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Paleomagnetic evidence for Neogene tectonic rotations in the northern Apennines, Italy

G. Muttoni [a,b,*], A. Argnani [c], D.V. Kent [b], N. Abrahamsen [d], U. Cibin [e]

[a] *Institute of Geophysics, ETH-Hönggerberg, CH-8093 Zürich, Switzerland*
[b] *Lamont-Doherty Earth Observatory, Palisades, NY 10964, USA*
[c] *Istituto di Geologia Marina, via Gobetti 101, I-40129 Bologna, Italy*
[d] *Department of Earth Sciences, Aarhus University, Aarhus, Denmark*
[e] *Servizio Cartografico e Geologico, Regione Emilia–Romagna, viale Silvani 4/3, Bologna, Italy*

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Abstract

Paleomagnetic analysis was carried out in the northern Apennines on Eocene to Pliocene Epiligurian units. Five Early Miocene and two Middle Miocene sites yielded dual polarity site-mean directions which show signs of clustering after correction for bedding tilt. These likely primary magnetizations, in conjunction with data from the literature, give an overall mean Late Oligocene–Middle Miocene paleomagnetic pole which shows a large and significant counterclockwise rotation of 52° ($\pm \approx 8°$) with respect to the Africa reference paleopoles (or a similar amount of rotation with respect to the coeval Europe reference paleopole). However, this paleopole falls close to the roughly coeval paleopole for Corsica–Sardinia, which is here calculated by averaging data from the literature. Three additional Early Miocene sites from an area west of Parma affected by Pliocene tectonics yielded site-mean directions which pass the fold test and are rotated counterclockwise by a lesser amount than the rest of the Miocene sites. Most of the remaining sites bear paleomagnetic directions acquired after tilting during a recent phase of remagnetization. We suggest that the large-scale rotation observed in the northern Apennines was associated with the motion of the Corsica–Sardinia block within the general context of the Africa–Europe relative motions. A compilation of published data from the central Apennines also shows a differential rotation of the northern relative to the southern Umbria belt which occurred after the motion of Corsica–Sardinia and may have been due to pivoting of the northern Umbria belt against a deep-seated lineament during the non-rotational opening of the Tyrrhenian Sea. © 1998 Elsevier Science B.V.

Keywords: paleomagnetism; Apennines; Neogene; tectonics

1. Introduction

The Apennines consist of an arc-shaped thrust-and-fold belt which developed essentially during the Neogene in conjunction with Corsica–Sardinia block migration and the subsequent opening of the Tyrrhenian Sea. Tectonic rotations associated with thrusting are documented paleomagnetically in large portions of the central and southern Apennines, e.g., [1–4], whereas data from the northern Apennines north of Val Marecchia are sparse, e.g., [5]. Therefore, we

* Corresponding author. Fax: +41 1 633 1065; E-mail: giom@mag.geo.phys.ethz.ch

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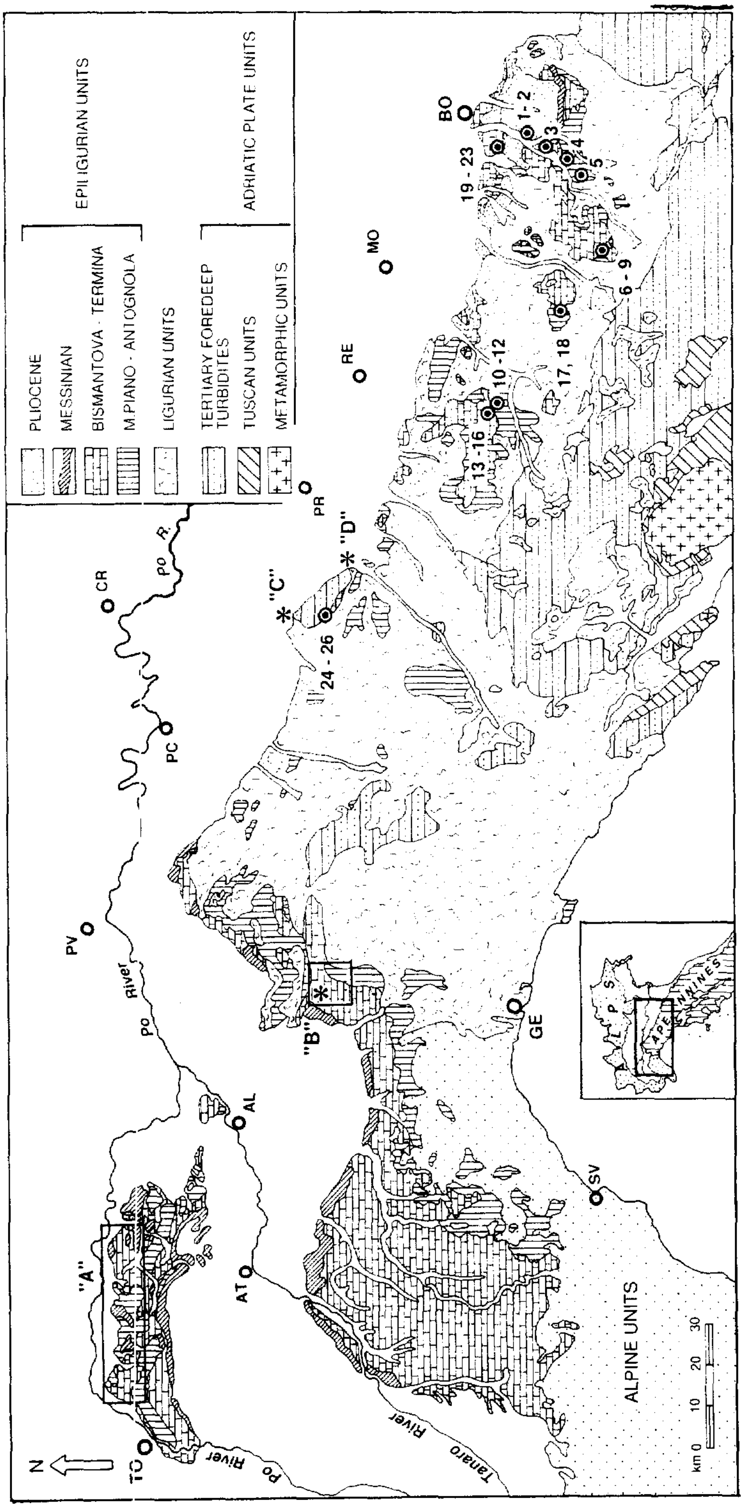


Fig. 1. Geological map of the northern Apennines with sampling site locations from this study (circles) and the literature (asterisks). Location *A* comprises two Miocene sites from [13], location *B* comprises ten Late Oligocene sites from [5], locations *C* and *D* are the Pliocene Stirone and Sant'Andrea Bagni sections of [12], respectively.

carried out paleomagnetic analysis on clastic formations of Eocene to Pliocene age outcropping in the Emilia–Romagna region of the northern Apennines. These results, combined with coeval data from the literature, allow us to constrain better the amount and timing of the rotations in the northern Apennines, and to understand their relationships with the motion of the Corsica–Sardinia block.

2. Geological setting

The northern Apennines are a stack of northeast-vergent thrust sheets. The Ligurian units are structurally on top of the tectonic pile and consist of biogenic and clastic sediments associated with ophiolite suites from the Mesozoic Ligurian ocean. The Ligurian units represent the accretionary wedge resulting from the subduction of the Ligurian ocean below the Corsica–Sardinia block, and were thrust during the Neogene to the northeast onto the Tuscan–Umbria carbonate successions of the Adria passive continental margin (Fig. 1). Thrusting was accompanied by clastic sedimentation in northeastward-migrating foredeeps [6]. The Tuscan–Umbria units were in turn thrust onto the 'autochthonous' metamorphic complex now exposed in the Apuane Alps [7]. Clastics referred to in the literature as Epiligurian units were also deposited in relatively undeformed basins located on top of the advancing Ligurian thrust sheets.

The Epiligurian units, which we sampled at 26 sites (Fig. 1), consist of Middle Eocene to Pliocene clastic sediments characterized by strong lateral variations in lithology and thickness. These sediments were mainly deposited in deep-water marine environments where tectonic activity often generated slumpings and olistostromes on unstable slopes. The Epiligurian succession can be subdivided into six stratigraphic units, each bounded by unconformities (Fig. 2); from bottom to top the units are:

(1) The Monte Piano Group (Middle–Late Eocene), which directly overlies the Ligurian thrust sheets and is comprised of slope and basinal mudstones with thickness ranging from some tens up to 200 m; this group also contains lenticular siliciclastic

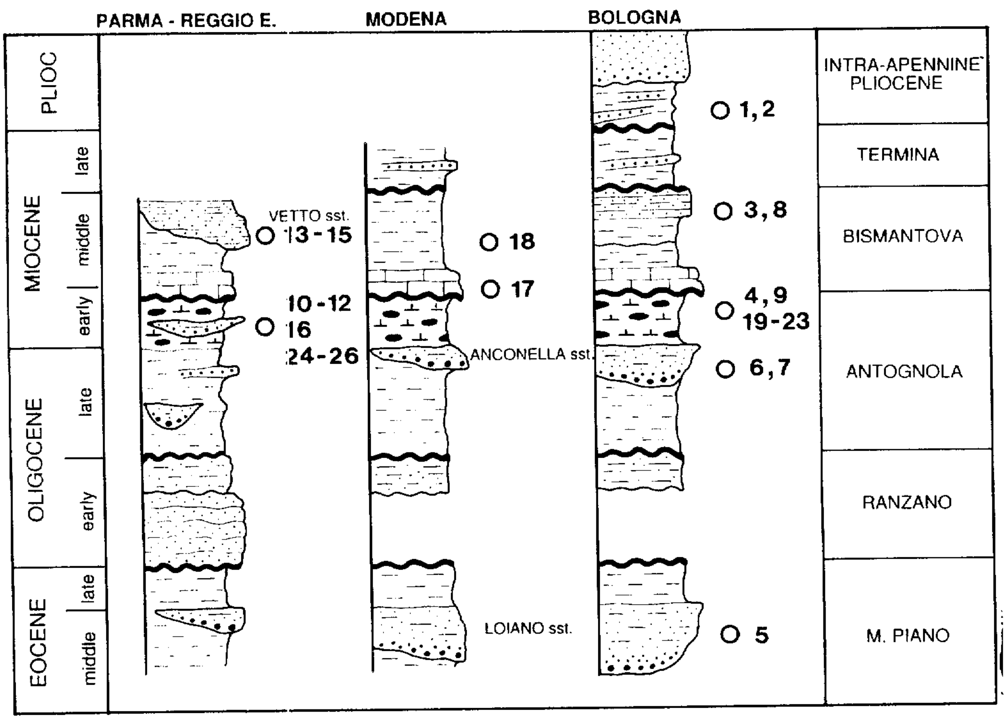


Fig. 2. Stratigraphy of the Epiligurian units of the Bologna–Parma Apennines with position of sampling sites from this study.

bodies of turbiditic origin up to 1000 m thick (e.g., the Loiano sandstones).

(2) The siliciclastic turbidites of the Ranzano Group (Early Oligocene), which we did not sample, follow on top of or directly overly the Ligurian thrust sheets.

(3) The Antognola Group (Late Oligocene–Burdigalian), which is comprised of slope and basinal mudstones up to 1000 m thick, locally also containing coarse-grained siliciclastic turbidites. Cherty marls characterize the upper part of the Antognola Group where volcaniclastic layers are also present at places.

(4) The Bismantova Group (Burdigalian–Serravalian), which is several hundreds of meters thick, consists of shallow marine, mainly bioclastic sandy limestones at the base, passing upwards to slope mudstones which are followed by basin-plain siliciclastic turbidites up to 1000 m thick (e.g., the Vetto sandstones).

(5) The muddy sediments of the Termina Formation (Tortonian–?Messinian) follow on top but were not sampled.

(6) Intra-Apennine Pliocene. These sediments, which outcrop mainly in the Bologna area with a thickness of over 1000 m, consist of shallow marine to continental sandstones.

We mainly sampled the Late Oligocene–Middle Miocene Antognola and Bismantova groups, but a few sites were also taken in the Middle–Late Eocene Monte Piano Group, and in the Pliocene Intra-Apennine deposits (Fig. 2).

3. Paleomagnetism

Samples were collected with a water-cooled rock drill and oriented with a magnetic compass. An average of ten 2.5-cm-diameter cores were taken per site. The natural remanent magnetizations (NRMs), varying from a minimum of 0.18 mA/m at site 5 (Loiano ss.) to a maximum of 34.5 mA/m at site 12 (Carpineti ss. of Antognola Group), were measured on a 2G cryogenic magnetometer at Lamont or a HSM SQUID-based spinner magnetometer at Aarhus. After pilot AF demagnetization studies at Aarhus, the majority of the standard 11-cm^3 specimens were subjected to progressive thermal demagnetization at Lamont. The initial magnetic susceptibility of each specimen was measured with a Bartington MS2 susceptibility bridge after each thermal demagnetization step to monitor any mineralogical alteration during heating. Least-square analysis [8] was applied to determine the component directions of NRM, chosen by inspection of vector end-point demagnetograms [9]. Site mean directions were determined with standard Fisher statistics. The ferromagnetic phases were investigated by means of acquisition curves of isothermal remanent magnetization (IRM) and thermal unblocking characteristics of orthogonal-axes IRM [10].

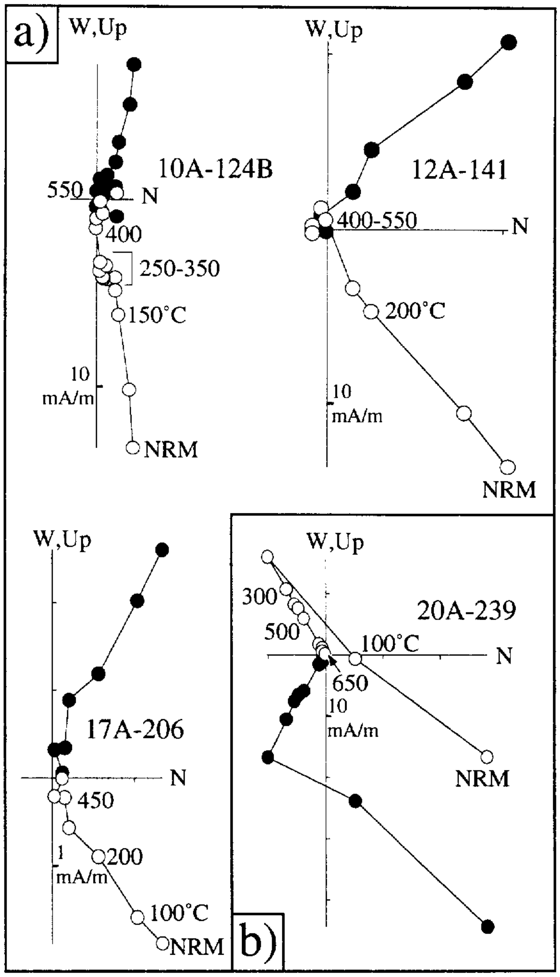


Fig. 3. Zijderveld demagnetograms of representative Epiligurian unit samples bearing normal (a) and reversed (b) polarity characteristic directions. Dots are projections onto the horizontal plane and circles are projections onto the vertical plane. All diagrams are in in-situ coordinates.

3.1. Primary paleomagnetic directions

NRM demagnetization diagrams in geographic coordinates for the Early Miocene sites 10, 12, 21 and 22 and Middle Miocene sites 17 and 18 show the presence of an occasional initial component which coincides with the present-day field direction, followed at higher unblocking temperatures by a north-

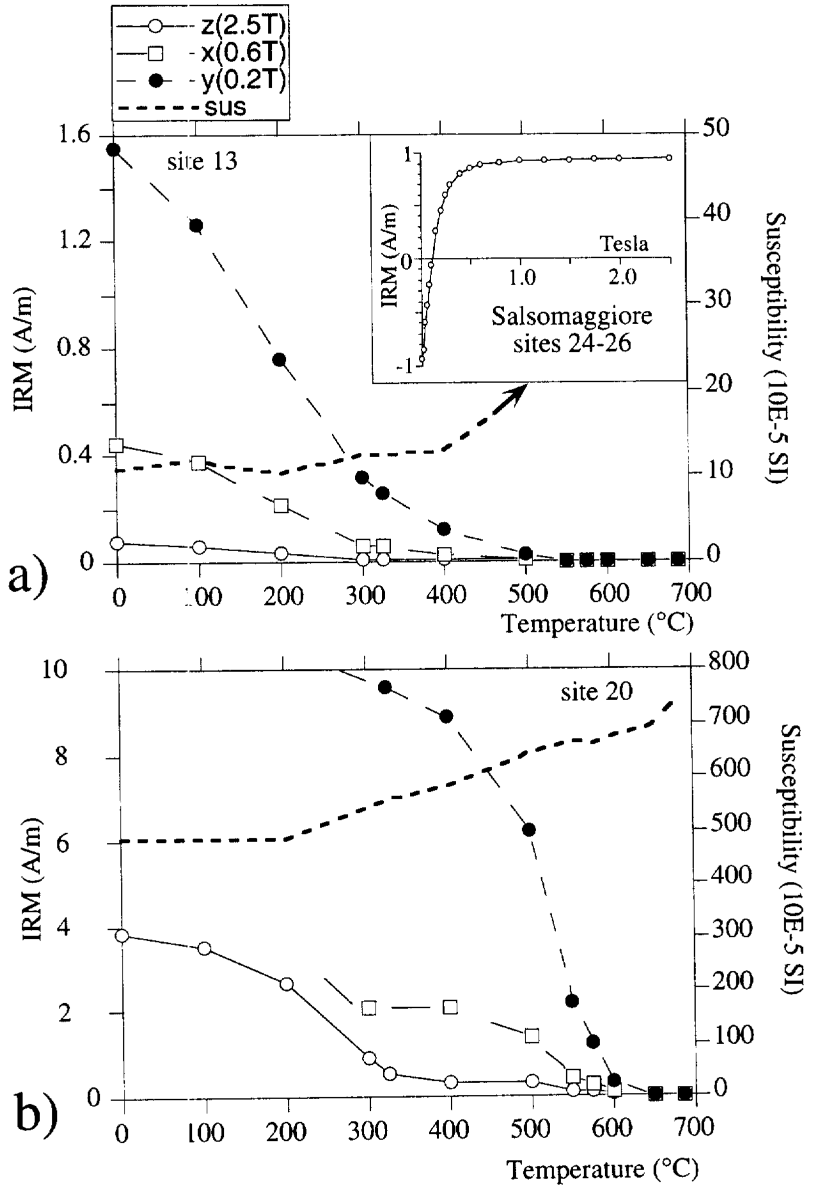
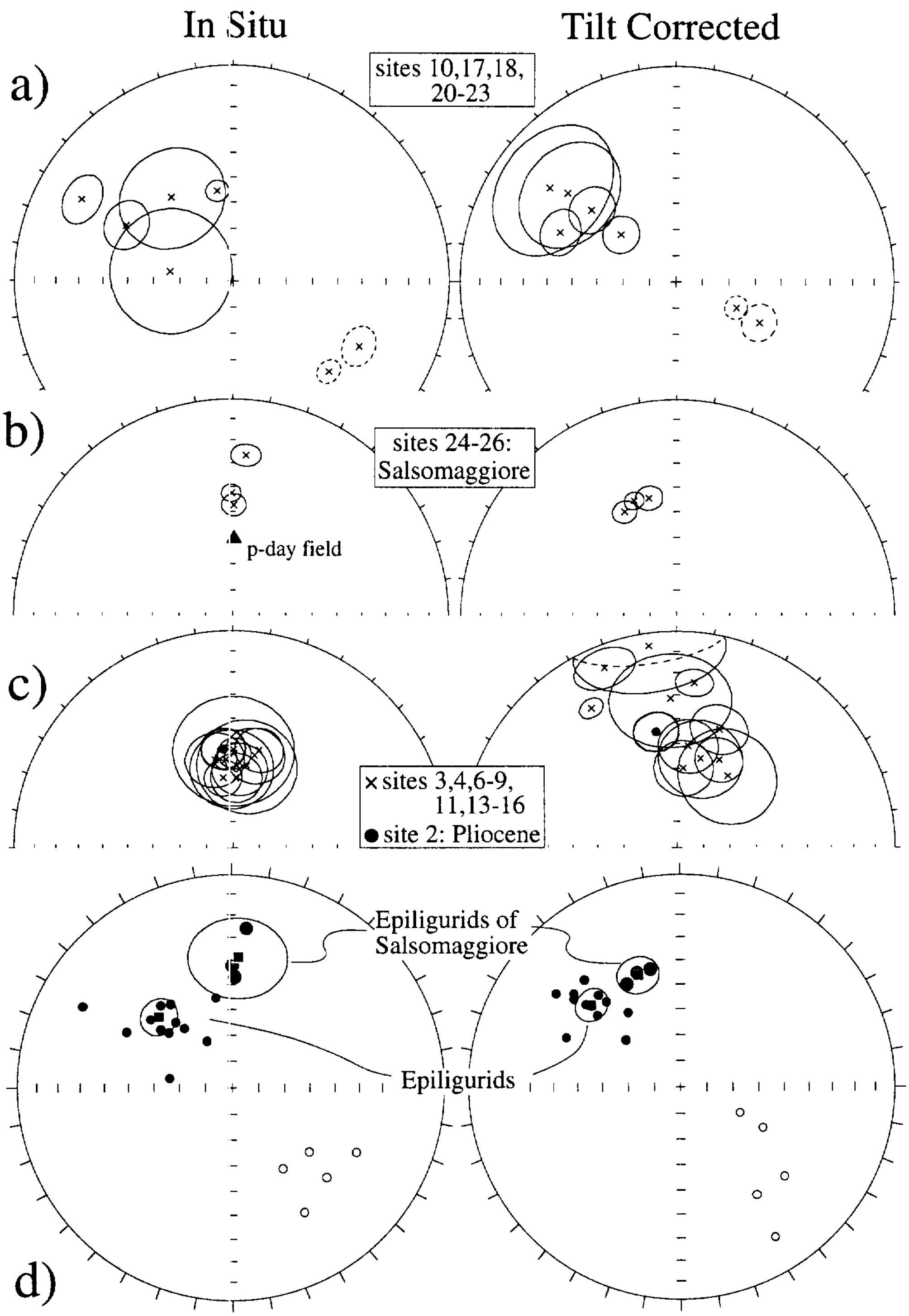


Fig. 4. Thermal decay of orthogonal-axes IRM for representative Epiligurian unit samples bearing dominant magnetite, probably coexisting with subsidiary sulfides or perhaps maghemite (a); some hematite may also be present at site 20 where the maximum unblocking temperature is about 650°C (b). The inset in (a) is a representative example of an acquisition curve of IRM where saturation is reached at fields of about 0.5 T. This curve was constructed by imparting a 2.5-T field along the sample $-z$-axis, and then progressively imparting an IRM along the $+z$-axis by means of a stepwise antiparallel field up to 2.5 T. This method allows us to obtain information on the coercivity of remanence and saturating field values.


In Situ
Tilt Corrected
a)
sites 10,17,18,
20-23
b)
sites 24-26:
Salsomaggiore
p-day field
c)
× sites 3,4,6-9,
11,13-16
● site 2: Pliocene
d)
Epiligurids of
Salsomaggiore
Epiligurids

west and downward characteristic 'Ch' component (Fig. 3a). An antipodal southeast and upward 'Ch' component is isolated at the Early Miocene sites 20 and 23, and at site 5 of Middle–Late Eocene age (Fig. 3b). Acquisition curves of IRM indicate saturation typically by about 0.5 T (Fig. 4, inset in a). Thermal demagnetization characteristics of orthogonal-axes IRM are consistent with the presence of a dominant low coercivity 570°C maximum unblocking temperature phase interpreted as magnetite, coexisting with subsidiary sulfides or maghemite with moderate coercivity and unblocking temperatures of 300–350°C (Fig. 4a). The red siltstones at site 20 may contain also subsidiary hematite with unblocking temperatures above 600°C (Fig. 4b). The dual polarity 'Ch' component from the seven Early and Middle Miocene sites (except site 12, which gave anomalously shallow directions, and site 5 of Eocene age) gives site-mean directions which show some improvement in degree of convergence after correction for bedding tilt (the precision parameter progressively increases by a factor of 1.9) (Fig. 5a; Table 1, upper part). However, the limited difference in bedding attitudes makes the fold test statistically inconclusive. The overall mean direction in tilt corrected coordinates is Decl. = 303.5°E, Incl. = 48° (Table 1) and possibly represents a record of the Early–Middle Miocene geomagnetic field. In contrast, the Early Miocene sites 24 to 26 located close to the Salsomaggiore tectonic unit (Fig. 1) show the presence, after removal of an occasional present-day field component direction, of a more northerly and downward 'Ch' component carried by dominant magnetite up to 570°C. The three site-mean directions pass the fold test at 95% level of confidence [11] (Fig. 5b), and the resulting overall mean direction (Decl. = 340°E, Incl. = 43.8°; Table 1) is more clockwise by a minimum of 16° (mean of 36°) with respect to the overall mean direction calculated for rest of the Miocene sites. Moreover, in the Salsomaggiore area Channell et al. [12] found at two sites located close to one another Pliocene directions with virtually no and large counterclockwise rotation (Fig. 1, location C and D, respectively). The tectonic complexity of the Salsomaggiore unit demands, therefore, further investigation to understand better the Miocene component of magnetization found at sites 24 to 26.

3.2. Secondary paleomagnetic directions

Most of the remaining sites of Late Oligocene age (sites 6 and 7), Early Miocene age (sites 4, 9, 11 and 16) and Middle Miocene age (sites 3, 8, 13–15) yielded a north and downward component carried mainly by magnetite which defines site-means in geographic coordinates which are undistinguishable from the present-day field direction (Fig. 5c). After correction for bedding tilt these directions clearly diverge, thus suggesting that this component of magnetization was acquired after deformation, either in the present-day field or during another recent period of normal polarity. Because of the widespread occurrence of this secondary magnetization, we cannot say whether the north and downward component found at Pliocene sites 1 ($N = 3$) and site 2 (tilt-corrected Decl. = 349.8°E, Incl. = 45.3°, $a_{95} = 8$, $k = 42$, $N = 9$) is a primary direction or a very recent overprint (Fig. 5c).

4. Comparison with published data from the northern Apennines

Paleomagnetic components of magnetization of supposed primary origin were found elsewhere in the northern Apennines. The Epiligurian-equivalent sediments of the Liguria–Piedmont Tertiary basin located in the Monferrato area at the northwestern edge of the northern Apennines revealed a complex pattern of magnetization, probably reflecting local tectonic rotations [13] (Fig. 2, location A). However, consistently rotated paleomagnetic directions were obtained at ten Late Oligocene sites from two localities outcropping in Epiligurian-equivalent sediments a few kilometers to the southeast [5] (Fig. 2, location B) (Table 1, central part). The seven Early–Middle Miocene site-mean directions from this study (i.e., except sites 24–26 from Salsomaggiore), in conjunc-

Fig. 5. Equal-area projections before and after bedding tilt correction of the characteristic component site-mean directions from (a) Early–Middle Miocene sites 10, 17, 18, 20–23, (b) Early Miocene sites 24–26 from the Salsomaggiore tectonic unit, (c) Late Oligocene to Middle Miocene sites 3, 4, 6–9, 11, 13–16, and Pliocene site 2 (in bold), and (d) Late Oligocene–Middle Miocene sites from this study as from panel (a) and from the literature, and Early Miocene sites 24–26 as from panel (b). Solid symbols refer to the lower hemisphere.

Table 1
Paleomagnetic directions from the northern Apennines from this study and the literature (when specified)

Site #	Locality	Lithology	Age	N	In situ				Tilt-corrected					
					Decl. (°)	Incl. (°)	k	α_{95} (°)	Decl. (°)	Incl. (°)	k	α_{95} (°)	Lat./Long. (°N)/(°E)	dp/dm (°)
Epiligurian sites														
5	Loiano	Loiano	M.–L. Eocene	5	133.2	8.5	16	19.6	139.5	−27.2	16	19.5	44.5/253.2	11.6/22
10	Carpineti	Carpineti	E. Miocene	5	278.5	65.9	12	23.3	306.7	27.9	12	23.3		
12	Carpineti	Carpineti	E. Miocene	9	301.4	52.6	34	9.0	330.7	9.4	24	10.7		
17	Pavullo	Bismantova	M. Miocene	7	297.7	43.8	48	8.8	310.5	47.4	47.5	8.8		
18	Pavullo	Bismantova	M. Miocene	7	323.6	50.2	11	19.4	309.3	35.5	11	19.4		
20	Mongardino	Cherty Marls	E. Miocene	12	117.7	−34.6	40.5	6.9	116.7	−54.6	41	6.9		
21	Mongardino	Cherty Marls	E. Miocene	8	298.5	22.1	46	8.2	293.1	41.3	46	8.2		
22	Mongardino	Cherty Marls	E. Miocene	6	349.9	55.0	253	4.2	310.7	62.5	91.5	7.0		
23	Mongardino	Cherty Marls	E. Miocene	10	133.6	−38.8	123	4.4	113.7	−65.2	123	4.4		
overall (except sites 5 and 12)			E.–M. Miocene	7	308.0	45.9	16	15.5	303.5	48.0	30	11.2	43.2/281.7	9.6/14.6
Epiligurian-equivalent sites from the Liguria–Piedmont Tertiary Basin [5]														
B	Ramero		L. Oligocene	7 sites	316.2	57.0	92	6.3	315.9	42.1	95	6.2		
B	Garbagna		L. Oligocene	3 sites	143.4	−46.0	37	20.6	141.7	−30.9	36	20.7		
overall	Ramero and Garbagna		L. Oligocene	10 sites	318.7	53.8	55	6.6	317.8	38.8	55	6.6		
overall from this study (7 sites) and the literature (10 sites)			L Oligo–M.Mio	17 sites	314.0	50.8	27	7.0	312.5	42.8	33	6.3	46.9/268.5*	4.8/7.8
Epiligurian sites from the Salsomaggiore tectonic unit														
24	Contignaco	Cherty Marls	E. Miocene	17	4.8	26.6	53	4.9	346.7	43.3	53	4.9		
25	Contignaco	Cherty Marls	E. Miocene	10	359.4	42.7	190	3.5	339.7	42.6	191	3.5		
26	Contignaco	Cherty Marls	E. Miocene	10	0.8	47.4	120	4.4	333.5	45.2	120.5	4.4		
overall	Contignaco	Cherty Marls	E. Miocene	3 sites	1.9	38.9	53	17.1	340.0	43.8	270	7.5	64.9/236.7	5.9/9.4

N = number of 11-cm^3 specimens used for statistical analysis, number of sites when specified; Decl., Incl. = declination and inclination; k = Fisher precision parameter; α_{95} = Fisher half-angle of cone of 95% confidence about the mean direction; Lat., Long = latitude and longitude of paleomagnetic pole (* = calculated for a point of 45°N, 10°E); dp, dm = semi-axes of the confidence oval about the paleomagnetic pole. Sites labelled as 'B' are from [5] and correspond to locality 'B' in Fig. 1.

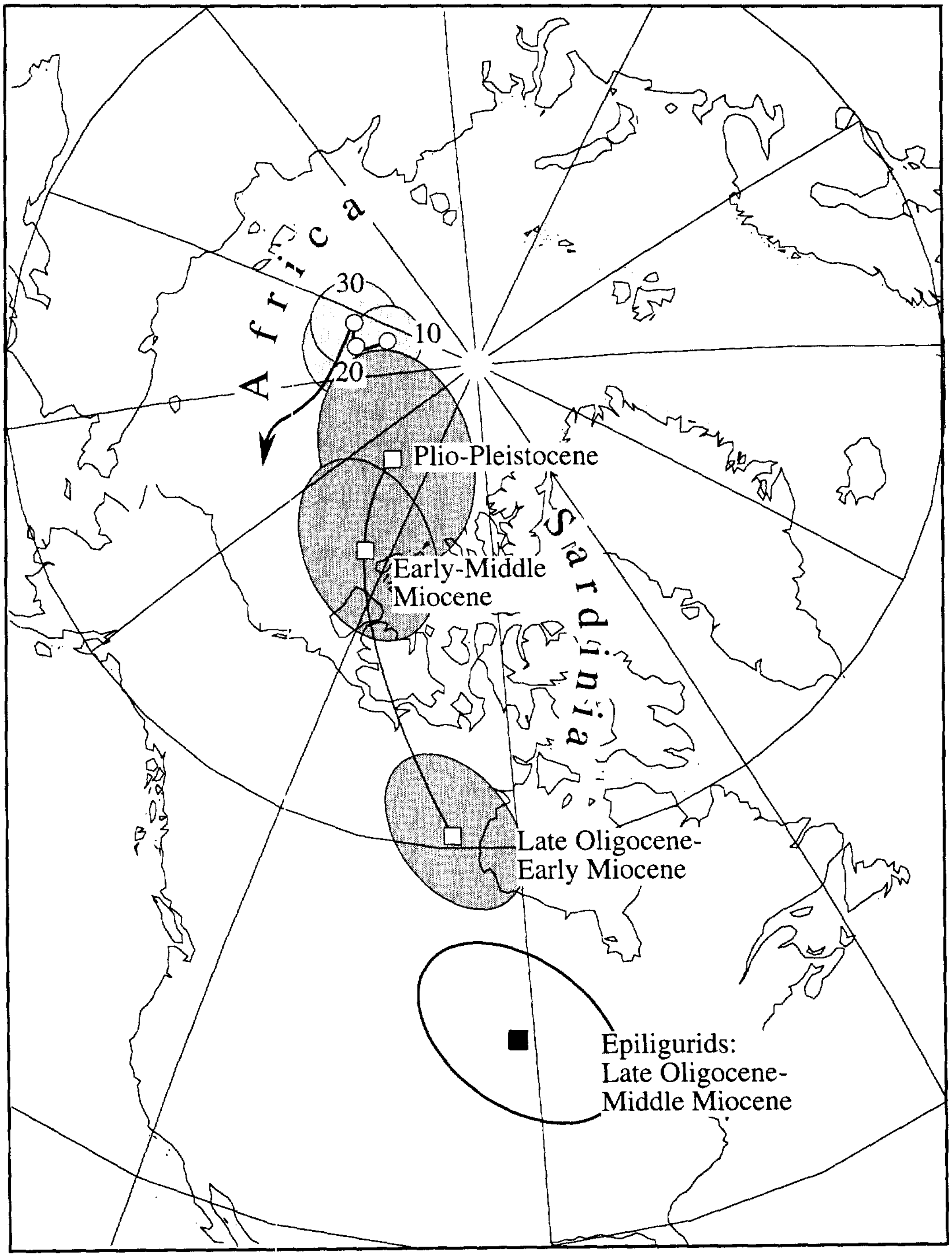


Fig. 6. The Late Oligocene–Middle Miocene paleomagnetic pole from the Epiligurian units (solid square) is compared with the apparent polar wander paths of Africa (open circles). and Corsica–Sardinia (open squares) (Table 2). See text for discussion.

tion with these ten Late Oligocene site-means from the literature, pass the reversal test [14] in geographic or bedding coordinates (Fig. 5d). Even though the overall ($N = 17$) fold test is statistically inconclusive, the precision parameter increasing only by a factor of 1.2 with full correction for tilting, we calculate an overall mean direction of Decl. = 312.5°E, Incl. = 42.8° in bedding coordinates. We regard this direction and its associated paleopole (47°N, 268.5°E) as the best proxy for the Late Oligocene–Middle Miocene Epiligurian clastics of the northern Apennines; note, however, that the Middle Miocene is represented by only two sites out of seventeen.

5. Comparison of paleomagnetic poles from the northern Apennines, Corsica–Sardinia and Africa / Europe

The rift-related motion of the Corsica–Sardinia block which may have occurred with respect to the south margin of stable Europe during the Miocene, e.g., [15], induced folding and thrusting in the Adria (i.e., Africa) passive continental margin, thus initiating the structuration of the (northern) Apennines, e.g., [16]. To check if this hypothesis is consistent with the available paleomagnetic data, we compare the Late Oligocene–Middle Miocene paleopole from the Epiligurids with the apparent polar wander path (APWP) for Corsica–Sardinia and the Cenozoic APWP for Africa and Europe (Fig. 6).

5.1. Construction of the Cenozoic Corsica–Sardinia APWP

To construct an APWP for Corsica–Sardinia, we calculated mean paleopoles by averaging site-mean directions from the literature, selecting those with $N \geq 3$ samples and a_{95}-values $\leq 20°$ (Table 2). Most of the data are from Sardinia because Corsica data are sparse, i.e., only one usable Eocene site with directions broadly consistent with Sardinia data and five Miocene sites of questionable magnetization age [17]. There is an open debate on whether Corsica–Sardinia behaved as a single block or was decoupled during drifting ([18] and references therein). However, any differential motion of Corsica relative to Sardinia which did take place must not have been large [18,19]. Therefore, for the purpose of this paper we consider Sardinia data broadly valid also for Corsica.

The main source of data to construct the Corsica–Sardinia APWP comes from the Bosano–Logudoro region of northwestern Sardinia where classic sections of Cenozoic volcanics were studied for paleomagnetism since the end of the 1960s ([20] and references therein). On the basis of preserved stratigraphic relationships, an older volcanic sequence consisting of the 'SA1' andesites and the overlying 'SI1' ignimbrites were recognized in this

Table 2
Cenozoic paleopoles for Corsica–Sardinia based on Sardinia data

#	Age	Lat. (°N)	Long. (°E)	k	dp/dm (°)	N	Locality
1	Late Oligocene–Aquitanian	61.1	260.3	15	3.9/6.2	59	Bosano–Logudoro–Arcuentu
2	Burdigalian–Serravallian (?)	76.7	233.4	20	3.9/6.0	52	Bos.–Logud.–Arcu.–Marmilla
3	Pliocene–Pleistocene	82.3	222.6	52	4.7/6.8	18	Orosei (east Sard.)–Logudoro

Lat. Long. = pole coordinates (all poles are calculated with respect to a point at 40°N, 9°E); k = Fisher precison parameter of the mean direction; dp, dm: semi-axes of the confidence oval about the paleomagnetic pole; N = number of site-mean directions used to calculate the pole.

#1: this entry is based on 21 sites from the 'SA1' volcanic series from Bosano–Logudoro [20], 35 sites from the 'SI1' volcanic series ([20] and [39] as reported in [40]), and, finally, 3 sites from Monte Arcuentu (i.e., sites 01419, 01421, 01422 of [41] as reported in [40]), that we attribute to the Formation 'B' of [25].

#2: this entry is based on 36 sites from the 'SA2' to 'SA3' series from Bosano–Logudoro [20], 9 sites from the Monte Arcuentu dykes (sites 01385, 01387, 01392–01394, 01400, 01405, 01417, 01420 of [41] as reported in [40]), that we attribute to Formation 'D' of [25], and, finally, 7 sites from [15] from the Logudoro marls (site M), Monte Arcuentu dykes (sites F–K, attributed to Formation 'D' of [25]), and Marmilla clastics (sites L, N) (the overall mean reported by [15] for these 7 sites is here recalculated as follows: before tilting Decl. = 349.4, Incl. = 44.6 [$k = 31$, $a_{95} = 10.9$]; after tilting Decl. = 349.9, Incl. = 40.5 [$k = 22$, $a_{95} = 13.1$]).

#3: this entry is based on 11 sites from Pleistocene basalts from Orosei [42] and Logudoro [43,44], and 7 additional sites from basalts of Pliocene to older age from Logudoro [42–44].

region [21], followed by a younger and largely superposed sequence comprised of andesites ('SA2'), rhyolites and dacites ('tau3'), ignimbrites ('SI2') and andesites ('SA3'). These volcanic series were also radiometrically dated by a number of authors [21–23], but a general consensus on their exact age is at present not fully met (see also discussion in [20]). According to the most recent data [23], the basal 'SA1' and 'SI1' series are comprised between 25 and 20.6 Ma (i.e., late Chattian–Aquitanian, or also Late Oligocene–Early Miocene, according to the Berggren et al. [24] time scale), whereas the ovelying 'SA2' to 'SA3' series should be bracketed between 19.6 and 16.6 Ma (i.e., Burdigalian, which is the late Early Miocene), but it could also be as young as 14 to 12 Ma (i.e., Serravallian, or late Middle Miocene) according to [21].

The Late Oligocene–Early Miocene paleopole of Corsica–Sardinia is then comprised of 56 sites from the 'SA1' and 'SI1' volcanic series, and 3 additional sites from the Monte Arcuentu region of southwestern Sardinia consisting of ignimbrites and lava flows which should belong to the 24- to 21-Ma-old Formation 'B' of [25]. The Early–Middle Miocene paleopole is instead comprised of 36 sites from the 'SA2' to 'SA3' series from Bosano–Logudoro, 9 sites from the Monte Arcuentu dykes which should belong to the Formation 'D' of [25] dated between 18.3 and 16.7 Ma [15,25], and, finally, 7 sites from [15] from the Logudoro marls (Monte Arcuentu dykes belonging to the Formation 'D' of [25]), and Marmilla clastics, which are comprised between 18.3 and 14.8 Ma. Finally, we calculated also a paleopole for the Pliocene–Pleistocene of Corsica–Sardinia based on 18 sites from basalts from Orosei (eastern Sardinia) and Logudoro (for detailed information and references, see footnote to Table 2). [1]

[1] In this compilation of Corsica–Sardinia data we excluded data from the Anglona region of northern Sardinia [15–20] because of the presence of inconsistent directions which were interpreted in terms of either local tectonic rotations or contamination by secular variations [15]. Similarly, we also excluded data from the Sarroch volcanics of southern Sardinia because they yielded anomalously rotated directions which may suggest local tectonics [37]. Finally, data from the Campidano region [38], as well as the recently acquired sites 'D' and 'E' of [15] from Logudoro, were also discarded because of difficult age attribution and questionable age data (?19.9 Ma), respectively.

5.2. Cenozoic APWP for Africa and Europe

The Cenozoic Africa and Europe reference paleopoles are critical to assess the amount of Corsica–Sardinia and northern Apennine rotation. Because the most recent compilation [26] only contains Paleogene to older mean poles, we adopted the Besse and Courtillot [27] version which contains 33 entries for Africa distributed over the entire Cenozoic, whilst the Eurasia APWP remains poorly defined with only 12 entries. We notice, however, that the Eurasia 10–30 Ma (i.e., Oligocene–Miocene) mean pole is not significantly different from the coeval Africa mean pole (81°N, 177°E, $N = 5$), whose location is also given additional and independent support by the Oligocene Africa paleopole of [28]. This coincidence of Oligo–Miocene poles for Africa and Eurasia is not surprising because by that time most of the convergence between Africa and Europe was already attained. Because the Oligocene to younger poles of Africa also seem broadly valid for Europe, we use the master APWP of Besse and Courtillot [27] in Africa coordinates (which is reinforced by additional data from North America) as the reference curve that we compare with the Oligocene–Miocene of Corsica–Sardinia and the Epiligurian units.

5.3. Tectonic rotations of the northern Apennines and Corsica–Sardinia

The Epiligurian paleopole is located at 47°N, 268.5°E (Table 1) and shows a large and significant counterclockwise rotation of 52° ($\pm \approx 8°$) with respect to the 10–30 Ma Africa reference paleopoles. The Late Oligocene–Early Miocene paleopole of Corsica–Sardinia shows a similar amount of rotation with respect to Africa (Fig. 6). The timing of the Corsica–Sardinia block motion heavily depends on radiometric age data whose reliability can however be questioned because contradictory results were obtained from the same rock unit. At present, it seems viable that most of the motion occurred sometimes between the Burdigalian and the Serravallian (i.e., late Early to late Middle Miocene), in partial agreement with the most recent analysis of [15]. Moreover, it is unclear whether there is also some minor later additional motion because on one hand the

Early–Middle Miocene Corsica–Sardinia paleopole seems to be still rotated counterclockwise with respect to Africa (and Europe) (Fig. 6), on the other hand the geological evolution of the Balearic basin suggests that this motion should not have continued much after the Middle Miocene (e.g., [29]). In any case, the paleomagnetic data from this study and the literature imply a similar amount of rotation for Corsica–Sardinia and the Epiligurian units of the northern Apennines. We suggest that the rotation in the Ligurian units during thrusting onto the Adria margin may be associated with the motion of Corsica–Sardinia in the general context of the relative motions between Africa and Europe during the Neogene. Confirmation of this hypothesis would require constraining the timing of the Corsica–Sardinia block motion, and sampling the end of the rotation in the northern Apennines in Late Miocene and younger sediments. Site 2 of Pliocene age shows directions with no or very small rotation, but it is at present unclear whether they are primary directions or secondary magnetization components. The correspondence between the Epiligurian and Corsica–Sardinia poles could, therefore, also simply be a coincidence, and this should be tested by more extensive study of Late Miocene–Pliocene Epiligurian sediments.

6. Comparison with data from the literature from the central Apennines

A wealth of paleomagnetic data are available from the Apennines south of the study area, where the Ligurian units are limited or absent on top of the Mesozoic Adria margin (Tuscan–Umbria) successions and Cenozoic foredeep sediments. Some of these regions were investigated since the 1970s, like the Mesozoic–Cenozoic Umbria Apennines, while others have been studied in detail only very recently, like the front of the Marche and Romagna Apennine belt in the northeast, or the Tuscan extensional basins in the southwest. We compile or calculate overall mean directions from selected studies from different regions of the central Apennines (Table 3) that we

Table 3
Paleomagnetic directions from the northern and central Apennines, and Sardinia (bottom)

#	Age	Decl. (°)	Incl. (°)	k	α_{95}	N	Locality	Reference	Ω (°)
1	L. Oligo–M. Mio	312.5	42.8	33	6.3	17	Epiligurids	this study	52 ± 8
2	Messinian	335.2	52.5	22	7.9	17	Marche–Romagna	[1] calculated	29 ± 8
3	Messinian	10.9	37.7	21	11.6	9	Sibillini–Cingoli	[1] calculated	−7 ± 12
4	Messin–E. Plio.	0.9	42.5	45	7.3	10	Acquasanta	[1] calculated	3 ± 7
5	Messin.–Pliocene	357.3	56.7	880	2.6	5	Tyrrhen. margin	[33–35]	7 ± 3.5
6a	Late Cretaceous	315	41	23	10.3	10	N. Umbria	[30]	26 ± 11
6b	Early Cretaceous	295	37	–	6.8 *	15	N. Umbria	[31]	28 ± 14
7a	Late Cretaceous	351	39	21	11.5	9	S. Umbria	[30]	−10 ± 12
7b	Early Cretaceous	318	36	–	8.3 *	16	S. Umbria	[31]	5 ± 15
8	Early Miocene	16	43	28	11.5	7	Prenestini	[2]	−11 ± 12
9	Late Oligo–Aquit.	329.2	44.7	15	4.9	59	Sardinia	this study	35 ± 7

Decl., Incl. = declination and inclination after tectonic correction; k, α_{95} = Fisher statistics, where (*) is the angular error (at the 95% confidence level) of the mean declination (see [31]); N = number of site means (#5 uses five overall means [33–35]); Ω = angular difference between observed declinations and expected declinations at a common site located at 43.5°N, 11.5°E (40°N, 9°E for Corsica–Sardinia, #9) as deduced from the Africa APWP of [27] (− is clockwise, otherwise counterclockwise); error based on squared root mean of α_{95} cones of confidence; Ω and attached errors are plotted as arrows in Fig. 7.
#2 and #3: the overall mean directions are calculated from site-mean directions from Table 1 of [1]. #4: same as for #2 and #3, with the addition of site FL9 of [45]. #6a: mean direction of the Maastrichtian north group of Table 1 of [30]. #7a: mean direction of the Maastrichtian south group of Table 1 of [30].
The angular difference Ω is calculated with respect to the following reference paleopoles. For entry #1, an Africa pole located at 83°N, 160°E, which results from averaging the 10 to 30 Ma Africa poles of [27]. For entries #2 to #5, the 10 Ma Africa pole of [27]. For #6a and #7a, a Late Cretaceous pole located at 64°N, 236°E (α_{95} = 4°, k = 122), which is based on 11 entries from stable Adria as reported in [46]. This pole is statistically undistinguishable from the Africa 80 and 90 Ma poles of [27]. For #6b and #7b, an Africa pole located at 52°N, 258°E, which results from averaging by means of Bingham statistics the 110 to 140 Ma Africa poles of [27].

compare with expected directions assuming that the Apennines were autochthonous with respect to Adria/Africa. The angular difference between observed and expected declinations using the Besse and Courtillot [27] paleopoles is an estimate of vertical-axis tectonic rotations (Table 3). Moving from the external part of the central Apennine chain southwestward (i.e., from the Adriatic to the Tyrrhenian margin), we observe the following trend. Paleomagnetic data from Messinian clastics outcropping in the Marche–Romagna foredeep at the front of the Apennine belt [1] indicate a significant counterclockwise rotation (Fig. 7, location 2), whereas virtually no rotation is observed in the Messinian Sibillini–Cingoli and Messinian–Early Pliocene Acquasanta foredeeps [1] (locations 3 and 4, respectively). Similarly, counterclockwise rotation is observed in the Early and Late Cretaceous pelagic sediments of northern Umbria [30,31] (location 6), whereas no rotation seems to characterize similar sediments from southern Umbria [30,31] (location 7) and the Miocene of the Prenestini Mountains [2] (location 8) (note, however, that the difference between paleomagnetic directions from Mesozoic sediments from northern

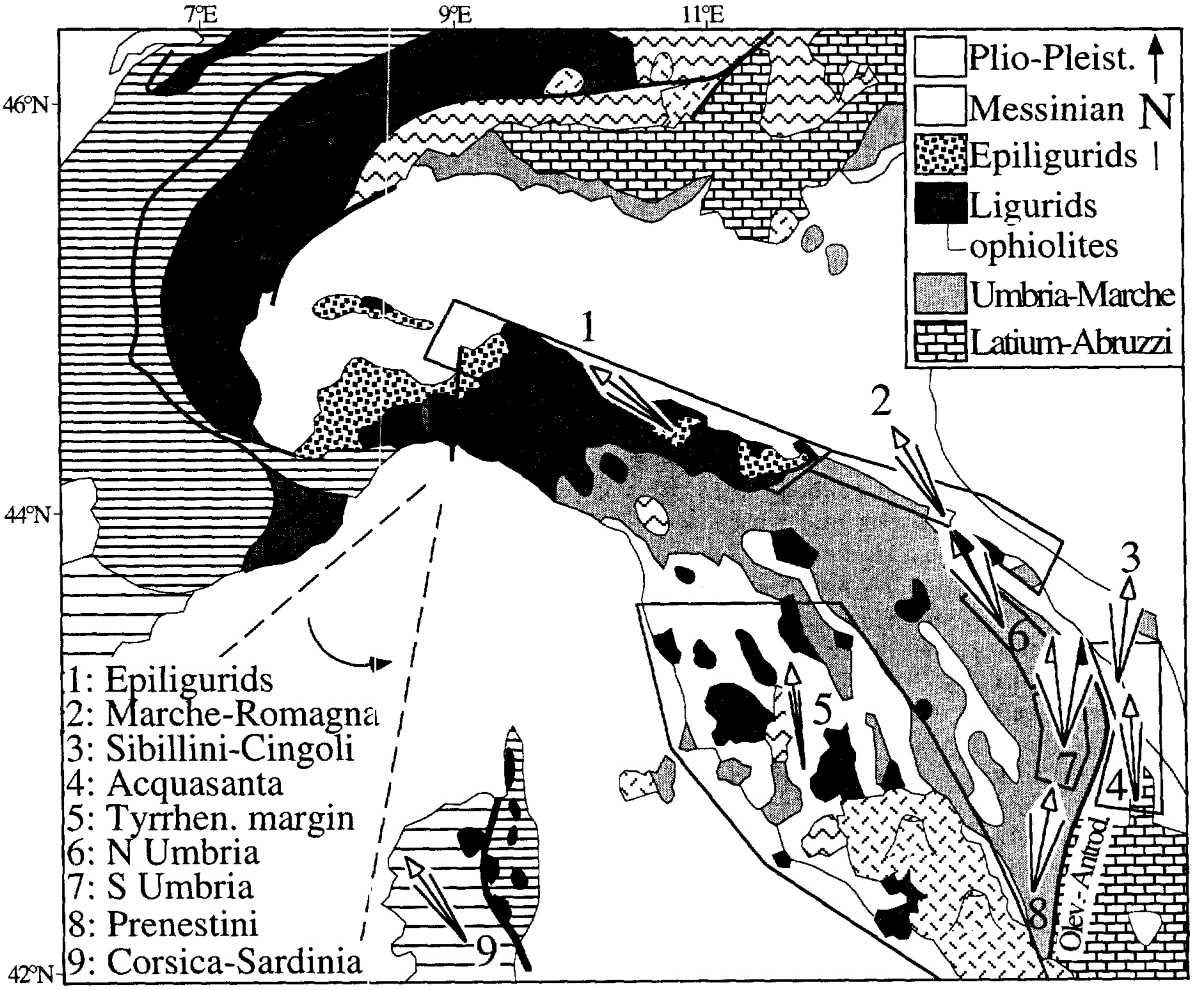


Fig. 7. Tectonic map of the northern and central Apennines from the *Carta Tettonica d'Italia* (1 : 500,000). Legend only for Apennine domains discussed in the text. *Olev.-Antrod.* stands for Olevano–Antrodoco Line. Arrows, with attached reference numbers, represent the angle Ω between observed and expected paleomagnetic directions as from Table 3. Black (white) semi-arrows refer to directions labelled as 6a and 7a (6b and 7b) in Table 3.

and southern Umbria may not be statistically significant; A.M. Hirt, pers. commun.; see also discussion in [31]). The Mesozoic Umbria sediments were likely to have deformed in syn- to post-Langhian–Tortonian (Middle–Late Miocene) times because, according to [6], this is the age of deformation in the overlying Marnoso–Arenacea foredeep turbidites. Deformation peaked in the Early Pliocene where a major episode of thrusting is documented at the front of the northern Apennine chain [32]. Therefore, the Mesozoic Umbria and Neogene foredeep sediments were deformed when most of the Corsica–Sardinia motion was probably already accomplished. Finally, moving further inward (i.e., to the southwest of the Apennine front), Messinian to Pliocene sediments and intrusives from Tuscany (location 5) show no rotation of paleomagnetic vectors [33–35]. At the time the central Apennine front was subject to compression and differential rotation, Tuscany was experiencing non-rotational extensional tectonics with the formation of NW–SE-trending grabens related to the opening of the Tyrrhenian Sea.

7. Discussion and conclusions

We found a dual-polarity component of magnetization of presumed Miocene age at ten sites comprised of Epiligurian clastic formations outcropping on top of the northern Apennine thrust sheets. This primary component survived a recent remagnetization phase that overprinted eleven of the remaining sixteen sites (the last five sites were rejected due to unstable magnetizations). Seven sites bearing primary directions, in conjunction with data from the literature, yielded a Late Oligocene–Middle Miocene overall mean direction which is significantly rotated counterclockwise with respect to the Africa reference directions by a similar amount as roughly coeval Corsica–Sardinia data.

The northern Apennine Ligurian units, which represent the accretionary wedge deposited in the Mesozoic Ligurian ocean between Corsica–Sardinia (Europe) and Adria (Africa), were rotated during and/or after the Middle Miocene. This rotation may be associated although not necessarily rigidly coupled with the motion of the Corsica–Sardinia block which probably occurred during the (late Early)–Middle Miocene. A different history instead characterizes the Adria margin successions of the central Apennines where paleomagnetic data allow us to define a syn- to post-Pliocene differential rotation of the northern relative to the southern Umbria sector along the Sibillini thrust front. This differential rotation apparently occurred in the same time frame as non-rotational extension that is documented along the northern Tyrrhenian margin (e.g., [33]). These two episodes, of compression at the chain front and extension internal to the front, occurred after the motion of Corsica–Sardinia and mainly during the opening of the Tyrrhenian Sea. (It is likely that post-Corsica–Sardinia rotations occurred also at the northern Apennine front, for example in the Salsomaggiore unit.) Because the northern Tyrrhenian Sea opening is non-rotational, rotation at the Umbria Apennine front must be accounted for by a mechanism that acted *only* at the thrust front. Recently, one of us (AA) suggested that a deep-seated WNW–ESE-trending lineament located in the Adriatic foreland, whose nature is presently under investigation, intersects the Apennine front where the large counterclockwise rotations are observed [36]; the northern Umbria belt may have collided and rotated against this feature, whereas the non-rotated southern Umbria belt, being located far from the lineament, was simply thrust along the N–S-trending Olevano–Antrodoco Line, which is a lateral ramp bounding to the west the Latium–Abruzzi carbonate platform.

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