) and (13) ‘directional groups’, Knight et al. (2004).
respectively). MM90 tests have been performed using simulation (McFadden 1990) when the hypothesis of a common precision parameter $k$ (Fisher 1953) failed. A summary of MM90 test results in between each pair of poles listed in Table 3 (and illustrated in Fig. 9b) is shown in Table 4.

(i) The new FZ paleopole is statistically distinct from the paleopole obtained by Hailwood & Mitchell (1971) from five FZ dyke sites. This is probably due to the incomplete demagnetization in previous study, along with the low number of sites/specimens (5/23). Conversely, the paleopole determined by Silva et al. (2006b) from six (fully demagnetized) FZ dyke margin sites is indistinguishable (‘quality A’, $\gamma_0 = 0.9^\circ < \gamma_C = 4.9^\circ$) from the new paleopole—obtained from 12 sites from the central part of the dyke.

From this the following conclusions can be made: (a) despite the VRM–CRM remagnetizations affecting the dyke margin, the magnetization acquired during dyke emplacement has been partially preserved; (b) there has been no important deformation at the dyke margins and (c) there was no (paleomagnetically) significant delay in remanence acquisition between the dyke centre and its margins.

(ii) The new IG+FZ paleopole gives ‘quality B’ positive MM90 test results tested against the new IG and FZ individual poles ($\gamma_0 = 5.6^\circ < \gamma_C = 8.2^\circ$ and $\gamma_0 = 5.2^\circ < \gamma_C = 5.8^\circ$, respectively). IG+FZ pole has been compared with other African paleopoles from those five paleomagnetic entries in the 200 ± 10 Ma age interval which have been included in BC2002 or T2008 APWPs, coming from igneous or sedimentary rocks.

One of these studies (Knight et al. 2004) has been duplicated in two entries accordingly with the different treatment applied by the authors to site-mean directions from 66 lavas and sediments from CAMP sections in Morocco. One pole (entry 10 in Tables 3 and 4) was calculated using all site-mean directions, which the authors considered not representative of a mean 200 Ma African pole, being distinct to the BC2002 200 Ma pole. Then, the authors identified five distinct directional groups within the lavas (associated with short periods of volcanic activity that lead to incomplete averaging of secular variation) and considered the mean of the directional groups the best way of calculating the palaeopole (entry 13 in Tables 3 and 4). Both poles are maintained here for comparisons, as the second is included in the T2008 APWP compilation although it is determined 200 Ma paleopoles gives negative MM90 test results. The T2008 200 Ma running mean in is between IG and FZ poles (Fig. 9a). So, the combined IG+FZ pole is indistinguishable from the T2008 one (‘quality B’, $\gamma_0 = 3.9^\circ < \gamma_C = 5.4^\circ$), but it is statistically distinct (negative MM90 test result) from the BC2002 200 Ma synthetic pole.

This discrepancy could be explained by the different kinematic models and paleomagnetic data selection criteria used in the construction of both APWPs. The T2008 200 Ma running mean is computed using 35 paleomagnetic poles mostly from North America (18) but also from Europe (6), Africa (five, all located in northwest Africa, Table 3), East Antarctica (2), Madagascar (1), South America (2) and India–Pakistan (1). The 19 paleopoles selected in BC2002 in the 20 Ma sliding window centred on 200 Ma (mean age computed from the data = 196.7 Ma) come from Antarctica (3), Australia (1), Europe (3), from BC2002 and particularly North America (12), and do not include any African paleopoles. We conclude that our new results from Morocco are in line with the APWP of T2008. Further analysis of the plate tectonic implications of our findings will be the focus of a future paper.

8 CONCLUSIONS

A detailed paleomagnetic study (23 sites, 188 samples included in the final analyses) of the IG and Fom Zguid dykes, which belong to the CAMP in the Anti-Atlas Ranges, Morocco, has been carried out. A stable, high unblocking temperature/coercivity, primary characteristic magnetization was recognized, supported by positive contact tests. It was readily distinguishable from low unblocking temperature/coercivity, secondary magnetizations that were principally due to a recent overprint or to lightning strikes. The magnetic mineralogy, very similar in both dykes, was dominated by single- and multidomain magnetite and low-Ti titanomagnetite, with minor contributions by oxidized magnetite and haematite.

Only normal polarities are found in IG and FZ ChRs. IG and FZ poles are distinct one from each other in agreement with different secular variation records related with relatively short, different CAMP magmatic stages. After combining VGP from both dykes, the geomagnetic dispersion ($S = 10.5^{+13.0}_{-8.1}$) of the corresponding mixed distribution is in line with that observed at the Messejana-Plasencia CAMP dyke in Iberia (Palencia-Ortas et al. 2010) and in the Moroccan CAMP lavas of Argana basin (Ruz-Martínez et al. 2007). These values for paleo secular variation at 200 Ma are here presented as new data entries in the compilation of PSV in the Jurassic (Biggin et al. 2008). Our new data points significantly differ from the CAMP aged entry of this dispersion curve at the same paleolatitude and may suggest a generally lower Jurassic PSV scatter than thus far assumed. The corresponding IG+FZ paleolatitude (23.7° ± 3.0°) is concordant with North Atlantic latitudinal reconstructions of CAMP continental rift basins (Kent & Tauxe 2005). IG+FZ combined results provide a new ca. 200 Ma paleomagnetic pole for NW Africa ($PLat = 73.0^\circ$, $PLon = 244.7^\circ$, with $N = 23$, $k = 54.9$ and $A_3 = 41.1^\circ$), which has a high-quality factor following the classification scheme of Van der Voo (1990).

Statistical comparisons with the available 20 Ma running window centred at 200 Ma of BC2002 and T2008 APWPs (in northwest Africa frame) and with poles of ‘similar’ ages (190–210 Ma) obtained from igneous and sedimentary rocks from the African Plate indicate dissimilar concordance results with the present IG+FZ paleopole.

The new IG+FZ pole provides an independent test of the available 200 Ma APWP running means, being in agreement with that recently proposed by T2008 and confirming the validity of the
corresponding segment obtained from paleomagnetic data of different plates (particularly influenced by North American data contribution), translated to northwest Africa through available kinematics models based on magnetic anomalies and fracture zones and realistic estimates of pre-breakup extension (T2008, and references therein).

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