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## Paleomagnetic and structural evidence for Neogene block rotations in the Central Apennines, Italy

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**Abstract.** Magnetic fabric and paleomagnetic analyses on sedimentary sequences in several structural units in the Central Apennines ranging from upper Cretaceous pelagic carbonates to upper Miocene turbidites provide evidence for at least two distinct phases of rotation. The first counterclockwise (CCW) rotation is well recorded in Eocene-Oligocene sediments and does not affect the lower-middle Miocene sequences. The second phase is clearly recorded in lower-middle and upper Miocene sediments and shows both CCW and clockwise (CW) rotations in concordance with trends of the different thrust structures. We detected three domains characterized by different rotation patterns. The westernmost is the southern Sabina area, an arcuate thrust belt which underwent a CW rotation after the early Miocene. The second domain is the Latium-Abruzzi carbonate platform, where a CCW rotation occurred after the late Miocene. The third is the Marsica area that underwent a CW rotation after the late Miocene. The magnetic fabric analyses confirm the existence of these different structural provinces and show a strong correlation between the present-day strike of the anisotropy of magnetic susceptibility magnetic lineation and the rotations recorded in Miocene sediments. We attribute present-day variations in orientation of the compressional structures in the Central Apennines to differential rotations about vertical axes due to strike-slip faults and out of sequence thrust activity, rather than to a change in the stress field orientation. We also suggest that this deformation mechanism could be common in other collisional chains around the world.

### Introduction

Structural and stratigraphic data suggest that complex patterns of deformation are common in the Neogene collisional chains within the Mediterranean region. This complexity is mainly expressed by the coexistence of thrust, normal, and strike-slip faults arranged in different structural domains, as seen, for example, in the Aegean area and in the Betic Cordillera. Paleomagnetic data from these regions show rotations of several structural units and suggest that rotations of large crustal blocks about the vertical axis accompanied the development of the main tectonic structures [e.g., Kissel and Laj, 1988; Allerton *et al.*, 1993].

Although in recent years many theoretical models have been proposed that link paleomagnetic data to structural features, the relationships between rotation about vertical axis and tectonics are still largely debated. In particular, investigations focused on the role of strike-slip, thrust, and normal faulting in vertical axis rotations and on the relationships between fault mechanics and block rotation mechanisms [Beck, 1976; Mc Kenzie and Jackson, 1986; Nur *et al.*, 1986; Wells and Heller, 1988; Lee *et al.*, 1990].

In this paper we describe a study from the Central Apennines (Italy) where both structural and paleomagnetic

data elucidate the Neogene tectonic evolution of the chain. We propose that the variability in the orientation of the compressional structures of the Central Apennines does not reflect a change in the orientation of the stress field but is rather due to differential rotations about vertical axis. We also suggest that this deformation mechanism can be a common feature in other collisional chains around the world.

### Brief Summary of Paleomagnetic Research in Italy

The paleomagnetic data collected in sedimentary sequences throughout the Italian peninsula show different patterns of rotation of the various geodynamic units. The Jurassic and Cretaceous sequences of the Apennines provide pieces of evidence for counterclockwise rotations of both the deformed Apenninic chain and the autochthonous Adriatic promontory with respect to the African VGP (see Lowrie [1986] and Channell [1992] for a review on this subject). Counterclockwise rotations detected in lower Pleistocene rocks in the Southern Apennines [Sagnotti, 1992; Scheepers *et al.*, 1993] and clockwise rotations detected in lower Pleistocene rocks in Southern Calabria and Sicily indicate the very young age of the bending of the Calabrian arc [Tauxe *et al.*, 1983; Aifa *et al.*, 1988; Scheepers *et al.*, 1993; Scheepers and Langereis, 1993; Scheepers *et al.*, 1994]. In contrast, no rotations have been detected in the neo-autochthonous lower Pliocene-Pleistocene sediments all along the northern Tyrrhenian margin [Sagnotti *et al.*, 1994] and in lower Pleistocene deposits of the Apulian foreland [Scheepers, 1992].

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Only a limited number of paleomagnetic data are available from the Central Apennines, most of which were collected in Cretaceous sequences. Clockwise rotations of the Marsica and Maiella structures with respect to the Gargano and Umbria areas have been proposed [Jackson, 1990; Marton and D'Andrea, 1992], whereas large counterclockwise rotations have been measured in the Gran Sasso chain, explaining its E-W strike [Dela Pierre et al., 1992]. The number and the age of rocks sampled for these paleomagnetic studies, however, do not allow a complete reconstruction of the Neogene tectonic evolution and of the rotations pattern that affected the numerous structural units cropping out in the Central Apennines. To better understand the region's complex deformation, shown in Figure 1, we performed new structural and paleomagnetic analyses in Cretaceous to upper Miocene sedimentary sequences cropping out in some of the main structures.

### Geological Setting

The Central Apennines are made up of sedimentary sequences of upper Triassic-upper Miocene age arranged in several thrust sheets progressively imbricated toward the Adriatic Sea [Accordi, 1966; Elter et al., 1975; Parotto and Praturlon, 1975; Castellarin et al., 1978; Parotto, 1980; Bally et al., 1986; Bigi et al., 1988], as shown in Figure 2. The

Apennines were built up mainly in late Miocene-Pliocene times with the development of a chain-foredeep-foreland system which migrated eastward thus deforming progressively more external paleogeographic domains [Parotto, 1980; Patacca and Scandone, 1987; Consiglio Nazionale delle Ricerche (CNR), 1989]. The existence of large thrust sheets has been largely confirmed by wells drilled in the region for geothermal and hydrocarbon exploration that also uncovered the presence of different detachment levels controlling the thrust geometry of the chain [Martinis and Pieri, 1964; Funicello and Parotto, 1978; Bally et al., 1986].

An extensional tectonic regime was active since late Miocene time and progressively migrated toward the east in response to crustal thinning associated with the opening of the Tyrrhenian Sea [Malinverno and Ryan, 1986; Kastens and Masche, 1990; Sartori, 1990]. The geometry of the chain is further complicated by out-of-sequence thrust sheets that form arcs which are convex toward the Adriatic Sea [Ghisetti and Vezzani, 1986, 1991; Patacca et al., 1990] and by extensive N-S right-lateral [Alfonsi et al., 1991] and NW-SE left-lateral strike-slip faults [Cavinato and Sirna, 1988; Montone and Salvini, 1991] shown in Figure 2. The result of this complex geodynamic evolution is a structural setting characterized by domains that differ both in their orientation and in the mechanism of the associated faults.

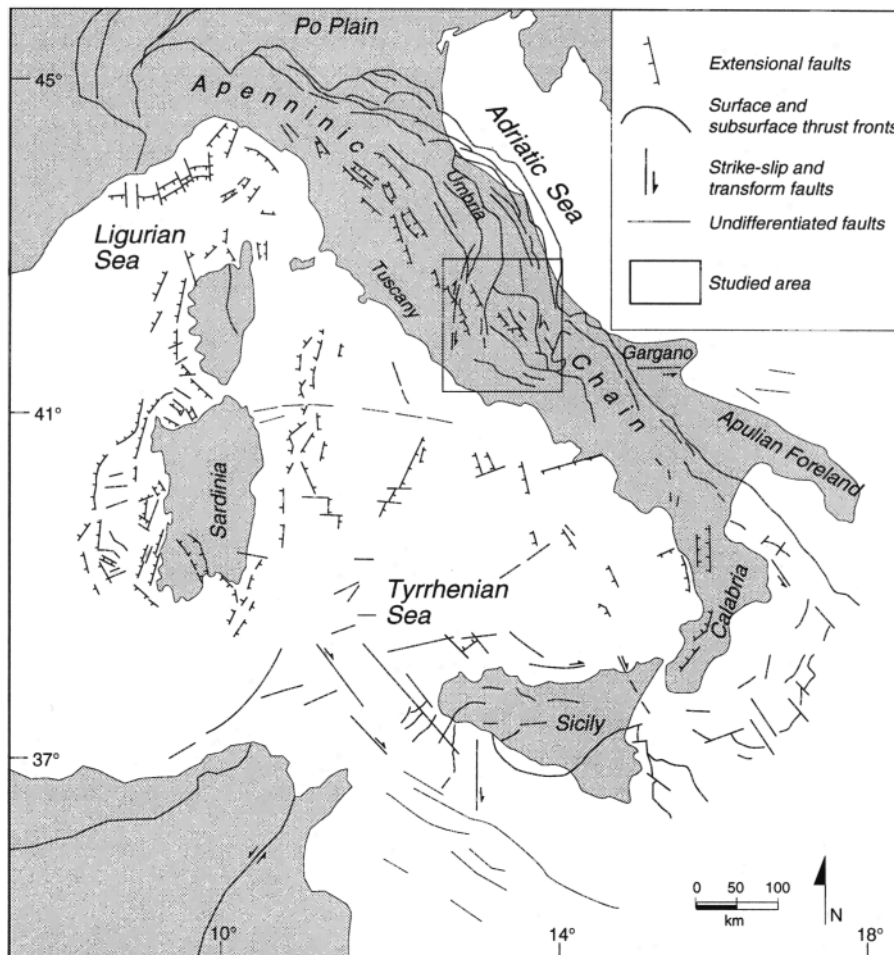
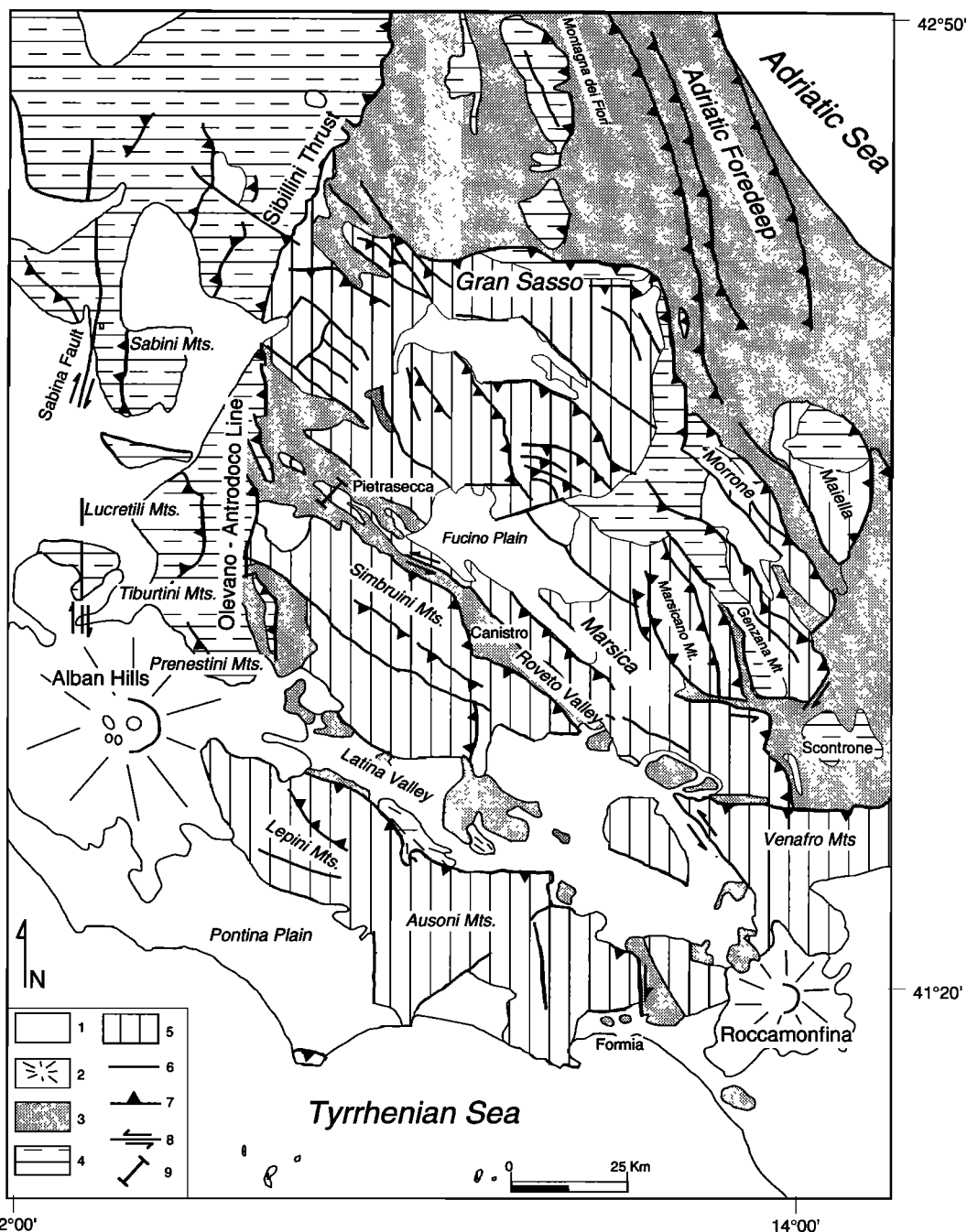


Figure 1. Structural sketch of the Italian peninsula (modified from Consiglio Nazionale delle Ricerche, [1989]).



**Figure 2.** Schematic map of the Central Apennines. 1, Pliocene-Pleistocene post-orogenic sequences of the Tyrrhenian margin and intra-Apenninic basins; 2, Quaternary volcanic sequences; 3, Tortonian-Messinian terrigenous sequences in the Latium-Abruzzi platform, Laga flysch (Messinian) and Pliocene-Pleistocene foredeep sequences; 4, Umbro-Sabina, Gran Sasso and Marsica transitional to basinal units (upper Triassic-upper Miocene) and Molisan basin units (Oligocene-Messinian); 5, Carbonatic units of the Latium-Abruzzi and Maiella-Morrone platforms (upper Triassic-upper Miocene); 6, normal faults; 7, thrusts; 8, strike-slip faults; 9, location of the cross section at Pietrasecca in Figure 11.

The present-day geometry of the Central Apennines has been explained with different models: (1) sequential deformation phases each characterized by a different orientation of the stress field [Castellarin *et al.*, 1978; Salvini and Vittori, 1982]; (2) arcuate geometry related to out-of-sequence thrust sheets, following the eastward retreat of the subducting Adriatic lithosphere [Royden and Karner, 1984; Royden *et al.*, 1987; Doglioni, 1991], separated by major N-S

oriented right-lateral strike-slip faults [Patacca and Scandone, 1987; Patacca *et al.*, 1990]. The complex tectonic evolution has also been related to the general counterclockwise rotation of the Italian peninsula indicated by paleomagnetic data collected in the past twenty years.

We investigated the portion of the Central Apennines shown in Figure 2. The western side (Sabina area) is composed of upper Triassic-upper Miocene sediments mainly of pelagic

facies in, at least, three main N-S to NW-SE striking thrust sheets that verge toward the Adriatic Sea. In the southern portion of the region (Tiburini Mountains) the structures are oriented NE-SW and form an arcuate structure convex toward the east. In the western side of the region a major N-S right-lateral strike-slip fault (Sabina Fault) dissects the earlier thrust sheets. It has been important in the Plio-Pleistocene tectonic evolution of the region [Alfonsi *et al.*, 1991]. The eastern boundary of the Sabina region is marked by the Olevano-Antrudoco line, where the pelagic sequences of the Sabina basin overthrust Latium-Abruzzi platform structures [Parotto and Praturlon, 1975].

The Latium-Abruzzi carbonate platform is formed by shallow water, upper Triassic to upper Miocene carbonate sequences stacked in thrust sheets, that are mainly NW-SE striking and NE verging. Locally, the thrust planes strike N-S defining an arcuate geometry of the structures like that clearly exposed in the Roveto Valley [Devoto, 1967; Parotto, 1971]. In their southwestern side the thrust sheets are dissected by very steep NW-SE trending faults. These faults bound NW-SE structural depressions filled with upper Miocene turbidite deposits that are progressively younger toward the northeast. Structural and stratigraphic data suggest both normal and left-lateral strike-slip motion for these faults, requiring a complex tectonic history [Parotto and Praturlon, 1975; Funiello *et al.*, 1981; Montone and Salvini, 1991].

In the Marsica area, at the eastern boundary of the Latium-Abruzzi platform, the upper Triassic to middle Miocene facies are of transitional to basinal type [Colacicchi and Praturlon, 1965; Praturlon, 1968]. The region is characterized by several thrust sheets oriented mainly NNW-SSE, although the presence of N-S to N30°E right-lateral strike-slip faults with associated back thrusts and minor strike-slip faults suggests that strike-slip faulting was also important in the tectonic evolution of this area [Corrado *et al.*, 1990; Ghisetti and Vezzani, 1991; Mattei and Miccadei, 1991].

Abundant stratigraphic and structural data collected in the past few years have shown that the available paleomagnetic record is inadequate to reflect the tectonic complexity and the age of the deformation in this region. In particular, the present-day structure of the Apenninic chain has been described as the result of tectonic deformation that began after late Miocene times and continued very rapidly during Plio-Pleistocene times. Structural domains characterized by different strike, regional strike-slip faults, and arcuate structures have now been recognized, suggesting that the mechanisms of block rotations played an important role in the tectonic evolution of the area.

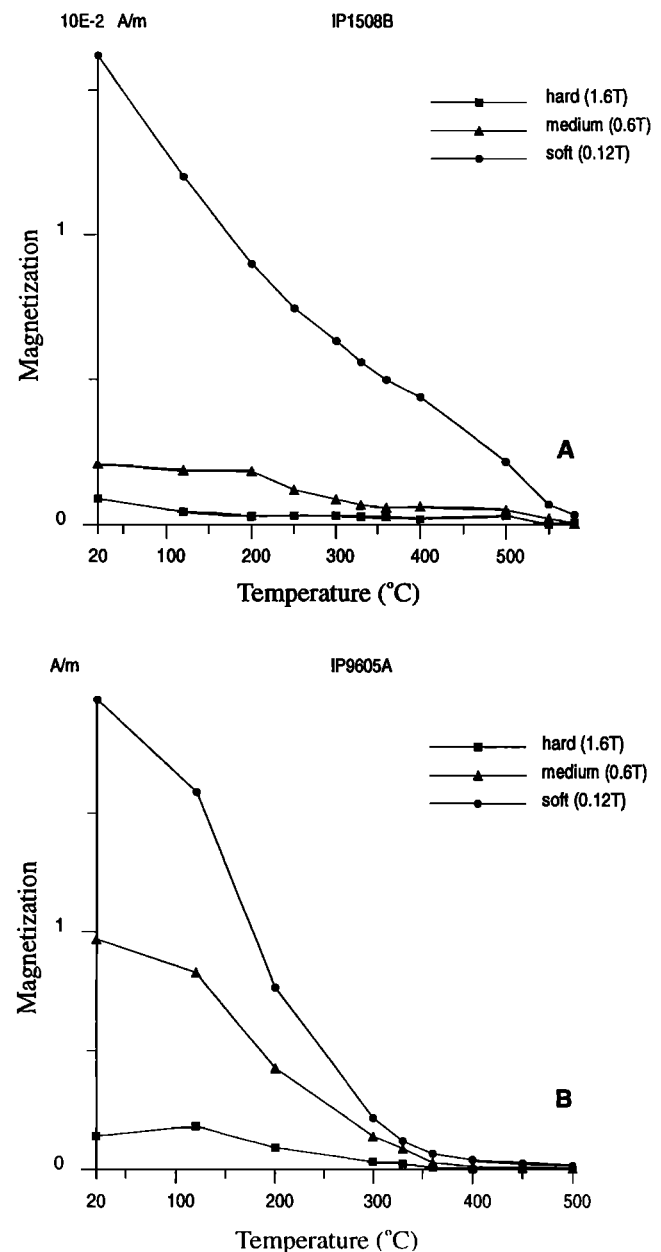
For all these reasons we decided to perform further paleomagnetic sampling. Sampling sites were selected in areas characterized by different orientation of the fold axes (from NW-SE in the Latium-Abruzzi platform to NE-SW in the southern Sabina area) and having different tectonic styles and deformation patterns. The sampled sequences range from upper Cretaceous to Messinian and represent the youngest sediments available for paleomagnetic studies in each structural domain. By sampling wide stratigraphic intervals in some particular structures (e.g., the Prenestini Mountains) we were able to obtain temporal control on the different rotations.

### Paleomagnetic Sampling and Laboratory Analyses

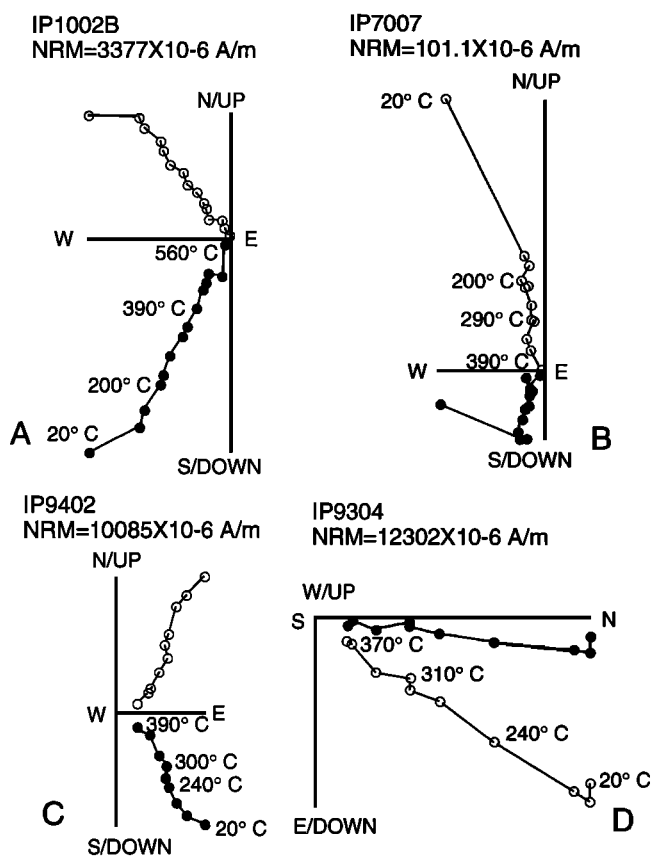
The paleomagnetic sampling was performed following standard techniques, using an electric drill connected to a

generator and a 25-mm magnetic corer with a diamond cutting edge. The orientation of the cores was obtained using a magnetic compass. Over 1100 cores were obtained from 108 sites distributed through the area.

We sampled the Scaglia Rossa (limestones and marly limestones with chert, upper Cretaceous-Eocene), the Scaglia Cinerea (marls and marly limestones with chert, interbedded with detrital limestones, Oligocene), the Guadagnolo Formation (marls and marly limestones interbedded with detrital limestones, lower-middle Miocene), the Bisciara Formation (limestones and marls with chert, lower Miocene), the Orbulina Marls, (marly limestones and marls, Tortonian), the turbidite sequences cropping out in the Latium-Abruzzi and Marsica region (sandstones and clays, Messinian), and clays with gypsum cropping out in the Formia area (Messinian).



**Figure 3.** Thermal demagnetization of three deliberately induced orthogonal components of IRM. Marly samples from (a) Guadagnolo Formation and (b) clayey turbidites samples from Latium-Abruzzi.



**Figure 4.** Thermal demagnetization vector diagrams (solid circles, horizontal projection; open circles, vertical projection) of specimens with a single stable component of magnetization. (a, b) Marly samples from Guadagnolo Formation and (c,d) clayey turbidites samples from Latium-Abruzzi.

Samples from a site have been collected over a wide stratigraphic range to average paleosecular variation.

The remanent magnetization was measured with a three axes-2G cryogenic magnetometer in a shielded room at Gif sur Yvette (France) and on a JR4 spinner magnetometer at L'Aquila (Italy). The anisotropy of the low-field magnetic susceptibility (AMS) was measured using a KLY-2 Kappabridge apparatus.

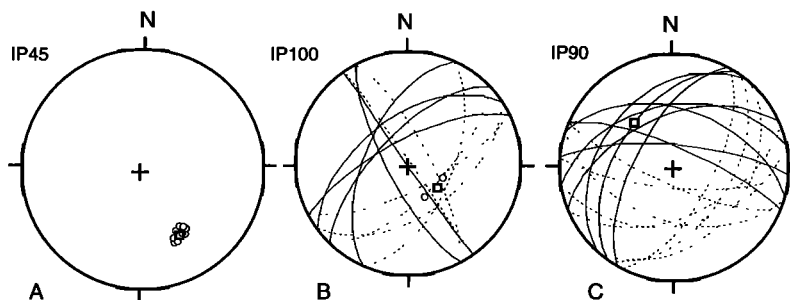
The natural remanent magnetization (NRM) ranges between  $5 \times 10^{-2}$  A/m, in the Orbulina Marls Formation, and less than  $2 \times 10^{-5}$  A/m in the Bisciario and Guadagnolo Formations.

Because of these very low NRM values, we were not able to study many of the sites where these two formations were sampled. Remaining samples were thermally demagnetized at 10 to 15 steps from room temperature up to the limit of reproducible results (320°C to 560°C). At each demagnetization step the bulk susceptibility was measured to monitor possible changes in magnetic mineralogy.

Rock magnetic experiments, such as acquisition of isothermal remanent magnetization (IRM), alternating field demagnetization of the saturation IRM (SIRM) and thermal demagnetization analyses of three-component IRM [Lowrie, 1990] were performed on some representative samples. These analyses showed that the red samples from the Scaglia Formation are mainly characterized by low-coercivity minerals such as magnetite with a small amount of high-coercivity minerals such as hematite. The Guadagnolo Formation, the white samples of the Scaglia Formation, and some of the sites in Messinian clays are characterized by low-coercivity minerals with a blocking temperature of 580°C (Figure 3a). Rock magnetic experiments demonstrate that these formations are dominated by magnetite. Some sites in Messinian clays are also characterized by low coercivity minerals with a blocking temperature of about 350°C (Figure 3b). These samples also show systematic decreases in susceptibility above temperatures of 200°C. These behaviors are typical of iron sulfides [Roberts and Turner, 1993]. Channell *et al.* [1982] showed that red Scaglia Formation limestones in the Umbria region acquired their magnetization in the early stages of diagenesis. Timing of the iron sulfide growth is unknown, but in rapidly sedimented marls it may take place during or a short time after deposition [Tric *et al.*, 1991; Roberts and Pillons, 1993]. Nevertheless, the field tests, performed for all the examined formations, show that blocking of magnetization was complete before sediments were folded and that these sites can be used for tectonic studies.

**Paleomagnetic Results**

For many specimens we obtained a stable component of magnetization, represented by a linear segment toward the origin in a Zijderveld plot (Figure 4). For other specimens we detected an overlap in the demagnetization spectra of two components of magnetization and the demagnetization results plot as great circles on an equal-area net [Halls, 1978]. Finally, in some sites the two behaviors are found in different samples (Figure 5). The mean characteristic remanent magnetization (ChRM) was thus calculated using either Fisher's statistic or the method proposed by *McFadden and*



**Figure 5.** Equal-area projections of the mean directions of magnetization (squares) for (a) sites with only stable linear paths, (b) linear paths and remagnetization circles, and (c) only remagnetization circles. Open circles and great circles represent data from individual samples.

*McElhinny* [1988]. For 47 sites the statistical parameters are fully satisfying ( $\alpha_{95} < 15^\circ$ ), while for 5 additional sites the  $\alpha_{95}$  values range between  $15^\circ$  and  $20.6^\circ$  (Tables 1 and 2).

Sites from Messinian rocks from the Roveto Valley, the lower-middle Miocene rocks from the Prenestini Mountains

and the Scaglia Formation in the Sabini Mountains pass the fold test of *McElhinny* [1964] at 95% confidence level (Table 3). Sites from the Roveto Valley and the Sabina Mountains display both reversed and normal polarity magnetization (Figure 6). For the Sabina area sites after tectonic correction,

**Table 1.** Summary of the Cretaceous-Oligocene Paleomagnetic Results

Site	<i>N</i> ( <i>n</i> , <i>c</i> )	<i>D</i>	<i>I</i>	<i>D'</i>	<i>I'</i>	<i>k</i>	$\alpha_{95}$	Strike	Dip	Age	Longitude	Latitude
<i>Tiburtni Mountains</i>												
IP83	7(2,5)	214	10	41	14	65	8.3	*	*	late Cretaceous	12°49'59"	41°57'25"
IP84	8(3,5)	113	11	56	36	29	10.7	*	*	late Cretaceous	12°49'04"	41°56'55"
IP51	9(9,0)	215	-22	215	-22	45	6.9	0	0	Eocene	12°52'51"	42°00'40"
IP85	8(8,0)	260	9	77	42	99	5.0	185	54	Oligocene	12°53'00"	42°02'20"
Means												
btc (4 sites)		8	-55			1	69.0					
atc (4 sites)				50	29	16	17.5					
<i>Sabina</i>												
IP100	8(2,6)	202	-42	129	-63	62	7.7	148	46	Paleocene	12°52'24"	41°53'40"
IP23	10(10,0)	11	43	335	44	321	2.0	176	34	Eocene	12°40'34"	42°23'30"
IP26	5(5,0)	130	-49	173	-43	53	8.6	328	39	Eocene	12°45'39"	41°18'25"
IP28	5(5,0)	177	-70	144	-46	96	7.1	*	*	Eocene	12°40'34"	42°23'18"
IP30	8(7,1)	205	-27	161	-36	85	6.8	*	*	Eocene	12°40'04"	42°25'50"
IP31	7(7,0)	285	-22	327	43	21	11.6	324	126	Eocene	12°38'41"	42°25'30"
IP39	9(9,0)	355	39	324	29	24	10.3	*	*	Eocene	12°39'54"	42°27'10"
IP43	9(9,0)	340	42	339	41	59	6.4	*	*	Eocene	12°39'44"	42°29'07"
IP45	9(9,0)	154	8	151	-34	234	3.4	78	44	Eocene	12°45'47"	41°15'30"
IP47	12(12,0)	174	-41	143	-46	46	6.0	*	*	Eocene	12°39'59"	41°16'55"
IP48	10(10,0)	218	-68	170	-61	38	7.2	*	*	Eocene	12°44'34"	41°17'45"
IP49	9(9,0)	354	35	330	46	43	7.1	*	*	Eocene	12°47'49"	41°16'43"
IP54	8(2,6)	172	-39	133	-40	9	20.6	152	45	Eocene	12°52'49"	41°52'53"
IP55	10(5,5)	1	52	338	46	26	9.9	*	*	Eocene	12°52'38"	41°53'15"
IP62	7(7,0)	218	62	136	-36	134	4.6	*	*	Eocene	12°54'47"	42°01'20"
IP63	8(8,0)	292	29	323	45	43	7.5	*	*	Eocene	12°55'54"	42°08'15"
IP29	8(8,0)	186	-64	146	-39	91	5.2	204	38	Oligocene	12°40'34"	42°23'20"
IP53	7(7,0)	333	69	312	45	25	10.6	*	*	Oligocene	12°55'05"	42°04'30"
IP64	6(6,0)	307	41	335	50	31	10.3	*	*	Oligocene	12°54'40"	42°11'10"
IP66	9(9,0)	147	-52	145	-52	49	6.6	*	*	Oligocene	12°46'59"	42°09'30"
IP86	6(6,0)	158	-38	144	-32	53	7.9	164	18	Oligocene	12°53'18"	41°55'20"
Means												
btc (21 sites)		346	45			7	12.8					
atc (21 sites)				329	44	52	4.0					
<i>Montagna dei Fiori</i>												
IP56	6(6,0)	360	51	345	32	224	3.8	*	*	Eocene	13°34'24"	42°48'05"
IP57	9(9,0)	135	38	321	40	20	10.5	*	*	Oligocene	13°37'29"	42°45'10"
IP58	7(7,0)	330	33	8	41	91	4.5	*	*	Oligocene	13°37'39"	42°42'10"
Means												
btc (3 sites)		10	67			2	54.2					
atc (3 sites)				345	39	18	18.6					
<i>Marsica</i>												
IP79	10(6,4)	348	30	348	43	33	9.4	58	12	late Cretaceous	13°58'00"	41°43'01"
IP80	9(9,0)	30	40	6	43	12	13.7	192	26	late Cretaceous	13°56'29"	41°48'05"
Means												
btc (2 sites)		8	37			10	30.5					
atc (2 sites)				357	43	76	11.3					

*N*, number of analyzed specimens (*n* number of linear paths; *c* number of remagnetization circles); *D*, *I*, declination and inclination, before tectonic correction; *D'*, *I'*, declination and inclination, after tectonic correction; *k*, precision parameter;  $\alpha_{95}$ , half-angle of the 95% confidence cone about the mean direction; btc, before tectonic correction; atc, after tectonic correction. Means were computed transferring all the data to the lower (normal polarity) hemisphere. All samples were thermally demagnetized.

\* bedding attitude variable within the site.

**Table 2.** Summary of the Miocene Paleomagnetic Results

Site	<i>N</i> ( <i>n</i> , <i>c</i> )	<i>D</i>	<i>I</i>	<i>D'</i>	<i>I'</i>	<i>k</i>	$\alpha_{95}$	Strike	Dip	Age	Longitude	Latitude
<i>Prenestini Mountains</i>												
IP06	8(4,4)	167	-57	188	-50	44	8.9	332	17	early Miocene	12°55'39"	41°54'40"
IP09	6(2,4)	164	-54	182	-33	168	6.7	308	27	early Miocene	12°56'59"	41°52'20"
IP10	7(2,5)	212	-14	208	-19	61	8.5	184	13	early Miocene	12°56'44"	41°51'56"
IP11	9(3,6)	148	-57	183	-50	31	10.0	331	26	early Miocene	12°54'35"	41°51'55"
IP12	10(3,7)	207	-42	207	-46	52	6.9	119	05	early Miocene	12°55'59"	41°52'28"
IP70	7(1,6)	170	-58	200	-56	38	11.2	*	*	early Miocene	12°55'49"	41°55'07"
IP71	6(2,4)	213	-30	203	-40	28	14.2	*	*	early Miocene	12°57'04"	41°53'20"
Means												
btc (7 sites)		9	48			10	19.5					
atc (7 sites)				16	43	28	11.5					
<i>Roveto Valley</i>												
IP87	8(8,0)	277	49	341	58	67	6.0	318	43	late Miocene	13°08'01"	42°07'00"
IP88	5(4,1)	355	34	338	35	17	19.8	162	25	late Miocene	13°09'01"	42°07'50"
IP90	8(0,8)	13	65	316	48	88	5.7	185	38	late Miocene	13°32'19"	41°48'40"
IP91	8(1,7)	266	59	335	40	20	14.0	286	53	late Miocene	13°42'00"	41°38'00"
IP93	6(6,0)	279	22	32	19	13	15.6	*	*	late Miocene	13°23'49"	41°56'15"
IP94	7(3,4)	192	-55	148	-40	39	10.5	101	40	late Miocene	13°16'39"	42°00'10"
IP96	6(5,1)	144	-47	171	-35	18	16.6	318	32	late Miocene	13°11'02"	42°06'00"
IP98	6(2,4)	152	-36	124	-40	20	16.9	130	36	late Miocene	13°08'01"	42°06'50"
IP99	6(6,0)	163	-57	175	-34	20	16.9	286	26	late Miocene	13°06'04"	42°13'03"
Means (apart from site IP93)												
btc (8 sites)		332	42			10	18.0					
atc (8 sites)				332	42	28	10.5					
<i>Marsica</i>												
IP76	10(2,8)	153	-30	219	-63	86	5.3	*	*	late Miocene	14°08'05"	41°47'03"
IP78	7(7,0)	146	-58	197	-58	42	8.2	348	26	late Miocene	14°03'55"	41°43'02"
IP82	7(0,7)	171	-11	190	-49	36	8.9	50	48	late Miocene	13°57'16"	41°45'51"
IP104	8(1,7)	111	-47	236	-14	39	10.9	*	*	late Miocene	13°50'09"	41°47'15"
IP105	6(0,6)	289	22	330	-44	31	10.3	328	59	late Miocene	13°47'24"	41°49'50"
Means (apart from site IP105):												
btc (5 sites)		329	39			8	24.4					
atc (5 sites)				4	48	9	22.9					
<i>Formia</i>												
IP17	7(7,0)	208	-42	219	-40	36	8.8	*	*	late Miocene	13°45'01"	41°17'05"

*N*, number of analyzed specimens (*n* number of linear paths; *c* number of remagnetization circles); *D*, *I*, declination and inclination, before tectonic correction; *D'*, *I'*, declination and inclination, after tectonic correction; *k*, precision parameter;  $\alpha_{95}$ , half-angle of the 95% confidence cone about the mean direction; btc, before tectonic correction; atc, after tectonic correction. Means were computed transferring all the data to the lower (normal polarity) hemisphere. All samples were thermally demagnetized.

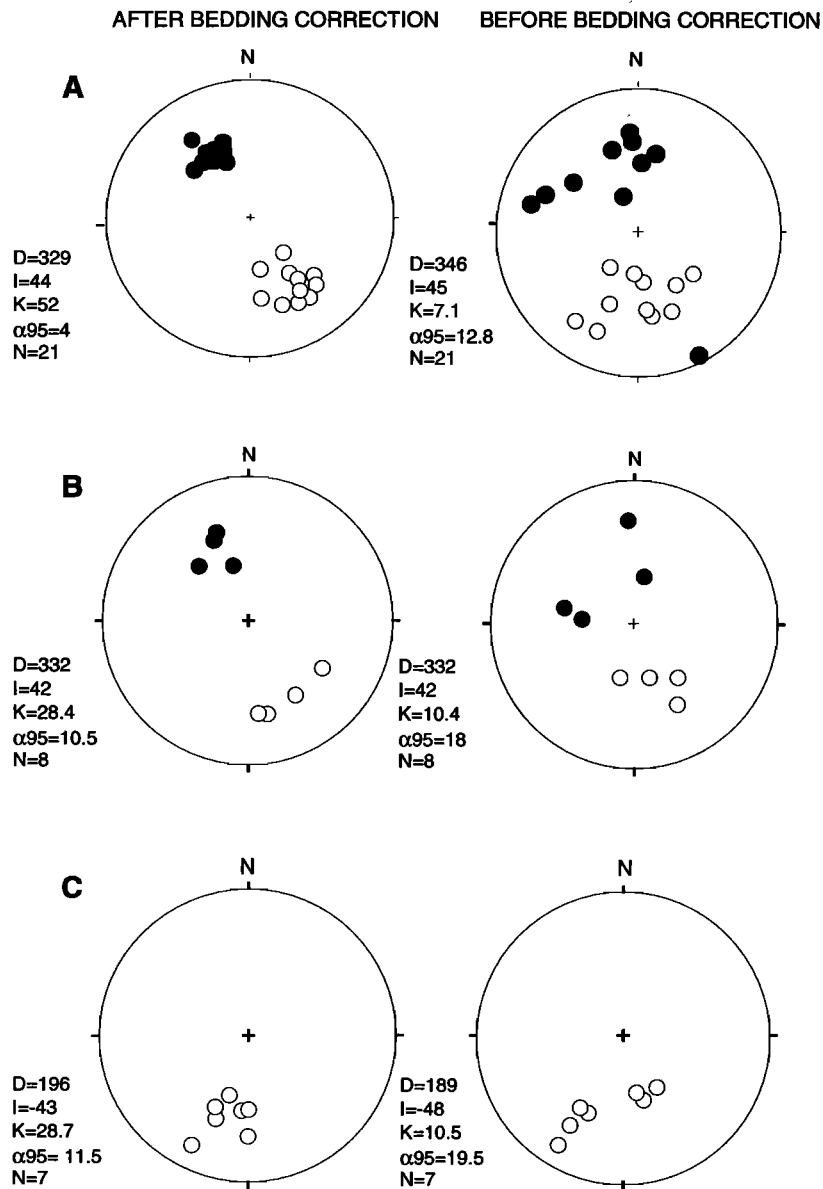
\* Bedding attitude variable within the site.

**Table 3.** Fold Tests

	<i>N</i>	<i>k1</i>	<i>k2</i>	<i>k2/k1</i>	$F_{(40,40)}(x, y)$ 5%
Scaglia Formation in Sabina area	21	7.1	52.0	7.32	1.69
Messinian sediments of the Roveto Valley	8	10.4	28.4	2.73	2.46
Guadagnolo Formation	7	10.5	28.7	2.73	2.69

Following *McElhinny* [1964].

*N*, number of sites; *k*, precision parameter before (*k1*) and after (*k2*) bedding correction;  $F(x, y)$ : limiting value derived from *F* tables with *x* and *y* degrees of freedom at the 5% significance level.



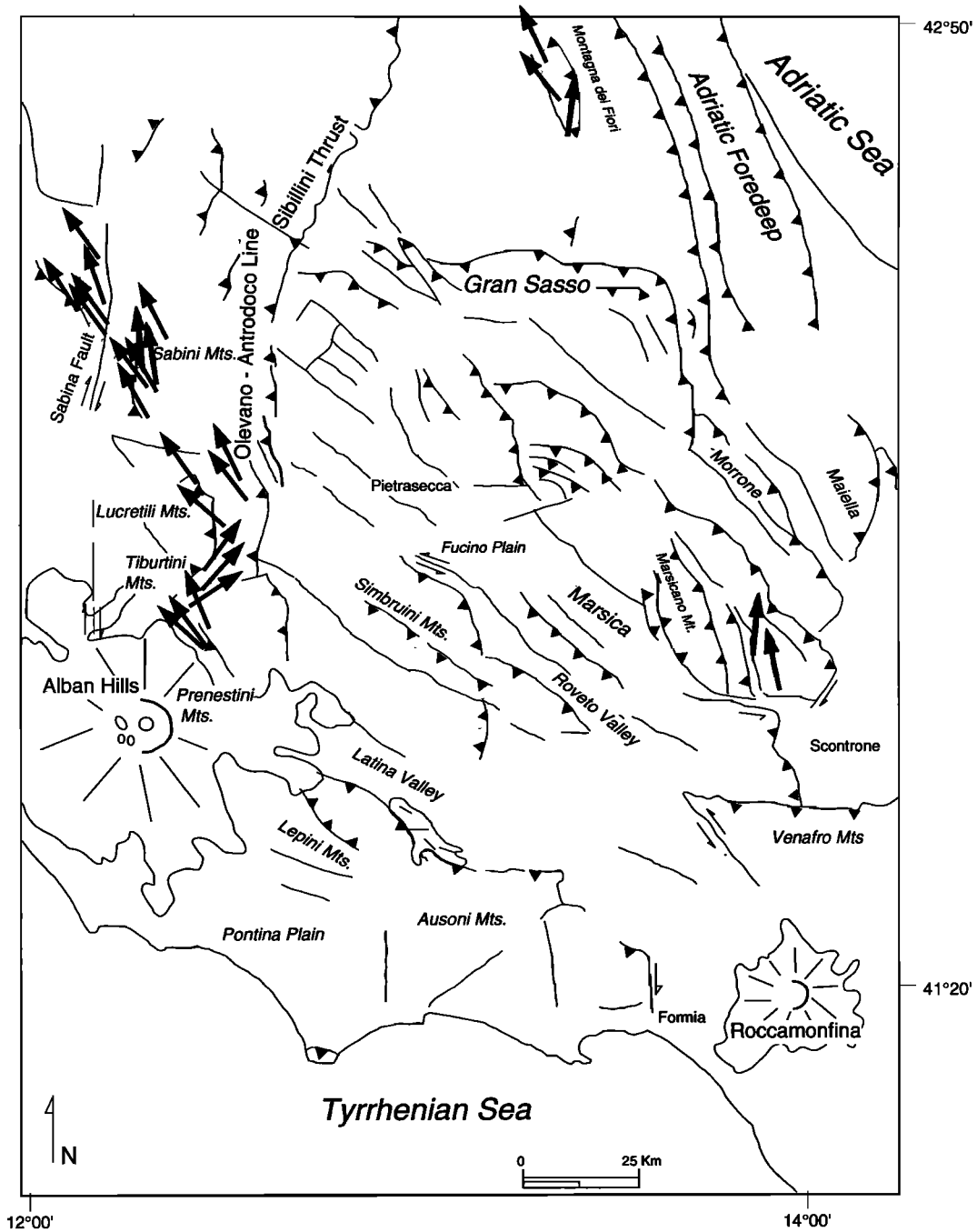
**Figure 6.** Equal-area projections of the (left) site-mean directions after and (right) before bedding correction. Solid circles, projections on lower hemisphere; open circles, projections on upper hemisphere. (a) Scaglia Formation in the Sabina area except the Tiburtini Mountains (see text for the explanation); (b) upper Miocene sediments of the Roveto Valley except site IP93 (see text for the explanation); (c) lower-middle Miocene sediments of the Guadagnolo Formation.

normal and reversed mean directions group in two antipodal clusters (reversal test of the type Rb according to *McFadden and McElhinny* [1990]:  $\gamma_0=1.5^\circ$ ;  $\gamma_c=8.8^\circ$ ). In the Roveto Valley the reversal test is indeterminate ( $\gamma_0=6.9^\circ$  and  $\gamma_c=24.1^\circ$ ). The magnetic mineralogy of most of the sites, the positive fold test, and the reversal test indicate that the ChRM was blocked before folding for all the studied formations. The paleomagnetic results can thus be interpreted in terms of rotations to constrain the tectonic evolution of the Central Apennines.

We examined the results from formations of different ages separately. In particular, we separated the data from the upper Cretaceous-Oligocene Scaglia Rossa and Scaglia Cinerea Formations, from data from the Miocene Guadagnolo Formation (lower-middle Miocene) and from the Latium-

Abruzzi terrigenous sequences (upper Miocene). These two data sets show different rotational patterns associated with two distinct events in the tectonic evolution of the Central Apennines.

Paleomagnetic results in the Scaglia Rossa and Scaglia Cinerea were obtained at various sites from the Sabina, Montagna dei Fiori, and Marsica areas. All the results obtained from those Cretaceous-Oligocene sites are reported in Figure 7 and in Table 1. In the Sabina area 21 sites from the Sabini Mountains, southward to the Prenestini Mountains have a mean westward declination of  $31^\circ$  ( $\alpha_{95}=4^\circ$ ,  $k=52$ ) which was measured. This declination is observed over the entire area except in the Tiburtini Mountains which instead show an eastward declination. The westward declination is also well defined in the Montagna dei Fiori area where a small eastward



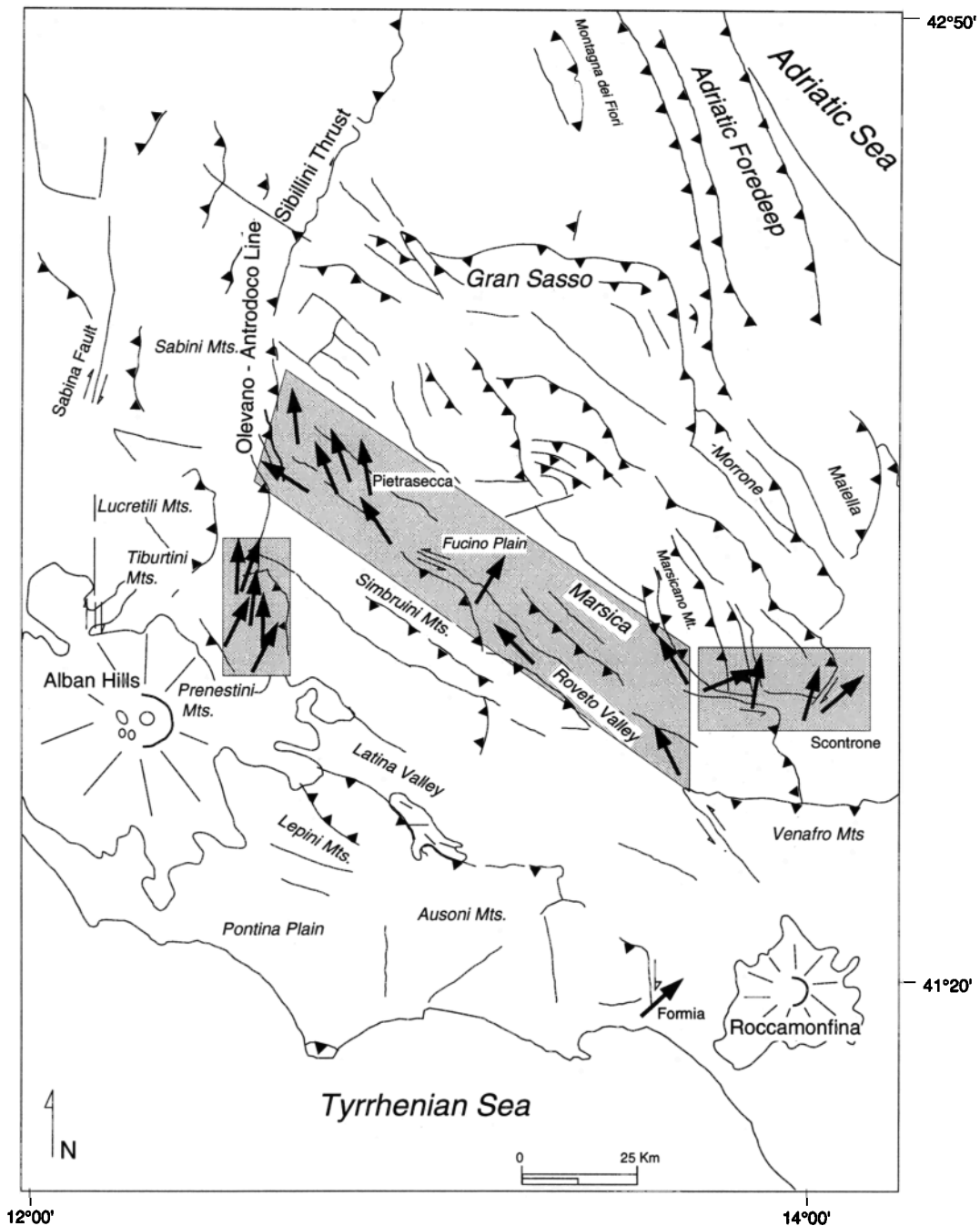
**Figure 7.** Paleomagnetic declination, after correction for the bedding tilt, of the Scaglia Rossa and Scaglia Cinerea Formations (upper Cretaceous-Oligocene). All the sites are reported in normal polarity. The arrows represent a site or group of sites.

declination was measured only in the southern part of the structure. In the Marsica area we obtained results only from two sites in upper Cretaceous sediments that show small eastward and westward declinations, respectively.

Although the results obtained from the upper Cretaceous to Oligocene formations are consistent over the studied area, the Miocene data show a more complex pattern of rotation (Figure 8; Table 2). We recognized at least three rotational domains of Miocene rocks. Due to the very low values of NRM in the Guadagnolo Formation we were able to obtain data only from 7 of 25 sites in the southernmost part of the Sabina area. These

sites are located along the NNW-SSE striking anticline of the Prenestini Mountains and show an eastward declination of  $16^\circ$  ( $\alpha_{95}=11.5^\circ$ ,  $k=28.7$ ). This is opposite that indicated by westward declinations in the Scaglia Cinerea Formation from the same area.

The second domain is characterized by a post-Messinian westward declination of  $28^\circ$  ( $\alpha_{95}=10.5^\circ$ ,  $k=28.4$ ) recorded in eight sites from the turbidite sequences of the Latium-Abruzzi sector. This rotation was clearly observable all along the NW-SE oriented structures represented by folded and thrustured upper Miocene sequences. Only in site IP93 we recognized an



**Figure 8.** Paleomagnetic declinations, after correction for the bedding tilt, of the lower-middle (Guadagnolo Formation) and upper Miocene sediments (Orbulina marls, flysch sequences of the Latium-Abruzzi platform, clays with gypsum in the Formia area). All the sites are reported in normal polarity. Note that the counterclockwise rotations measured in the Scaglia Formation in the Marsica and Prenestini Mountains (Figure 7) are not recorded in the lower-middle Miocene sequences of the same areas. The arrows represent a site or group of sites. Shaded areas represent structural domains that underwent differential rotations.

eastward declination of  $32^\circ$  in the opposite sense with respect to the general trend of the area. This site is located along a segment of the Simbruini Mountains thrust front where the strike of the structure changes from NW-SE to N-S [Parotto, 1971; Funicello et al., 1981].

Finally, a complex pattern of rotation was detected in upper Miocene sequences of the Marsica and Formia areas. We only found five useful sites in this area because of the scarcity of

available outcropping sequences. Eastward declination was found in four sites, whereas westward declination was recorded only in one site IP105 (Table 2).

### Discussion of the Paleomagnetic Results

The present data demonstrate that the Central Apennines underwent at least two phases of rotation after Oligocene. The

older counterclockwise rotation was clearly detected in almost all the Sabina area and in the Montagna dei Fiori structure. This counterclockwise rotation is well constrained to be late Oligocene-early Miocene age in the Sabina area, because it does not affect the Guadagnolo Formation stratigraphically overlying the Scaglia Cinerea Formation.

To better define the amount of this rotation we compared our results with African paleopoles listed by *Besse and Courtillot* [1991], following the method proposed by *Demarest* [1983]. In particular we calculated rotations referred to the 35 Ma African paleopole for the Eocene-Oligocene sites, and to the 15 Ma African paleopole for the early-middle Miocene sites. The Eocene-Oligocene sites show a counterclockwise rotation of  $35^{\circ} \pm 5^{\circ}$  while the early-middle Miocene sites show a clockwise rotation of  $12^{\circ} \pm 13^{\circ}$  respect to the African paleopole. The total amount of this rotation is about  $47^{\circ}$  ( $35^{\circ}$  counterclockwise in the Scaglia Formations plus  $12^{\circ}$  clockwise in the Guadagnolo Formation). In the Marsica area we also observed a different sense of rotation in the Cretaceous units than in Messinian units. Messinian turbidites carry eastward declinations and the upper Cretaceous Scaglia Formation carries N-S declinations. A similar difference between the Cretaceous-Oligocene and the Miocene rotations was also obtained in other regions of the Central Apennines. The Montagna dei Fiori structure, for example, shows counterclockwise rotation in the Cretaceous-Eocene Scaglia Formation and no rotation in the upper Miocene Laga flysch Formation [*Dela Pierre et al.*, 1992].

The lack of well-distributed Eocene-Oligocene data in the Italian peninsula and the poor definition of the African apparent polar wander path (APWP) for Cenozoic times make very controversial the geodynamic history of the Apulian plate for this time span. For example, *Lowrie* [1986] proposed a Cenozoic counterclockwise rotation of about  $17^{\circ}$  respect to Africa for the Gargano, Istria and Umbria regions, whereas *Channell* [1992] argued that the Apulian plate rotated with Africa during Mesozoic and Cenozoic times. On the other hand, in the Central Mediterranean the main geodynamic event during the early Miocene is represented by the counterclockwise rotation of the Corsica-Sardinia block [*Montigny et al.*, 1981]. The eastern boundary of the region involved in this rotation has not been yet defined, and it would not be surprising that it might involve even some portion of the Apulian plate. Nevertheless, we believe that further data in Oligocene-middle Miocene sequences are necessary to better define and to understand the geodynamic framework of the counterclockwise rotation recognized in the Sabina region.

The results obtained in Miocene sediments are clearly more directly related to the Miocene-Pliocene emplacement of this sector of the Apenninic chain. The scarcity of Miocene data in the other regions of the Italian peninsula precludes a comparison of our data with the neighboring regions. As a consequence, we still have some difficulty in distinguishing the local block rotations from the regional rotations. However, based on our data it is possible to identify the relative rotations between structural blocks and to reconstruct the tectonic evolution of this sector of the Apenninic chain.

The southern Sabina area shows clockwise rotation of  $12^{\circ}$  ( $\pm 13^{\circ}$ ) with respect to the African APWP after the lower-middle Miocene. The poor exposure and the coarse composition of the upper Miocene turbidites in this region did not allow us to obtain data from these rocks. Therefore we can not compare the age of the rotation of the Guadagnolo

Formation with that of the rotation found in the upper Miocene rocks sampled in the neighboring Latium-Abruzzi platform.

The area to the east of the Olevano-Antrdoco line underwent a counterclockwise rotation of about  $28^{\circ}$  since late Miocene. This rotation affected the entire NW-SE oriented structure of the Roveto Valley that is representative of the tectonic arrangement of the Latium-Abruzzi region. A local clockwise rotation was recognized near the Canistro village along the anomalous N-S trending segment of the Roveto Valley (IP93). We relate this opposite sense of rotation to transpressive mechanisms of this tectonic structure, as also recognized in the inner part of the Simbruini-Ernici range [*Cavinato et al.*, 1990].

The eastern boundary of the Latium-Abruzzi platform is characterized by clockwise rotations recognized in the Messinian sediments from the Marsica region and in the Formia area. The tectonic setting of this region is characterized by NNW-SSE to N-S local structures resulting from the activity of transpressive mechanisms which have been recognized along the major N-S tectonic elements [*Mattei and Miccadei*, 1991; *Ghisetti and Vezzani*, 1991].

### Low-Field Anisotropy of Magnetic Susceptibility (AMS) Results

In the past few years AMS data yielded very important results concerning the strain history of rocks, in particular very weak or undeformed sedimentary sequences for which no other methods could be applied [*Lowrie*, 1989]. Although the AMS studies cannot substitute the petrofabric analyses in the strain studies, a strong correlation between the magnetic fabric detected by AMS analyses and the tectonic elements has been largely proved all around the world [*Kligfield et al.*, 1981; *Borradaile*, 1988].

We measured AMS for sites sampled for paleomagnetic analyses. Data were analyzed using both the maximum density orientation and the tensorial statistics of *Jelinek* [1978]. The magnetic fabric is described by an ellipsoid in which  $K_{max}$ ,  $K_{int}$ , and  $K_{min}$  represent the maximum, intermediate, and minimum axes. The anisotropy degree ( $P'$ ), the foliation ( $F$ ) and the lineation ( $L$ ) parameters were also examined to determine the shape parameters of the susceptibility ellipsoid [*Hrouda*, 1982].

We were unable to measure the anisotropy of magnetic susceptibility for most of the samples collected in the Scaglia Rossa, Scaglia Cinerea, and Bisciaro Formations because their values were lower than  $10^{-5}$  SI or showed an isotropic magnetic fabric. We obtained good results from the Guadagnolo Formation, in the turbidite sequences of the Latium-Abruzzi and Marsica area and from some sites in the Scaglia Rossa Formation.

The Guadagnolo Formation is characterized by low values of magnetic susceptibility (between  $1.2 \times 10^{-5}$  SI to  $12.3 \times 10^{-5}$  SI) and anisotropy degree ( $1.007 < P' < 1.045$ ). The sites sampled in this formation show, in any case, a good resolution of the susceptibility ellipsoid. The upper Tortonian-Messinian turbidites of the Latium-Abruzzi region are characterized by values of magnetic susceptibility ranging from  $2.2 \times 10^{-5}$  SI to  $70.1 \times 10^{-5}$  SI. These sites are also characterized by an increase of  $L$  and  $P'$  parameters compared to the other more carbonatic sequences. These low values of the bulk susceptibility indicate that the main magnetic

contribution is due to the paramagnetic fraction [Hrouda and Tarling, 1993] and that ferromagnetic minerals (iron sulphides and magnetites) slightly influence the magnetic fabric.

We resolved the magnetic fabric in 45 sites (Table 4). The magnetic fabric ranges from oblate ellipsoids of pure sedimentary origin ( $K_{max}=K_{int}$  with  $K_{min}$  perpendicular to the bedding) to prolate ellipsoids related to tectonic deformation ( $K_{max}$  parallel to the fold axes and  $K_{min}=K_{int}$ ). For most of the sites the magnetic fabric is intermediate (tectonic and sedimentary) with a magnetic lineation parallel

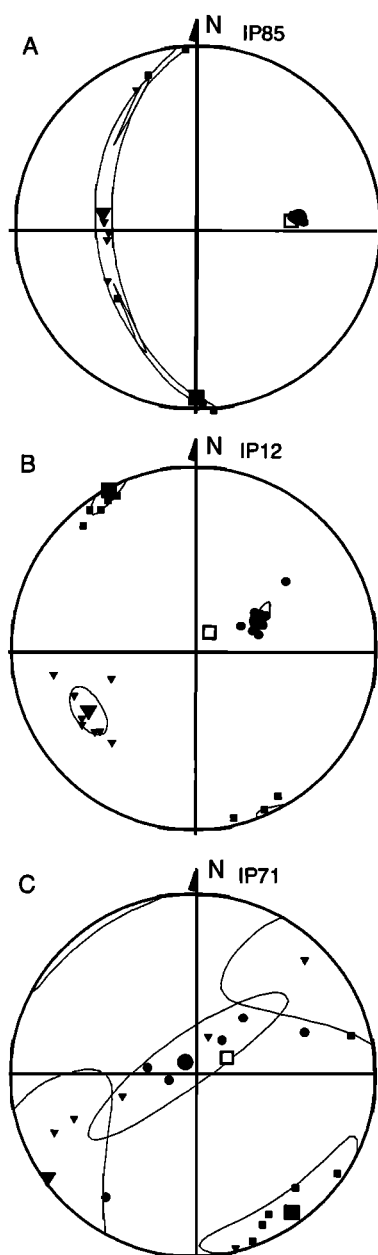
to the axes of the folded structures and  $K_{min}$  still perpendicular to the bedding (Figure 9). In only four sites (IP17, 78, 82, 94) a structural transport lineation (almost perpendicular to the fold axes) was recognized. We never observed magnetic foliation parallel to the cleavage, as found in other thrust belts [Kligfield *et al.*, 1981], and this suggested a low deformation for these sedimentary sequences.

The magnetic lineation is better developed in the marls and clays (Guadagnolo Formation and turbidite sequences of the Latium-Abruzzi area) than in calcareous sequences of the

**Table 4.** List of Anisotropy Parameters Computed at Each Site

Site	SI	$K_{maxD}$	$K_{maxI}$	$K_{minD}$	$K_{minI}$	E12	E13	L	F	P'	Age
IP72	15.2	350	10	100	63	23.7	11.9	1.018	1.012	1.033	late Cretaceous
IP83	90.3	245	16	106	70	65.3	12.6	1.006	1.014	1.020	late Cretaceous
IP54	43.0	291	2	25	70	68.1	28.7	1.001	1.005	1.007	Eocene
IP55	21.0	345	1	78	70	62.6	33.1	1.004	1.016	1.020	Eocene
IP40	31.5	284	2	178	83	29.9	20.0	1.006	1.006	1.012	Oligocene
IP46	37.9	212	4	315	72	33.2	12.9	1.004	1.008	1.012	Oligocene
IP58	31.1	160	10	264	54	58.2	10.4	1.004	1.015	1.019	Oligocene
IP85	33.6	182	7	85	45	61.4	1.4	1.002	1.009	1.012	Oligocene
IP09	20.8	324	14	72	50	8.6	4.7	1.014	1.009	1.023	early Miocene
IP10	24.0	148	5	52	51	25.2	8.4	1.021	1.018	1.040	early Miocene
IP11	59.1	148	14	275	68	18.2	8.2	1.013	1.009	1.022	early Miocene
IP12	34.0	332	1	64	57	10.6	4.2	1.014	1.010	1.025	early Miocene
IP13	12.0	143	4	48	50	26.2	3.1	1.008	1.012	1.020	early Miocene
IP14	15.1	209	32	40	57	67.7	7.6	1.002	1.005	1.007	early Miocene
IP15	123.8	158	12	320	78	19.5	4.3	1.015	1.029	1.045	early Miocene
IP44	25.6	209	43	75	37	57.9	18.3	1.004	1.023	1.028	early Miocene
IP60	22.2	332	0	62	23	23.4	5.7	1.010	1.017	1.028	early Miocene
IP61	21.3	150	12	348	77	25.5	7.9	1.011	1.017	1.028	early Miocene
IP70	31.2	160	13	290	70	20.9	11.5	1.015	1.011	1.026	early Miocene
IP71	25.5	144	7	325	83	33.4	11.3	1.015	1.012	1.027	early Miocene
IP16	307.3	127	9	15	67	25.3	6.1	1.020	1.113	1.136	late Miocene
IP17	218.8	150	14	288	71	35.8	14.5	1.004	1.033	1.038	late Miocene
IP18	182.1	333	23	241	4	21.3	11.1	1.018	1.026	1.044	late Miocene
IP76	281.2	184	32	299	33	12.9	6.0	1.006	1.050	1.056	late Miocene
IP78	173.0	119	25	282	63	19.4	7.9	1.008	1.046	1.054	late Miocene
IP81	22.0	346	17	112	62	30.6	8.1	1.006	1.019	1.025	late Miocene
IP82	165.0	130	42	331	46	20.4	9.8	1.006	1.055	1.062	late Miocene
IP87	657.4	317	9	224	15	16.1	6.6	1.034	1.056	1.093	late Miocene
IP88	392.7	189	10	68	70	62.2	8.5	1.004	1.087	1.091	late Miocene
IP89	76.2	305	16	53	46	13.8	3.5	1.014	1.018	1.033	late Miocene
IP90	196.5	295	24	72	59	9.2	3.4	1.016	1.036	1.052	late Miocene
IP91	241.0	296	20	193	32	7.8	6.4	1.015	1.045	1.061	late Miocene
IP92	220.6	283	39	47	35	14.0	5.4	1.004	1.026	1.031	late Miocene
IP93	507.8	174	11	72	45	7.6	4.9	1.055	1.064	1.122	late Miocene
IP94	478.2	181	39	14	50	23.0	9.2	1.021	1.128	1.153	late Miocene
IP96	347.5	147	0	238	67	22.6	11.5	1.026	1.067	1.095	late Miocene
IP98	189.0	134	6	38	48	65.1	8.2	1.003	1.054	1.057	late Miocene
IP99	414.2	130	2	222	55	34.9	9.8	1.020	1.056	1.078	late Miocene
IP102	195.8	177	17	280	37	20.7	6.8	1.012	1.006	1.018	late Miocene
IP103	289.8	45	32	263	52	36.5	7.8	1.006	1.052	1.058	late Miocene
IP104	541.9	344	9	78	23	5.7	3.0	1.032	1.179	1.217	late Miocene
IP105	381.6	120	30	234	36	12.3	8.2	1.023	1.049	1.073	late Miocene
IP106	701.4	328	44	210	26	7.9	6.9	1.027	1.078	1.107	late Miocene
IP107	173.8	323	1	233	13	44.7	12.3	1.007	1.038	1.049	late Miocene
IP108	221.2	129	2	222	51	13.0	5.7	1.012	1.040	1.052	late Miocene

Values show the tensorial means [Jelinek, 1978]. SI, mean susceptibility in  $10^{-6}$  SI;  $K_{maxD}$ ,  $K_{maxI}$  declination and inclination of the  $K_{max}$ ;  $K_{minD}$ ,  $K_{minI}$  declination and inclination of the  $K_{min}$ ; E12, E13, half-angle of the 95% confidence ellipse around the mean  $K_{max}$  axis in the  $K_{max}$ - $K_{int}$  and  $K_{max}$ - $K_{min}$  planes, respectively;  $L=K_{max}/K_{int}$  (lineation);  $F=K_{int}/K_{min}$  (foliation);  $P'=\exp\sqrt{2}[(h_1-h)^2+(h_2-h)^2+(h_3-h)^2]$  (corrected anisotropy degree).



**Figure 9.** Typical magnetic fabric recognized in central Italy. (a) Sedimentary fabric ( $K_{min} < K_{int} = K_{max}$ ); (b) sedimentary and tectonic fabric ( $K_{min} < K_{int} < K_{max}$ ); (c) tectonic fabric ( $K_{max} > K_{min} = K_{int}$ ). Squares,  $K_{max}$ ; triangles,  $K_{int}$ ; circles,  $K_{min}$ . Open squares represent bedding poles; 95% confidence ellipse around the mean direction are also drawn (tensorial statistics of *Jelinek*, [1978]).

Scaglia Formation. Figure 10 shows the direction of the magnetic lineations for the Miocene sites. Lineation is almost everywhere parallel to the nearby major fold axes. NNW-SSE to N-S lineations were recognized in the Sabina area all along the Sabini Mountains and the Prenestini Mountains and along the eastern side of the Marsica region. East of the Olevano-Antrodoco line the NW-SE orientation prevails and was recognized in the Roveto Valley and in the Latina Valley parallel to the NW-SE structural trend of the Latium-Abruzzi region. A N-S orientation was only found in the N-S segment

of the Roveto Valley where the structures have a meridian trend.

Paleocurrent directions of the upper Miocene turbidites show a main NW-SE direction, quite parallel to the magnetic lineation, in the Roveto Valley [*Bellotti et al.*, 1981]. In the lower Miocene marls of the Guadagnolo Formation, in the Prenestini Mountains, the sedimentation is mainly due to settling processes and, subordinately, to gravity flows, that came from the Latium-Abruzzi carbonate platform in directions approximately perpendicular to the magnetic lineation [*Civitelli et al.*, 1986]. On the other hand the existence of a magnetic lineation in rocks with different sedimentation mechanisms rules out the possibility of its sedimentary origin. Hence in our opinion the tectonic origin of the magnetic lineations can be demonstrated all along the Roveto Valley mainly in the Pietrasecca fold (Figure 11). This structure consists of a NW-SE asymmetric anticline with the northeastern flank dipping approximately  $70^\circ$  and the southwestern flank dipping approximately  $25^\circ$ . The structure is complicated by minor internal thrusts which define antiformal stack geometries having transport toward the northeast. The magnetic fabric of the upper Miocene clays from the steep northeastern limb has a lineation that parallels the fold axis, but a pure sedimentary fabric was found in the same stratigraphic level from the shallow southwestern limb.

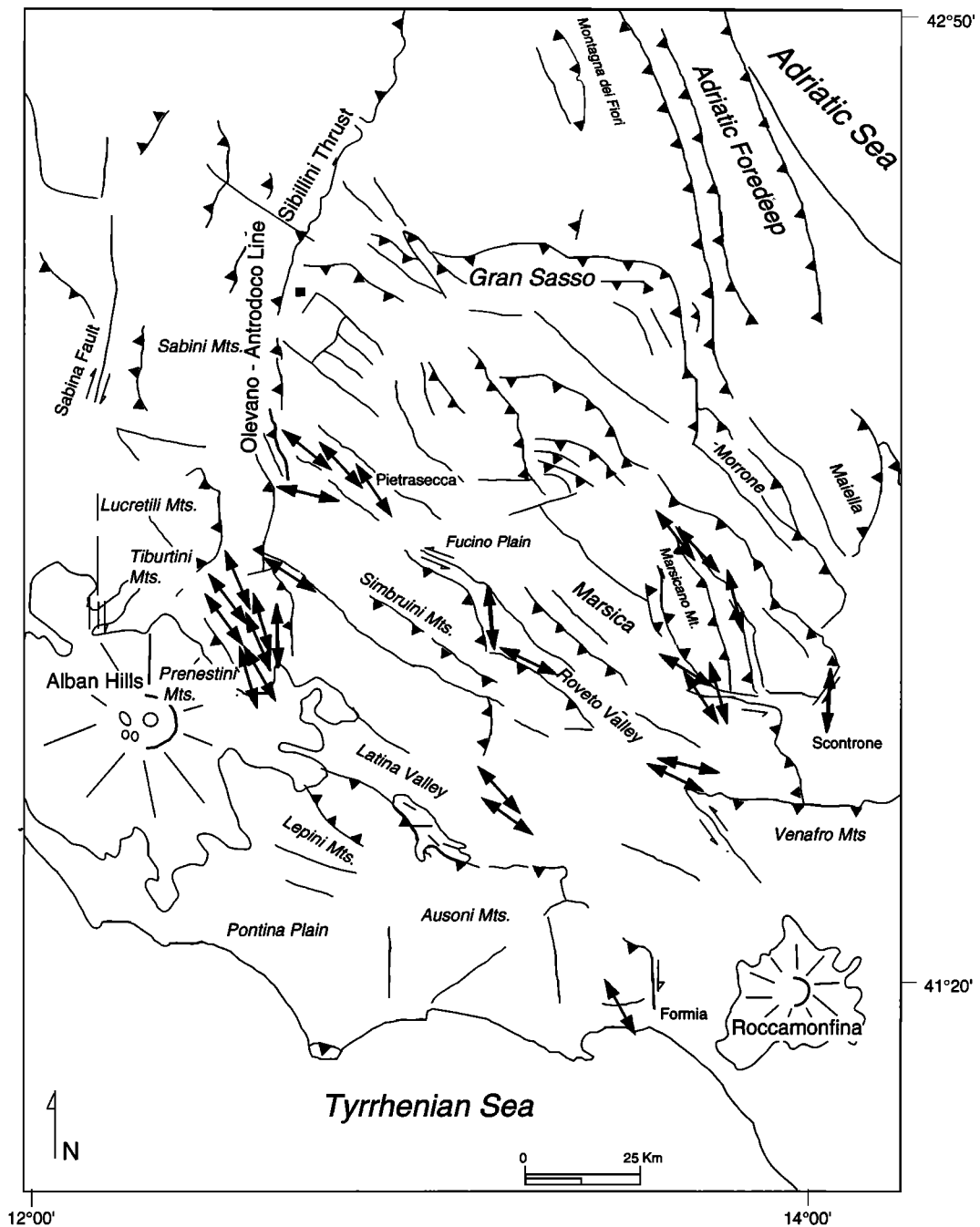
The magnetic lineation in all the sites is of tectonic origin, despite their low deformation. Based on the following considerations, we exclude a sedimentary origin for this lineation: - the magnetic lineations are parallel to the fold axes in sites of different ages (Cretaceous to Messinian) and with different mechanisms of deposition; - agreeing with the general vergency of the thrust belt, the magnetic lineation is best developed in the eastern, more deformed, sides of the structures. A magnetic lineation of exclusive sedimentary origin should be present in both the limbs of the folds; - the prolate fabrics, of tectonic origin, show a magnetic lineation which has the same strike as the lineation observed in triaxial ellipsoids in which the sedimentary fabrics, related to sedimentary compaction processes, are not completely overprinted.

The magnetic lineation formed in the early stages of deformation during the ENE oriented compressional event. The late deformative events do not cause further significant internal strain. This is probably due to rock hardening and compaction related to the early deformative processes.

### Significance of the Block Rotations in the Tectonic Evolution of the Central Apennines

Based on the new paleomagnetic, AMS and structural data, we propose a new model of the tectonic evolution of the Central Apennines in which block rotations accompanied deformation of the different structural units and the activity of the major tectonic elements.

Westward declinations are predominant in the Cretaceous-Oligocene rocks and were observed in all of the Sabina area with the exception of the eastward declinations recorded in the Tiburtini Mountains (Figure 12). The structural anomaly of the Tiburtini Mountains has been discussed by several investigators [*Mattei et al.*, 1986; *Cosentino and Montone*, 1991]. These investigators describe NE-SW oriented thrust planes with a SE sense of motion accompanied by a second generation of mesofolds with a NW-SE to NE-SW axes



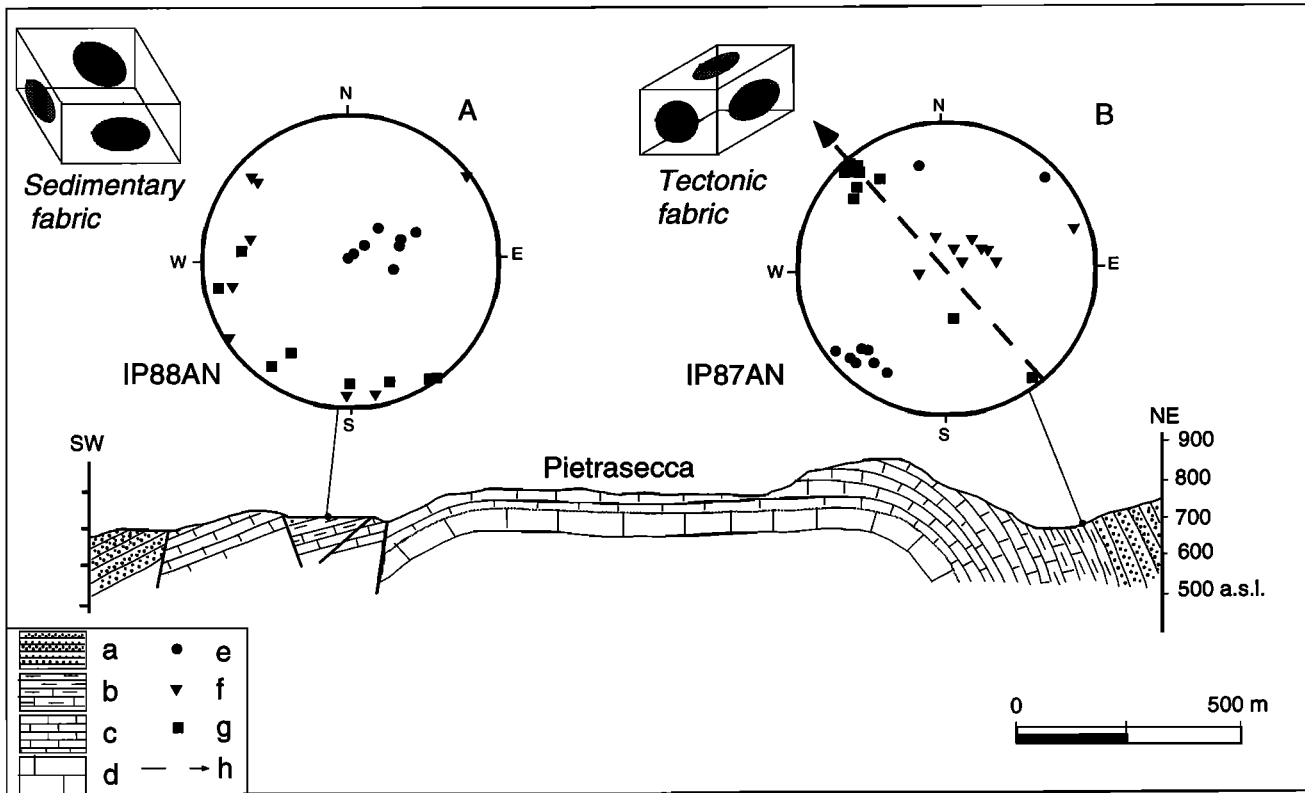
**Figure 10.** Magnetic lineation map. The data were examined following both tensorial and maximum density analyses and projected on a horizontal plane. The magnetic lineation is almost everywhere parallel to the fold axes. The arrows represent a site or group of sites.

previously interpreted as the results of two events of deformation with different sense of transport. The paleomagnetic data confirm the peculiarity of the structures in the Tiburtini Mountains and indicate that the anomalous strike of the Tiburtini Mountains is due to a younger clockwise rotation which bent the preexisting NW-SE structures to the present-day NE-SW orientations. Unfortunately, the lack of paleomagnetic data from Miocene sediments in this structure does not allow a clearer determination of the age of this clockwise rotation. Based on structural data we can assume that it occurred during late Miocene-early Pliocene times according

to the age of deformation of this sector of the Apenninic chain [Cosentino and Parotto, 1986].

The results obtained from Miocene samples (Figure 8), can be directly related to the recent tectonic evolution of the Central Apennines. Clockwise rotations are present mainly in the Sabina area and in the Marsica region. These two areas represent the western and eastern boundaries of the Latium-Abruzzi carbonate platform which instead underwent mainly counterclockwise rotations.

The Sabina region is a thrust belt, mainly N-S oriented, representing the southern part of the Northern Apenninic arc.



**Figure 11.** Schematic cross section of the Pietrasecca anticline (see Figure 2 for the location); A and B magnetic anisotropy plots. a) Flysch sequences of the Roveto Valley (upper Tortonian-Messinian); (b) *Orbulina* marls (upper Tortonian); (c) briozoi and litotamni limestones (middle-upper Miocene); (d) rudist limestones (upper Cretaceous); (e) Kmin; (f) Kint.; (g) Kmax; (h) axis of the Pietrasecca anticline. The magnetic lineation is clearly observable in the northeastern flank, while the southwestern flank shows a sedimentary fabric.

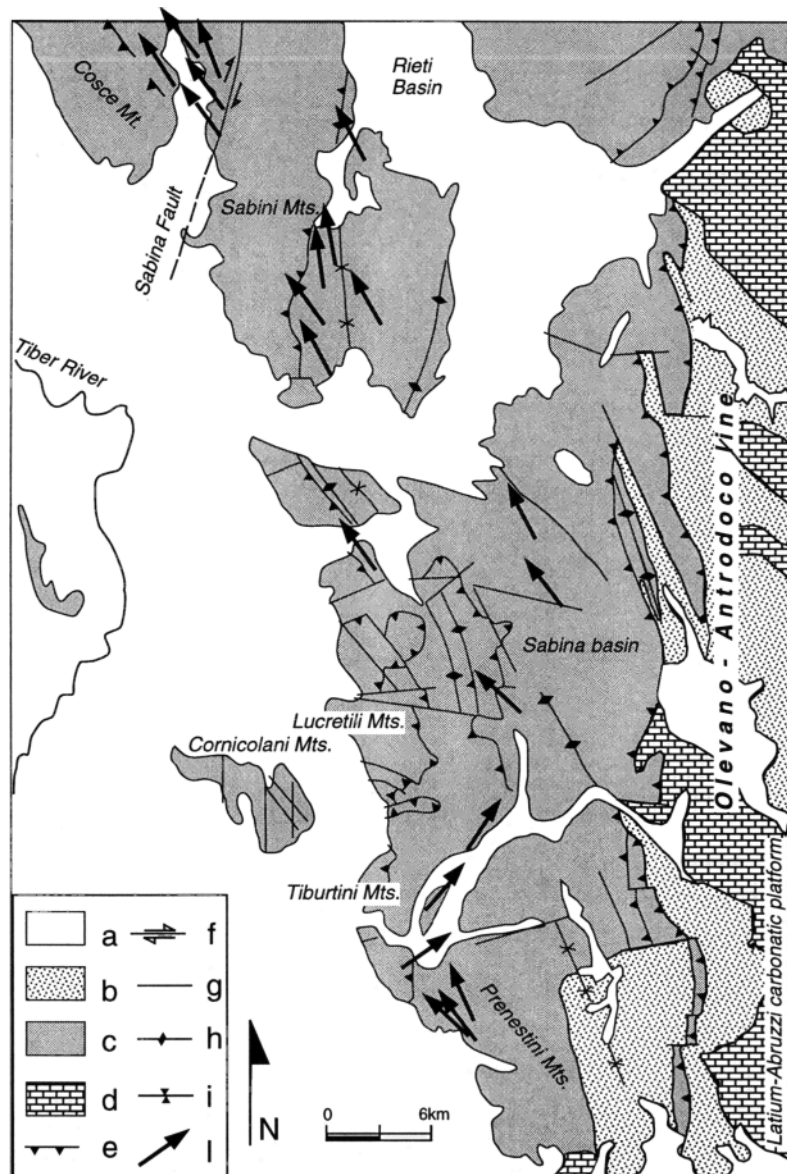
The eastern boundary of the Sabina thrust belt is the Olevano-AnTRODoco front along which the Sabina sequences were thrust over the Latium-Abruzzi carbonatic platform. This tectonic boundary has been interpreted as a Messinian right-lateral strike-slip fault reactivated during early Pliocene as a thrust front [Castellarin *et al.*, 1978; Parotto, 1980], as a thrust front activated several times during Messinian-Early Pliocene with different directions of motion [Salvini and Vittori, 1982; Cavinato *et al.*, 1986], or as a lateral ramp of the main Sibillini thrust outcropping in the Umbria-Marche region [Bally *et al.*, 1986; Calamita and Deiana, 1986; Lavecchia, 1986].

Paleomagnetic analyses confirm the importance of the Olevano-AnTRODoco line demonstrating that it separates two areas which underwent different rotations after Miocene times. Moreover, structural and stratigraphic data show that the Olevano-AnTRODoco line is not associated with the chain-foredeep migrating system of the Apenninic chain, but is an out-of-sequence thrust, that affects terrigenous sequences of two different foredeep systems which developed during the late Tortonian (Latina Valley) and early Messinian (Roveto Valley) [Cipollari and Cosentino, 1992]. Our data suggest that the N-S present-day orientation of this thrust is the result of clockwise rotation during the emplacement of the Sabina structures. Magnetic lineations and fold axes which developed parallel to the main NNW-SSE orogenic trend later were rotated toward a N-S trend.

Clockwise rotation seems responsible for the structural features of the eastern Marsica boundary of the Latium-Abruzzi platform. A NNW to N-S trend of the main structural units in this area is the result of right-lateral transpressive and strike-slip activity of the main tectonic elements [Corrado *et al.*, 1990; Mattei and Miccadei, 1991; Ghisetti and Vezzani, 1991].

To quantify the relationship between structural trends and rotations we tested the correlation between the paleomagnetic declinations of Miocene sites and both the fold axes and the orientation of the intersection magnetic lineations (obtained by the tensor statistical analysis) following the method proposed by Lowrie and Hirt [1986]. These correlations exist at a 99% confidence level both for fold axes ( $T=7.43$ ,  $N=22$ ) and magnetic lineations ( $T=5.96$ ,  $N=15$ ), while the hypothesis of no correlation can be rejected, as shown in Figure 13. The angular coefficients are close to 1 (95% confidence interval is between 0.822 and 1.654 for the declination versus lineation and between 0.811 and 1.443 for the declination versus fold axes), indicating that the present orientation of the fold axes and magnetic lineations is totally due to the differential rotations which affected structures that were parallel throughout the studied area.

The paleomagnetic, AMS, and structural data show that the chain-foredeep system evolved with a NNW-SSE trend in a constant oriented stress regime that migrated toward the Adriatic Sea. In Figure 14a this orientation of the chain-



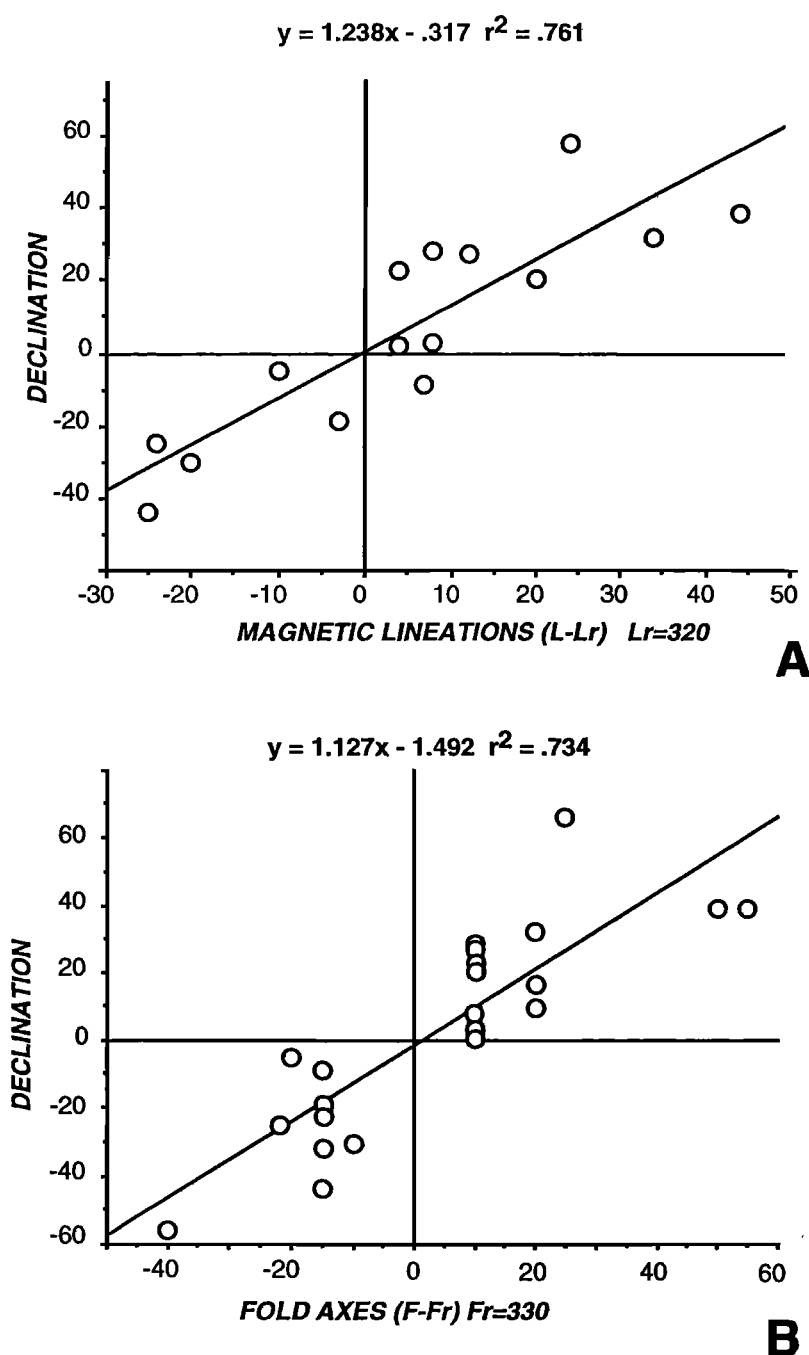
**Figure 12.** Structural map of the Sabina area. (a) Plio-Pleistocene postorogenic sedimentary and volcanic units; (b) Flysch sequences (upper Tortonian-Messinian); (c) Sabina basinal sequences (upper Triassic - upper Miocene); (d) Carbonatic units of the Latium-Abruzzi platform (upper Triassic-upper Miocene); (e) thrusts; (f) strike-slip faults; (g) normal faults; (h) axes of anticlines; (i) axes of synclines; (l) paleomagnetic declination in the Scaglia Formation.

foredeep system was reconstructed by rotating the different structures backward for the measured rotations.

The present-day structural configuration is a product of the different rotations which occurred during the activation of out-of-sequence thrusting (i.e., Gran Sasso chain thrust sheets, Olevano-Antrodoco thrust) and the right-lateral strike-slip along N-S trending faults (i.e., Sabina Fault), as shown in Figures 14b and 14c. Domains with different structural orientations result from differential rotations accommodated by regional discontinuities (Olevano-Antrodoco line, Sabina Fault).

This deformation mechanism leads to a new interpretation of several structural features of the Central Apennines and, in particular, of the evolution of the thrust sheets and the role of

strike-slip tectonics. The evolution of thrust sheets which today show different strikes is the result of differential rotations that occurred during their emplacement. The tectonic evolution recognized for the Neogene structures of the Central Apennines could also be common in regions which underwent compression. Rotations accompanying thrusting have been detected in many, but not all, collisional chains as, for example, in the Sicilian fold and thrust belt [Channell *et al.*, 1990; Oldow *et al.*, 1990], in the eastern Betic Cordillera [Allerton *et al.*, 1993], or in the Taiwan range [Lee *et al.*, 1990]. Although we are not able to define the mechanical constraints on the rotations of the thrust sheets, we can demonstrate that thrust rotations were important deformation features during the evolution of the Apenninic chain.

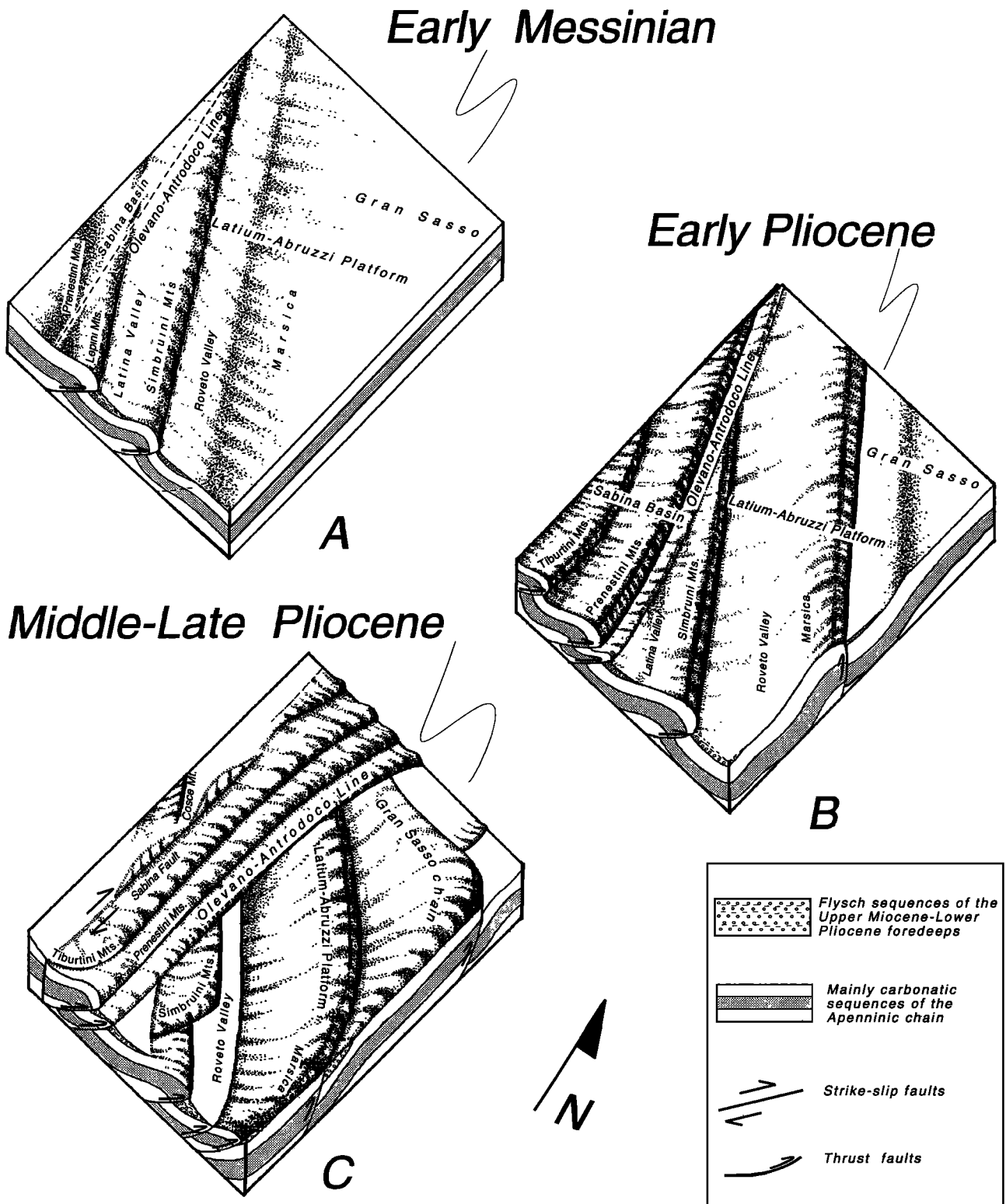


**Figure 13.** Diagrams showing declination for Miocene rocks of the Central Apennines relative to (a) magnetic lineation strike deviations and (b) fold axis strike deviations. Fr and Lr are the reference directions for the fold axes and magnetic lineations; F and L are the fold axis and magnetic lineation ( $E_{12} < 45$ ) at each site. The angular coefficient near 1 in both the regression lines testifies that the actual different strike of the structures is due to differential rotations of the structural units and that they were parallel to each other during the development of the chain-foredeep systems. In both the cases the positive T test demonstrated the noncasualness of these correlations.

Moreover, this rotation involved out-of-sequence thrust sheets while toward the east the chain-foredeep systems migrated following a constant NNW-SSE orientation.

Oblique-slip motion and fault-plane reactivations have been widely recognized in the Central Apennines [Salvini and Vittori, 1982; Cavinato *et al.*, 1986], including along major tectonic lineaments. In particular, NW-SE left-lateral strike-

slip faults (i.e., Roveto Valley Fault) and roughly N-S right-lateral strike-slip faults (e.g., Sabina Fault, Scontrone Fault, Canistro area) have been recognized. This pattern of deformation cannot be explained following classical block-rotation models [McKenzie and Jackson, 1986]. These models predict driving faults (right-lateral, N-S oriented) which bound accommodating NW-SE striking left-lateral faults, that cause a



**Figure 14.** Schematic block diagrams showing the tectonic evolution of the Central Apennines. The sketch shows the main structural features related to the migrating chain-foredeep system and the complex pattern of rotations associated with the strike-slip tectonics and the out-of-sequence thrusts. The internal or external position of the main structural units is derived from the age of the terrigenous sequences whereas their orientation derives from paleomagnetic data. (a) In a first phase the chain-foredeep system involved different paleogeographic domains (Sabina basin and Latium-Abruzzi platform) following a constant N30°W orientation. In this deformative phase the magnetic lineation was formed parallel to the fold and thrust orientation. (b) The development of out-of-sequence thrust (e.g., Olevano-Antrdoco line, Gran Sasso structure) and (c) right-lateral strike-slip faults (Sabina fault, Scontrone fault) caused the differential rotation of the thrust sheets with a clockwise rotation of the Sabina and Marsica regions and counterclockwise rotation of the Latium-Abruzzi structure and Gran Sasso chain [Dela Pierre et al., 1992].

clockwise rotation which is opposite respect to the counterclockwise rotation observed in the Roveto Valley.

Scotti *et al.* [1991] demonstrate that block rotation can generate wide zones characterized by domains of faults. Adjacent domains have different orientations and different fault slip as well. A similar pattern of distributed deformation can be recognized in the Central Apennines. In particular the N-S striking, southern edges of out-of-sequence arcuate thrusts fronts show a right-lateral component of slip, due to the clockwise rotation of the thrust sheets, while NW-SE oriented left-lateral components are mainly observed along structures which underwent counterclockwise rotations.

Our paleomagnetic results do not resolve this main problem, and relations between fault motions and block rotations need to be further investigated, especially specifying fault mechanics, timing of deformation and time of rotations, but such results should be fully considered in the reconstruction of the tectonic evolution of the Central Apennines.

## Conclusions

Based on paleomagnetic, AMS, and structural data, we propose a new interpretation of the structural evolution of the Central Apennines. We recognized two different rotation phases. The older was a counterclockwise rotation detected in the Sabina and Montagna dei Fiori regions and measured in the Eocene-Oligocene sediments of the Scaglia Formation. The second phase involved both clockwise and counterclockwise rotations of Miocene sediments within different isolated structural blocks. The relationships between the structural domains and the sense and amount of the measured rotations show that the main migrating chain-foredeep-foreland system developed with a constant NNE-SSW orientation in a constantly oriented stress regime. The structures were rotated to the present-day configuration during a later episode of strike-slip and out-of-sequence thrust activity. The possibility that in mountain ranges different structural domains be the result of a complex pattern of rotations, which have progressively modified a preexisting more simple configuration, should be tested performing paleomagnetic, AMS, and structural analyses.

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