ANNALI DI GEOFISICA, VOL. XXXVI, N. 2, May 1993

Neogene tectonic evolution of the Central Apennines (Italy) revealed by paleomagnetic and magnetic fabric analyses

Massimo Mattei(1), Renato Funiciello(1), Catherine Kissel(2) and Carlo Laj(2)
(1) *Dipartimento di Scienze della Terra, Roma, Italia*
(2) *Centres des Faibles Radioactivités CNRS-CEA, Gif sur Yvette, France*

Abstract
We present in this paper a set of paleomagnetic and magnetic fabric analyses performed on 108 sedimentary sites widespread over different units of the central Apennines. The age of the studied formations ranges from upper Cretaceous to Messinian. The results show that the Central Apennines underwent at least two successive phases of rotations. A first counterclockwise one is well recorded in Eocene-Oligocene sediments over the studied area. The sense and the amount of the younger rotation, clearly recorded in lower and upper Miocene sediments, depend on the structural setting of the studied units. Three areas have been recognized. The westernmost one is the southern Sabina area, an arcuate thrust belt that experienced a clockwise rotation after the lower Miocene. The second one is the Latium-Abruzzi platform, where counterclockewise rotation occurred after the upper Miocene. The third one is the Marsica area, affected by a post-upper Miocene clockwise rotation. As far as this young rotation is concerned, we observe that the angle between the trends of the structures and the magnetic declinations is constant all over the Central Apennines. The same relationship is also observed between the magnetic lineation and the structural trend. These results, integrated in the structural framework, yield us to propose a new model for the Neogene tectonic evolution of the area.

1. Introduction

During the last three decades, geological and geophysical studies have demonstrated that the deformations of the convergent boundaries of the major lithospheric plates are very complex. In particular, paleomagnetic studies have shown that block rotation is one of the major deformative processes within many active continental margins around the world. For example, such block rotations have been documented both in the eastern and western parts of the Mediterranean Alpine chain resulting from the European / African convergence (Kissel and Laj, 1988; Osete *et al.*, 1989).

In central Mediterranean, the Apennines have often been described as a regular thrust belt oriented NW-SE to N-S and verging eastward to north-eastward. It has been formed during upper Miocene-Pliocene time and it was then affected by extensional tectonics creating NW-SE–oriented normal faults. This extensional episode is related to both the opening of the Tyrrhenian Sea and the alkali-potassic volcanic activity. In this context, the existence of E-W thrusts and of N-S right-lateral strike-slip faults is difficult to understand and the origin of these features in the tectonic evolution of the Apennines is still a matter of discussion (Castellarin *et al.*, 1978; Parotto, 1980; Salvini and Vittori, 1982).

The purpose of this paper is to present a new combined structural and paleomagnetic study of different major structural units of the Central Apennines. We will see how the new data contribute to a better understanding of the deformational evolution of this area.

2. Geological setting

The investigated area of the Central Apennines is schematically shown in fig. 1. The main

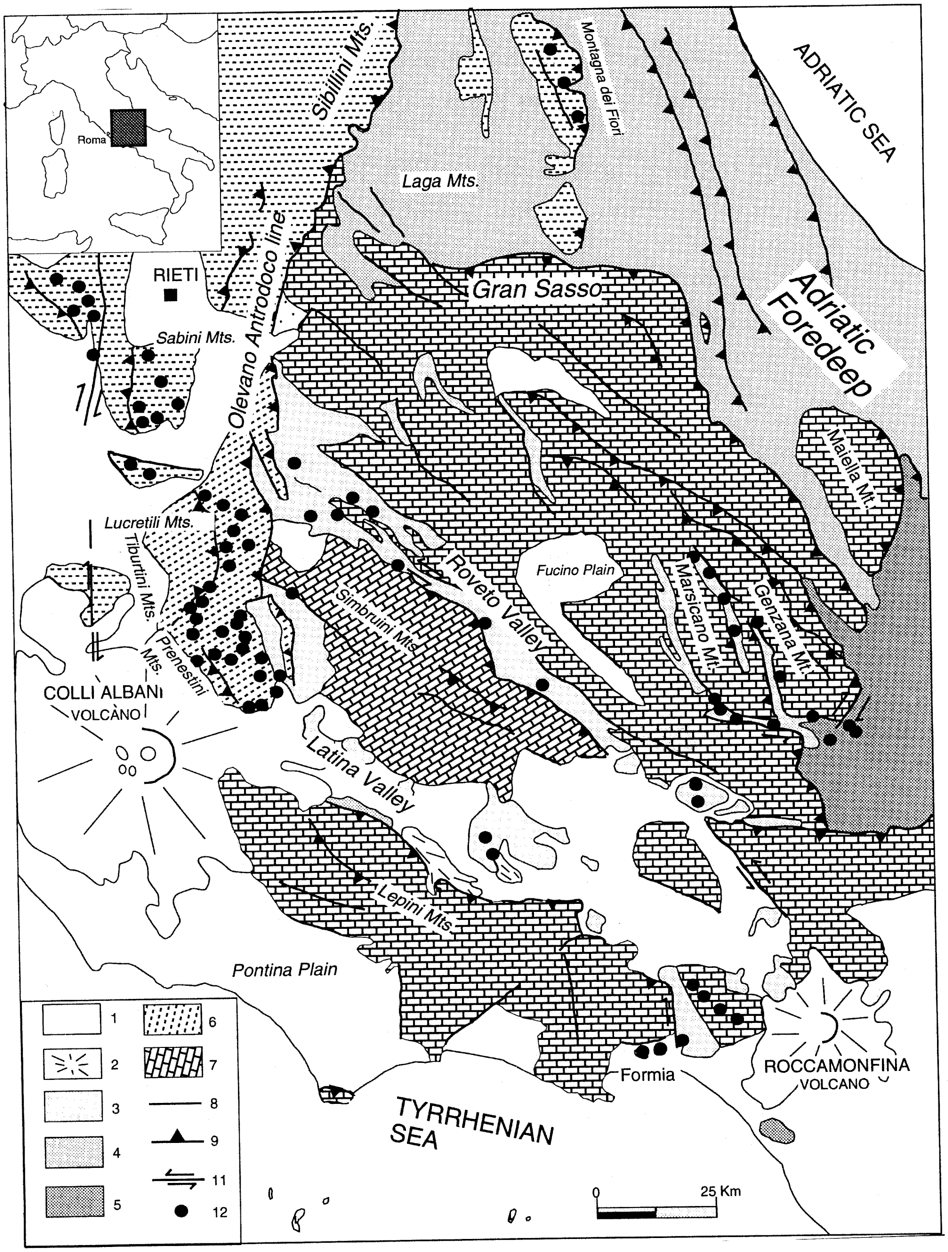

Fig. 1. Sampling map of paleomagnetic and AMS sites. 1) Plio-Pleistocene post-orogenic sequences of the Tyrrhenian margin and intra-Apenninic basins. 2) Quaternary volcanic sequences. 3) Tortonian-Messinian terrigenous sequences in the Latium-Abruzzi platform. 4) Laga flysch (Messinian) and Plio-Pleistocene foredeep sequences. 5) Molisan basin units (Oligocene-Messinian). 6) Umbro-Sabina transitional to basinal units (upper Triassic-upper Miocene). 7) Carbonatic units of the Latium-Abruzzi and Maiella-Morrone platforms, and transitional to basinal sequences of Gran Sasso and Marsica units (upper Triassic-upper Miocene). 8) Normal faults. 9) Thrusts. 10) Strike-slip faults. 11) Sampling sites.

tectonic feature in this zone, called the Olevano-Antrodoco line, separates the Latium-Abruzzi carbonatic shelf from the Sabina basin (Parotto and Praturlon, 1975). The latter is also cut in its western part by a regional right-lateral strike-slip fault (Sabina fault), oriented N010 and outcropping over 30 km. This fault cuts all the other structural elements of the region and thus illustrates the Plio-Pleistocene tectonic activity of the area (Alfonsi *et al.*, 1991). The kinematic and the geometry of these structural features are still a matter of discussion. However, most of the authors now agree on the existence of polyphased tectonic activity which starts during the upper Tortonian, and which is well documented by mesostructural and sedimentological analyses (Castellarin *et al.*, 1978; Cosentino and Parotto, 1986; Mattei *et al.*, 1986).

The Latium-Abruzzi platform constitutes the major structural and paleogeographic unit of the Central Apennines. It is characterizd by NW-SE–trending thrust sheets, verging north-eastward, and emplaced during the late Messinian-early Pliocene period. These thrusts are dissected in the south-western part of the platform by very steep faults that show clear evidences for both normal and left-lateral movements (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 basin to transitional type. From a structural point of view, this basin is controlled by N-S strike-slip faults, back thrusts and minor strike-slip fault systems (Corrado *et al.*, 1990; Mattei and Miccadei, 1991). The paleomagnetic sampling has been conducted in these different areas characterized by various tectonic styles. We sampled the upper Cretaceous to Eocene limestones and marly-cherty limestones of the «Scaglia Rossa Formation», the Oligocene marls and marly limestones of the Scaglia Cinerea formation, the early Miocene Bisciaro formation (marls and cherty limestones), the early-middle Miocene Guadagnolo formation (marls interbedded with detritic limestones) and finally the Messinian turbiditic sequences. A total of 108 sites were distributed all over the area (fig. 1). At each site, a minimun of 10 cores, well distributed over the outcrop, were drilled using standard paleomagnetic techniques.

3. Laboratory analyses and significance tests

Analyses of the Anisotropy of the low-field Magnetic Susceptibility (AMS) show that the majority of the sites which have positive susceptibility values are characterized by a magnetic fabric of sedimentary origin indicating that the deposition occurred in a calm environment. Moreover, in most cases, an intersection magnetic lineation of tectonic origin is present. The significance and the interpretation of this lineation will be presented later.

The magnetic mineralogy analyses such as the Isothermal Remanent Magnetization acquisition curve (IRM), the alternative field demagnetization of the Saturated IRM (SIRM) have been conducted on one typical sample per site.

They show 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 as hematite. The Guadagnolo formation, the Messinian clays and the white samples of the Scaglia formation are only characterized by low-coercivity minerals such as magnetite or sulphides. This magnetic mineralogy determination is confirmed or precised by the demagnetization process.

In 54 sites out of 108, the NRM values were too low to be accurately studied even using the cryogenic magnetometer (lower than 3×10^{-5} A/m). All the other samples were thermally demagnetized with ten to fifteen steps from room temperature up to the limit of reproducible results (320 to 540 °C). At each demagnetization step the bulk susceptibility has been measured in order to monitor possible changes in the magnetic mineralogy. The Messinian clays are characterized by a rapid decrease of the NRM between 20 and 320 °C, accompanied by a sharp increase of the low-field susceptibility values at $(320 \div 340)$ °C. This indicates that the low-coercivity minerals carrying the remanent magnetization are sulphides and that they transform into magnetite during thermal demagnetization. Tric *et al.* (1991) have argumented that the formation of the sulphides that can be found in this kind of marls occurs during or just after the deposition of the sediment. This almost primary origin of the magnetization will be confirmed below by the field tests that have been applied to the results. For all the other samples, even the red ones, the complete removal of the NRM was obtained between 400 and 540 °C without any significant change of the susceptibility values indicating that magnetite is the main magnetic carrier.

For some samples, orthogonal demagnetization diagrams isolate a single stable component of magnetization. Other samples are characterized by two components with overlapping temperature spectra. The demagnetization behaviour of these samples perfectly fits on great circles. Finally, in other sites, the samples are characterized by one or the other of the two behaviours. The mean directions of the Characteristic Remanent Magnetization (ChRM) were thus calculated for each site using either Fisher's statistic (1953) or the method given by McFadden and McElhinny (1988). They are accurately defined in the great majority of the sites (Alfa-95 < 15).

For all the studied formations we could perform statistical significance tests in order to establish the precocity and the stability of the magnetization. Both within various sites and at the regional scale the Scaglia formation and the Messinian turbidites within the Roveto valley cleary show significantly positive reversal tests. Moreover, at the regional scale, the scatter of the data is significantly smaller after tectonic correction than before. This tilt test is positive at 99% for the Cretaceous-Eocene-Oligocene Scaglia formation and at 95% for the Guadagnolo formation and for the Messinian deposits of the Roveto valley. We can thus conclude that the age of the magnetization predates the folding of the structures, which took place in this region during the upper Miocene-early Pliocene period.

The laboratory analyses and the different positive tests thus establish that the observed ChRM is of primary origin and that mean direction obtained from each site can be used to define the tectonic evolution of the Central Apennines.

4. Paleomagnetic results and discussion

These new paleomagnetic data show a complex pattern of the block rotations depending both on the age and on the tectonic setting of the sites. While the Cretaceous to Oligocene sites show rather coherent results all over the area, the Neogene ones vary between three different tectonic regions that are from west to east the Sabina area, the Lazium-Abruzzi platform and the Marsica area.

In the Sabina area, the results obtained from the Cretaceous to Oligocene formations show declinations that are very consistently deviated toward the west by about 31°. In the same area, the middle Miocene sites are characterized by easterly deviated declinations (about 16°). This young clockwise rotation has been superimposed to the older one. This indicates that the area has undergone a post-Oligocene–pre-middle Miocene counterclockwise rotation of about 47°. This rotation is very coherent all over the area except in the Tiburtini Mts located in the southeastern portion of the Sabina region that have undergone a clockwise rotation of about 25° during the same period. This difference in the angle of rotation may be related to the local deflection of the trend of the structures in this area. A counterclockwise rotation is also observed in the other Cretaceous to Oligocene sites located both in the Marsica basin and in the Montagna dei Fiori. This counterclockwise rotation observed in the Cretaceous to Oligocene rocks is thus rather coherent over the area and can be related to the similar one observed in other regions in the Apennines (see references in Lowrie, 1986).

As far as the Miocene period is concerned, the pattern of rotations in the central Apennines is much more complex and seems to be fully related to the more recent tectonic evolution of the area. We have already mentioned that the Sabina area has undergone a clockwise rotation of about 16° since middle Miocene. The data obtained in the Roveto valley within the Latium-Abruzzi platform show that this area has been affected by a post-Messinian counterclockwise rotation of about 28°. Finally, the Marsica and Formia areas were also affected by a post-Messinian clockwise rotation. In order to check the consistency of the data in the studied area, we have applied the *t*-tests proposed by Lowrie and Hirt (1986). These tests are positive in the Central Apennines when we consider both declinations *versus* magnetic lineations (t value = 5.96, N = 15) and declinations *versus* fold axes orientations (t value = 7.43, N = 22). This indicates that a constant

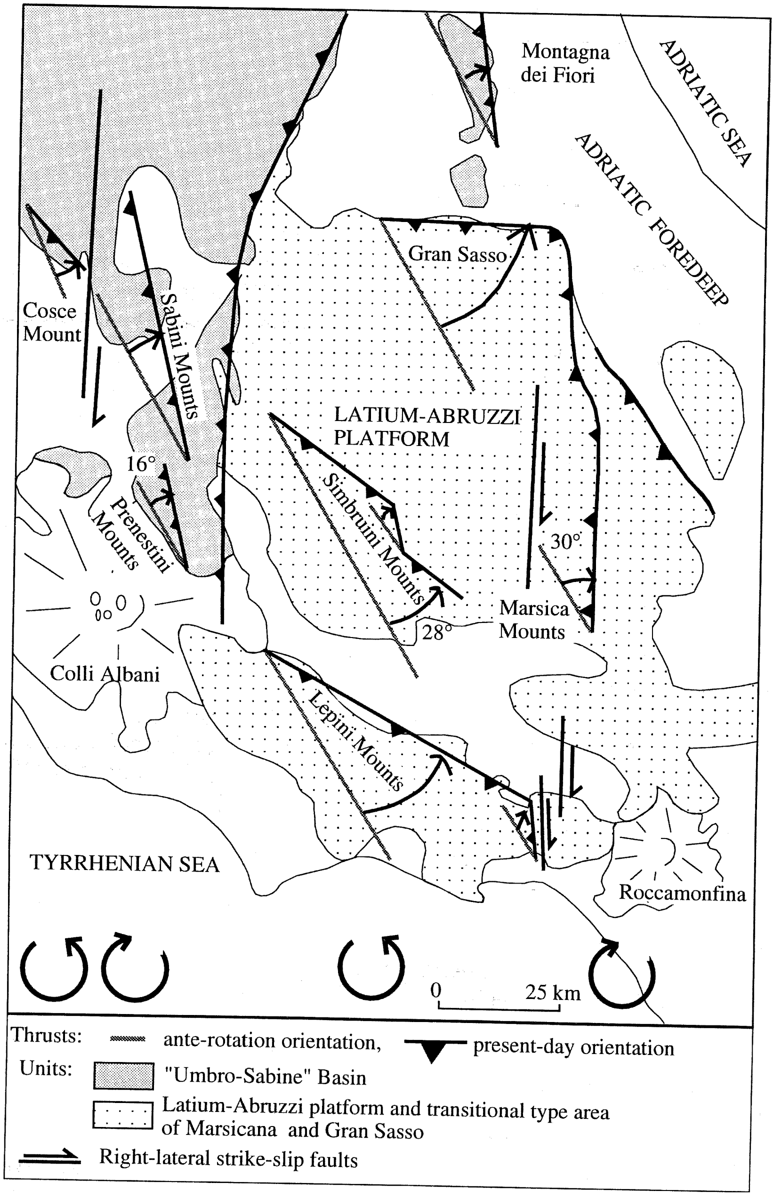

Fig. 2. Simplified structural scheme of the Central Apennines after the post-Miocene rotations. The dashed lines represent the strike of the main units before rotations occurred. The rotations indicated with numeric values are detected by paleomagnetic analyses, while the others derive from the magnetic lineations strike (the thick double arrows represent the actual position of the AMS lineations, while the thin double arrows represent the hypothized orientations before rotations occurred). The rotations of the Gran Sasso chain are by Ghisetti *et al.* The right-lateral strike-slip faults delimit the clockwise and the counterclockwise domains. They also correspond with the eastern the western boundary of the Latium-Abruzzi platform. The poles of rotation are defined on the base of the chain vergence.

angular relationship exists between these three parameters and particularly that compressive structures and magnetic lineations are almost parallel.

The observed magnetic fabrics are characterized in a great majority of the sites by a magnetic lineation parallel to the axes of the folded structures, the minimun axis of the ellipsoid remaining perpendicular to the bedding. These magnetic fabrics, the sedimentary origin of which is still preserved, are interpreted as clearly related to the early stages of deformations in agreement with other reported results (Kissel *et al.*, 1986; Lowrie and Hirt, 1987; Lee *et al.*, 1990). This tectonic origin is confirmed by the observation in a few sites of prolate ellipsoids, the axes of which are parallel to the local fold axes. In only three sites, the magnetic fabric is characterized by a transport lineation (almost perpendicular to the fold axes) that has been clearly evidenced in the Marsica basin and in the Roveto valley near regional thrusts.

We can use this new dataset to reconstruct the tectonic evolution of the Central Apennines. First, the rotation back of the different units allows us to describe the middle Miocene orogenic system. We thus obtain linear and parallel folds trending about N330 all over central Apennines (fig. 2). We have mentioned that the magnetic lineation was certainly created by an earlier stage of deformation. It thus corresponds to a shortening oriented about N060, perpendicular to the Miocene orientation of the structures. This orientation is also perpendicular to the present-day orientation of the Plio-Pleistocene foredeep basins in the external Central Apennines (Patacca and Scandone, 1987). This suggests that the principal direction of shortening remained constant from the late Miocene to present day.

The later evolution of the structural domains has been controlled by the paleogeographic discontinuities bounding the Latium-Abruzzi platform. These boundaries have been reactivated as right-lateral strike-slip faults during upper Miocene to Pleistocene time, dissecting the thrust sheet structures and giving rise to the large clockwise rotations measured in the Sabina and Marsica areas. At the same time the presence of the left-lateral strike-slip faults trending NE-SW only in areas where post-upper Miocene counterclockwise rotations occurred implies that strong correlations exist between this activity and the sense of rotation. We suggest that, within specific fault-bounded units, the rotations were accommodated by large preexisting normal and thrust faults reactivating in strike-slip faults or again thrusts, depending on their new orientation (rotated one) with respect to the direction of maximum compression. It is also clear that the tectonic mechanisms responsible for local clockwise rotation of the Simbruini thrust sheet and of the Tiburtini Mts. are related to lateral ramps emplacements giving rise to the torsion of the thrust sheets from NE-SW to N-S and NE-SW orientations (fig. 2). These second-order rotations are distributed in narrow areas and are superimposed to the regional rotation of the Latium-Abruzzi and Sabina area. Finally, paleomagnetic and geological evidences of activity of right-lateral strike-slip faults at the boundaries of the Latium-Abruzzi platform suggest that these discontinuities may control the location and the evolution of Quaternary volcanic complexes settled on the southern margin of the Latium-Abruzzi platform.

The recognized pattern of rotations thus implies a new interpretation of the complex present-day geometry of the Central Apennines. This new data show that it results from rotations and reactivations of preexisting tectonic structures in a constantly oriented stress field during late Miocene Pliocene times.

REFERENCES

ALFONSI, L., R. FUNICIELLO, M. MATTEI, O. GIROTTI, A. MAIORANI, M. PREITE MARTINEZ, C. TRUDU and B. TURI (1991): Structural and geochemical features of the Sabina strike-slip fault (Central Apennines), *Boll. Soc. Geol. Ital.*, **110**, 217-230.

CASTELLARIN, A., R. COLACICCHI and A. PRATURLON (1978): Fasi distensive trascorrenze e sovrascorrimenti lungo la «linea Ancona-Anzio» dal Lias medio al Pliocene, *Geol. Rom.*, **17**, 161-189.

COSENTINO, D. and M. PAROTTO (1986): Assetto strutturale dei Monte Lucretili settentrionali (Sabina): nuovi dati e schema tettonico preliminare, *Geol. Rom.*, **25**, 73-90.

CORRADO, S., D. COSENTINO and C. GIOIA (1990): Sistema di retroscorrimenti nella Marsica orientale (Abruzzo, Appennino centrale), *Mem. Soc. Geol. Ital.*, **45**, 591-603.

FISHER, R. A. (1953): Dispersion on a sphere, *Proc. R. Soc.*, **217**, 195-305.

KISSEL, C., E. BARRIER and C. LAJ (1986): Magnetic fabric in «underformed» marine clays from compressional zones, *Tectonics*, **5**, 769-781.

KISSEL, C. and C. LAJ (1988): The Tertiary geodynamical evolution of the Aegean arc: a paleomagnetic reconstruction, *Tectonophysics*, **144**, 183-201.

LEE, T., C. KISSEL, E. BARRIER, C. LAJ and R. CHI (1990): Paleomagnetic evidence of a diachronic clockwise rotation of the Coastal Range, eastern Taiwan, *Earth Planet. Sci. Lett.*, **104**, 245-257.

LOWRIE, W. (1986): Paleomagnetism and the Adriatic promontory: a reappraisal, *Tectonics*, **5**, 797-807.

LOWRIE, W. and A. HIRT (1986): Paleomagnetism in the arcuate mountain belts, in «The Origin of Arcs», edited by F.C. WEZEL (Elsevier, Amsterdam), pp. 141-158.

LOWRIE W. and A. HIRT (1987): Anisotropy of magnetic susceptibility in the Scaglia Rossa pelagic limestones, *Earth Planet., Sci. Lett.*, **82**, 349-356.

MATTEI, M., P. MONTONE and F. SALVINI (1986): Analisi strutturale dei rilievi del margine appenninico a Tivoli (Roma), *Mem. Soc. Geol. Ital.*, **35**, 579-589.

MATTEI, M. and E. MICCADEI (1991): Strike-slip tectonics between the Marsica Range and the Molisan Basin in the Sangro Valley (Abruzzo, Central Italy), *Boll. Soc. Geol. Ital.*, **110**, 737-745.

MCFADDEN, P. and MCELHINNY (1988): The combined analysis of remagnetization circles and direct observations in paleomagnetism, *Earth Planet. Sci. Lett.*, **87**, 161-172.

MONTONE, P. and F. SALVINI (1991): Evidences of NW-SE Late Miocene strike-slip tectonics in Central Apennines near Tagliacozzo, Abruzzi, *Boll. Soc. Geol. Ital.*, **110**, 617-619.

OSETE, M., R. FREEMAN and R. VEGAS (1989): Paleomagnetic evidence for block rotations and distributed deformation of the Iberian-African plate boundary, in «Paleomagnetic Rotations and Continental Deformation», edited by C. KISSEL and C. LAJ, *NATO ASI Series*, **254**, 381-392.

PAROTTO, M. and A. PRATURLON (1975): Geological summary of Central Apennines, in «Structural Model of Italy», edited by L. OGNIBEN, M. PAROTTO and A. PRATURLON, *Quad. Ric. Sci. C.N.R.*, **90**, 257-306.

PAROTTO, M. (1980): Apenin Central, in Introduction à la géologie générale d'Italie, 26 Congr. Inter., Paris, pp. 33- 37.

PATACCA, E. and P. SCANDONE (1987): Structural evolution of the outer margin of the Apennines and related foredeep system, in *The Lithosphere in Italy, Advances in Earth Science Research*, edited by A. BORIANI, M. BONAFEDE, G.B. PICCARDO and G.B. VAI (Accademia Nazionale dei Lincei, Roma), pp. 139-142.

SALVINI, F. and E. VITTORI (1982): Analisi strutturale della linea Olevano-Antrodoco-Posta (Avona-Lanzio Auct.): metodologia di studio delle deformazioni fragili a presentazione del tratto merodionale, *Mem. Soc. Geol. Ital.*, **21**, 337-355.

TRIC, E., C. LAJ, C. JEHANNO, J. P. VALET, C. KISSEL, A. MAZAUD and S. IACCARINO (1991): High resolution record of the Upper Olduvai transition from Po valley (Italy) sediments: support for dipolar transition geometry?, *Phys. Earth Planet. Int.*, **104**, 245-257.