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Late Miocene remagnetization within the internal sector of the Northern Apennines, Italy

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Abstract

Paleomagnetic and geologic evidence indicates that Upper Jurassic radiolarian cherts of both the Tuscan Cherts Formation (continental margin, Tuscan Units) and the Monte Alpe Cherts Formation (oceanic crust, Ligurian Units) were remagnetized during Miocene orogenesis of the Northern Apennines of Italy. Characteristic overprint magnetizations with reversed polarities have been found over a large area within the internal sector of the Northern Apennines, including eastern Liguria, Elba Island and the Thyrrenian margin, and west of the Middle Tuscan Ridge. The reversed-polarity overprint (average direction: $D=177°$, $I=-52°$, $\alpha_{95}=15°$) was most likely acquired during Late Miocene uplift and denudation of the orogenic chain, and thermochemical remagnetization was a probable consequence of increased circulation of orogenic fluids. Similarly, mostly reversed-polarity directions of magnetization have been found by other workers in overlying post-orogenic Messinian sediments ($D=177°$, $I=-57°$, $\alpha_{95}=3°$), which show little counterclockwise (CCW) vertical-axis rotation with respect to stable Europe ($-8 \pm 5°$). The Monte Alpe Cherts sampled at sites in the external sector of the Northern Apennines, close to major tectonic features, have normal-polarity overprint directions with in situ W–SW declinations. Since the overlying post-orogenic Messinian sediments have not been substantially rotated about vertical axes, the evidence points to an earlier, pre-Late Miocene remagnetization in the external parts of the orogenic chain.

Keywords: Paleomagnetism; Remagnetization; Northern Apennines; Italy

1. Introduction

Paleomagnetic investigations, combined with other geophysical analytical methods, have provided useful information on the kinematics of orogenic regions such as the distribution and amount of vertical-axis rotation of thrust sheets (e.g., Channell, 1992; Channell et al., 1992), oroclinal bending (e.g., Lucente and Speranza, 2001; Schill et al., 2002), horizontal-axis tilting of intrusive rocks (e.g., Varga et al., 1999) and latitudinal displacements and rotations of allochthonous terranes (e.g., Beck, 1980; Irving et al., 1985; Hagstrum and Murchey, 1993). Partial to complete remagnetization of rocks, however, is common in orogenic settings, and can often obliterate primary components (i.e., remanent magnetizations acquired during or soon after deposition for sedimentary rocks).

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Magnetic overprinting can be produced by thermal and/or chemical effects, often associated with uplift and enhanced fluid flow, either during or after orogenesis (Pullaiah et al., 1975; McCabe et al., 1983; Kent, 1985), and remagnetization can affect large continental areas (e.g., Kechra et al., 2003). Magnetic overprints are the dominant (characteristic) magnetizations of many tectonic units in the Mediterranean orogenic belt (Burmester et al., 2000; Kechra et al., 2003; Schill et al., 2002; Thomas et al., 1999), and are widespread in other orogenic regions as well (e.g., McCabe and Elmore, 1989). Overprint components might also provide useful information on both the tectonics and kinematics of orogenic regions, although questions concerning the structural attitude of rock units at the time of overprinting and remagnetization must be carefully considered.

A previous paleomagnetic study of Middle to Upper Jurassic radiolarian cherts of both Tuscan and Ligurian Units in the Northern Apennines of

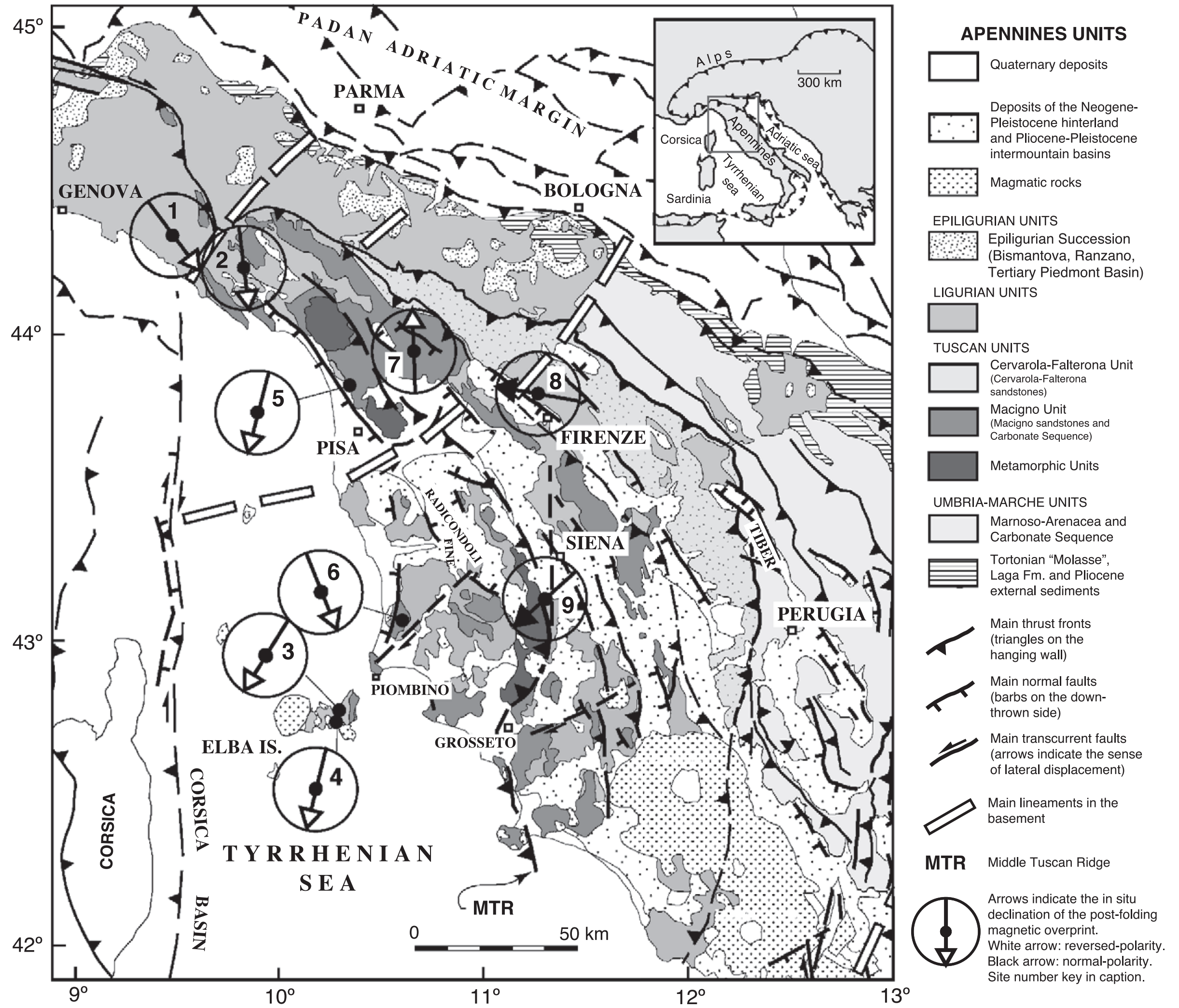

Fig. 1. Schematic geologic map of the Northern Apennines of Italy. Sampling sites of Middle to Upper Jurassic radiolarian cherts are also shown. Samples from sites 1 (Monte Zenone), 2 (Rocchetta di Vara), 3 (Nisporto), 4 (San Felo), 8 (Figline di Prato) and 9 (Murlo) are from the Monte Alpe Chert Formation of the Ligurid Domain; samples from sites 5 (Monti d'Oltreserchio), 6 (Campiglia), and 7 (Lima Valley) are from the Tuscan Chert Formation of the Tuscan Domain.

Italy showed that the characteristic magnetization of these rocks is generally a reversed-polarity, post-folding overprint magnetization with in situ southerly declinations and moderate inclinations (Aiello and Hagstrum, 2001). In the Tuscan Cherts of the Lima Valley, the acquisition of this magnetic component is constrained by the age of the youngest formation involved in the folding phase (Late Miocene) that predates remagnetization (Fazzuoli et al., 1998). Remagnetization of the radiolarian cherts likely occurred during Late Miocene regional uplift and denudation of the Northern Apennine orogenic belt (fission-track age data of Abbate et al., 1999), after overthrusting of the Tuscan Units by the Ligurian Units (Aiello and Hagstrum, 2001). Soffel (1981) also found an overprint magnetization with reversed-polarity directions in a Middle to Upper Jurassic ophiolite series (gabbro, basalts and radiolarian cherts) within the Ligurid Domain on eastern Elba Island.

The southerly directions of the reversed-polarity magnetic overprint characterizing many radiolarian chert sections within the internal sector of the Northern Apennines were interpreted by Aiello and Hagstrum (2001) as indicating that little or no vertical-axis rotation of the tectonic units had occurred since remagnetization. The lack of rotations in the internal sector was apparently corroborated by similar paleomagnetic directions from late Messinian to early Pliocene post-orogenic marine sediments of the Tuscan Tyrrhenian margin (Mattei et al., 1996a, b), which unconformably overlie both the Tuscan and Ligurian Units (Fig. 1). In contrast, directions of primary magnetization for Eocene to Pliocene Epiligurian (syn- and post-orogenic) Units within the easternmost (external) sector of the Northern Apennines show significant and variable counterclockwise (CCW) rotations that were probably the consequence of eastward migration of the compressional front (Muttoni et al., 1998). Moreover, oroclinal bending of the Northern Apennines might have deep roots: Seismic imaging beneath the orogenic chain reveals the apparent shape of a lithospheric slab subducted below the belt (Lucente and Speranza, 2001). At depth (>100 km), the slab shows evidence of lateral bending, which mimics the curved shape of the Northern Apennines. Thus, the oroclinal bending of the Northern Apennines is possibly due to lateral bending of the subducted Adriatic Plate (Lucente and Speranza, 2001).

In order to investigate further the extent, timing and geodynamic significance of the remagnetization components, we have extended our previous paleomagnetic study to other Middle to Upper Jurassic radiolarian chert sections in the Northern Apennines. Most of the new sites are located within the internal sector, and an additional site is located within the external sector of the orogenic chain (Fig. 1).

2. Geologic and tectonic setting of the Northern Apennines

Rocks of the arcuate Northern Apennines mountain chain are generally regarded as having been emplaced in an accretionary prism, which formed during Tertiary convergence between the European and Adrian plates (Abbate et al., 1970; Principi and Treves, 1984). Tectonic accretion caused eastward thrusting of oceanic units (Ligurid Units) over continental margin units (Tuscan and Umbria-Marche Units) in two main stages: (i) the Ligurid Phase from Late Cretaceous (?) to Eocene time, which included subduction and accretion within the Ligurid Units; and (ii) the Collisional Phase, during Oligocene to Miocene time, when the Ligurid Units were first thrust over the Tuscan Units and later the Ligurid and Tuscan Units together were thrust over the more external Umbrian Units (Abbate et al., 1970, 1980). According to Faccenna et al. (2001), subduction was dominated by sinking of the Ionian–Adrian lithospheric slab (slab-pull), which the authors have imaged by seismic tomography beneath the Italian peninsula. Slab-pull controlled both the opening of the Liguro-Provençal basin, and the eastward shortening of the accretionary prism (Faccenna et al., 2001). In general, a west dipping subduction zone has been proposed for the Collisional Phase. In two contrasting models, however, east dipping (Alpine type; e.g., Boccaletti et al., 1980) and west dipping (Apennine type; e.g., Principi and Treves, 1984; Abbate et al., 1986; Bortolotti et al., 2001) subduction geometries have been proposed for the Ligurid Phase. Alternatively, Marroni and Treves (1998) suggest that the lack of a magmatic arc in the Northern Apennines is better explained by strike-slip displacements that caused transpressional convergence during the Ligurid Phase.

The post-orogenic tectonic phases (mostly extensional) of Late Miocene to Pliocene age followed eastward migration of the compressive front, and geomorphically reshaped the Northern Apennines. A main physiographic feature is the arcuate metamorphic ridge (Middle Tuscan Ridge) that includes both Apuan Alps Units and the Monticiano Roccastrada Unit, and divides the Northern Apennines into internal (western) and external (eastern) sectors (Fig. 1). It is unclear whether exhumation of the Middle Tuscan Ridge was due to isostatic unroofing in a regional extensional setting (e.g., Carmignani and Kligfield, 1990) or to syn-collisional exumation processes (Jolivet et al., 1998).

The Mesozoic continental margin and oceanic units of the Northern Apennines, together with the tectonic units of other orogenic regions in the Perimediterranean area (e.g., Southern Apennines, Alps, and Bethic cordillera), are remnants of Western Tethys, which formed as a narrow oceanic basin after left-lateral, E–W strike-slip motion that occurred between the African and Eurasian plates (Abbate et al., 1980, 1986; Dercourt et al., 1986). Within the Ligurid Units of the Northern Apennines, only the Vara Unit (also referred to as the "Internal Ligurids") includes remnants of Jurassic oceanic crust. In the other Ligurid Units ("External Ligurids") ophiolites occur only as olistholithes or olistostromes in Cretaceous to Eocene Helminthoid turbidites. According to Principi and Treves (1984), these rocks were deposited during the Ligurid Phase in eastward-migrating turbiditic basins (trenches) created by subduction of the Ligurian–Piedmontese oceanic basin under the European margin. The ophiolitic suite is typically composed of a serpentinized peridotite basement (residual mantle) and subordinate gabbroic rocks, and an overlying cover of ophicalcites, ophiolitic breccias, basalts, radiolarian cherts, pelagic carbonates (Calpionella Limestone) and pelagic shales (Palombini Shales) (Abbate et al., 1980; Cortesogno et al., 1978). The radiolarian cherts of the Tuscan Unit (Tuscan Cherts) represent the late Jurassic pelagic phase of a sedimentary marine cycle, which began with the collapse of Triassic reefs and carbonate platforms along the Adrian continental margin. Radiolarian biostratigraphy indicates that pelagic sedimentation of carbonate-free, radiolarian-rich sediments began within the Tuscan and Ligurian Domain by the end of the Middle Jurassic (Middle Bathonian) (Chiari et al., 1997; Cortese, 1995).

The external sector of the Northern Apennine thrust belt is characterized by NE-verging imbricated thrust sheets deformed mainly during Miocene to Recent uplift (Fig. 1). The area of uplift migrated

Table 1
Paleomagnetic data for Middle to Upper Jurassic radiolarian cherts and ophiolitic rocks in the Northern Apennines

Site	Locality	La (°N)	Lo (°E)	Domain	N	In situ				Corrected for tilting				$2(N-1)$	k_1/k_2	P_F
						I (°)	D (°)	k_1	α_{95} (°)	I (°)	D (°)	k_2	α_{95} (°)			
1	Monte Zenone[a]	44.44	9.51	Ligurian	7	−42.2	143.0	21	14.6	49.8	148.3	4	37.5	12	5.3	0.01
2	Rocchetta di Vara[a]	44.37	10.26	Ligurian	9	−47.7	173.1	16	14.2	22.4	193.2	9	19.6	16	1.8	>0.05
3	Nisporto (Elba Island)	42.49	10.24	Ligurian	11	−50.2	212.0	84	5.3	−40.9	232.9	26	9.7	20	3.2	0.01
4	San Felo (Elba Island)	42.49	10.24	Ligurian	3	−51.7	193.6	1841	3.5	−56.8	267.7	339	8.2	4	5.4	>0.05
5	Monti d'Oltreserchio	43.50	10.24	Tuscan	7	−57.9	194.5	21	14.5	−63.4	193.6	5	34.4	12	4.2	0.01
6	Campiglia	43.04	10.36	Tuscan	10	−48.5	157.9	53	4.6	−57.0	204.5	15	11.5	18	3.5	0.01
	Mean (sites 1–6)	43.39	10.14		6	−52.2	177.4	22	14.6	−33.3	205.3	2	58.1	10	11.0	>0.01
7	Lima Valley[a]	44.05	10.28	Tuscan	29	−76.3	356.5	10	8.9	−78.6	318.1	6	11.8	56	1.7	–
8	Figline di Prato[a]	43.92	11.10	Ligurian	8	62.4	281.1	72	7.0	50.1	239.8	47	8.8	14	1.5	>0.05
9	Murlo	43.10	11.24	Ligurian	10	34.8	228.0	20	11.6	38.8	230.8	14	13.9	18	1.4	>0.05
10	Elba Island[b]	42.49	10.24	Ligurian	25	−45.4	232.2	9	9.2	−38.0	199.3	19	6.4	48	(2.1)	0.05

In situ characteristic magnetization of Middle to Upper Jurassic radiolarian cherts and coeval ophiolite rocks in the Northern Apennines; sampling sites (see Fig. 1). La, latitude of site in degrees N; Lo, longitude in degrees E; N, number of samples; I, inclination in degrees; D, declination in degrees; k, Fisher (1953) concentration parameter; α_{95}, radius of 95% confidence circle about mean in degrees; $2(N-1)$, degrees of freedom; P_F, significance of fold test (McElhinny, 1964).

[a] Aiello and Hagstrum (2001).

[b] Soffel (1981).

northeastward from Middle–Late Miocene time on. Post-orogenic, mostly extensional, tectonics affected the internal sector during Late Miocene time (Late Tortonian; Boccaletti et al., 1999) as indicated by the development of several NW–SE-trending, shallow marine basins. Plutonic and effusive magmatism also occurred starting within the Tyrrhenian domain and subsequently migrated eastwards (Serri et al., 1993). Apatite fission-track data generally indicate an older age of uplift and exhumation for the internal sectors of the orogenic wedge. Similar data from the Ligurian Units of eastern Liguria and the Macigno Formation of the Tuscan Unit, on both sides of metamorphic units in the Apuan Alps tectonic window (Middle Tuscan Ridge), indicate that the final denudation event occurred during Late Miocene time. In contrast, exhumation of the Marnoso–Arenacea Formation within the Umbrian Units in the easternmost sector of the orogenic belt apparently started later during Early Pliocene time (Abbate et al., 1999).

3. Previous paleomagnetic work

Radiolarian chert beds of the Monte Alpe Cherts were collected in an overturned ophiolite sequence (Vara Unit) at Monte Zenone and Rocchetta di Vara (sites 1 and 2, respectively; Fig. 1; Table 1; Aiello and

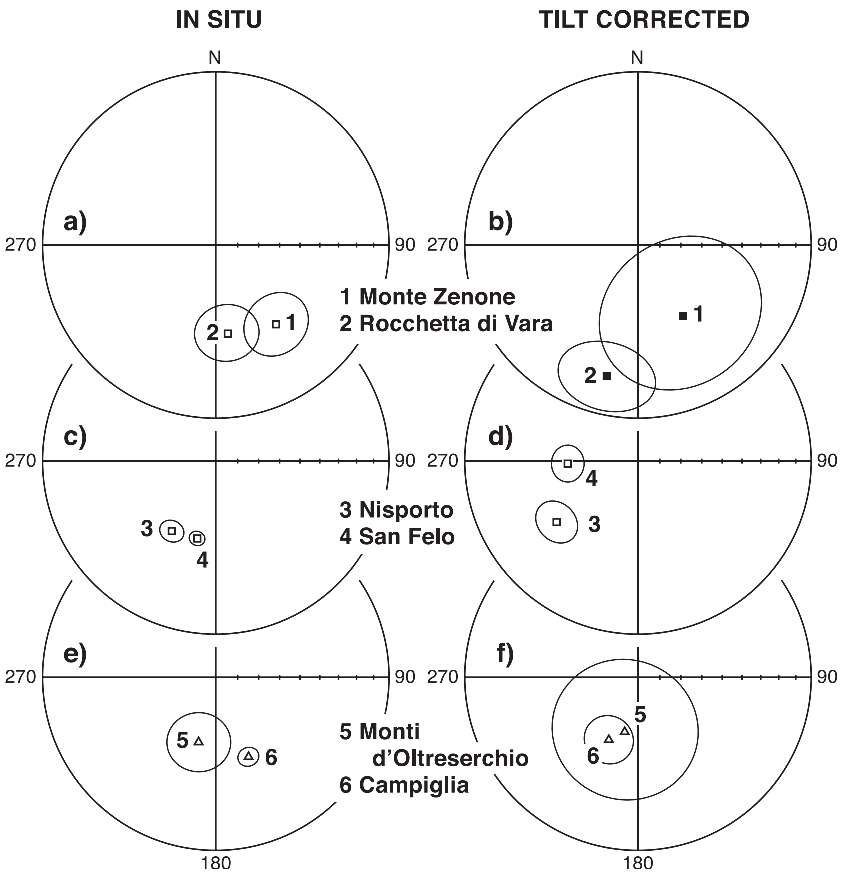

Fig. 2. Equal-area plots of characteristic site-mean directions for cherts sampled in the internal sector. In all cases, the in situ magnetic overprint has reversed polarity and southerly declinations. Closed (open) symbols indicate lower (upper) hemisphere projections, squares indicate ophiolitic units, and triangles indicate continental margin units. In situ (a) and corrected (b) mean directions of component B for Monte Zenone (1) and Rocchetta di Vara (2). In situ (c) and corrected (d) mean directions of component B for Nisporto (3) and San Felo (4). In situ (e) and corrected (f) mean directions of remagnetization B for Monti d'Oltreserchio (5) and Campiglia (6). Overall mean direction of the magnetic overprint (sites 1–6) is $D = 177.4°$, $I = -52.2°$, $\alpha_{95} = 14.7°$.

Hagstrum, 2001). At Monte Zenone, the Monte Alpe Chert formation is exposed in the overturned limb of an east-dipping recumbent fold with its axis oriented approximately N–S. The formation, locally ~80 m thick, is overlain by the gabbroic Monte Zenone Breccia (Aiello, 1994; Cortesogno et al., 1978). A

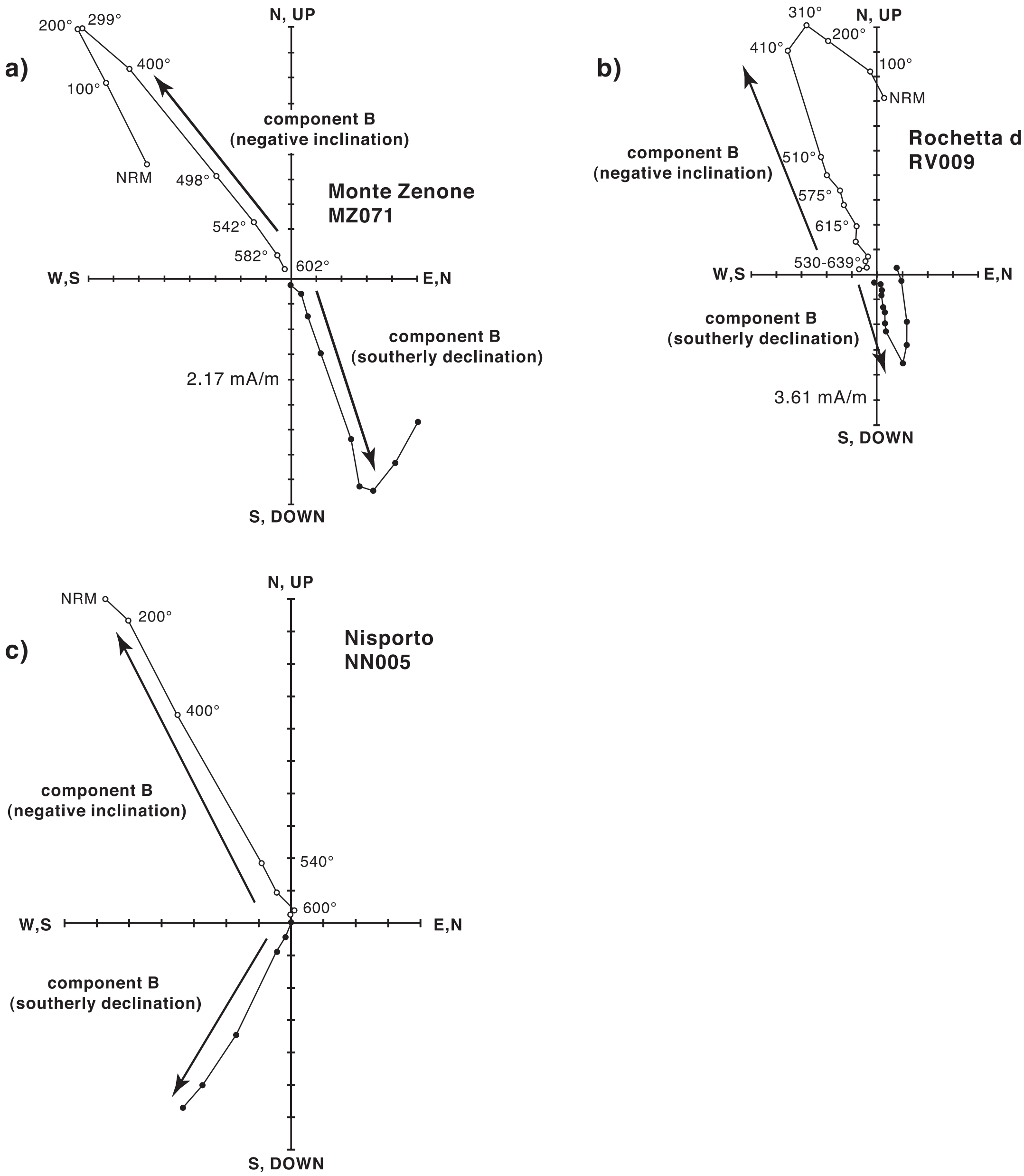

Fig. 3. Orthogonal projections (in situ) of thermal demagnetization vector endpoints for selected chert samples showing direction of remagnetization with negative inclinations and southerly declinations (reversed polarity). Filled circles indicate projections onto the horizontal plane (declination), and open circles onto the vertical plane (inclination). Arrows highlight inclination and declination of component B. (a) Sample MZ071 from site 1 at Monte Zenone; (b) sample RV009 from site 2 at Rocchetta di Vara; and (c) sample NN005 from site 3 at Nisporto on Elba Island.

similar stratigraphic and tectonic setting occurs at Rocchetta di Vara, where the Monte Alpe Cherts are ~ 150 m thick and are deformed in a north-dipping recumbent fold having a roughly E–W-oriented axis. Samples from these sections contain the regional reversed-polarity (B) component of magnetization, removed between 300 and 600 °C, which fails the fold test for each section (Figs. 2a,b and 3a,b).

Aiello and Hagstrum (2001) also sampled three sections of Tuscan Cherts in the Lima Valley at the front of the Tuscan nappe (site 7) where a tectonic window exposes Mesozoic rocks of the Tuscan Domain (Fig. 1). The dominant structural feature of the area is a large recumbent fold with northeastern asymmetry, which formed in two coaxial phases during the Late Miocene (Fazzuoli et al., 1998). Overall, two components of remanent magnetization were isolated (Figs. 4a,b and 5a,b). A high-unblocking temperature (>580 °C) component (C) is inferred to be a primary magnetization because of its polarity stratigraphy and positive fold test (Fig. 5a,b; see Aiello and Hagstrum, 2001). The second characteristic component, removed in most specimens, is a post-folding component of magnetization with steep negative inclinations and northerly declinations (Figs. 4a,b and 5a,b).

In the Monte Alpe Cherts at Figline di Prato (northern Tuscany), the overprint component has moderate to steep positive inclinations and westerly declinations (Figs. 4c,d and 5c,d). The site is located near the trace of the Livorno–Sillaro fault just northwest of Florence (Fig. 1; site 8) where the cherts crop out in an upturned sequence overlain by pillow basalts. This ophiolite series occurs in an uncertain stratigraphic position within a younger (Late Cretaceous to Eocene) flysch of the external Ligurian Unit of Monte Morello.

The declination of the primary magnetization found in the Tuscan Cherts of Lima Valley indicates significant (~ 90°) post-Jurassic CCW vertical-axis rotation with respect to stable Europe. Similar CCW rotations of Mesozoic tectonic units have also been

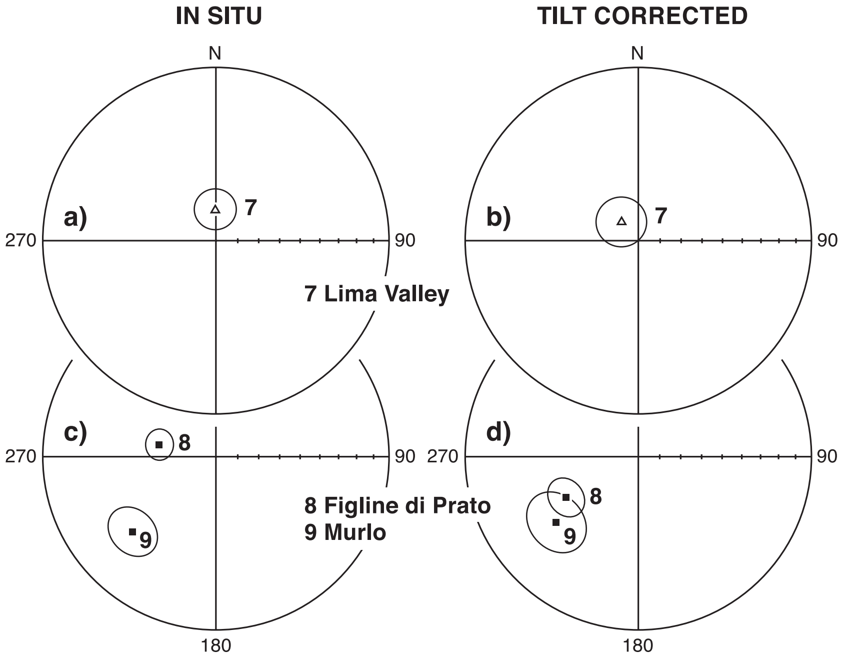

Fig. 4. Equal-area plots of characteristic site-mean directions for cherts sampled in the external sector. Filled symbols indicate lower hemisphere points; open symbols indicate upper hemisphere points. Squares indicate ophiolitic units and triangles indicate continental margin units. In situ (a) and corrected (b) mean directions of the magnetic overprint (component B) for the Lima Valley sections (Monte Pratofiorito, Monte Mosca and Cava Termini; locality 7). In situ (c) and corrected (d) mean directions of component B for Figline di Prato (8) and Murlo (9).

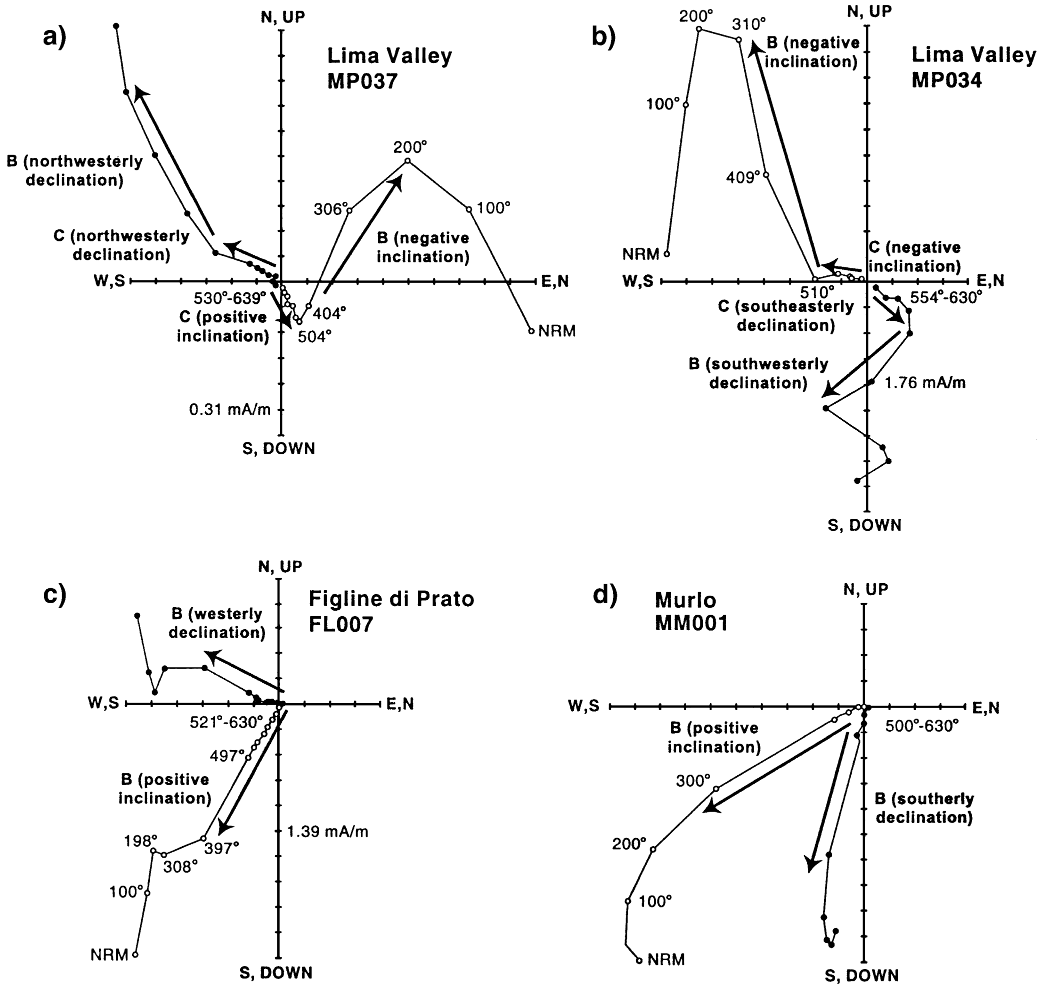

Fig. 5. Orthogonal projections (in situ) of thermal demagnetization vector endpoints. Filled circles indicate projections onto the horizontal plane (declination), and open circles onto the vertical plane (inclination). Arrows highlight polarity and declination of component B. (a) Sample MP037 and (b) sample MP034 from locality 7 (Lima Valley, Monte Pratofiorito section). Both samples show a viscous remanent magnetization (VRM, component A), a component B having reversed polarity, and a high unblocking temperature (>500 °C) component C (inferred primary magnetization); the latter has normal polarity in sample MP037 and reversed polarity in sample MP034. (c) Sample FL007 from site 8 (Figline di Prato) and (d) sample MM001 from site 9 (Murlo). Both samples show characteristic magnetizations having normal polarities and westerly declinations.

reported from the central Apennines (Gattacceca and Speranza, 2002; Speranza et al., 2003), southern Apennines (Gattacceca and Speranza, 2002) and Southern Alps, and have been interpreted as resulting from CCW rotation of Africa with respect to Europe during the Mesozoic (Channell, 1992; Channell et al., 1992), CCW rotation of Corsica–Sardinia during the Tertiary, and local post-orogenic thrust sheet movements (Channell, 1992; 1996). In addition, a post-Early Tertiary 15° CCW rotation with respect to stable Europe of late Mesozoic pelagic limestones in the Southern Alps has been reported (Vandenberg and Wonders, 1980).

Neogene post- or syn-folding remagnetizations and vertical-axis rotations have also been determined for Mesozoic tectonic units in the Alps (Aubourg and Chabert-Pelline, 1999; Thomas et al., 1999), and have been interpreted as chemical remanent magnetizations

(CRM) acquired during growth of ferrimagnetic minerals from tectonically driven fluids during orogenesis. Late Jurassic rocks of the Briançonnais sedimentary cover in the western Alpine arc (Thomas et al., 1999) have a reversed-polarity post-folding magnetization acquired prior to late Cenozoic Alpine extensional tilting. Paleomagnetic declinations of this overprint component ($I = -57°$, $D = 142°$, $\alpha_{95} = 8°$) and kinematic models for the Western Alps support a CCW rotation of ~40° for the Penninic Alps relative to stable Europe during Tertiary time. In the subalpine basins of the French Alps, about 40° of CCW rotation is also indicated by a Neogene normal-polarity overprint magnetization in Late Jurassic shales (Aubourg and Chabert-Pelline, 1999).

Paleomagnetic investigations of syn- and post-orogenic Tertiary and Pliocene sediments from the Northern Apennines highlight two different geodynamic regimes for the internal (Tyrrhenian) and the external sector of the orogenic chain (Muttoni et al., 1998). Eocene to Pliocene Epiligurian Units in the external sector of the Northern Apennines have an overall mean Late Oligocene–Middle Miocene paleomagnetic pole indicating ~52° of CCW rotation with respect to an African reference paleopole, but the pole is also similar to a coeval paleopole for Corsica–Sardinia (Muttoni et al., 1998). Paleomagnetic data from late Miocene and Pliocene shallow-water deposits of the post-orogenic basins of the Tyrrhenian region indicate no significant regional rotation since late Messinian (Mattei et al., 1996a,b).

4. Paleomagnetism (this study)

Cherts are too durable to drill in the field, so oriented hand samples were collected and bedding attitudes were taken for each bed collected. The hand samples were drilled in the laboratory with a water-cooled drill press and the core samples were cut into specimens 2.5 cm in length. Specimens were subjected to progressive thermal demagnetization in a magnetically shielded oven (internal field $< 4\gamma$) to temperatures ≤ 680 °C. Remanent magnetizations were measured using a cryogenic magnetometer, and both demagnetization and measuring instruments are situated inside a shielded room-size enclosure (paleomagnetic analyses were performed in the laboratories of the USGS in Menlo Park, CA, USA). Lines representing the characteristic and overprint magnetization directions were fitted to the demagnetization end-points using a least squares method based on principal component analysis (Kirschvink, 1980). The statistics of Fisher (1953) were used in analyzing the mean directions and are also given in Table 1.

Two sections of Monte Alpe Cherts were sampled within Ligurid Units of the Vara Unit on Elba Island at Nisporto and San Felo (sites 3 and 4, respectively; Fig. 1; Table 1). Both chert sections belong to the allochthonous ophiolite series of eastern Elba Island (Complex IV of Trevisan, 1951; Ophiolite Units of Bortolotti et al., 2001), and are near the sampling locality of Soffel (1981); our data thus supercede those of Soffel. The Ophiolite Unit lies on top of Upper Carboniferous to Lower Jurassic units with various degrees of metamorphism (Complexes II and III), which, in turn, overlie the 6 Ma granitic intrusion of Monte Capanne (Complex I). The section sampled at Nisporto (site 3) is located just east of the village of Nisporto on the western flank of Monte Capannello where the Monte Alpe Cherts are exposed in the eastern limb of a broad NNW-trending syncline (Bortolotti et al., 2001). At San Felo (site 4), about 2.5 km north of Porto Azzurro, the Monte Alpe Chert Formation is exposed in a small syncline trending NE and is only 6 m thick. The characteristic magnetizations at both Nisporto and San Felo on Elba Island have moderate negative inclinations, southerly declinations, and fail individual fold tests (sites 3 and 4; Table 1; Figs. 2c,d and 3c).

The section of Tuscan Cherts sampled at Monti d'Oltreserchio (site 5) is located near the village of Vecchiano about 7 km north of Pisa (Fig. 1). The outcrop is part of a homoclinal structure dipping ~30° NW including rocks of the Tuscan Domain; Middle Jurassic cherty limestones (Selcifero della Val di Lima) and Lower Cretaceous pelagic limestones units (Maiolica Formation) stratigraphically bracket the Tuscan Cherts. The section sampled at Campiglia (site 6) is located just north of the village of Campiglia Marittima (10 km NE of the coastal town of Piombino). The structural setting of this area is the result of complex tectonic events that occurred during the Miocene compressive phase. The Tuscan Unit tectonically overlies metamorphic rocks of the Monticiano–Roccastrada Unit (Middle Tuscan

Ridge) and is tectonically overlain by the Ligurid Unit. The post-orogenic phase is characterized by extensive magmatism of Pliocene age, and in particular by the 4.4 Ma San Vincenzo rhyolite (Feldstein et al., 1994). Moderately negative inclinations, southerly declinations, high unblocking temperatures, and failure of the fold test also characterize the dominant component of magnetization of the Tuscan Cherts at Monti d'Oltreserchio and Campiglia in southern Tuscany (Fig. 2g,f).

At Murlo, about 10 km south of Siena (site 9; Fig. 1; Table 1), the sampled section of Monte Alpe Cherts overlies pillow basalts and is located just east of the Monticiano–Roccastrada Unit (Middle Tuscan Ridge). Monte Alpe Cherts, and the Ligurid Unit in which they occur, are unconformably overlain by Pliocene sediments of the Siena basin, which were sampled for paleomagnetism by Mattei et al. (1996a). The characteristic magnetization at this locality has moderate to steep positive inclinations and westerly declinations (Figs. 4c,d and 5c,d).

Table 1 lists the directions, both in situ and corrected for bedding tilt, of the characteristic magnetization from Upper Jurassic radiolarian cherts and other coeval rocks in tectonic units of both the Ligurian and the Tuscan Domains of the Northern Apennines. Table 1 also includes previous paleomagnetic results relevant to this study (40 radiolarian chert samples collected at five sites).

5. Discussion: timing and origin of the magnetic overprint

The characteristic component of magnetization for Upper Jurassic radiolarian cherts of the Northern Apennines has unblocking temperatures between 200 and 500 °C, and fails the fold test at each locality with the exception of Lima Valley (Table 1). The sampled section at Lima Valley has a uniform bedding correction, so the fold test at this locality is inconclusive. In tectonic units west of the Middle Tuscan Ridge (Monte Alpe Cherts in eastern Liguria and Elba Island, and Tuscan Cherts at Monti d'Oltreserchio and Campiglia), the characteristic magnetization has reversed polarity, moderate inclinations, and southerly declinations ranging from SSE in the north (sites 1 and 2) to SSW (sites 3–6) in the south (Fig. 1). It has reversed polarity, anomalous steep inclinations and northerly declinations in the Tuscan Cherts sections of Lima Valley (site 7), which are located at the structurally complex front of the Tuscan nappe. The overprint component has normal polarity, moderate to steep inclinations and westerly declinations in the Monte Alpe Cherts at Figline di Prato (site 8) and Murlo (site 9); both of these sections have uncertain stratigraphic positions and are situated near major tectonic lineaments. Individual rotations for sites 1 through 6 are given in Table 2.

Although the sampled sections are only a few scattered points within a large orogenic region, it is worth noting that all the Jurassic radiolarian chert sections and coeval lithologies sampled so far in the internal sector of the Northern Apennines have similar characteristic components of secondary magnetizations. This observation supports the hypothesis that this magnetic component is a regional thermochemical overprint acquired over a broad sector of the Northern Apennines subsequent to the thrusting phase, and during regional uplift of the orogenic belt. At this time, conditions for pore fluid circulation, and thus for chemical alteration and precipitation of ferromagnetic minerals, were most favorable. Our paleomagnetic data suggest that the magnetic overprint was possibly acquired simultaneously across the westernmost (innermost) part of the orogenic belt in a reversed-polarity geomagnetic field (localities 1 through 7 in Fig. 1; Fig. 2). The moderate inclinations

Table 2
Vertical-axis rotations of remagnetized internal sector rocks

Site	Locality	La (°N)	Lo (°E)	Rotation (°)
1	Monte Zenone[a]	44.44	9.51	− 42 ± 16
2	Rocchetta di Vara[a]	44.37	10.26	− 12 ± 17
3	Nisporto (Elba Island)	42.49	10.24	27 ± 7
4	San Felo (Elba Island)	42.49	10.24	9 ± 5
5	Monti d'Oltreserchio	43.50	10.24	10 ± 22
6	Campiglia	43.04	10.36	− 27 ± 6
	Mean (sites 1–6)	43.39	10.14	− 8 ± 19
	Eurasian pole (8 Ma)[b]	84.1	149.1	$\alpha_{95} = 2.2°$

Vertical axis rotations of sites within the internal sector relative to a Late Miocene Eurasian reference pole. See Table 1 notes. Clockwise (CW) rotations (with 95% confidence limits) are positive, and counterclockwise (CCW) rotations are negative.

[a] Aiello and Hagstrum (2001).

[b] Besse and Courtillot (1991).

of this component indicate that the tectonic units were most likely located near to their modern latitudinal position during overprinting.

In Lima Valley where the characteristic magnetization is a syn-folding overprint (Aiello and Hagstrum, 2001), the age of remagnetization must be younger than the youngest formation involved in the first phase of folding (i.e., Late Miocene). The Late Miocene is a time of tectonic resurgence within the internal sector of the orogenic chain, following the ensialic collisional stage of the Northern Apennines characterized by large-scale geologic processes such as magmatism, hydrothermalism and tectonism (mostly extensional). Uplift of the Middle Tuscan Ridge (Fig. 1) has occurred mostly since the Tortonian, but was particularly active in the Messinian. Moreover, during Messinian time magmatic bodies intruded into rocks now exposed on Elba and Giglio Islands (Fig. 1). From Tortonian to Messinian time, polyphasic extensional basins were opening west of the Middle Tuscan Ridge (e.g., the Volterra and Baccinello basins). Later, between the Messinian and Pliocene, extensional tectonics migrated east of the Middle Tuscan Ridge (Val d'Elsa and Siena basins) together with the locus of magmatic activity (e.g., Larderello's pluton and Roccastrada effusives).

The paleomagnetic directions of late Messinian to early Pliocene sediments of western Tuscany, which unconformably overlie Ligurian and Tuscan Units, offer further constraints to the timing of the overprint. The mean direction of the characteristic magnetization for these sediments is $D=357.3°$, $I=56.9°$, $\alpha_{95}=3.1°$ (Mattei et al., 1996a,b), or $D=177.3°$, $I=-56.9°$, since most of the Messinian samples have reversed-polarity magnetizations. The mean direction of the Messinian sediments is similar to the mean direction of the reversed-polarity magnetic overprint found west of the Middle Tuscan Ridge (sites 1–6; $D=177.4°$, $I=-52.2°$, $\alpha_{95}=14.7°$; Fig. 1; Table 1).

As demonstrated in analogous studies of paleomagnetic overprints in orogenic belts, the uniform reversed polarity of the magnetic overprint for the internal sector might indicate relatively rapid remagnetization ($\leq 10^6$ years; Thomas et al., 1999). Magnetic overprinting of both Ligurian and Tuscan units was likely acquired at shallow crustal depths, after most of the uplift and denudation of the internal sector had occurred. Fission-track determinations give a Serravallian–Tortonian age for the final phase of uplift and denudation (Abbate et al., 1999).

The three sites that have "anomalous" overprint directions (sites 7, 8 and 9) are all located near major tectonic fronts in the Northern Apennines. Lima Valley is at the front of the Tuscan nappe, Murlo is adjacent to the Monticiano–Roccastrada thrust front, and Figline di Prato is near the Livorno–Sillaro fault system (Fig. 1). Aiello and Hagstrum (2001) interpreted the northerly declination of the overprint magnetization in the Tuscan Cherts of the Lima Valley as a synfolding magnetization (site 7; Fig. 3; Table 1). In the section at Monte Pratofiorito, located on the normal flank of a large recumbent fold, the overprint has steep negative inclinations dipping at high angles with respect to bedding. Assuming intermediate Northern Hemisphere latitudes for the Tuscan Cherts at the time of remagnetization, the chert beds must have been dipping steeply to the south in order for the overprint component (B) to match the expected Miocene direction of a reversed geomagnetic field. Considering the structural geology of Lima Valley, a northward tilting of the chert beds after overprinting is much more likely than a vertical-axis rotation of 180°.

The normal polarity and the westerly directions of the component of characteristic magnetization found for the Monte Alpe Cherts at Figline di Prato and Murlo (sites 8 and 9) suggest that the magnetic overprinting was acquired in these units in pre-Late Miocene times. In fact, the paleomagnetic directions reported from the Messinian to Pliocene sediments of the Siena basin, which unconformably overlie the Ligurid Unit at Murlo indicate that little vertical-axis rotation occurred after their deposition (Mattei et al., 1996a).

6. Conclusions

In this investigation, we have found the widespread occurrence of a post- and syn-folding remagnetization in Middle to Upper Jurassic radiolarian chert sections and coeval ophiolite rocks of the Tuscan (continental margin) and Ligurian (oceanic) Units of the Northern Apennines thrust belt in Italy. For most of the chert sections analyzed from the internal sector of the thrust belt (six out of nine), the characteristic magnetization is a post-folding overprint component of reversed polarity having southerly declinations and moderate inclinations. Paleomagnetic and stratigraphic evidence indicates that the thermochemical remagnetization was acquired after the Oligo-Miocene thrusting of the Ligurian Units over the Tuscan Units, and during enhanced circulation of orogenic fluids during the Late Miocene uplift of the internal sector of the Northern Apennines. The southerly declinations of this reversed-polarity overprint found in radiolarian cherts of eastern Liguria, southern Tuscany, and Elba Island, indicate that no significant vertical-axis tectonic rotations have occurred over a large area of the internal Northern Apennines since the time of overprinting. No further tectonic rotations are indicated by a previous paleomagnetic investigation of Messinian sediments that unconformably overlie Tuscan and Ligurian Units in southwestern Tuscany.

The reversed-polarity magnetic overprint is also recorded in Tuscan Cherts sections of the Lima Valley, east of the Middle Tuscan Ridge and near a major thrust front. Northerly directions and steep inclinations dipping at high angles with respect to bedding indicate a syn-folding remagnetization, and suggest protracted post-remagnetization compressional activity in the external sector of the Northern Apennines. Two Monte Alpe Cherts sections sampled east of the Middle Tuscan Ridge, both located next to major tectonic features, carry a normal-polarity magnetic overprint that has in situ westerly declinations. We suggest that these units, located in the external sector of the Northern Apennines, acquired their magnetic overprint in pre-Late Miocene times, as little vertical-axis rotation is indicated by previous paleomagnetic analyses of overlying Messinian post-orogenic sediments.

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