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Notes

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Abstract: The continental Argana Basin of Morocco is the trans-Atlantic counterpart of the extensively studied Fundy, Hartford and Newark basins in north-eastern America, that have provided the astrochronologically tuned geomagnetic polarity timescale (GPTS) for the late Triassic and earliest Jurassic. The Argana red-bed successions also show astronomically driven time control, which allowed trans-Atlantic correlations and revealed that the interval towards volcanism of the Central Atlantic Magmatic Province (CAMP) is without any significant hiatuses. Here, we present palaeomagnetic results from the cyclically bedded upper Triassic red-beds and the intercalated volcanics associated with CAMP. Our composite Argana section comprises an interval of 3.5–4.0 Ma, but its magnetostratigraphic pattern does not allow a straightforward correlation to the Newark GPTS. The continental red-bed deposits of the Bigoudine Formation demonstrate a dominant magnetic overprint that could only be removed at temperatures above 600 °C. We suggest that this overprint could have been caused by a period of (Jurassic, *c*. 170 Ma) magmatism that caused pervasive overprinting of the Triassic palaeomagnetic signal. Correlations between the sections in the Tazantoute region are not straightforward, hampered by the presence of a magmatic sill. The CAMP lava sequences of Tazantoute are all of normal polarity and record secular variation in a manner that agrees with short-lived pulses of CAMP activity in Morocco. Our results indicate that the sedimentary successions of the Argana Basin have the potential to evaluate the Newark GPTS, but that detailed palaeomagnetic analyses of more suitable sections with long(er) cyclostratigraphic records are required.

During the late Triassic, a series of half-graben and strike–slip basins formed along the presently eastern North American, north-western African and south-western European margins, associated with the break-up of Pangea (Fig. 1). The succession of upper Triassic sedimentary facies in the Argana Basin of Morocco is very similar to that found in the Bay of Fundy, Maritime Canada (Smoot & Olsen 1988; Olsen *et al.* 2000; Whiteside *et al.* 2007). Both basins were at that time positioned at 20–25°N latitude where deposition took place under semi-arid to arid conditions (Hay *et al.* 1982; Kent & Tauxe 2005). The Moroccan basins as well as their trans-Atlantic counterparts in North America show thick piles of tholeiitic lavas on top of upper Triassic clastic sediments. These subaerial lavas are part of the largest continental flood basalt province of the Phanerozoic: the Central Atlantic Magmatic Province, CAMP (Marzoli *et al.* 1999). The link between this flood basalt province and the end-Triassic mass extinction, one of the 'big five' of the Phanerozoic (Raup & Sepkoski 1982), was first proposed by Rampino & Stothers (1988) and subsequently by several others (e.g. Courtillot 1994; Courtillot & Renne 2003). It became more widely debated in recent years when several different intra-CAMP basins correlations were proposed (Olsen *et al.* 2002; Knight *et al.* 2004; Marzoli *et al.* 2004; Whiteside *et al.* 2007; Cirilli *et al.* 2009). Recently, with a multi-disciplinary approach, the onset of CAMP in Morocco has been linked to the major end-Triassic mass extinction documented in the marine realm (Deenen *et al.* 2010). This correlation has been confirmed in continental sections by Whiteside *et al.* (2010) and in marine sections by Ruhl *et al.* (2010).

Integrated stratigraphic studies focusing on cyclostratigraphy, magnetostratigraphy and basalt geochemistry (Deenen *et al.* 2010; Ruhl *et al.* 2010) have suggested that a series of short CAMP volcanic pulses took place 20–120 ka after a characteristic short (*c*. 25 ka) reverse polarity interval (E23r), first recognized in the Newark Basin (Kent & Olsen 1999). The Argana Basin of Morocco forms a key region for trans-Atlantic CAMP correlation and is ideally suited for testing the records of the North American basins. This requires, of course, high-resolution time control on both sides of the Atlantic. Astronomical timing of the magnetostratigraphic record provides such a high-resolution timescale for the volcanic and biologic events straddling the Triassic–Jurassic

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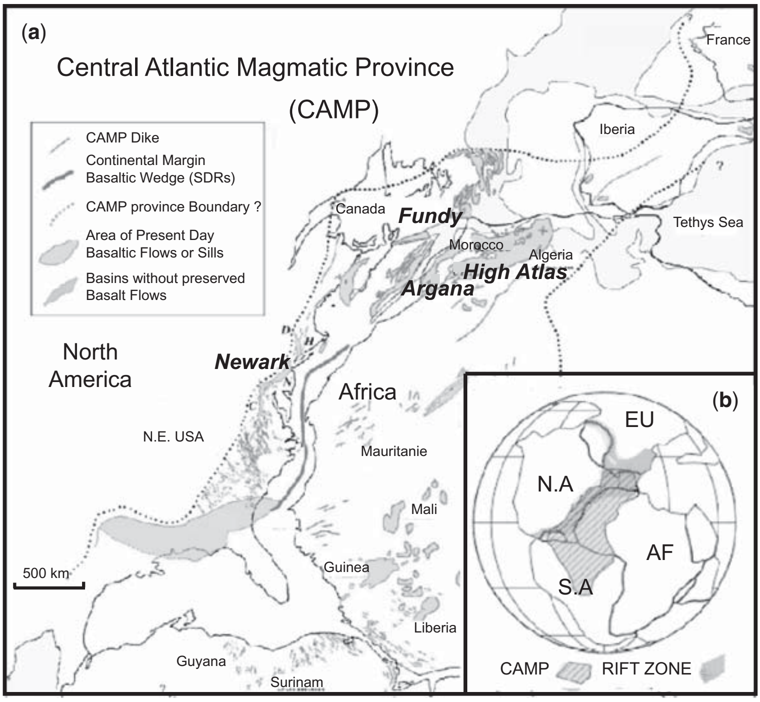

Fig. 1. Palaeoreconstruction (*c.* 200 Ma) of the Central Atlantic Magmatic Province (CAMP). (**a**) The important basins discussed in this study are indicated in large bold font. The extent of this magmatic province on the four continents surrounding the present-day Atlantic Ocean is indicated in (**b**). Maps are modified after McHone (2000).

boundary interval. Here we present palaeomagnetic analyses of upper Triassic red-beds and CAMP basalts on several sections in the Argana Basin, aiming to evaluate the late Triassic geomagnetic polarity timescale (GPTS) derived from the Newark supergroup basins (Kent *et al.* 1995; Kent & Olsen 1999, 2008) and the duration of the volcanic CAMP pulses (Knight *et al.* 2004).

The Argana Basin: geological setting and orbital forcing

Geological setting

Upper Permian, Triassic and lowermost Jurassic continental deposits are well exposed in the Argana Basin, situated between the Moroccan cities of Agadir and Marrakech along the western edge of the High Atlas mountain chain. The Argana Basin is the westwards extension of the Essaouira Basin, now separated from it due to Alpine orogeny (Hofmann *et al.* 2000). Middle- to Upper Triassic rocks in the Argana Valley consist of at least 2500 m of coarse- to fine-grained red-brown fluvial, lacustrine and floodplain clastic deposits (Olsen *et al.* 2003). A succession of eight lithofacies essentially consists of a lower coarse stream-laid unit derived from nearby uplands, a middle lacustrine and deltaic complex and an upper aggradational mud-plain unit that passed westwards into an extensive salt flat (Hofmann *et al.* 2000). Thickness and lateral continuity of the sedimentary units vary considerably and this is attributed to a rather complex relation between sedimentation and differential movement of basement horsts and grabens during basin development.

Eight lithostratigraphic units prior to CAMP emplacement have been described by Tixeront (1973) and are discussed in more detail by Hofmann *et al.* (2000). In this study we sampled the Bigoudine formation, the CAMP basalts and the red-beds above CAMP. The stratigraphy in the southern part of the Argana Basin is laterally changing on a scale of kilometres (Fig. 2). The thickness of the complete lava sequence is thinning out towards the south of the basin, which indicates that emplacement of CAMP may occur as pulses on a restricted, regional scale. Additionally, the most southern part of the basin is characterized by the presence of intrusives (sills, dykes) of several tens of metres thickness. These intrusives have also been described by Ait Chayeb *et al.* (1998), who argued that they have a middle Jurassic age (K–Ar dating) of between 151 ± 8 and 157 ± 9 Ma (Brown 1980). In our sampled sections the intrusives are intercalated in and on top of the Bigoudine Formation (Fig. 2), and thus stratigraphically below the first CAMP volcanics.

Cyclostratigraphy of the upper Triassic sediments (Bigoudine Formation)

The best-studied and hence best-known basin that formed during the break-up of Pangea is the Newark Basin of New York, New Jersey and Pennsylvania. Scientific coring provided a *c.* 5000 m thick composite section for the entire Upper Triassic and lowermost Jurassic, therefore comprising one of the longest records of climatic cyclicity. The combination of magnetostratigraphy and cyclostratigraphic control makes it the reference GPTS for the Late Triassic (Kent *et al.* 1995; Kent & Olsen 1999). The *c.* 20 ka precession cycles are termed Van Houten cycles and range 3–6 m in thickness in the Newark Basin. The expression of this cycle is modulated by other orbital frequencies, notably by eccentricity variations with periods around 100 ka and – most prominently – of 404 ka, the cycle referred to as the McLaughlin cycle. Since the 404 and 100 ka cycles are constant during geological time, they can be used to obtain time control in cyclic sections, pinpoint events in a relative timescale and correlate to an absolute time frame if the relative timescale is tied to the radioisotopically dated CAMP volcanics.

The same orbital variations appear to have controlled the depositional environment in the Argana Basin. Hofmann *et al.* (2000) observed various cycle thicknesses in the field and assumed that the smallest scale cyclicity would correspond to the precessional variation (*c.* 20 ka). Hence, they derived a sedimentation rate just prior to the onset of CAMP (in unit T8) of *c.* 9.5 cm ka^{-1} or *c.* 1.90 m per precession cycle. Deenen *et al.* (2010) studied a 200 m long uppermost Triassic section (AB-section in Fig. 2) in the Argana Basin for Milankovitch forcing on a high-resolution magnetic susceptibility record. They concluded that their most prominent *c.* 6 m cycle (Fig. 2, photo AB) was attributed to the *c.* 100 ka eccentricity cycle, while other peaks in the spectral analyses agreed very well with the orbital periods predicted for the latest Triassic. These results provided a first-order control on sedimentation rates (5.4 cm ka^{-1}) for the south-western part of the Argana Basin (Deenen *et al.* 2010).

Palaeomagnetic analyses of the Argana Basin

Palaeomagnetic sampling and methods

We densely sampled three red-bed sections in the western Argana Basin (Sections 1–3 in Fig. 2) to obtain a high-resolution composite magnetostratigraphy for the time interval around CAMP emplacement. A short interval of clastic sediments just prior to the first lavas of the CAMP (MO-series in Fig. 2) was earlier analysed to locate the short reverse chron E23r (Deenen *et al.* 2010). We also sampled the Argana CAMP lava flows near the village of Tazantoute, both along the road near Tazantoute and in the valley along the river including one level of baked sediment. Since the lavas along the road were quite weathered and gave questionable results, we resampled several lavas in a section up-hill (a total of 13 flow units with 4–11 cores per flow; Table 1) to determine polarity as well as palaeosecular variation (PSV) for comparison with the results of lavas in the High Atlas (Knight *et al.* 2004).

Samples were demagnetized both thermally (TH) and by alternating fields (AF). Thermal demagnetization was performed with temperature increments of 50–100 °C up to *c.* 500 °C followed by smaller steps (10–20 °C) towards 680 °C, in a magnetically shielded laboratory-built furnace. Alternating field demagnetization has been applied (up to 100 mT with increments of 5–10 mT) on an in-house developed robot, which let the samples pass through a 2G Enterprises SQUID magnetometer (noise level 10^{-12} Am^2). The natural remanent magnetization (NRM) of the thermally demagnetized samples was measured on a horizontal 2G Enterprises DC SQUID cryogenic magnetometer (noise level 3×10^{-12} Am^2). Orthogonal projection diagrams (Zijderveld 1967) were interpreted using principal component analysis (Kirschvink 1980). We used Fisher (1953) statistics to derive mean directions, after applying a variable cut-off (Vandamme 1994) to the corresponding virtual geomagnetic pole (VGP) distributions.

Upper Triassic red-beds (Bigoudine Formation)

Demagnetization diagrams in the three sampled sections have similar characteristics as the diagrams of samples from the central Argana Basin (Deenen *et al.* 2010) and the Fundy Basin in Canada (Kent & Olsen 2000; Deenen *et al.* 2011). The NRM generally consists of two components (Figs 3 & 4), in addition to an occasional small component removed at low temperature steps (<150 °C) likely reflecting a recent viscous overprint. The first component (A) is the most persistent and is usually observed in linear demagnetization trajectories in the temperature range 150–600/620 °C (or occasionally slightly higher which leads to the conclusion that this component most likely resides in haematite, which is confirmed by thermal decay curves; Fig. 3d). Considering its consistent direction of invariably normal polarity, we conclude that this

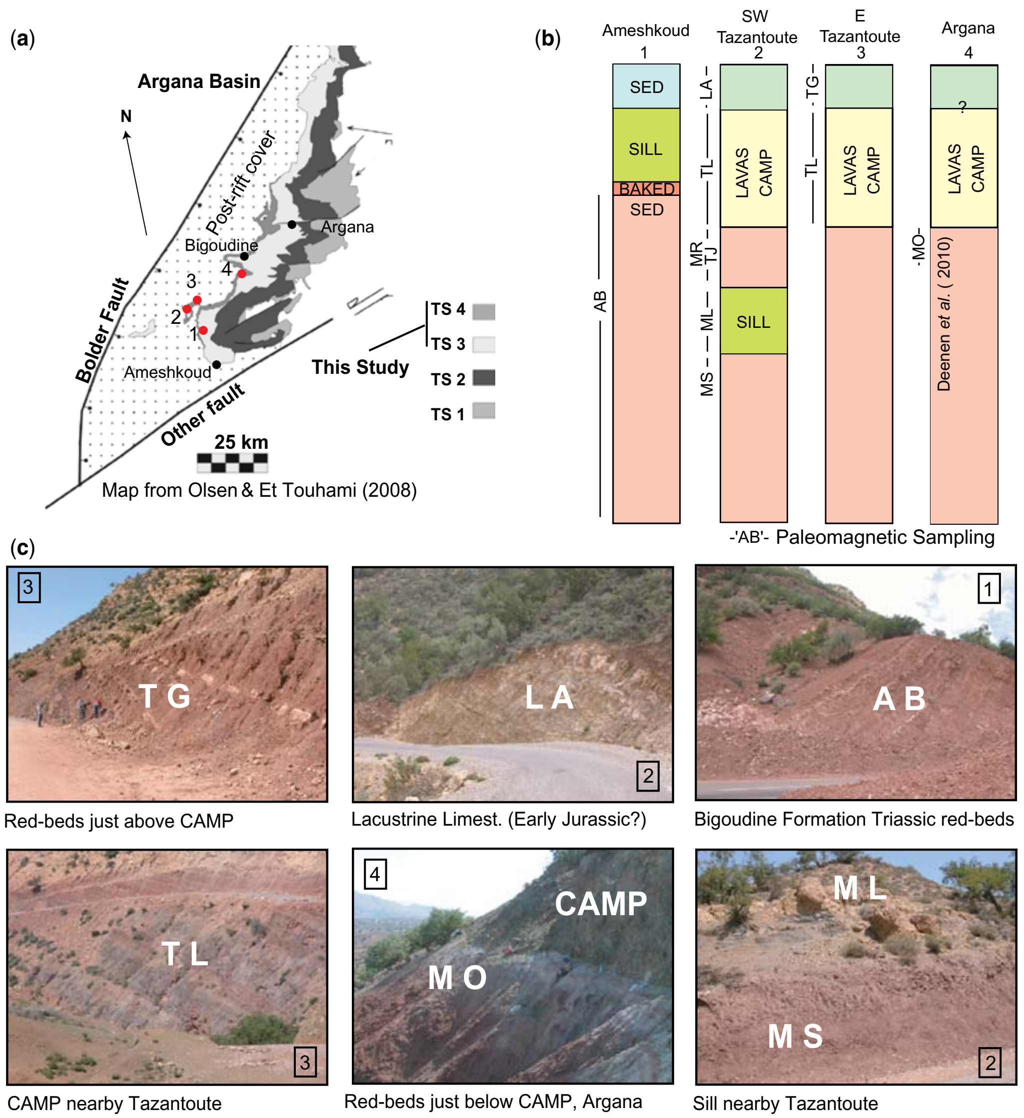

Fig. 2. Overview of Argana sections. (**a**) Geological map of the Argana Basin modified from Olsen & Et Touhami (2008) showing the sampling locations. TS 3 indicates the sediments of late Triassic age deposited prior to CAMP. TS 4 indicates CAMP basalts and the overlying younger sediments (latest Triassic–earliest Jurassic age). TS 1&2 represent Permian to middle–upper Triassic deposits which have not been considered in this study. (**b**) Schematic overview of the studied sections within the Argana Basin. Locations are indicated in (a). Lines and abbreviations along the columns correspond to palaeomagnetic sample tracks and codes used in the sections. (**c**) Photographs of the studied sections, numbers and abbreviations as in (a) and (b).

is a persistent overprint. A present-day or recent origin can be excluded here, because this component shows a substantial anticlockwise rotation and has much lower inclinations than the present-day geocentric axial dipole (GAD) field for the Argana Basin (Fig. 3a). The second component (B) is only removed at the highest temperatures, well above 500–600 °C and up to 680 °C, and was often not reliably determined because intensities became too low or the component was overprinted by the A component too much. This component most likely resides in haematite as well and is considered as the characteristic remanent magnetization (ChRM) for these red-beds (Deenen *et al.* 2010, 2011).

Table 1. *Palaeomagnetic results of the Tazantoute Valley lavas*

Site	Geochemical unit	N_{dem}	N_{sel}	Dec	Inc	k	α95	Strike	Dip	Dec-up	Inc-up	Strike-up	Dip-up	Dec-tc	Inc-tc
05A	IU	7	7	352.5	49.5	119.9	5.5	228	7	352.1	39.5	229.4	12.2	347.9	29.0
07A	IU	9	7	13.5	30.1	171.0	4.6	228	7	11.7	20.9	229.4	12.2	8.8	13.2
08A	IU	9	7	351.6	47.3	24.5	12.4	228	7	351.4	37.3	229.4	12.2	347.6	26.7
09A	LU	11	11	4.6	45.0	264.1	2.8	228	7	2.6	35.3	229.4	12.2	357.9	26.0
13A	IU	8	6	316.1	50.9	136.2	5.8	313	23	321.6	42.3	315.0	14.9	334.2	38.9
20A	IU	9	7	331.0	36.0	110.2	5.8	333	30	332.9	26.5	334.3	20.4	342.9	25.2
20B	IU	6	5	333.0	37.1	312.4	4.3	333	30	334.8	27.5	334.3	20.4	345.0	25.5
TL13	IU	6	3	302.2	51.5	96.3	12.6	313	23	309.9	44.3	315.0	14.9	324.4	43.7
TL14	IU	4	3	319.1	46.6	353.6	6.6	313	23	323.5	37.8	315.0	14.9	334.1	34.2
TL15	IU	7	6	312.9	43.0	564.2	2.8	320	18	317.5	34.8	321.2	9.3	324.0	34.9
TL16	IU	8	7	316.1	38.4	118.7	5.6	320	18	319.7	29.9	321.2	9.3	325.0	29.7
TL17	IU	8	8	333.5	39.8	136.2	4.8	320	18	335.4	30.2	321.2	9.3	340.3	27.5
TL18	IU	8	7	335.1	40.9	163.9	4.7	320	18	336.9	31.2	321.2	9.3	342.0	28.3
TS1 +2	sed	6	6	340.9	47.2	119.3	6.2	318	22	342.2	37.3	319.7	13.4	350.4	31.3

Geochemical unit as defined in Deenen *et al.* (2010). N_{dem}, number of demagnetized samples; N_{sel}, number of usable samples; Dec, declinations; Inc, inclinations; k, estimate of the precision parameter; α95, cone of confidence derived from the ChRM directions; Strike/Dip, bedding plane used for tectonic correction; Dec-up, Inc-up, Strike-up and Dip-up, declinations, inclination and tectonic bedding plane corrected for dipping anticline; Dec-tc and Inc-tc, declination and inclinations corrected for both bedding plane and dipping anticline.

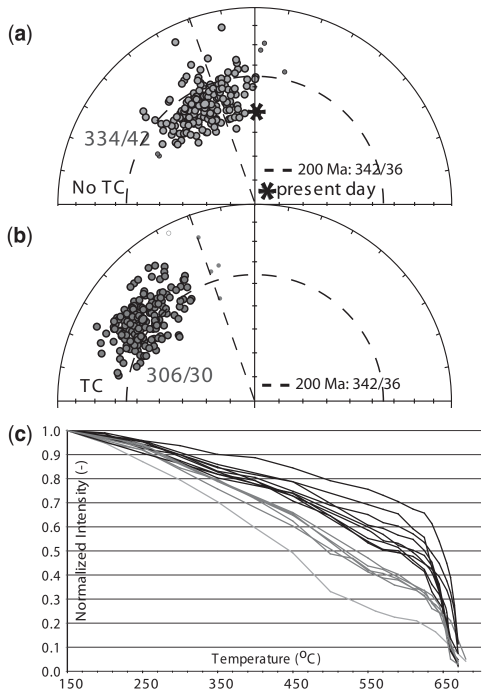

Fig. 3. Palaeomagnetic results of the A-component (overprint) from the Ameshkoud section. (**a**, **b**) Equal area projections for the uncorrected (No TC) and tectonically corrected (TC) A-component, in general derived from the 100–600 °C interval. Small symbols represent directions rejected by the Vandamme (1994) cut-off. We additionally show (dashed lines) the expected end-Triassic (200 Ma) direction for the Argana Basin calculated from the African palaeopole of Torsvik *et al.* (2008). (**c**) Representative normalised (150 °C) decay curves for thermally demagnetized samples throughout the section.

Several samples of the Ahmeskoud section (Fig. 2, Section 1) show evidence for reversed (R) field behaviour, because they clearly pass the origin of the Zijderveld diagrams (Fig. 5). The B component does not show clear antipodal normal and reverse directions, since it was not possible to reliably determine these high-temperature directions. The polarity, however, can be established with a variable degree of confidence and we interpret this component to be of primary (Triassic) origin since it shows both normal and reverse polarities (Fig. 3).

The palaeomagnetic results for the samples obtained from the red-beds below and above the sill near Tazantoute (MS and MR in Fig. 2; Section 2) show a straightforward behaviour. We find only normal directions for both A and B components for all measured samples (Fig. 4; see Deenen 2010 for details), although some samples (e.g. TJ 14, Fig. 4c) have a tendency to pass the origin at the highest temperatures. The directions of the A and B components are almost indistinguishable, and the persistent A component hampers a reliable determination of ChRM directions.

The palaeomagnetic results for the red-beds overlying the CAMP sequences (Fig. 2; Section 3) are not straightforward. We again observe a pervasive and normal polarity overprint direction in almost all samples (Fig. 6). The high-temperature component is mostly insufficiently resolved, although some samples tend to go to reversed polarity at the highest temperatures (see Deenen 2010 for details). These results are generally of poor quality and we must conclude that a straightforward magnetostratigraphic pattern of the sediments above CAMP cannot be resolved.

The directions of the A component could be reliably established in all three sections and the mean results are presented in Table 2 before (no tc) and after applying tectonic corrections (tc). A fold test applied to these directions is clearly negative, which indicates that the A component overprint is of post-folding origin (Fig. 7).

The CAMP lavas (Tazantoute sections)

Palaeomagnetic results from the lavas have been obtained from two sections near the village of Tazantoute (east- and SW Tazantoute sections, Fig. 2). Both sections form the limbs of a gently north-dipping (*c.* 10°) anticlinal structure. The succession of lavas corresponding to the Lower Unit (LU) and Intermediate Unit (IU) was sampled along the road as well as inside the valley along the river, which surprisingly gave different results. All lava flows of the road section show directions corresponding to the present-day field before tectonic correction suggesting that they have all subrecently been remagnetized. Only two lavas of the later sampled up-hill west section give results (Fig. 8). The Tazantoute lavas in the valley section, however, clearly give different results (Table 1). A small viscous component is removed in the first steps (max. 150 °C or *c.* 20 mT), after which most demagnetization diagrams indicate that the NRM has been completely removed at fields of 100 mT or temperatures of 580 °C. This indicates that (Ti-poor) magnetite is the main carrier of the magnetic signal in the lavas. It provides very consistent ChRM directions, which we interpret as primary components. We only present here the results from the lava flows that recorded primary late Triassic directions (Fig. 8).

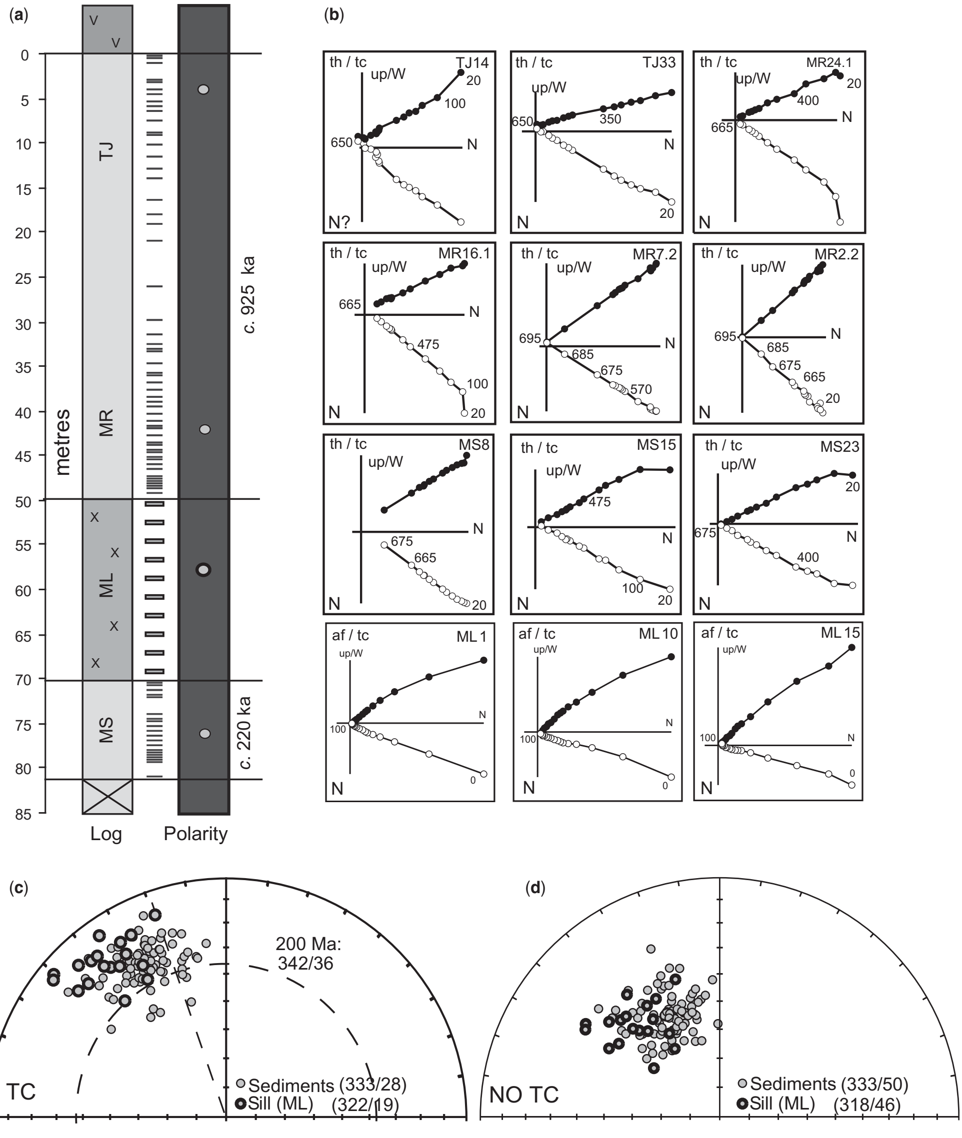

Fig. 4. Palaeomagnetism of the lower SW Tazantoute (sill) section. (**a**) Lithological column with sample levels indicated, all showing normal polarity. Approximate time present in the section is shown on the right and is derived from the average sedimentation rate in the nearby Ameshkoud section (*c.* 5.4 cm ka^{-1}). (**b**) Representative Zijderveld diagrams (TC) from the red-bed samples (MS, MR, TJ) and for the sill (MS) samples. Abbreviations (MS–ML–MR–TJ) correspond to sample tracks given in Figure 2. (**c**, **d**) Equal area projection of the high-temperature components before (no TC) and after (TC) tilt correction. Different symbols reflect sill and sediment samples. The expected Triassic direction at Argana is indicated by dashed lines.

Discussion

Pervasive overprint in the Argana red-beds: a Jurassic feature?

All sampled red-bed sediments below the first CAMP lavas show a very persistent overprint direction (component A), hampering the reliable determination of the primary B component. The A component must be of post-tilt origin since it is consistent in all three red-bed sections, but becomes randomly directed after tilt correction (Fig. 7). It does not correspond to the GAD direction at the present latitude, since it shows a significant *c.* 30°

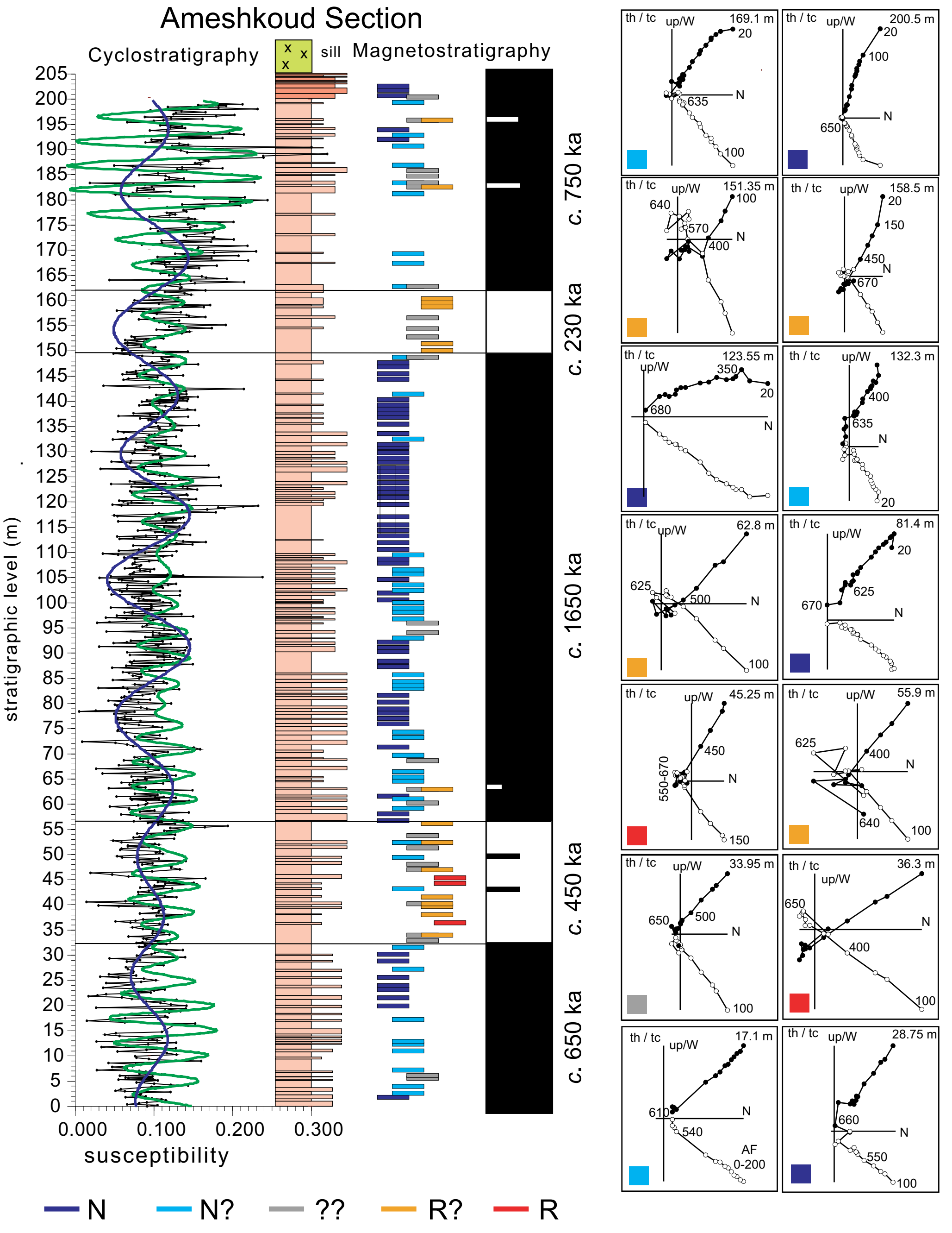

Fig. 5. Magnetostratigraphy for the cyclostratigraphically investigated Ameshkoud section. Magnetic susceptibility data are shown in the left panel together with the filtered 100 and 400 ka eccentricity signal (green and blue lines, respectively) according to Deenen *et al.* (2010). Palaeomagnetic directions cannot accurately be derived because of a pervasive overprint (Fig. 3). Our estimate of the polarity is indicated by N – N? – ?? – R? – R, where N(?) denotes (likely) normal, R(?) denotes (likely) reversed and ?? is uncertain. On the right are representative Zijderveld diagrams (all tectonically corrected) throughout the section; numbers refer to alternating field steps (mT) or temperatures (°C). Durations of the polarity zones are derived from the filtered 100 ka cycles.

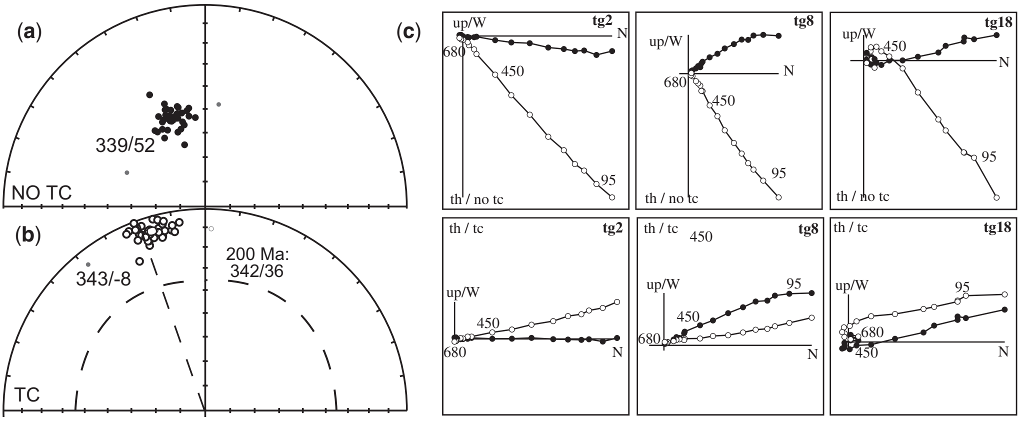

Fig. 6. Palaeomagnetic results for sediments above the CAMP lavas just NE of Tazantoute (TG sampling track in Section 3, Fig. 2). (**a**, **b**) Equal area projections for the uncorrected (no TC) and tectonically corrected (TC) overprint component, generally derived from the 100–600 °C interval. Small symbols have been rejected by the Vandamme (1994) cut-off. (**c**) Representative Zijderveld diagrams; numbers and symbols as in Figure 5.

anticlockwise declination deviation. Consequently, the overprint must be related to a post-Triassic and post-tilting pervasive remagnetization event affecting the Argana Basin.

To estimate the age of this remagnetization event, we compared the overall mean direction of the A component before tilt correction with the directions derived from the apparent polar wander path (APWP) of the last 200 Ma (Torsvik *et al.* 2008) for the location of the Argana Basin. It shows that two specific time intervals appear as likely periods of remagnetization: the early Jurassic interval of 190–160 Ma and the early Cretaceous interval of 110–100 Ma (Fig. 7). The older period roughly coincides with the assumed age of the sill intrusion (Brown 1980), which has been linked to a major thermal event caused by emplacement of plutonic bodies dated at *c.* 160 Ma in Triassic sedimentary rocks of the High- and Middle Atlas Basins (Rais 2002). We conclude that this event is the most likely candidate to have caused the pervasive overprint A component. This would imply, however, that folding and tilting of the Argana Basin had already occurred in Jurassic times. Alternatively, remagnetization may have been caused by processes related to inversion, folding and thrusting of the Atlas, which has been argued to have occurred between 30 and 20 Ma ago (Beauchamp *et al.* 1999). Indeed, the inclination of component A also coincides with Africa's inclination of the last 30 Ma (Fig. 7). This scenario would then require that our sections underwent a *c.* 25° counter-clockwise Late Oligocene or younger rotation. This is unlikely because our basalt directions – that now fit well with the directions from CAMP basalts in the High Atlas (Knight *et al.* 2004; Fig. 8) – would then have to be corrected by *c.* 25°. Such corrected directions would then strongly disagree with the High Atlas results (unless the High Atlas has also experienced the same rotation) and both Argana and High Atlas would not have recorded Triassic directions. On the principle of least astonishment, we retain a Jurassic thermal event as the cause for remagnetization.

Trans-Atlantic correlation of upper Triassic red-beds

The very long and supposedly continuous continental record of the US Newark Basin makes it the reference section by choice, to which important events in the late Triassic can be correlated. Several studies, however, have questioned the completeness of the Newark record. In particular, the interval just below the first CAMP lavas has been suggested to contain a major unconformity, mainly because biostratigraphic studies have implied a Norian age for the sediments just below the end-Triassic palynologic turnover event (van Veen 1995; Kozur & Weems 2007; Cirilli *et al.* 2009). Consequently, these authors assumed a major hiatus in the Newark Supergroup Basin approximately one precession cycle below the first CAMP extrusives, for which there is no evidence in the field (Kent & Olsen 1999).

The Triassic–Jurassic palaeomagnetic pattern in the Newark Basin (Fig. 9) is characterized by normal polarity data, with only a very short reverse interval (E23r, *c.* 25 ka) of reverse directions just below the first CAMP lavas. This short reverse polarity chron is therefore of crucial importance

Table 2. *Summary of palaeomagnetic results*

Section	N_{dem}	N_{sel}	Dec	Inc	k	α95	K	A95	ΔD_x	ΔI_x	Dec_tc	Inc_tc	k	α95	K	A95	ΔD_x	ΔI_x
AB	174	169	335.5	42.2	43.3	1.8	38.8	1.8	1.9	2.3	306.1	30.3	49.1	1.6	53.8	1.5	1.6	2.4
TG	34	32	339.3	51.5	170.5	2.0	129.6	2.2	2.6	2.4	343.3	−8.0	170.5	2.0	281.7	1.5	1.5	3.0
ML (sill)	18	18	317.5	46.0	48.1	5.0	42.5	5.4	6.0	6.6	322.2	18.9	48.1	5.0	68.6	4.2	4.3	7.7
MS	*22*	*22*	*335.6*	*52.5*	*176.1*	*2.3*	*145.7*	*2.6*	*3.1*	*2.7*	*332.8*	*26.7*	*176.1*	*2.3*	*290.2*	*1.8*	*2.9*	*3.1*
MR	*31*	*30*	*330.2*	*52.9*	*74.5*	*3.1*	*47.8*	*3.8*	*4.6*	*4.0*	*332.0*	*26.0*	*97.6*	*2.7*	*121.5*	*2.4*	*2.5*	*4.1*
TJ	*31*	*31*	*330.6*	*45.8*	*31.3*	*4.7*	*25.9*	*5.2*	*5.8*	*6.4*	*331.4*	*30.9*	*31.3*	*4.7*	*35.5*	*4.4*	*4.6*	*7.1*
MS + MR + TJ	84	81	332.6	50.3	55.3	2.1	44.5	2.4	2.8	2.7	332.6	27.9	63.4	2.0	79.7	1.8	1.8	3.0
All sediments	3	3	335.8	48.0	216.5	8.4	252.1	7.8	8.9	9.1	328.2	17.5	8.5	45.1	13.8	34.6	35.1	64.4

N_{dem}, number of demagnetized samples; N_{sel}, number of usable samples; Dec, declinations; Inc, inclinations; k, estimate of the precision parameter based on ChRM directions; α95, cone of confidence derived from the ChRM directions; K, estimated of the precision parameter determined from Virtual Geomagnetic Poles (VGPs); A95, cone of confidence determined from VGPs; ΔD_x and ΔI_x, declination and inclination error; _tc, corrected for bedding tilt.

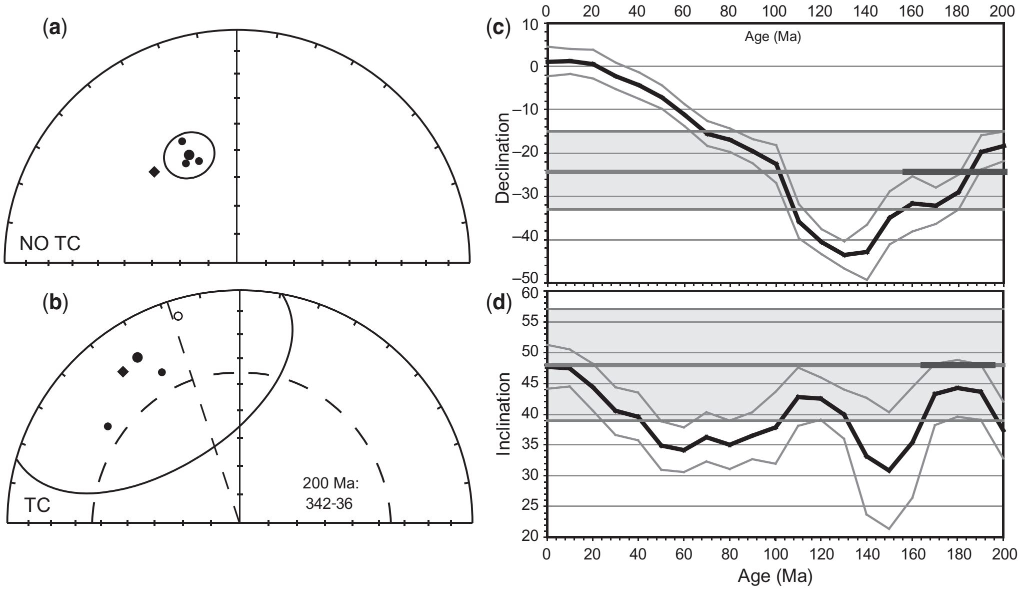

Fig. 7. Comparison of the mean overprint direction (**a**) before and (**b**) after tilt correction from the Ameshkoud section (Fig. 4), the SW Tazantoute (sill) section (Fig. 4) and the SW Tazantoute (above CAMP) section (Fig. 6). The sill mean direction (diamond) is shown separately. The means of the overprint directions are consistent before tilt correction, but highly scattered after tilt correction. (**c**, **d**) The mean of the (no TC) overprints is compared with the expected directions (declination and inclination) for Argana for the last 200 Ma (from Torsvik *et al.* 2008); shaded areas represent the confidence interval. The most likely fit of the mean overprint direction with the expected directions is indicated by a thick line; shading indicates the errors in declination and inclination. A best fit is found in either Jurassic or early Cretaceous times. The Jurassic magmatic pulse *c.* 160 Ma (Brown 1980; Ait Chayeb *et al.* 1988) seems a good candidate to have caused the overprint.

for intra-CAMP correlation based on palaeomagnetism. The topmost sedimentary interval just prior to the first CAMP in the Argana Basin also comprises an interval with transitional and reversed directions, correlated to E23r (Deenen *et al.* 2010). Cyclostratigraphic estimates further indicate a similar duration for this reversed interval as E23r in Newark. Moreover, chron E23r has also been resolved in the uppermost Triassic sediments of the Fundy Basin, a few centimetres below the transition to the CAMP (Partridge Island) basalt (Deenen *et al.* 2011). These three consistent recoveries of chron E23r indicate that the red-bed sections in Newark, Argana and Fundy are continuous and complete at least until the base of E23r, making further hypotheses on a hiatus in the Newark Supergroup record at the younger faunal turnover obsolete.

Marine–continental correlations for the uppermost Triassic Rhaetian Stage are also in disagreement with palaeomagnetic and cyclostratigraphic data (see Hounslow & Muttoni 2010; Hüsing *et al.* 2011). The hypothesis for a short (*c.* 1 Ma) Rhaetian Stage (Krystyn *et al.* 2002, 2007; Gallet *et al.* 2007; Kozur & Weems 2007), based on palaeontological arguments (conchostracans and equal ammonite duration) is in serious disagreement with the palaeomagnetic correlations from many sections in the Tethys realm that favour a significantly longer Rhaetian of *c.* 9 Ma (Kent *et al.* 1995; Channell *et al.* 2003; Muttoni *et al.* 2004, 2010; Hüsing *et al.* 2011).

The Rhaetian controversy can probably only be solved by detailed cyclostratigraphic correlations that confirm the astronomical duration of the Newark polarity pattern (Hüsing *et al.* 2011). Our composite magnetic polarity stratigraphy for the sediments deposited in the Argana Basin cannot however be correlated straightforwardly with the Newark Basin (Fig. 7). The cyclostratigraphic estimates for the Ameshkoud section suggest a polarity pattern with chron durations of >600 ka (N1), *c.* 450 ka (R1), *c.* 1600 ka (N2), *c.* 230 ka (R2) and an unknown interval (N3) until the base of CAMP. The most logical correlation to E21n, E21r, E22n, E22r and E23n results in unacceptable mismatches of up to *c.* 1 Ma. Potential explanations for these failed correlations are hiatuses in either Newark or Argana, incorrect stratigraphic correlations in the Argana Basin and unresolved

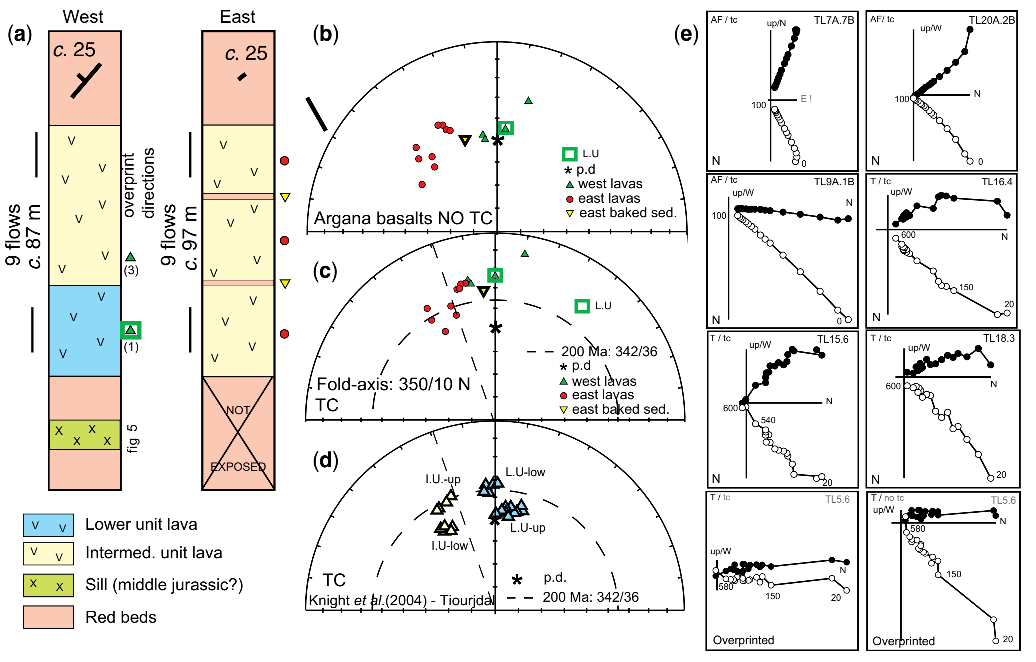

Fig. 8. Palaeomagnetism of the CAMP lavas. (**a**) Schematic overview of the sampled CAMP sections SW and east of Tazantoute. Colours (blue and yellow) correspond to the geochemical signature (lower- and intermediate unit, respectively; Deenen *et al.* 2010). Symbols on the right side of the columns correspond to the symbols used in (b–d). All lavas show normal polarity directions only. Equal area projections (**b**) uncorrected (no TC); (**c**) plunge plus tilt corrected; and (**d**) tilt corrected lavas from the High Atlas of Knight *et al.* (2004) for comparison with the Argana data. Dashed line represents the expected latest Triassic (200 Ma) direction at Argana (Torsvik *et al.* 2008). (**e**) Representative Zijderveld diagrams; numbers and symbols as in Figure 5.

palaeomagnetic signals in the Bigoudine red-beds. A far better match can be made to Newark chrons E15n, E15r, E16n, E16r and E17r, implying a substantial hiatus in our Ameshkoud section of *c.* 8 Ma (most likely at the level of the sill).

We conclude that an unequivocal correlation between the two trans-Atlantic basins is not yet feasible based on the present results. Future attempts should include more careful demagnetization in the 600–680 °C temperature interval and incorporation of more and longer cyclostratigraphic records, at locations where there is a clear continuous transition to the CAMP lavas. Alternatively, high-resolution sampling of the uppermost Triassic red-beds in the Fundy Basin – or in another suitable basin – may further improve the intra-CAMP basins correlation.

Duration of the CAMP pulses

Palaeomagnetic research on the CAMP lavas in the High Atlas, Morocco (Knight *et al.* 2004) together with their geochemistry (Marzoli *et al.* 2004) suggests that CAMP in the High Atlas has been emplaced in three short consecutive pulses (Lower, Intermediate, Upper Units or LU, IU and UU) followed by one younger pulse (Recurrent Unit or RecU). These pulses each have a characteristic geochemical signature. Marzoli *et al.* (2004) use TiO_2 to discriminate between the different units. Deenen *et al.* (2010) show that these separate pulses are better distinguished/diagnosed with typical Rare Earth Elements (REE) ratios, in particular Y/Nb v. Lu/Hf. Previous geochemical results indicate that the lower- and intermediate units have been emplaced in the Argana Basin (Marzoli *et al.* 2004; Deenen *et al.* 2010), very similar to the emplacement in the High Atlas (Knight *et al.* 2004).

In general, our palaeomagnetic results for the IU-group lavas within the Argana Basin show directions that are very comparable to those predicted by the APWP (Fig. 8; Table 1; Torsvik *et al.* 2008). We therefore conclude that these lavas record the original palaeomagnetic field of the latest Triassic. This has also been shown for the IU-group lavas in the High Atlas (Fig. 8e; Knight *et al.* 2004). Our directional data from the Tazantoute IU-group

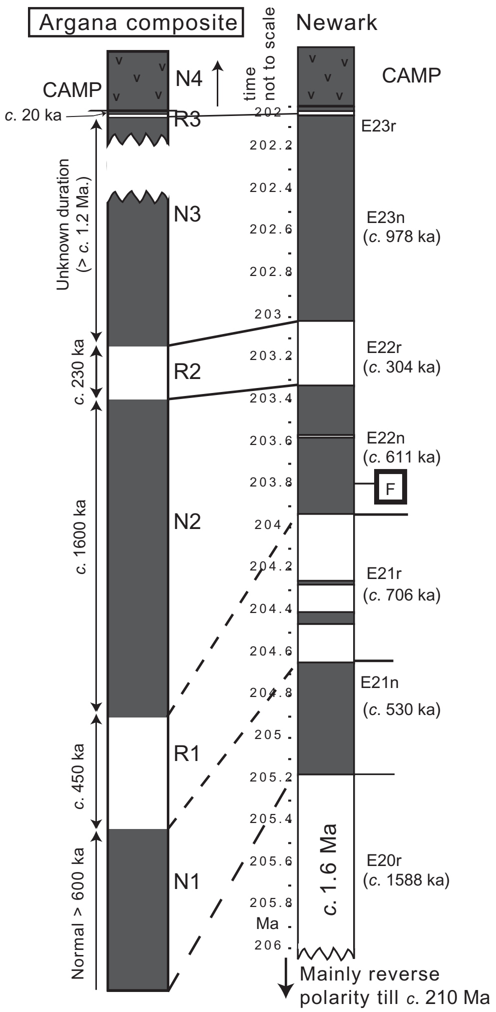

Fig. 9. A composite magnetostratigraphy of the Argana sequences deposited below the first CAMP lavas compared to the Newark GPTS (Kent & Olsen 1999) and Fundy Bay composite (Kent & Olsen 2000; Deenen 2010). Possible faults are indicated with 'F'. Correlations – or the lack thereof – are discussed in the text.

in the Argana Basin are also in very good agreement with those of the same unit from the High Atlas (Knight *et al.* 2004).

We obtained only one reliable direction from a LU-group lava (Fig. 8; Table 1), which is interpreted as a pre-folding direction of most probably latest Triassic origin. This LU lava flow shows a distinctly different direction with no rotation, but very similar to the directions observed in the High Atlas LU lavas (Fig. 8d; Knight *et al.* 2004). In the High Atlas samples, the mean direction of the LU-group was shown to agree with a Triassic inclination. Secular variation of the field, recorded as distinct directional groups reflecting the short CAMP volcanic pulses, has been put forward to explain the difference between LU and IU directions (Knight *et al.* 2004). Our results from Tazantoute are in good agreement and support the conclusion that the onset of volcanism in Morocco (both in the High Atlas and Argana basins) occurred in many short synchronous pulses.

Conclusions

The palaeomagnetic signal of the upper Triassic red-beds of the Argana Basin in Morocco shows a pervasive overprint, carried by haematite, that is of post-folding origin but significantly different from post-early Cretaceous directions expected at the location of the Argana Basin. It must therefore have been acquired before the late Cretaceous. Plotted against the expected directions of the last 200 Ma it appears to be most likely of Mesozoic origin related to a remagnetization event at 190–160 Ma, in agreement with a Jurassic magmatic pulse around 160 Ma (Brown 1980; Ait Chayeb *et al.* 1988).

A dual-polarity component is revealed at high temperatures of 500–680 °C, also residing in haematite, which is interpreted as the primary magnetic signal. The topmost sedimentary interval just prior to the first CAMP comprises a short interval with transitional and reverse directions. This correlates to chron E23r (Deenen *et al.* 2010), indicating that the red-bed sections in Argana, Newark, and Fundy are continuous and complete at least until the base of E23r. An unequivocal correlation of the upper Triassic Argana magnetostratigraphy of the Ameshkoud and Tazantoute red-bed sections to the Newark GPTS is not yet feasible; future attempts should include more careful demagnetization in the 600–680 °C temperature interval and incorporation of longer cyclostratigraphic records that are demonstrably continuous up to the CAMP lavas.

The palaeomagnetic signal in the CAMP lavas of the Tazantoute sections shows significantly different results for the Lower Unit and Intermediate Unit. These results are in good agreement with the results from CAMP lavas of the High Atlas (Knight *et al.* 2004) and support the conclusion that the onset of volcanism in Morocco (both in the High Atlas and Argana basins) occurred in many short synchronous pulses.

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Earth's and life's history: from core to biosphere (CoBi) of the Utrecht University.

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