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Paleomagnetic evidence for a Neogene two-phase counterclockwise tectonic rotation in the Northern Apennines (Italy)

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Abstract

Paleomagnetic directions have been determined for a new collection of Early Oligocene and Late Miocene–Pliocene Epiligurian clastic sediments from the frontal portions of the northern Apennines. These results are combined with Cenozoic data from the literature to evaluate whether rotations of units in this region are related to the Oligo-Miocene Corsica–Sardinia rotation and/or to younger phases of deformation of the Apennine chain. When Corsica/Sardinia moved counterclockwise off the coast of France, the Ligurian units located at its front were presumably pushed eastward and rotated counterclockwise above a main boundary thrust onto the Adria/Africa margin. We propose that about 24 out of a total of 52° of rotation observed in the Epiligurian units can be related to the Oligo-Miocene motion of the Corsica–Sardinia block, in partial agreement with previous conclusions, and the remaining 28° to the Pliocene tectonic phase at the Apennine chain front, which may have (re)activated thrust planes in the Adria/Africa succession below the Ligurian wedge. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Apennines; Italy; Neogene; paleomagnetism

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1. Introduction: paleomagnetism and Apennine tectonics

The Apennines are a Neogene thrust-and-fold belt that developed in conjunction with the Oligo-Miocene Corsica–Sardinia block rotation and the subsequent opening of the Tyrrhenian sea in the Late Miocene and Pliocene. Tectonic rotations associated with thrusting have recently been documented paleomagnetically along the NW–SE-trending, rectilinear northern Apennines (Muttoni et al., 1998), as well as in other portions of the northern and central Apennines (Mattei et al., 1996; Speranza et al., 1997). We present new data from the northern Apennines and review data from the literature to evaluate whether the observed tectonic rotations are related to the Oligo-Miocene Corsica–Sardinia rotation and/or to younger phases of structuration of the Apennine chain.

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1.1. Oligocene–Miocene Corsica–Sardinia rotation

The Apennines are composed of, among others, sediments and ophiolites from the Mesozoic Ligurian ocean. The Ligurian ocean was formed as a consequence of the breakup of Pangea and separation of Africa from Europe in the Jurassic and was located between Corsica–Sardinia, which at that time was attached to the southern European margin of France, and the Africa margin of western Adria. Later, during the Africa/Europe convergence since Late Cretaceous times, the Ligurian oceanic units underwent deformation due to the subduction of the Ligurian ocean below the European margin of Corsica–Sardinia. In the Oligo-Miocene, Corsica–Sardinia rifted off Europe and moved away, rotating counterclockwise to attain its present-day position in the middle of the eventual western Mediterranean basin (e.g. Alvarez, 1972; Vigliotti and Langenheim, 1995). As a consequence of the motion of Corsica–Sardinia, the Ligurian accretionary wedge was thrust onto the Cenozoic foredeep sediments, which were progressively deposited at the front of the Ligurian thrust sheets as these were migrating to the northeast onto the Adria passive continental margin (e.g. Boccaletti et al., 1990).

Recently, Muttoni et al. (1998) carried out a paleomagnetic study on clastic sediments deposited in relatively undeformed basins located on top of the advancing Ligurian thrust sheets. These clastics, referred to in the literature as Epiligurian units, yielded a component of magnetization of Late Oligocene–Middle Miocene age. The derived paleomagnetic pole shows a large and significant counterclockwise rotation with respect to the coeval (10–30Ma) African reference paleopoles (Besse and Courtillot, 1991). The Late Oligocene–Early Miocene paleopole of Corsica–Sardinia shows a similar, yet smaller, amount of rotation with respect to European reference paleopoles. Therefore, Muttoni et al. (1998) suggested that the thrusting of the Ligurian units onto the Adria margin was accompanied by the counterclockwise rotations of the thrust sheets, and that these rotations may have been associated, although not necessarily rigidly coupled, with the counterclockwise motion of the Corsica–Sardinia block.

1.2. Late Miocene–Pliocene Tyrrhenian opening

The deformation of the Apennines continued after the end of the rotational motion of the Corsica–Sardinia block. With the opening of the Tyrrhenian sea since the Late Miocene, compressional deformation occurred at the front of the northern-central Apennines, while internal to the front, along the Tyrrhenian margin, the continental crust has been subject to tension with the formation of NW–SE-trending grabens. Deformation peaked in the Early Pliocene when a major episode of thrusting took place at the front of the northern Apennines (Boccaletti et al., 1990). Paleomagnetic data from Messinian clastics outcropping in the Marche-Romagna foredeep at the front of the northern-central Apennine belt (Speranza et al., 1997) indicate a significant counterclockwise rotation, whereas Messinian to Pliocene sediments and intrusives from the Tyrrhenian margin of Tuscany show no rotation of paleomagnetic vectors (Lowrie and Alvarez, 1979; Sagnotti et al., 1994; Mattei et al., 1996). Therefore, at the time the Apennine front was subject to compression and rotation, Tuscany was experiencing non-rotational extension (cf. Speranza et al., 1997).

To confirm the hypothesis that the paleomagnetic rotations observed by Muttoni et al. (1998) in the Epiligurian units were associated with the motion of the Corsica–Sardinia block, the precise timing of the Corsica–Sardinia block motion would need to be constrained. This can be accomplished by finding the end of the northern Apennines rotation in Late Miocene or younger Epiligurian sediments, thus allowing separation of the effects of the 'Corsica–Sardinia' from the 'Tyrrhenian' tectonic phases. This paper presents new paleomagnetic data from Early Oligocene and Late Miocene–Pliocene sediments of the Epiligurian units, and discusses again the conclusions attained by Muttoni et al. (1998) in the light of these new results and data from the literature.

2. Age and location of the sampling sites

This study focuses primarily on the youngest portion of the Epiligurian clastic succession, which crops out in the Bologna area (Fig. 1a). Steeply

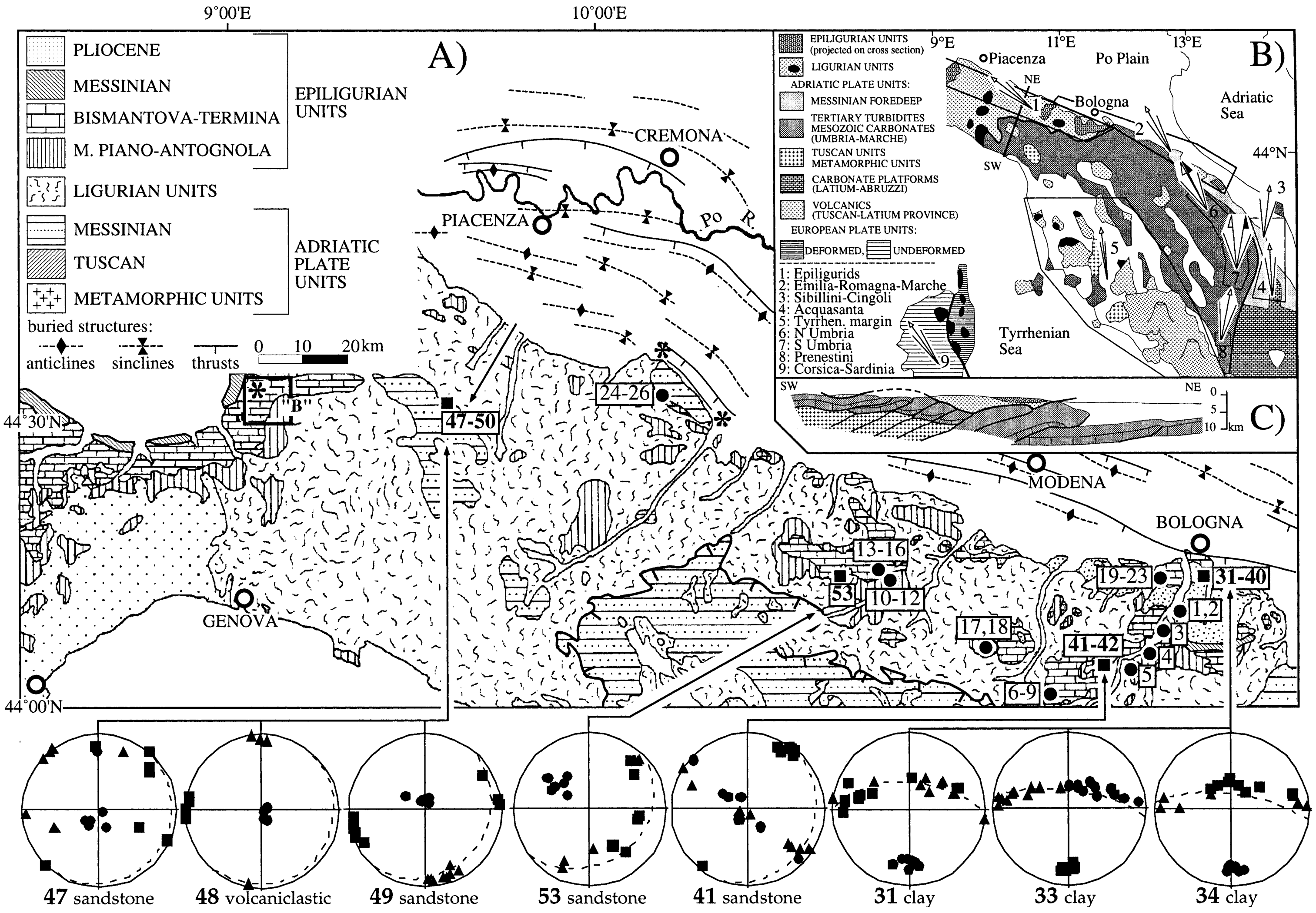


Fig. 1. Geological map of the northern Apennines (a) with sampling site locations from this study (squares), Muttoni et al. (1998) (circles), and Thio (1988) (asterisk, location 'B', which comprises 10 Late Oligocene sites). Lower hemisphere, equal area projections of the principal axes of the AMS of individual samples are also reported; squares represent k axes, triangles represent k_2 axes, and circles represent k_3 axes. Bedding altitudes (reported as azimuth of dip/dip) are as follows: site 31, 4°E/60° (i.e. strata dipping to the NNE by 60°); sites 33 and 34, 3°E/74°; site 41, 114°E/14°; sites 47 and 48, 135°E/4°; site 49, 134°E/16°; site 53, 150°E/27°. Tectonic map of the northern and central Apennines from the Carta Tettonica d'Italia (Funiciello et al., 1981) (b). Arrows, with an associated reference number represent the angle, Ω, between the observed paleomagnetic declinations and those expected from the Africa APWP of Besse and Courtillot (1991) for nine regions of the Apennines (see Muttoni et al., 1998 for further information). The geological cross-section across the northern Apennines (c) is oriented NE–SW on tectonic map (b).

dipping clay-rich sediments of the Late Miocene succession were collected at seven sites, and the overlying Intra-Apennine Pliocene was sampled at three additional sites located a few kilometers to the south in almost flat-lying sediments. The Late Miocene succession consists of Tortonian pre-evaporitic clays (Termina Formation), sampled at sites 31–34, followed by the Messinian evaporites related to the Mediterranean salinity crisis and, finally, by post-evaporitic clays with resedimented gypsum derived from the Colombacci Formation of Messinian age, sampled at sites 35–37. The Intra-Apennine Pliocene consists of over 1000 m of shallow marine to continental clastics. We sampled the marine clays of the Argille Azzurre Formation at sites 38 and 39, and some harder concretions within looser Pliocene marine sandstone beds at site 40. Further sampling was done in the flat-lying, older portion of the Epiligurian succession to confirm and expand the previous results of Muttoni et al. (1998), and namely, we sampled in the Early Oligocene siliciclastic turbidites of the Ranzano Sandstones at sites 41 and 42, 47–49 and 53 (Fig. 1a). Site 48 is a volcanoclastic level located within the Ranzano Sandstones.

3. Rock-magnetic properties

The magnetic mineralogy of selected samples that gave reliable paleomagnetic directions from sites 31 and 33 (Tortonian Termina Formation clays), 35 (Messinian Colombacci Formation clays), 40 (Pliocene sandstones) and 48 (Early Oligocene Ranzano Sandstones), that we consider representative of the main lithologies encountered, was determined using standard rock-magnetic experiments. An incremental isothermal remanent

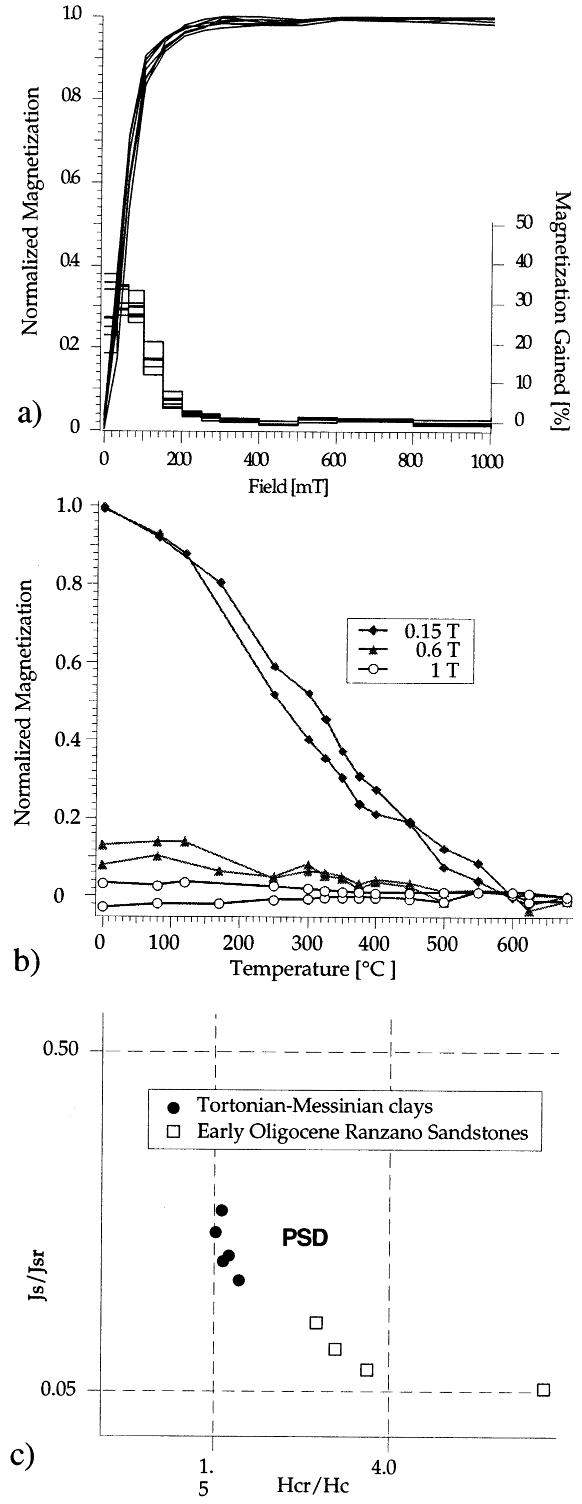


Fig. 2. Rock-magnetic properties of selected Epiligurian clastics samples deduced from the acquisition curves of isothermal remanent magnetization (IRM) (a), the thermal unblocking characteristics of orthogonal-axes IRMs (Lowrie, 1990) induced at fields of 1, 0.6 and 0.15 T (b), and, finally, the ratios of the hysteresis parameters coercivity of remanence (Hcr), coercivity (Hc), saturation remanence (Jrs) and saturation magnetization (Js) plot on a Day et al. (1977) diagram (c). See text for discussion.

magnetization (IRM) was imparted at 25–50 mT steps along the sample *z*-axis, and remanence was measured after each magnetization step up to a maximum magnetizing field of 1 T. The IRM was then AF-demagnetized to determine the value of the median destructive field (MDF). Finally, a composite IRM at 1, 0.6 and 0.15 T fields was induced along sample orthogonal axes and thermally demagnetized up to 680°C in 20–100°C steps, measuring remanence after each demagnetization step (Lowrie, 1990).

All samples have very similar IRM acquisition curves that saturate at fields between 0.25 and 0.3 T (Fig. 2a). The median destructive fields are of 22 ± 9 and 16.9 ± 15 mT for the Mio-Pliocene clays and Early Oligocene sandstones, respectively. The thermal unblocking characteristics of orthogonal-axes IRM show the presence of a dominant low coercivity (<0.15 T) magnetic phase with maximum unblocking temperatures of 570°C (Fig. 2b). These observations suggest that magnetite is the main carrier of the magnetic remanence. Hysteresis loops and backfield demagnetization of selected samples were measured using a Micromag alternating gradient field magnetometer. Most of the samples show a large paramagnetic component of the induced magnetization. The values of the coercivity of remanence (Hcr), coercivity (Hc), saturation remanence (Jrs) and saturation magnetization (Js), when corrected for the paramagnetic signal, plot on a Day diagram (Day et al., 1977) in the pseudo-single domain (PSD) range (Fig. 2c). Samples from sites 31 and 33 from the Termina Formation clays of Tortonian age and from site 35 from the Colombacci Formation clays of Messinian age have lower Hcr/Hc and higher Jrs/Js ratios compared to Early Oligocene samples from the Ranzano Sandstones, suggesting a different magnetic grain size. The Hc and Hcr values are comprised between 12 and 23 and between 28 and 33 mT, respectively, and are compatible with those expected for magnetite.

4. Magnetic fabric

The anisotropy of magnetic susceptibility (AMS) has been measured to determine whether the sediments have undergone any significant deformation (Sagnotti et al., 1998). The AMS was measured on an AGICO KLY-2 susceptibility bridge where the anisotropy can be expressed as a second-order tensor with principal axes $k_1>k_2>k_3$. An average ellipsoid was defined using a modified version of the principal component analysis of Jelinek (1978). The AMS was measured at 77 K, using the same approach as Hirt and Gehring (1993), for one sample per site to investigate the minerals responsible for the observed magnetic fabric.

The Tortonian clays of the Termina Formation from sites 31, 33 and 34 near Bologna at the Apennine front possess a lineation of under 1% and a weak compaction of less than 1.5% (Fig. 1, Table 1). Site 33 exhibits an inverse fabric in which the k_1 axes are sub-parallel to the bedding pole, and the k_2 and k_3 axes are distributed in the bedding plane (bedding attitudes are reported on the AMS stereoplots and in the caption to Fig. 1).

Table 1
Normalized magnitude and in-situ orientation of the principal axes of the ansiotropy of magnetic susceptibility $k_1>k_2>k$[a]

Site	k_1	Declination	Inclination	k_2	Declination	Inclination	k_3	Declination	Inclination	Lineation	Foliation
31	1.007	279.0	24.1	1.000	47.1	55.2	0.993	278.9	24.0	1.008	1.006
33	1.007	178.6	19.6	0.997	278.9	26.7	0.996	56.8	55.9	1.010	1.001
34	1.005	35.9	61.0	1.004	271.7	17.3	0.991	174.3	22.5	1.001	1.013
41	1.017	38.4	4.9	0.992	133.1	43.4	0.992	303.3	46.2	1.025	1.001
47	1.013	85.9	8.3	1.004	354.1	11.8	0.984	210.3	75.5	1.009	1.021
48	1.063	270.7	5.4	1.024	1.4	7.21	0.919	143.9	81.0	1.038	1.114
49	1.023	252.0	2.5	1.014	161.5	9.5	0.964	356.7	80.2	1.009	1.052
53	1.079	110.9	37.8	1.037	206.5	7.2	0.895	305.5	51.3	1.041	1.158

[a] The lineation is defined as k_1/k_2 and the foliation as k_2/k_3.

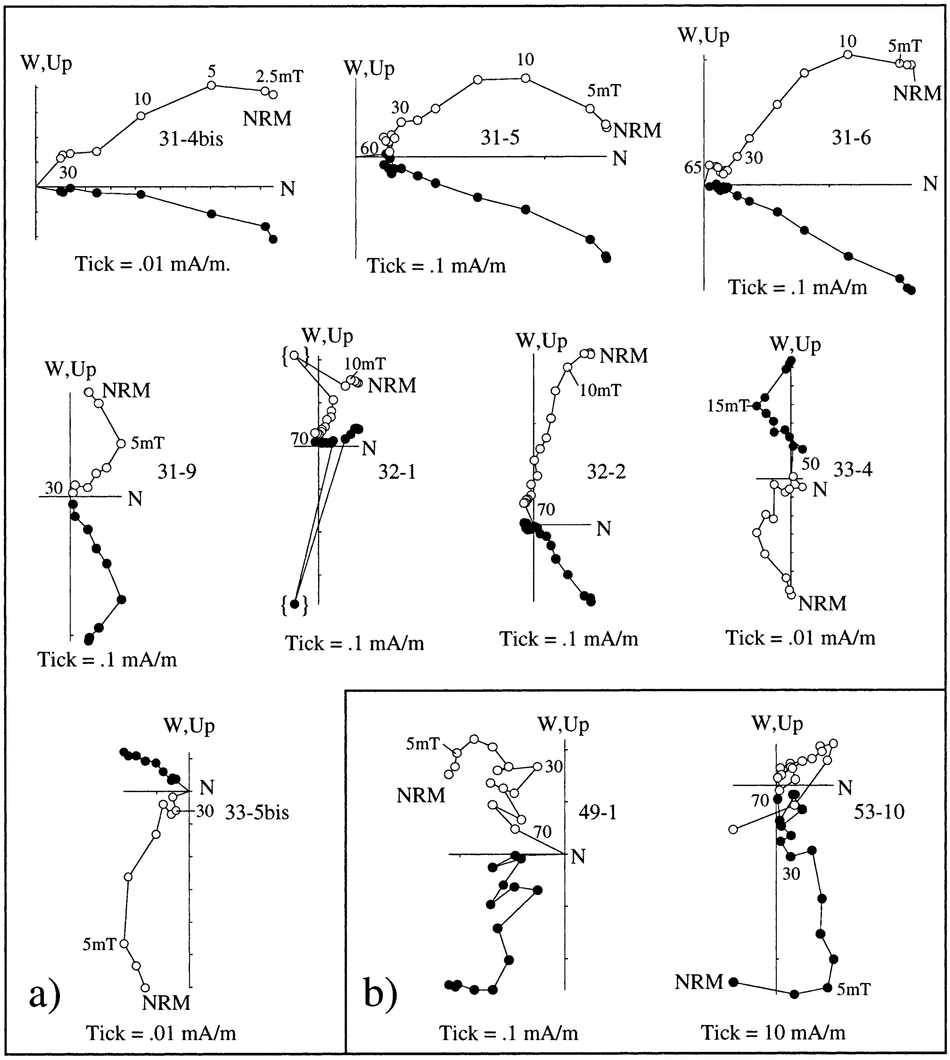


Fig. 3. Zijderveld demagnetograms of representative Epiligurian units samples from the Tortonian clays oucropping at the northern Apennines front at Bologna (a) and from the Early Oligocene flat-lying sandstones located at sites internal to the chain front (b). Closed symbols are projections onto the horizontal plane, and open symbols are projections onto the vertical plane. All diagrams are in geographic coordinates.

In the flat-lying older portion of the Epiligurian succession internal to the Apennine front, we studied the AMS fabric in the Early Oligocene siliciclastic turbidites of the Ranzano Sandstones at sites 41, 53 and 49–47 (Fig. 1, from east to west; Table 1). Site 41 has a lineation of 2.5% and a prolate AMS where the k_1 axes are sub-parallel to the structural fold trend and the k_2 and k_3 axes are distributed as expected for the superposition of a horizontal compaction on the bedding compaction. The magnetic fabric at site 53 is the best developed with an average flattening of 16% in the bedding plane. Although the average lineation is 4%, the k_1 axes are distributed in the bedding plane. The magnetic fabric at site 47 is dominated by the bedding compaction, although the fabric is

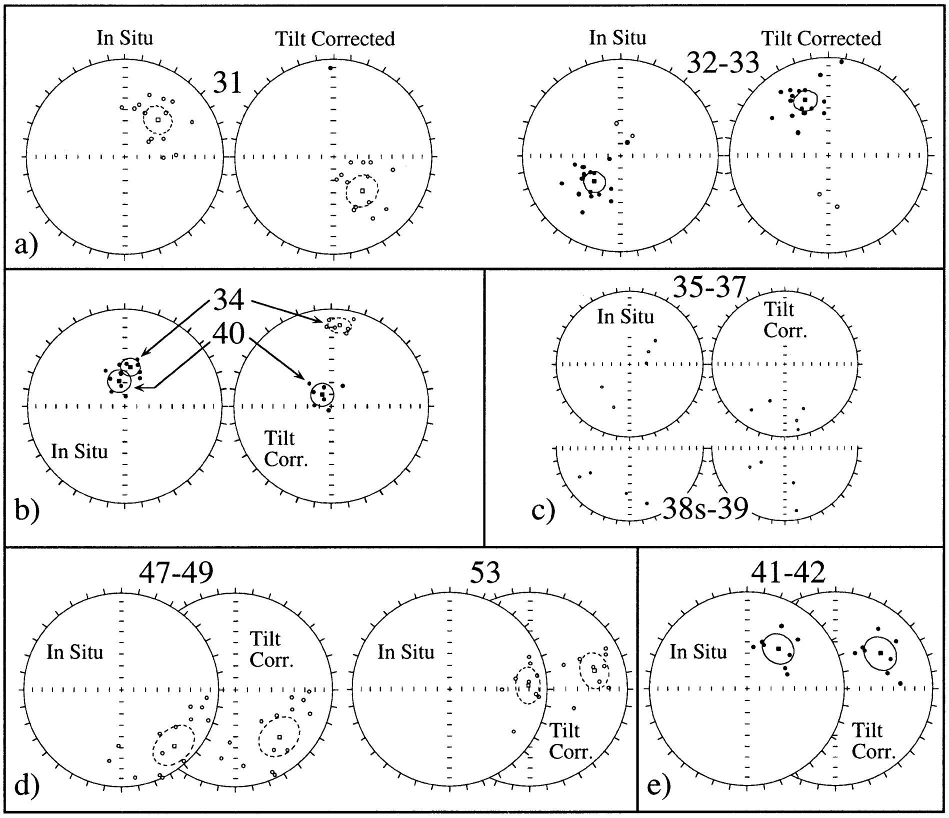


Fig. 4. Equal-area projections before and after bedding-tilt correction of the characteristic component directions from Epiligurian clastics at Tortonian site 31 and site 32–33 combined from the northern Apennine chain front (a), Tortonian and Pliocene sites 34 and 40 (b), Messinian and Pliocene sites 35–39 (c), and from Early Oligocene site 47–49 combined and site 53 (d), and site 41–42 combined from flat-lying sandstones located internal to the chain front (e). Solid symbols refer to the lower hemisphere.

weakly developed. Sites 48 and 49 display bedding compaction but also a well-developed lineation that is similar to the structural trends in the region.

The orientation of the principal axes of the AMS ellipsoids did not change at 77 K, but all sites except 48 and 53 showed an increase by a factor of 3.0–3.8 in the intensity of the principal susceptibilities at 77 K. This is in broad agreement with the Curie–Weiss Law for a purely paramagnetic material, and therefore, we conclude that paramagnetic minerals dominate the magnetic fabrics at these sites. Sites 48 and 53 showed an increase in the susceptibility at 77 K by a factor of 2, which suggests that ferromagnetic minerals are also responsible for the observed fabric at these sites.

In conclusion, the magnetic fabric of the Tortonian clays at the Apennine front is generally weak, whereas that of the Ranzano Sandstones internal to the front is dominated by bedding compaction.

5. Paleomagnetic results

Paleomagnetic samples were collected with a water-cooled rock drill and oriented with a magnetic compass. The natural remanent magnetization (NRM) was measured on a 2G D.C.-squid cryogenic magnetometer at ETH Zürich. After pilot thermal and alternating field (AF) demagnetization studies, all the standard 11.4 cm^3 specimens were subjected

Table 2
Paleomagnetic directions from the northern Apennines from this sudy and the literature[a]

Ref.	Site number	Locality	Coordinates	Lithology	Age	*n*	In situ				Tilt corrected				Latitude/ longitude	dp/dm or
							Decl. (°)	Incl. (°)	*k*	a95 (°)	Decl. (°)	Incl. (°)	*k*	a95 (°)	(°N)/(°E)	A95 (°)
Epiligurian sites at the deformed Apennine front																
A	31	Parco dei Gessi	(44°26′N/11°26′E)	Termina clays	Tortonian	14	41.3	−48.4	13	11.6	140.4	−52.2	10	13.2		
A	32–33	Parco dei Gessi	(44°26′N/11°26′E)	Termina clays	Tortonian	18	223.9	58.6	16	8.9	337.2	39.5	16	9.0		
A	34	Parco dei Gessi	(44°26′N/11°26′E)	Termina clays	Tortonian	6	Remagnetized in the present-day field									
A	35–37	Parco dei Gessi	(44°26′N/11°26′E)	Colombacci clays	Messinian	5	Scattered/unstable									
A	38–39	Ca'Bazz.–Zena	(44°22′N/11°24′E)	Argille Azzurre	Piocene	6	Scattered/unstable									
A	40	Ca Bazz.–Zena	(44°22′N/11°24′E)	Concretions in sandstones	Pliocene	7	Remagnetized in the present-day field									
B		Marche–Romagna		Clays	Messina	17S	155.2	−52.0	9	12.8	155.2	−52.5	22	7.9		
Overall from A (two sites, i.e. 31, 32–33) and B (17 sites)					Tort. Messiniano	19S	148.2	−56.6	6.5	14.3	154.6	−51.8	23	7.1	67.0/259.9[b]	6.6/9.7
Epiligurian sites internal to the Apennine front and 'undeformed'																
A	41042	Rioveggion	(44°17′N/11°12′E)	Ranzano Ss.	E. Oligocene	8	38.0	46.9	19	12.9	52.0	40.9	17	13.7		
A	47–49	Campagna	(44°43′N/09°15′E)	Ranzano Ss.	E. Oligocene	13	133.1	−20.6	8	15.9	132.9	−33.1	7	16.3		
A	53	Zermagnone	(44°31′N/10°15′E)	Ranzano Ss.	E. Oligocene	9	87.3	−20.5	18	12.6	74.0	−31.8	16	13.4		
C	10	Carpineti	(44°27′N/10°31′E)	Carpineti Ss.	E. Miocene	5	278.5	65.9	12	23.3	306.7	27.9	12	23.3		
C	17	Pavullo n. Frign.	(44°19′N/10°50′E)	Bismantova Ss.	M. Miocene	7	297	43.8	48	8.8	310.5	47.5	47.5	8.8		
C	18	Pavullo n. Frign	(44°19′N/10°50′E)	Bismantova Ss	M. Miocene	7	323.6	50.2	11	19.4	309.3	35.5	11	19.4		
C	20	Mongardino	(44°25′N/11°12′E)	Cherty Marls	E. Miocene	12	117.7	−34.6	40.5	6.9	116.7	−54.6	41	6.9		
C	21	Mongardino	(44°25′N/11°12′E)	Cherty Marls	E. Miocene	8	298.5	22.1	46	8.2	293.1	41.3	46	8.2		
C	22	Mongardino	(44°25′N/11°12′E)	Cherty Marls	E. Miocene	6	349.9	55.0	253	4.2	310.7	62.5	91.5	7.0		
C	23	Mongardino	(44°25′N/11°12′E)	Cherty Marls	E. Miocene	10	133.6	−38.8	123	4.4	113.7	−65.2	123	4.4		
Epiligurain equivalent sites from the Liguria–Piedmont Tertiary Basin, internal to the Apennine front and undeformed																
D	B*	Ramero & Garbagna	(44°47′N/9°E)		L. Oligocene	10S	318.7	53.8	53.8	55	6.6	317.8	38.8	55	6.6	
Overall from A (one site, i.e. 47–49), C (seven sites), D (10 sites)					E. Oliogo–M.. Mio	18S	313.9	49.1	23	7.3	312.5	42.2	34	6.0	46.7/268.3[c]	4.5/7.4

[a] Ref: 'A' is this study, 'B' is Speranza et al. (1997), 'C' is Muttoni et al. (1998), and 'D' is Thio (1988). Locality: 'Parco de Gessi' is a naural reserve located just southeast of Bologna. 'Ca'Bazz.' stands for Ca'Bazzone on the Zena river. 'Campagna' is a small village in the vicinity of Pracovera, Zermagonone is a locality close to the village of Mussatico, 'Pavullo n. Frign' stands for Pavulo nel Frignano, and 'Castiglione Pep.' stands for Castiglione de'Peopli. Coordinates: latitude and longituded of sampling site. *n*: number of 11cc specimens used for statystical analysis (the suffix 'S' is number of sites when specified). k: Fisher precision parameter; a95: Fisher half-angle of cone of 95% confidence about the mean direction. Latitude/longitude: latitude and longitude of a paleomagnetic pole calculated at the site; dp, dm: semi-axes of the confidence oval about the paleomagnetic pole.

[b] Paleomagnetic pole calculated at a common locality at 44°12′N/12°E.

[c] Paleomagnetic pole calculated at a common locality at 44°42′N/10°E.

to progressive AF demagnetization. A least-squares analysis was applied to determine the component directions of NRM (Kirschvink, 1980), chosen by inspection of vector end-point demagnetization diagrams (Zijderveld et al., 1967). Site mean directions were determined using standard Fisher statistics.

The Tortonian clays at site 31 and site 32–33 (i.e. sites 32 and 33 combined) are characterized by an average NRM intensity of 0.87 mA/m. After removal of an occasional present-day field component in the 0–5 to 10 mT range, a bipolar characteristic remanent magnetization (ChRM) oriented NE and up or SW and down in geographic coordinates was isolated up to a maximum of 70 mT (Fig. 3a). Upon application of the bedding tilt, the ChRM directions become SE and up (NW and down) (Fig. 4a, Table 2). Other clay samples of Tortonian, Messinian and Pliocene age from sites 34, 35–37 combined and 38–39 combined, respectively, as well as the Pliocene sandstones at site 40, with NRM intensities normally comprised between 0.71 and 66 mA/m, were discarded because the paleomagnetic components were either remagnetized in the present-day field direction (Fig. 4b) or were unstable or scattered (Fig. 4c). The older Epiligurian site 47–49 combined and site 53, comprising the Ranzano Sandstones of Early Oligocene age, are characterized by an average NRM intensity of 250 mA/m. AF demagnetization revealed the occurrence of a characteristic magnetization component oriented E or SE and up in geographic and tilt-corrected coordinates (Figs. 3b and 4d; Table 2). Finally, site 41–42 combined, sampled in the Early Oligocene Ranzano Sandstones at Rioveggio (Fig. 1), with an average NRM intensity of 520 mA/m, yielded a characteristic component of magnetization-oriented NE and down (i.e. rotated clockwise) in both geographic and tilt-corrected coordinates (Fig. 4e, Table 2).

6. Paleomagnetic regional mean directions and paleopoles

The litologies sampled come from the frontal portions of thenorthern Apennines, which are characterized by a generally linear NW–SE thrust-fold trend (Fig. 1a), suggesting substantial tectonic coherence during Ligurian thrust sheets emplacement. In the Umbria-Marche Adriatic units underlying the Ligurian allochthon (Fig. 1c), the thrust fronts are also mainly linear and trending parallel to the Apennine front, as suggested by the spatial distribution of the Miocene foredeep depocentres. It is only in the Pliocene that local deviations from linearity of the front occurred, as testified by the formation of small-scale arc-shaped thrust fronts buried under the Po Plain sediments. Therefore,

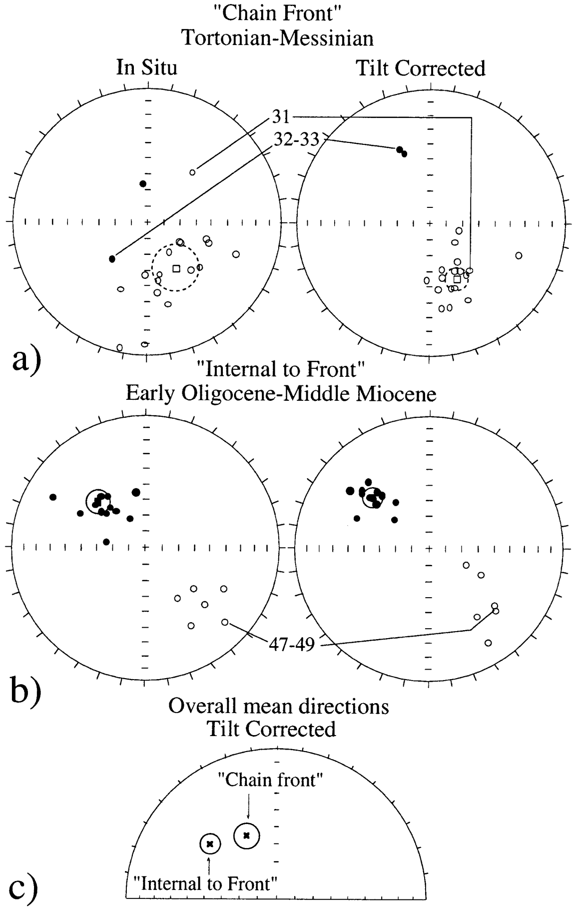


Fig. 5. Equal-area projections before and after bedding correction of the characteristic component site-mean directions from the Tortonian–Messinian sites located at the Apennine chain front (a), and the Early Oligocene–Middle Miocene Epiligurian flat-lying clastics located at sites internal to the chain front (b). Numbers refer to the sites from this study. Solid symbols refer to the lower hemisphere. (c) Comparison of the overall mean directions from (a) and (b).

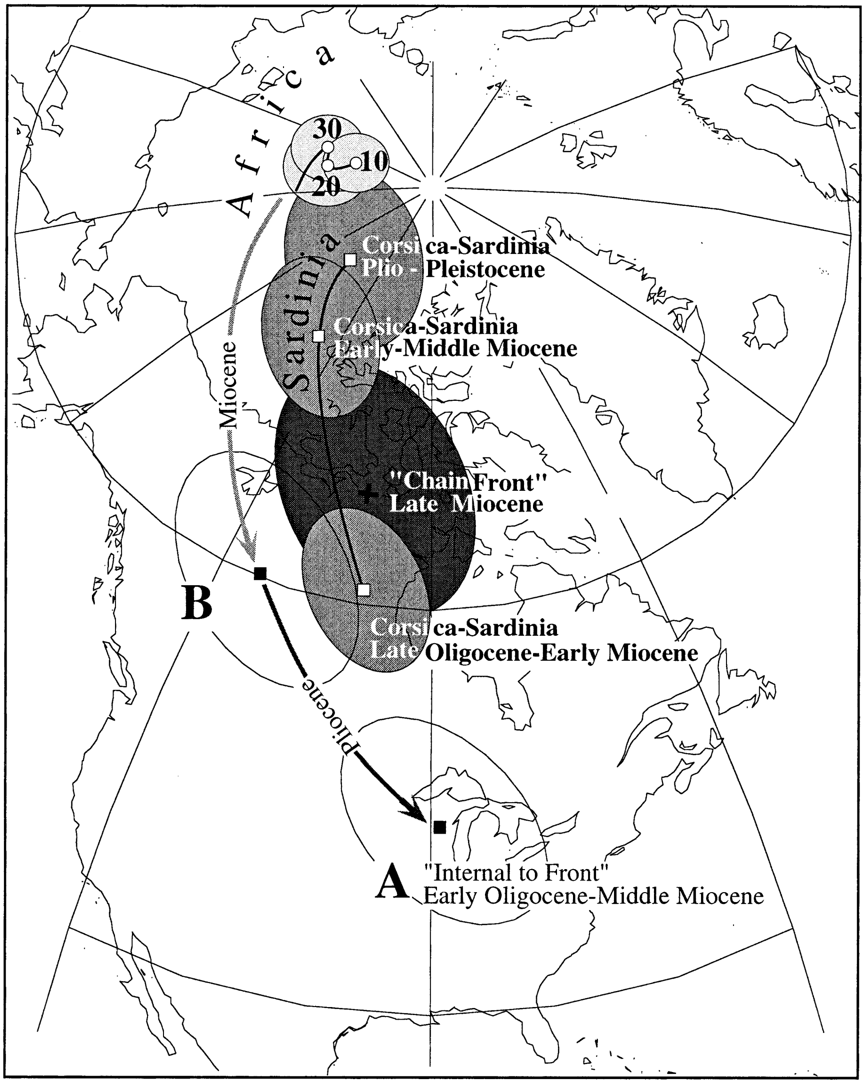
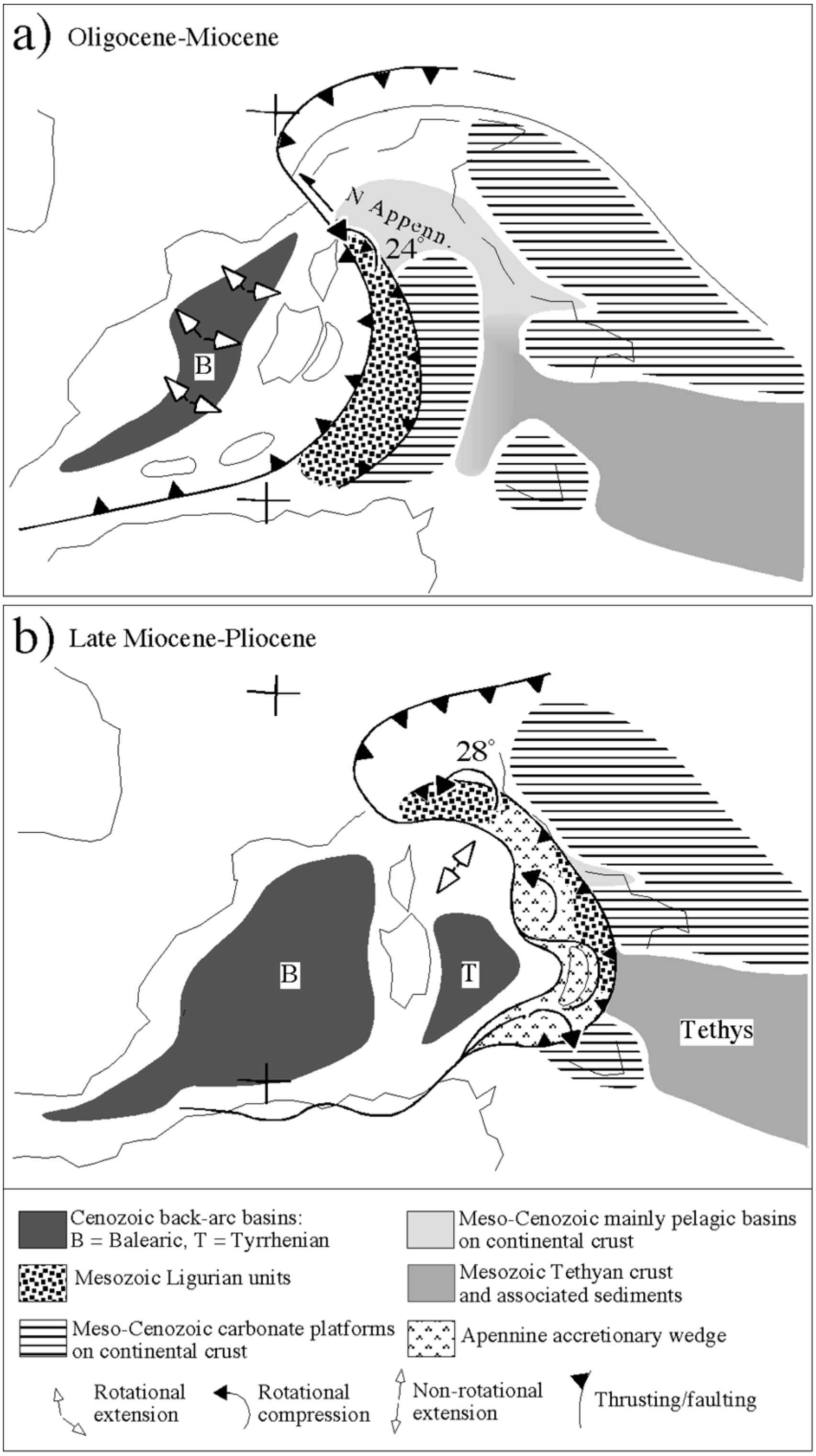


Fig. 6. Late Miocene Apennine Chain Front-paleomagnetic pole (solid cross) and the Early Oligocene–Middle Miocene paleopole from the Epiligurian flat-lying units internal to the front (solid square, position 'A') are compared with the apparent polar wander paths of Africa (open circles, Besse and Courtillot, 1991), and Corsica–Sardinia (open squares, Muttoni et al., 1998). The Early Oligocene–Middle Miocene Internal to Front-paleopole, when restored for the 28° Pliocene chain front rotation (solid square, position 'B'), falls close to the Late Oligocene–Early Miocene Corsica–Sardinia paleopole. See text for discussion.

the deformation that affected the Epiligurian sediments during the emplacement of the Ligurian allochthon did not generally disrupt the original stratigraphic relationships. This allows us to calculate overall paleomagnetic mean directions from site-mean directions from this study and the litera-

Fig. 7. Schematic reconstruction of the western Mediterranean area for the Oligocene–Miocene Corsica–Sardinia rotation phase (a) and the Late Miocene–Pliocene Tyrrhenian-opening phase (b). The positions of Africa and Europe relative to fixed North America are based on Euler poles derived from Central Atlantic marine magnetic anomalies 6 and 5, respectively (Dewey et al., 1989).


a) Oligocene-Miocene
N Appenn.
24°
B
b) Late Miocene-Pliocene
28°
B
T
Tethys
Cenozoic back-arc basins:
B = Balearic, T = Tyrrhenian
Meso-Cenozoic mainly pelagic basins
on continental crust
Mesozoic Ligurian units
Mesozoic Tethyan crust
and associated sediments
Meso-Cenozoic carbonate platforms
on continental crust
Apennine accretionary wedge
Rotational
extension
Rotational
compression
Non-rotational
extension
Thrusting/faulting

ture that we consider representative of the regional thrust-fold trend of the frontal portions of the northern Apennines. We exclude from calculation site 41–42 combined and site 53. These sites were likely affected by local deformation related to tectonic structures oriented transversal to the regional NW–SE Apennine trend, as reported along the Setta river close to site 41–42 (Panini, 1994; Bertolini and Pizziolo, 1997; Camporesi and Pizziolo, 1997) and in the Vetto syncline area at site 53 (Papani et al., 1987; Denardo et al., 1992), where the bedding strike is also nearly perpendicular to the regional structural trend.

Paleomagnetic data from the Tortonian clays of site 31 and site 32–33 combined from this study indicate a counterclockwise rotation similar to data from 17 sites from Messinian age clastics outcropping south of the study area in the Marche-Romagna foredeep at the front of the Apennine belt (Speranza et al., 1997) (Fig. 1b, area 2). These 19 Tortonian–Messinian sites are therefore combined (Fig. 5a), and an overall site-mean direction in tilt corrected coordinates of Dec. = 334.6°, Inc. = 51.8° is calculated (Table 2). The Tortonian–Messinian overall paleomagnetic direction, positive in the fold test according to the McFadden (1990) criteria, is considered representative of sites affected by the Pliocene deformation at the Apennine front.

The overall site-mean direction from the flat-lying Early Oligocene–Middle Miocene Epiligurian clastics outcropping internal to the front (Fig. 1b, area 1), and therefore not directly affected by the Pliocene frontal deformation, is upgraded from Muttoni et al. (1998) with sites 47–49 combined from this study (Table 2).

The overall mean directions and the associated paleomagnetic poles in tilt-corrected coordinates of the Tortonian–Messinian sites at the Apennine front and the Early Oligocene–Middle Miocene sites internal to the front are statistically different (Fig. 5c, Table 2). The Tortonian–Messinian paleopole is rotated counterclockwise with respect to the Africa reference paleopoles (Besse and Courtillot, 1991) by about 28(±9.5)° (Fig. 6, Chain Front-paleopole). The Early Oligocene–Middle Miocene paleopole is rotated with respect to coeval Africa poles by about 52(±7)° (Fig. 6, Internal to the Front-paleopole in position A).

7. Discussion and conclusions

The Early Oligocene–Middle Miocene Internal to Front-paleopole falls close to, yet displaced counterclockwise with respect to, the Late Oligocene–Early Miocene Corsica–Sardinia paleopole of Muttoni et al. (1998) (Fig. 6). We propose that this offset can be associated with the Pliocene tectonics at the chain front. By subtracting the approximately 28° counterclockwise rotation of the Tortonian–Messinian Chain Front-paleopole to the Early Oligocene–Middle Miocene Internal to the Front-paleopole, we find a good match between this latter paleopole and the Corsica–Sardinia paleopole (Fig. 6, Internal to Front-paleopole in position B). This observation has important geological implications, namely the possibility that the Pliocene frontal tectonics may have affected also the Ligurian units at least as far into the chain, as inferred from the geographical distribution of the sampled Epiligurian units (i.e. Fig. 1b, area 1).

A tectonic model can now be proposed for the Cenozoic evolution of the northern Apennines. About 24 out of a total of 52° of counterclockwise rotation observed in the Epiligurian units internal to the Apennine front can be related to the Oligo-Miocene counterclockwise motion of the Corsica–Sardinia block, in partial agreement with the conclusions of Muttoni et al. (1998). When Corsica–Sardinia moved off the coast of France, the Ligurian units were presumably pushed eastward and rotated above a main boundary thrust onto the Adria/Africa margin (Fig. 7a). The remaining 28° of the total rotation can be related to the Pliocene frontal deformation of the Tyrrhenian-tectonic phase (Fig. 7b) which might have (re)activated thrust planes in the Umbria-Marche succession below the Ligurian wedge (Fig. 1c). The Pliocene rotational compression along the Apennine front was accompanied along the Tyrrhenian margin by non-rotational extension associated with the Tyrrhenian sea opening (Speranza et al., 1997 and references therein) (Fig. 1b, area 5; Fig. 7b). The rotations associated with the Tyrrhenian-tectonic phase were explained by Argnani and Frugoni (1997) as being due to oblique collision of thrust fronts against an obstacle located in the Adriatic foreland. Alternatively, the differential rotations of thrust sheets in the northern Apennines were recently interpreted as the result of the lateral bending of a lithospheric slab subducting under the Apennine front (Lucente and Speranza, 1998).

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