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The 125–150 Ma high-resolution Apparent Polar Wander Path for Adria from magnetostratigraphic sections in Umbria–Marche (Northern Apennines, Italy): Timing and duration of the global Jurassic–Cretaceous hairpin turn

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Abstract

A new high-resolution Apparent Polar Wander Path (APWP) segment has been obtained from the magnetostratigraphy of four Kimmeridgian to Lower Aptian sections in the Northern Apennines (Italy). The use of paleomagnetic data for determination of the Adria APWP was hampered by the large local rotations linked to Apennine tectonics, characterized by folds and thrusts developed during the Neogene. To overcome this problem, we have computed relative rotations between time overlapping sections and realigned them in a common declination reference frame (namely the Bosso section). We synthesized a new high-resolution 150 to 125 Ma APWP for Adria, which has a similar shape to the time-equivalent segment of the synthetic APWP of Africa of Besse and Courtillot [J., Besse, V., Courtillot, Apparent and true polar wander and the geometry of the geomagnetic field over the last 200 Myr, J. Geophys. Res. 107(B11) (2002), doi:10.1029/200JB000050]. A 26° clockwise rotation of our combined Adria APWP places it in almost perfect overlap with African data of same age, confirming that the Adria promontory moved coherently with Africa during this time span, whereas the counterclockwise rotation of Adria with respect to Africa was introduced later, most probably during Apennines orogenesis.

Finally, we discuss in relation with worldwide plate evolution the peculiar shape of our APWP, which displays a hairpin turn during Berriasian time, and dates the main Late Jurassic/Early Cretaceous change in plate motion at around anomaly M16.

Keywords: paleomagnetism; Apparent Polar Wander Path; magnetostratigraphy; Adria, Italy

1. Introduction

The accurate determination of Apparent Polar Wandering Paths (APWPs) of major cratons is an important goal pursued by the paleomagnetic community. They are a prerequisite to meaningful paleogeographic reconstructions, which are the basis for constraining as diverse geodynamic problems as climate modeling, mantle

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dynamics and even understanding Earth's present deep interior structure. They provide the paleogeographic reference for studies of terrane displacements or major events involving large-scale intracontinental deformation.

Despite the large effort performed by the paleomagnetic community over the last five decades, one of the major problems that plague the determination of the APWP is the partial or total lack of data for certain periods. For example, North America and European plates have an adequate number of poles to allow the construction of a sufficiently continuous APWP based on their own data [1]. However, each craton has periods during which there are insufficient good-quality pole determinations. To overcome this strong limitation, it has been proposed to use "composite" or "synthetic" APWPs, based on selected best data of major continents transferred using high-quality plate kinematic models onto a common single plate (see for example [2–4]). The overall transferred data set is then averaged, for example in 10 or 20 m.y. time-windows. The resultant "master" path can be transferred back in turn on each continent. This allows data from each plate to be checked or supplemented if there is a time gap. Even with this method, the number of data remains insufficient for certain periods, due to several reasons (including few numbers of available poles, impracticality of the fold test on tabular outcrops, difficulty in dating of sediments, incompletely averaged secular variation for igneous rocks). As a result, the temporal resolution and spatial accuracy of APWPs are variable and generally decrease going back in the geological time. For example, Besse and Courtillot [4] selected a large number of data (more than 30) in each of the 0–30 and 50–80 Ma time windows, but 120–130, 130–140 and 140–150 Ma time windows contained by contrast only 20, 12 and 8 paleopoles, respectively. However, a precise documentation of this time span is crucial since it marks the end of a fast APW track beginning at 170–180 Ma for all major plates, which lasted until the beginning of Cretaceous, when track directions changed and a major plate re-organization occurred. Unfortunately, paleomagnetic data from stable plates are of poor quality for this period.

In this study, we used a different approach, trying to reconstruct a magnetostratigraphy-derived high-resolution APWP using data from a single but not stable plate. We studied sediments from the Apennines (Italy), deposited on the Adria passive paleomargin. Adria has been considered, on the basis of paleomagnetic data, as a microplate that has moved independently from both Africa and Europe [5–7] or as a rigid African promontory [8–12]. Paleomagnetic data from the relatively unrotated portion of Adria (Southern Alps, Gargano, Apulia, Iblei and Istria) proved that Adria has mirrored the African drift since at least Early Permian times [10].

A great number of paleomagnetic studies focused on geodynamic, tectonic and magnetostratigraphic interpretation of data from Umbria–Marche (see, for example, [13–15]). However, the use of the large amount of available paleomagnetic data to reconstruct APWP is hampered by the large local tectonic rotations linked to Alpine and Apennine orogenesis. The Jurassic to Eocene Italian Umbria–Marche sections of the Apennines have demonstrated their exceptional magnetic and biostratigraphic potential for magnetostratigraphy but are unfortunately affected by large rotations which occurred during Miocene–Pleistocene time. Recently, Speranza et al. [16] reappraised the Kimmeridgian to Lower Aptian succession (150 to 125 Ma) belonging to Calcari a Saccocoma ed Aptici (referred as Calcari ad Aptici hereinafter) and Maiolica Formations, sampled from four sections located in the Umbria and Marche regions (Fig. 1). A polarity vs. time sequence was measured and successfully correlated to the magnetic polarity time scale of Gradstein et al. [17] and Channell et al. [18]. In this paper, we now investigate the evolution of directions vs. time, using the new Geologic Time Scale from Gradstein et al. [19] now available. All four sampled sections present a common time overlap that allows a measurement of their respective relative rotations and the realignment of all sections in a common declination reference frame (Bosso section). The aim of the work is to: (1) compute a common high resolution 125 to 150 Ma APWP for Adria; (2) compare our data with similar age APWP segment for Africa; (3) discuss the fine details and resolution of these APWPs in relation with worldwide plate evolution and True Polar Wander.

2. Geological setting and studied sections

The Umbria–Marche region belongs to the Northern Apennines folds and thrusts belt. This chain, which developed during Neogene time, is characterized by curved fronts verging toward the Adriatic foreland. The stratigraphic sequence cropping out in Umbria–Marche area is predominantly formed by a Meso–Cenozoic sedimentary succession, deposited along the Tethyan margin of Adria. Two extensional tectonic phases, the main during Triassic and another one in Early Jurassic time, affected the Triassic peritidal carbonate platform [20–22]. The last phase is documented by successions cropping out in the Apennines. It divided the Triassic–Early Jurassic carbonate platform in persistent carbonate

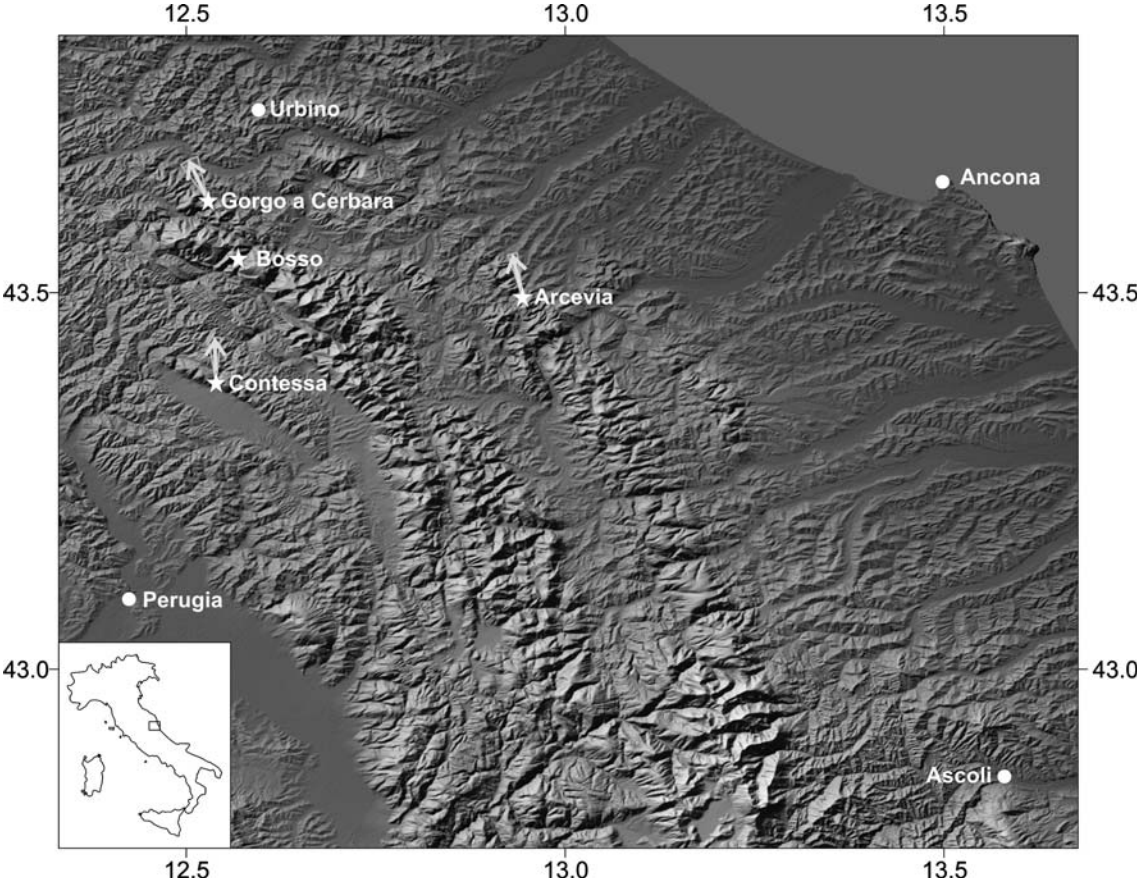

Fig. 1. Digital elevation model of the Umbria and Marche regions (Northern Apennines, Italy) with location of the studied sections. Light grey arrows: rotations of sections with respect to Bosso section, with error shown in grey.

platform (Lazium–Abruzzi area) and basinal (Umbria–Marche area) domains. The Jurassic to Early Cretaceous pelagic succession is characterized by great variability of facies and thickness: lithologies are mainly carbonatic, but in some portions, clays and cherts predominate. The depositional environment was influenced by differential subsidence and characterized by seamounts and deeper basinal area. The seamounts are bounded by Jurassic normal faults and topped by a lacunose and condensed succession, whereas basinal area are characterized by thicker successions, many intraformational slumpings and calcarenitic beds. The differential subsidence was terminated before Aptian time and facies and thickness became rather uniform in all the basinal area. The convergence between Africa and Europe, started in Late Cretaceous time, caused by closure of the Tethys ocean, and continued to the formation of the Apennines during Late Miocene–Pleistocene time, as documented by the age of siliciclastic deposits [23].

We analyzed samples from Calcari ad Aptici and Maiolica Formations. The Calcari ad Aptici Fm. is usually characterized by greenish limestones with black-grey cherts containing ammonite aptychi, but shows great variability in lithologies and thickness. Biostratigraphic data from ammonites and radiolarians indicate ages comprised between Early Kimmeridgian and Late Tithonian [24–26]. The Maiolica Fm. consists mainly of thin-bedded white to grey micritic limestones containing nodules and layers of dark chert. It has a variable thickness, from ca. 100 m on seamounts, to 400–500 m in the deeper basinal areas. Biostratigraphic data from nannofossil (e.g., [27–29]), calpionellids and planktonic foraminifera (e.g., [32,33]), radiolarians [25] and ammonites [29,30] indicate an age ranging from Late Tithonian to Earliest Aptian. The lower boundary of the Maiolica Fm. was constrained in age to the Early Cretaceous in the Arcevia section based on magnetostratigraphic data [16]. Previous studies on the Maiolica Fm. have shown that magnetization is carried by magnetite [34], and has been acquired during early diagenesis [30]. Furthermore, despite the magnetic remanence being very weak, the Maiolica Fm. yields a very stable magnetic signal.

Samples come from four sections (Fig. 1) exposed within the cores of NW-trending anticlines in the Umbria–Marche Apennines: Gorgo a Cerbara, Contessa, Arcevia and Bosso. We refer to Speranza et al. [16] for a detailed description of the sections. The Gorgo a Cerbara section, located 4 km east of Piobbico along the Candigliano River, has been studied for magnetostratigraphy and biostratigraphy by several authors since 1980s (see, for example, [13,14,34,35]). The Contessa section, located in a quarry few kilometres NW of Gubbio, is well known in the literature for magnetostratigraphic studies on the Paleogene Scaglia Fm. [35] and the Albian Marne a Fucoidi Fm. [36]. The Arcevia section is located within a quarry north of Arcevia town. Finally, the Bosso section is located along the road from Secchiano to Pianello. This section is well known in the literature for magnetostratigraphic and biostratigraphic studies [15,30].

Dating of the sections (see Speranza et al. [16]) was made by comparing the magnetozones to the geomagnetic polarity time scales [17,18], using biostratigraphic data from literature ([15,30,31] and reference therein) and analyzing the nannofossil content from the Calcari ad Aptici Fm. at Arcevia for the lowermost 20 m of the Maiolica Fm. at Contessa (Fig. 2).

3. Analysis and results

We refer the reader to the study by Speranza et al. [16] for detailed magnetic properties from the four sections. Alternating field demagnetization (AF) was chosen for routine measurement of the Maiolica Fm. samples, while samples from the Calcari ad Aptici Fm. were demagnetized thermally. Since the determination of a reliable APWP requires an accurate separation of the magnetization components, we have added complementary measurements for the present study. Indeed, the occurrence of a negative reversal test [37] in part of the sections in Gorgo a Cerbara and Contessa suggested the presence of unresolved magnetic components in the Maiolica Fm. samples.

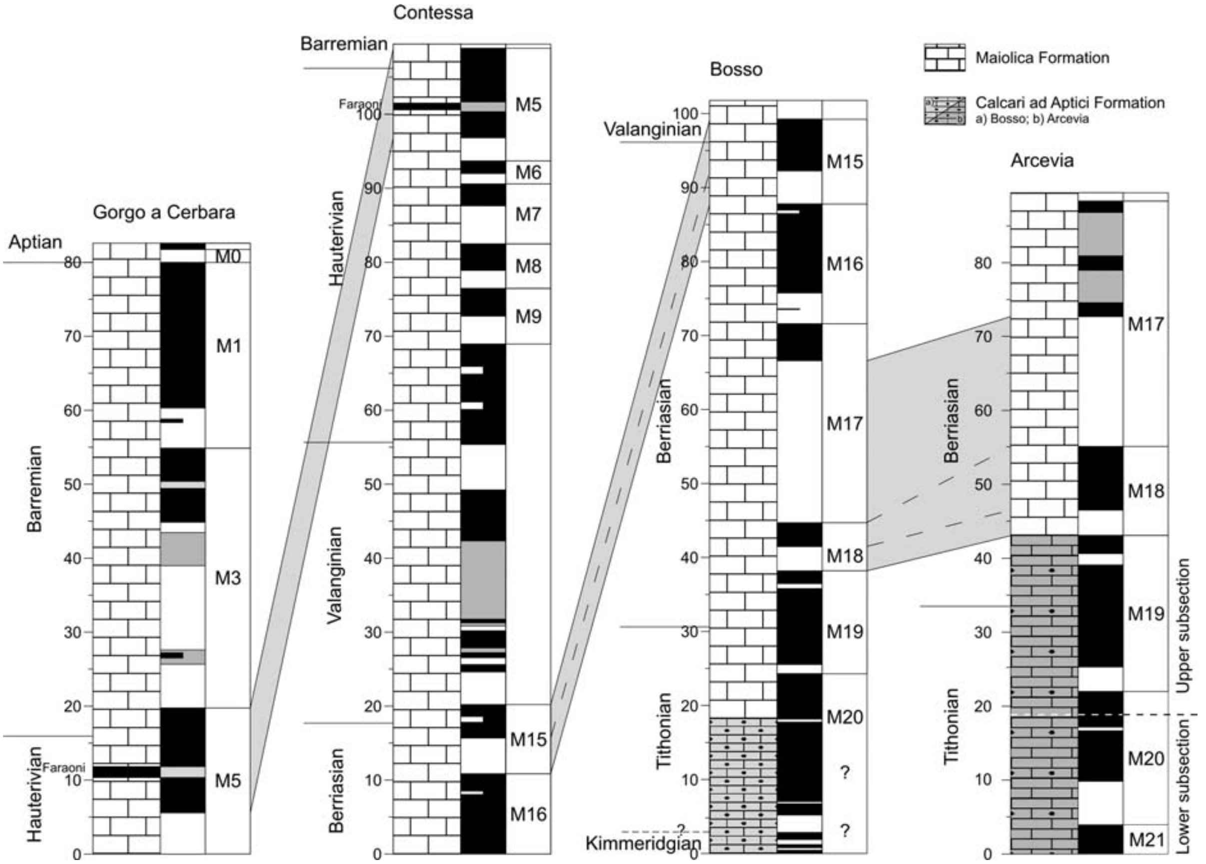

Fig. 2. Lithologies, ages (after Gradstein et al. [12]) and magnetostratigraphies of the studied sections (modify from Speranza et al. [16]; the Arcevia stratigraphic column is made by merging the upper and lower stratigraphic subsection and restoring the displacements of faults as explained in Speranza et al. [16]). Sections were realigned in a common declination reference frame (the Bosso section) using the common time overlaps shown in grey.

New pilot samples for each section were thermally demagnetized in 14 steps between 20 °C and 580 °C and magnetic remanence was measured with a 2G vertical DC-SQUID cryogenic magnetometer in the paleomagnetic laboratory of the Institut de Physique du Globe de Paris. All data were analyzed using Paleomac 6.1 software [38].

As visible from Zijderveld diagrams [39], three components were isolated (Fig. 3a, c, d):

1) a viscous component in the 20–200 °C range close to the present field direction, also observed with AF cleaning between 0 and 10–20 mT (Fig. 3b).
2) an intermediate temperature (ITC) secondary component (Figs. 3a, c, d and 4, Table 1) was observed using thermal demagnetization only in the 200–340 °C range at Contessa and in the 120(200) °C–250 (300) °C range in the other sections. The direction of the ITC components isolated in the four sections is very similar to that isolated by [30] in the Marne a Fucoidi Fm. and attributed to a remagnetization acquired during a Tertiary reversed polarity chron. This direction was not isolated by AF demagnetization.
3) a high temperature characteristic remanent magnetization (ChRM) direction most probably carried by a mineral of the titano-magnetite family, isolated between 380 °C and 580 °C at Contessa, and between 300 °C or 460 °C to 580 °C in the other sections (Fig. 3a, c, d, Table 1). The AF Zijderveld plot of Fig. 3b shows a component with a polarity identical to its thermally demagnetized sister sample, but illustrates the difficulty of determining a precise component, due to a non-linearity of the 10 to 40 mT segment which in this case does not pass through the origin, and the jaggy pattern above 40 mT.

We observed identical mean directions using both AF and thermal methods at Arcevia (coherently with a positive reversal test) and only slight differences at Bosso.

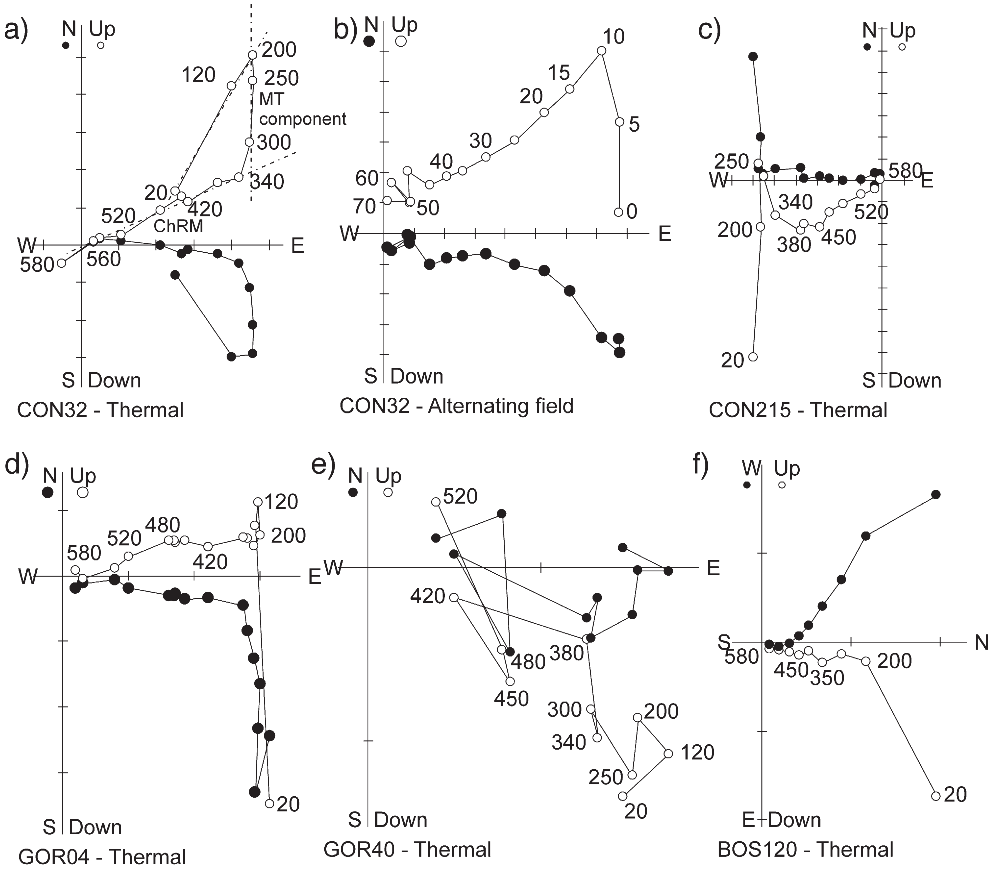

Fig. 3. Vector diagrams [34] obtained by thermal demagnetization, in situ coordinates. Open and solid symbols represent projection onto the vertical and horizontal planes, respectively. (a, b) Diagrams showing the difference between thermal and AF cleaning at Contessa in a normal polarity sample; (c) diagram showing the three components in reverse polarity at Contessa; (d) diagram showing the thermal demagnetization at Gorgo; (e) example of discarded sample from Gorgo a Cerbara; (f) diagram showing the overlapping components at Bosso.

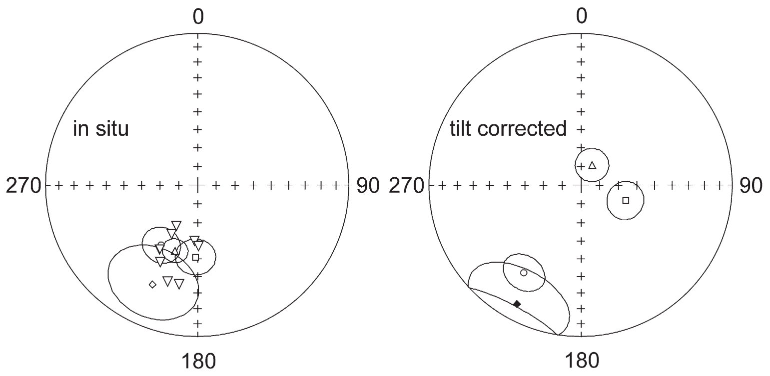

Fig. 4. Equal-area projections showing the secondary ITC components, in in situ and in tilt corrected coordinates; solid and open symbols represent projection onto the lower and upper hemisphere, respectively; lozenge = Gorgo a Cerbara; circle = Contessa; square = Arcevia; triangle up = Bosso; triangle down: data from [30].

On the contrary, differences both in normal and reverse mean directions were found at Gorgo a Cerbara and Contessa. Furthermore, mean normal and reversed directions obtained only with AF demagnetization were clearly not antipodal. Due to an overlap of the coercivity spectra, the AF cleaning is insufficient to remove the secondary ITC component at Contessa (Fig. 3a, b), and is responsible for the differences in declination obtained using AF and thermal heating.

In order to improve the quality of data, all the Maiolica Fm. samples from Gorgo a Cerbara and Contessa sections were thus systematically thermally demagnetized. We used only steps where the characteristic components of magnetization (ChRMs) are isolated on the pilot samples. For the determination of ChRMs we used 7 steps between 380 °C and 560 °C and 6 steps between 300 °C and 460 °C for samples from Contessa and Gorgo a Cerbara, respectively.

Directions were computed ([40,41], Table 1) considering always thermal heating, and discarding samples that show either very bad vector diagrams (Fig. 3e), evidence for overlapping components that could be

Table 1
Secondary and mean directions from the four sections

Section	Coordinates	N	Range	n (AF+TH)	D_{is}	I_{is}	α_{95}	k	D_{tc}	I_{tc}	α_{t95}	k
ITC directions												
Gorgo a Cerbara	43°35′N 12°33′E		120(200)–250(300)	14	204.5	−29.1	21.8	4.3	208.3	12.2	22.8	4.0
Contessa	43°22′N 12°33′E		200–340	25	211.0	−51.9	9.9	9.6	213.0	−31.7	10.4	8.7
Arcevia	43°30′N 12°56′E		120(200)–250	16	181.6	−50.9	10.0	14.1	108.9	−64.7	10.0	14.5
Bosso	43°31′N 12°34′E		120(200)–250(300)	20	198.9	−52.4	6.6	25.3	28.8	−77.7	8.9	14.4
All together					200.2	−49.6	5.8	8.9	197.3	−59.5	12.3	2.8
Mean directions												
Gorgo all	43°35′N 12°33′E	192		64 (11+53)	257.1	2.2	3.8	22.7	269.2	37.8	3.6	24.6
Gorgo normal				39 (7+32)	254.6	7.9	4.2	30.0	271.1	42.5	4.4	27.7
Gorgo reverse				25 (4+21)	80.9	6.8	5.8	25.5	86.8	−30.3	5.4	29.2
Contessa all	43°22′N 12°33′E	226		152 (10+142)	274.6	31.8	2.2	27.9	287.8	40.8	2.2	27.5
Contessa normal				92 (8+84)	275.2	33.2	2.6	32.0	288.5	41.9	2.7	30.8
Contessa reverse				60 (2+58)	93.8	−29.7	3.8	23.7	106.7	−38.9	3.8	23.7
Arcevia all	43°30′N 12°56′E	202		158 (33+125)	299.4	49.0	2.7	18.5	273.8	31.6	2.0	32.2
Arcevia normal				94 (18+76)	299.2	47.1	3.7	16.3	274.8	31.6	2.8	28.8
Arcevia reverse				64 (15+49)	119.8	−51.8	3.7	23.7	92.4	−31.7	2.9	39.0
Bosso all	43°31′N 12°34′E	234		173 (87+86)	315.3	29.0	3.4	11.0	290.3	36.0	2.3	22.7
Bosso normal				120 (49+71)	315.7	25.8	3.8	12.5	291.9	35.7	2.9	21.3
Bosso reverse				53 (37+16)	134.2	−36.4	6.8	9.2	106.2	−36.6	3.8	27.7

N = total number of samples; range = temperature interval where secondary components are isolated; n = number of reliable samples, AF and TH = alternating field and thermal demagnetized respectively; D_{is}, I_{is}, and D_{tc}, I_{tc} are site-mean declination and inclination in in situ and tilt corrected coordinates, respectively; α_{95} and k are statistical parameters after [35].

resolved by remagnetization circles analysis [41] (particularly from the Calcari ad Aptici Fm. of Bosso; Fig. 3f), or directions close to the present field direction.

The ChRMs directions are plotted on Fig. 5, before and after tilt correction. A close visual inspection shows antipodal directions, ascertained by positive reversal tests [37] of class A for Contessa, Arcevia and Bosso sections (respectively $\gamma=2.3°$ and $\gamma_c=4.4°$; $\gamma=2.1°$ and $\gamma_c=4.1°$; $\gamma=4.5°$ and $\gamma_c=4.9°$, where γ is the angle between mean normal and reverse directions and γ_c is its critical angle). At Gorgo a Cerbara, the test is negative considering all samples ($\gamma=13.2°$, $\gamma_c=6.9°$), but is positive of class B in the lowermost part of the section ($\gamma=8.1°$, $\gamma_c=8.4°$ between 0 and 49 m) and negative in the uppermost part ($\gamma=19.7°$, $\gamma_c=15.9°$, between 49 and 82 m). The presence of a motion (rotation) during the time span covered by this section may account for this feature.

These results strongly suggest a primary nature of the magnetization, and allow the use of our paleomagnetic directions to compute a high-quality APWP.

4. Interpretation

Sedimentary successions in the Apennines are affected by important tectonic rotations linked to the Messinian–Pliocene orogenesis. Usually, rotations on vertical axis prevent the use of paleomagnetic data from such regions for the construction of APWPs. To overcome this problem, we analyzed sections sharing a common temporal overlap (see Fig. 2). As we expected variation in declination with time, we compared parts of the sections that have exactly the same age. For this reason, we discarded chrons or subchrons whose upper or lower limits were not definite. We derived mean declinations averages for each overlap in order to “realign” each section into a common reference frame. We selected Bosso as the reference section, because simple tectonic setting and absence of faults characterized it. It is also well known in the literature for both bio- and litho-stratigraphy. As shown in Fig. 2, we compared chron M5n between Gorgo a Cerbara and Contessa ($n=18$ and 17, respectively), chron M15 between Contessa and Bosso ($n=16$ and 23, respectively) and finally chrons M17r and M18 between Bosso and Arcevia ($n=37$ and 31, respectively). We obtained the following rotations, with respect to Bosso: Arcevia 13.3°±5.5° counterclockwise (CCW); Contessa 1.3°±8.2° CCW; Gorgo a Cerbara 25.5°±12.1° CCW (24.2°±8.9° CCW with respect to Contessa). The rotation angles with respect to Bosso are also shown, with their error bars, in Fig. 1.

The directions from all sections were rotated into the Bosso reference frame and then averaged at the magnetostratigraphic chron level (i.e., both normal and reversed samples of a given anomaly are averaged) for anomalies M20, M17 and M16. The directions of anomaly M18, which represents a very short time interval, are combined with those of anomaly M19. A gap in the correlation of the Contessa section with the Magnetostratigraphy Polarity Time Scale [16] led us to compute an undifferentiated M10 to M15 average. Finally, M1 to M3, M5 to M6, M7 to M9 and M21 to M22 were also grouped. The mean declinations, inclinations and paleolatitudes are plotted on Fig. 6a, b and c, respectively. The absolute ages are those from the recent international time scale of Gradstein et al. [19]. The evolution of declination vs. time show a quick clockwise (CW) rotation of 16.9°±6.7° between chrons M21–M22 and chron M16 (significant at the 95% level of confidence). Around M16 (i.e., between 140 and 145 Ma), the sense of the rotation changes to CCW, followed by a possible standstill during chrons M5–M6 to M1–M3 (around 130 Ma). The value of the CCW rotation (8.4°±5.4°) is also statistically significant. The analysis of the inclinations (or paleolatitudes) shows a similar evolution. Inclinations first decrease (8.0°±6.7°) from M21–M22 to M18–M19 and then gently increase (6.4°±5.4°) till M1–M3. As discussed in [16], the lowermost part of the Arcevia section (corresponding to M20–M21 anomalies on Fig. 2) is not in tectonic continuity with the upper part of this section and is furthermore affected by faults that may also lead to slight differential rotations. We computed the average directions both with and without these data (Fig. 6a, b). The interpretation does not change, but our final choice was to discard the lower Arcevia data from further computations in order to increase the reliability of our results in term of plate motion.

The Bosso section was previously investigated both for pole position and magnetostratigraphic purpose and we compared our data (Fig. 6a, b) to others in the literature [15,18,43,44]. Directions obtained by [43] were not considered since they were most probably biased [18], due to the demagnetization performed by alternating field only. A reasonable agreement was found between our data and former paleomagnetic sites [9,44] (light grey closed symbols in Fig. 6a, b) despite the low number of samples studied by these authors. A good agreement was found with the directions derived from magnetostratigraphies from a more consistent number of samples, both around M5–M6 [18], M18 and M20 [15] (open symbols in Fig. 6a, b).

The Virtual Geomagnetic Poles (VGPs) from all sections in Bosso coordinates were used to synthesize a new APWP segment between 150 and 125 Ma (Fig. 7).

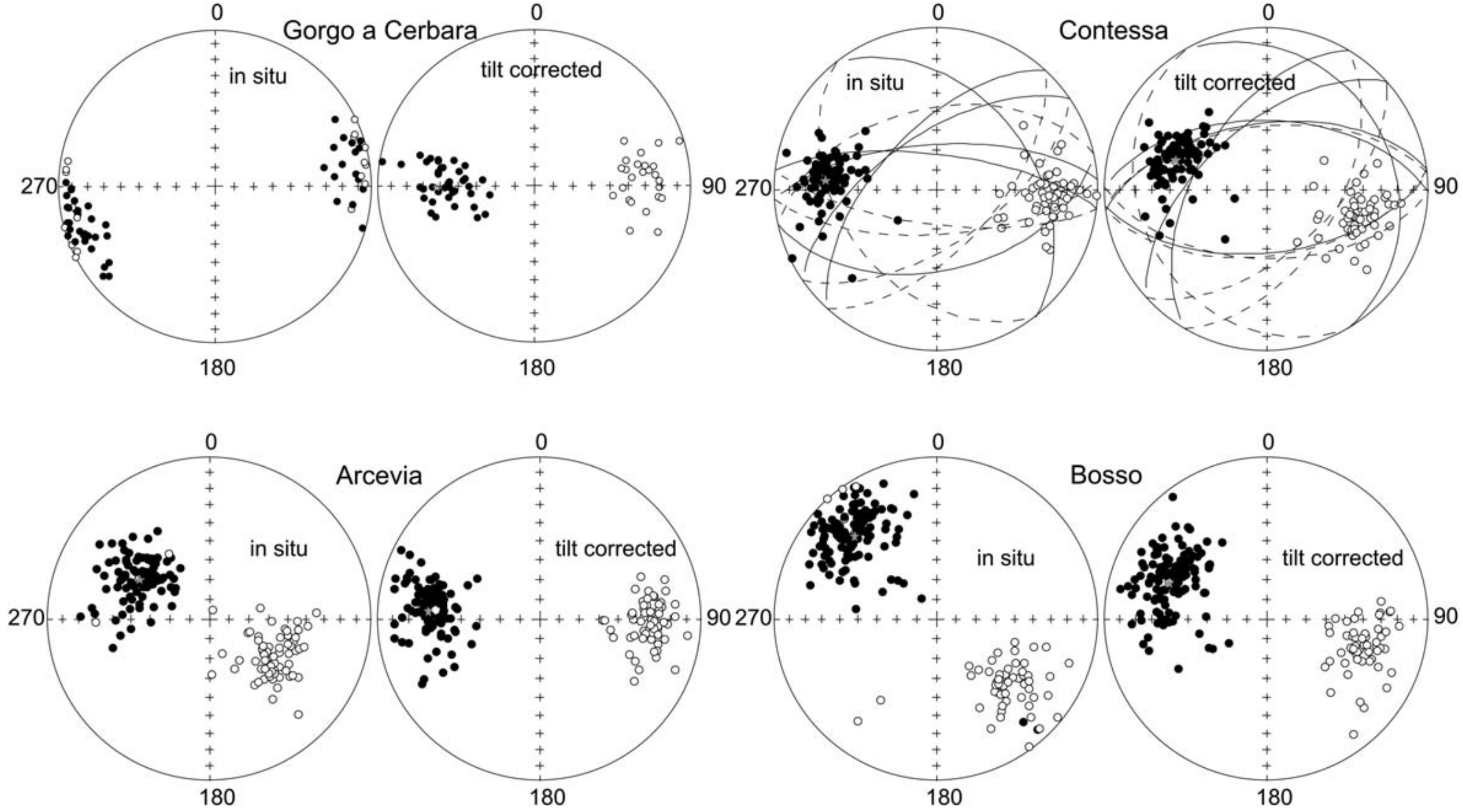

Fig. 5. Equal-area projection showing ChRMs, in in situ and in tilt corrected coordinates; solid and open symbols represent projection onto the lower and upper hemisphere, respectively; grey stars indicate the mean directions in normal polarity.

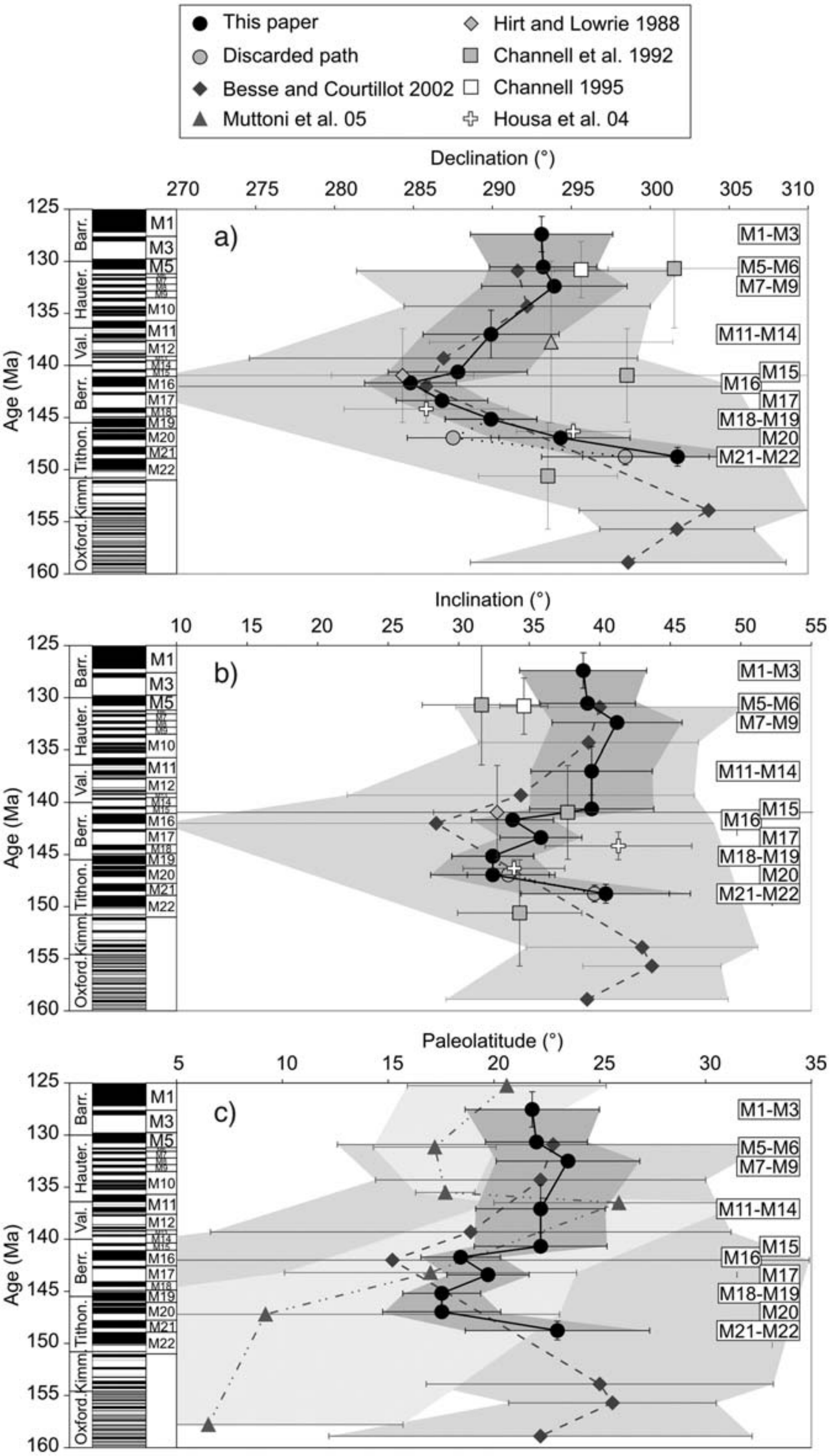

Fig. 6. Comparison of declinations (a), inclinations (b) and paleolatitudes (c) with previous data from the literature, all reported in Bosso coordinates (see text for details). Black solid circles: new data from this study; light grey solid circles: discarded data from Arcevia; dark grey solid symbols: data from [4,45]; light grey solid symbols: data from previous sites from Bosso [9,44]; open symbols: data from previous magnetostratigraphic studies in Bosso section [15,18]. Error bars from this study, from[4] and from [45] are shown in dark grey, grey and light grey shadow areas, respectively.

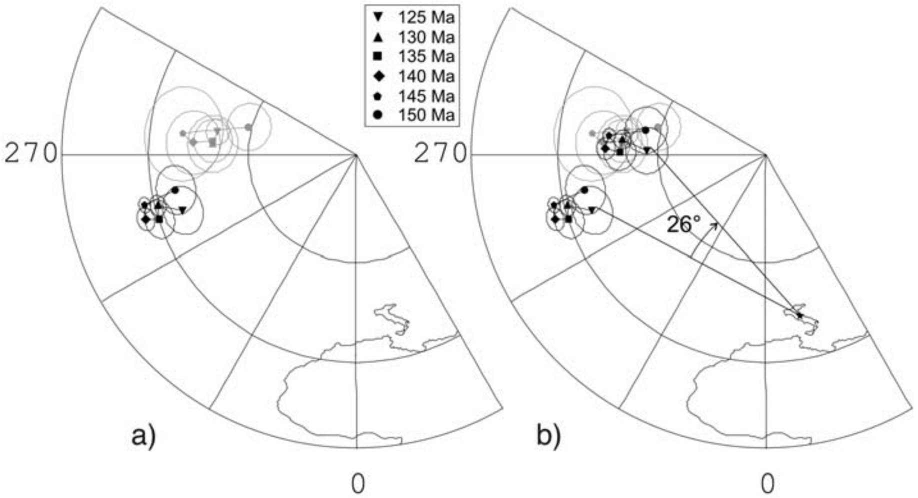

Fig. 7. The new 150–125 Ma APWP segment compared with APWP from Besse and Courtillot [4], computed every 5 m.y. with sliding-windows of 10 m.y. A complete overlap was obtained by rotating the new segment of 26° CW.

To compute the APWP we used the sliding-windows method described by Besse and Courtillot [4] (rather than a mean at chron level as in Fig. 6) to make the two segments directly comparable. Whatever method we used to compute the paleopoles means we obtain the same results. We computed an average pole every 5 m.y., using a 5 m.y. window, so that we have no time overlap in the computed means (Table 2). Each paleopole is averaged using a number of data comprised between 20 (at 125.1 Ma) and 163 (at 145.1 Ma). The A95 values range between 1.9° and 6.1°. Maximum A95 are found at 120 (6.1°) and 150 Ma (6.1°), due to the lower number of VGPs used to compute these poles.

We then compared our path with the South African 10 m.y. sliding-windows synthetic APWP segment of Besse and Courtillot [4] for the same time span. Albeit we used GTS 04 [19] and they used GTS 89 [42] time scale, we did not rescale their poles ages since the time differences remain small: indeed the maximum age difference between the two time scales for the considered time of interest is only 1.8 m.y. at the Barremian/Hauterivian boundary. The shape of the two APWPs is very similar, paleogeographically implying a CW rotation and slight southward motion of Adria between 150 and 145 Ma, followed by CCW rotation and northward motion. The change in the sense of motion between 145 and 140 Ma is characterized by a very short standstill, if any. We found an almost perfect overlap by a 26° CW rotation of the Apennine APWP with respect to Africa (i.e., Apennines units in Bosso have rotated CCW with respect to Africa). The estimation of the error bars for this rotation is not a simple task if one considers individual error bars on each pole for the Apennine and global APWPs. Computing the average error (using 10 m.y. sliding windows) would lead to a mean error of 8.6°, which is probably an overestimate. An estimation based on 20 m.y. averages leads to a mean error of 6.4° (min is 3.8° and max is 8.7°), and seems to be more realistic. The similar shape of both APWPs demonstrates that Adria promontory moved coherently with Africa at least between 150 and 125 Ma ago, giving more credit to the studies of [8–12]. Furthermore, the 26° CW rotation necessary to overlap the two data sets provides the value of the rotation induced at Bosso during the Neogene orogenesis. A 26° CCW rotation must be added to the relative rotation of all sections with respect to Bosso to obtain their total rotation with respect to Africa.

In Fig. 6a, b, c we compare our data with those expected in Bosso (latitude = 43.5°N; longitude = 12.6°E)

Table 2
Apparent Polar Wander Path computed from the four Umbria–Marche sections between 125 and 150 Ma

Window	Age	*N*	Lat	Long	A95	*k*
125.1	125.9±0.8	20	38.0	288.0	6.1	29.9
130.1	130.4±1.2	90	32.0	284.5	2.5	36.9
135.1	134.9±1.4	46	32.1	288.3	4.7	21.2
140.1	141.0±0.9	128	26.0	287.2	2.8	21.4
145.1	145.4±1.4	163	26.9	283.6	1.9	36.4
150.1	148.6±0.9	24	37.5	281.2	6.1	24.5

The lowermost part of the Arcevia section was rejected as it is not in tectonic continuity with the upper part of this section and is affected by faults that may also lead to slight differential rotations. Window = age of the center of the window; Age = mean age computed from the data; *N* = number of samples for the window; Lat = pole latitude; Long = pole longitude; A95, *k* = statistical parameters after [35].

using the global Besse and Courtillot APWP with 10 m.y. averages [4] after a 26° CCW rotation. We found again an almost perfect agreement between the two sets of data, most of respective declination and inclination means being included in the confidence interval of the other. Moreover, the excellent correspondence furthermore supports a dipolar nature of the field during this period, within our error bars.

Finally, we compared paleolatitudes (Fig. 6c) computed from our data with data from Muttoni et al. [45] in the Southern Alps. The comparison of declinations is hampered by the presence of tectonic rotations between Umbria–Marche region and Southern Alps. If their paleolatitudes are similar to ours around 140 Ma (albeit describing a jagging track), they disagree from 147 Ma and older periods. They interpreted their low inclination values between 145 and 165 Ma as a paleolatitudinal drift of the Lombardian basin (Southern Alps) during Middle–Late Jurassic, that would have caused a variation in biosiliceous productivity, hence change in

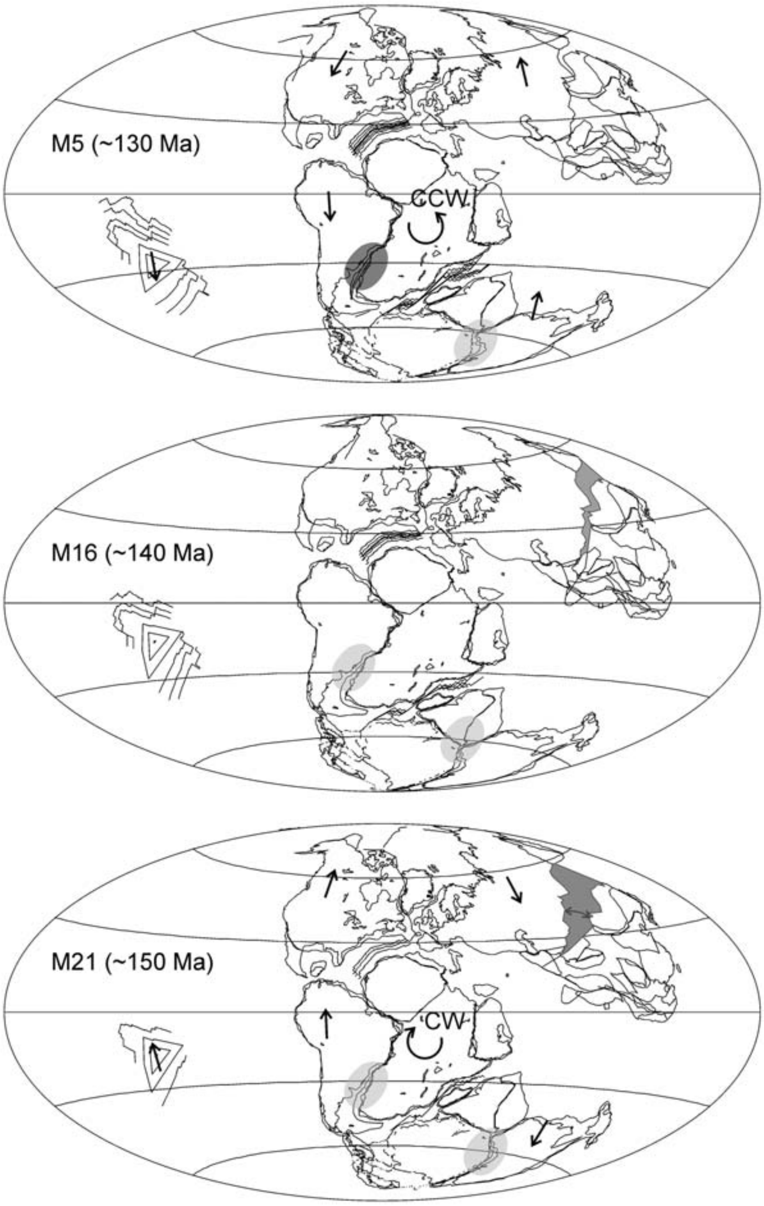

Fig. 8. Reconstruction of plate motion between 150 and 130 Ma computed integrating the new 150–125 Ma segment with 170–150 Ma and ca. 130 Ma data from [4]. Light grey shadow areas: future rising plumes; dark grey shadow area: actual plumes; medium grey shadow area: Mongol–Okhotsk Ocean.

facies. Our data do not support low latitudes for our sections during Kimmeridgian–Tithonian.

5. Discussion

We used our new 150–125 Ma APWP rotated to Africa to reconstruct global plate motion (Fig. 8) using the procedure described by Besse and Courtillot [4]. This reconstruction is indeed very close to one that would use their 10 m.y. average path. Oceanic kinematic parameters are first used to place the major continents in their relative positions, and our paleomagnetic data are then used to fix the paleolatitude grid. We have also attempted to restore the shape of the ancient central and south Asian active margin using the well-documented Cretaceous dataset, such as the paleomagnetic studies on Cretaceous rocks from Tarim, Junggar block and Tibet (for a review see [46,47]). The paleo-position of the Chinese blocks and Indochina are restored using the paleomagnetic data of [48,49]. Fig. 8 shows that Africa rotated first CW (at least since 170 Ma), and began to rotate CCW at 145 Ma with a northward drift component without significant standstill. This directional change is also supported by main continents APWPs [3], in which a Late Jurassic cusp is systematically evidenced, and sometimes referred as to the “J2 cusp” (see, for example, [50] for North America).

The abrupt change of direction should reflect important changes in the sum of forces acting on plates such as new ocean openings, new subduction initiations or large-scale collisions. Alternatively, episodes of True Polar Wander (TPW), the shift of the whole Earth with respect to its spin axis linked to the evolution of mass heterogeneities within the mantle with respect to time, may also play an important role.

Our change in direction is dated around anomaly M16 (141–142 Ma according to [17]), and no major direction change of similar age is recorded in the anomaly pattern of either the Central Atlantic or the Somaly basin of the Indian Ocean [51]. The onset of the South Atlantic opening is marked first by the effusion of a large igneous province trap at 133 Ma ± 1 Ma [52], followed by oceanic accretion with a first recognized magnetic anomaly at ca. 130 Ma (M5). Thus, our directional change predates by some 10 m.y. the first surface expression of the South Atlantic oceanic opening. However, the error bars, albeit significantly reduced in our study, do not rule out completely a link with the South Atlantic opening. Large orogens that may have also triggered this change of motion have been recognized during this period, such as the collision closing the Mongol–Okhotsk Zone, at around 145 Ma [53], or the Nevadan collision between the America block and Siberia in the western part of North America, although this event is possibly slightly older and most probably of much smaller extent [54].

A striking feature is that all plates follow the same global change of motion during this period. Even the Pacific plate linked to the Indo-Atlantic bordering plates using the independent hot-spot reference frame [51,55] displays a motion in good agreement with the general motion of the other plates. Moreover, the pattern of the known magnetic anomalies within this Ocean [55] does not suggest any important change in their direction of spreading, although its history remains poorly known for these early periods. Another explanation would be a change in conditions generating TPW. Indeed, a major direction change of TPW has already been recognized by [4] around 140 Ma, with however limitations due to the hot-spot reference frame reliability [56], and the Pacific not being considered in their model. Possible candidates for triggering changes of TPW could be the competitive effect of slab detachments sinking in the mantle during either the Mongol–Okhotsk or even the slightly older final Jurassic Paleotethys closure [57], and/or the rising main plumes in the mantle later responsible for the abundant Cretaceous volcanic eruption such as Rajmahal, and Parana/Etendeka traps or Ontong–Java plateau [58,59].

6. Conclusions

The analysis of four Kimmeridgian to Early Aptian sections from the Northern Apennines allowed us to reconstruct a high-quality 150–125 APWP segment for Adria. The new segment perfectly documents an APW loop close to the Jurassic/Cretaceous boundary (around 140 Ma), showing a fast and abrupt change in plate motion centered on anomaly M16, without any significant standstill. The direction change evidenced in our Apennine APWP is also displayed in the APWP of most continents, and allows for a precise dating of the J2 cusp centered around anomaly M16. The comparison between the new segment with a 5 m.y. resolution and the synthetic APWP computed from Besse and Courtillot [4] proves that Adria has an indistinguishable motion with respect to Africa during this period. The CCW rotations of Apennine nappes were induced later on, most probably by Neogene orogenesis. The explanation of the global change in plate motion is either linked to large-scale collisions in Asia, TPW events possibly linked to the rising numerous Cretaceous hot-spots or sinking slabs, or possibly to the South Atlantic opening.

The similarities between the two segments allow us to confirm results from Besse and Courtillot [4] that the geocentric axial dipole hypothesis is adequate for the 125–150 Ma time span.

Finally, the high quality of the obtained segment demonstrates that is possible to reconstruct APWP using data from orogenic belts, when it is possible to solve tectonic rotations linked to the orogenesis.

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