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QUATERNARY GEODYNAMICS OF THE APENNINE BELT

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ABSTRACT: E. Mantovani *et al*., *Quaternary geodynamics of the Apennine belt.* (ISSN IT 0394-3356, 2009).
The drastic tectonic reorganization that the Apennine belt has undergone around the middle Pleistocene is interpreted as a consequence of the fact that since that time the Adriatic plate has accelerated carrying the outer sectors of the Apennines, formed by the Molise-Sannio units, the eastern part of the Latium-Abruzzi platform and the Romagna-Marche-Umbria and Ligurian units. The consequent oblique separation between such mobile units and the western almost fixed part of the belt has been accommodated by sinistral transtensional deformation in the axial part of the chain. During this process the belt-parallel push of the Adriatic has caused rapid uplift, bowing and outward extrusion of the outer mobile units. It is argued that this geodynamic interpretation provides a plausible and coherent explanation for the observed deformation pattern in the Apennines and that, on the other hand, such a result can hardly be achieved by the alternative geodynamic models so far proposed.

RIASSUNTO: E. Mantovani et al.*,* Geodinamica quaternaria della catena appenninica*. (ISSN IT 0394-3356, 2009).*
Il notevole cambiamento di stile tettonico che si è verificato nella catena appenninica attorno al Pleistocene medio è interpretato come conseguenza dell'accelerazione della placca adriatica, che ha coinvolto nel suo movimento la parte esterna della catena (Unità Molise-Sannio, parte orientale della piattaforma Laziale-Abruzzese, Unità Romagna-Marche-Umbria e Unità Liguridi). La conseguente separazione obliqua tra la parte esterna mobile della catena e quella interna, pressoché immobile, ha generato le deformazioni transtensive sinistre riconosciute nella parte assiale della catena. La spinta dell'Adriatico, circa parallela all'asse principale dell'Appennino, ha inoltre determinato il forte sollevamento della parte esterna mobile della catena. La compatibilità del complesso quadro deformativo pleistocenico con le implicazioni del modello geodinamico qui proposto e le notevoli difficoltà che le interpretazioni alternative devono affrontare per spiegare tali evidenze sono infine discusse.

Keywords: Quaternary; Apennines; Geodynamics

Parole chiave: Quaternario; Appennini; Geodinamica

1. INTRODUCTION

It is widely recognized that the deformation style in the Apennine belt (Fig.1) has considerably changed around the middle Pleistocene (e.g. Hyppolite *et al*., 1994; Galadini, 1999; Bartolini, 1999; 2003; Piccardi *et al*., 2006 and references therein). The Southern Apennines passed from a dominant compressional to an extensional/transtensional sinistral regime and underwent a marked acceleration of uplift. In the Central and Northern Apennines extensional deformation and uplift has accelerated. Moreover, intense volcanic activity built up the Roman and Campanian magmatic provinces. As most of the tectonic processes which started at that time are still active and control seismic activity, understanding their driving mechanism may be particularly useful. Considering the huge amount of information presently available on the Quaternary evolution of the Apennines, one would expect that the search of the driving mechanism which best accounts for the post-middle Pleistocene deformation pattern had led identifying a unique well defined model. Instead, in the relevant literature many different and even opposite geodynamic interpretations have been proposed, all claiming to be compatible with the observed features. Most often, crustal deformation is explained as an effect of subduction-related driving forces. In particular, several authors suggest that the formation of the Tyrrhenian-Apennines system has been driven by roll back of the underlying slab (e.g., Malinverno & Ryan, 1986; Royden, 1993). However, this interpretation can hardly account for the most recent evolution of the Apennines belt, with particular reference to the marked acceleration of uplift (Viti *et al*., 2006; Mantovani *et al*., 2007a, 2008a). To overcome this problem, various hypotheses have been advanced. One suggests that crustal uplift has occurred in response to the break of the underlying slab (e.g., Cinque *et al*., 1993; Westaway, 1993). Other hypotheses invoke mantle upwelling to explain the coeval occurrence of uplift and extension in the Apennine belt (D'Agostino *et al*., 2001) or the contemporaneous action of the above mechanisms and other driving forces (e.g., Meletti *et al*., 2000). A completely different interpretation, not involving subduction related forces, has been proposed by other authors (e.g., Viti *et al*., 2006; Mantovani *et al*., 2007a, 2008a), who suggest that the post-middle Pleistocene evolution of the Apennine belt has been considerably influenced by the acceleration of the Adriatic plate, in the framework of a tectonic context dominated by the convergence of the surrounding plates.

In this work, we argue that the present ambiguity on the geodynamic setting can be considerably mitigated if the major constraints imposed on the model by the available evidence are taken into due account. To this purpose, we discuss the compatibility of the various geodynamic models so far proposed with a large amount of observed tectonic features in the Apennines belt and surrounding regions. Particular attention is devoted to discussing the mechanism responsible for the recent evolution of the Northern Apennines. In this regard, we point out the importance of the extensional event that led to the formation of the Lower Arno basin as discriminant evidence among the various interpretations so far proposed. This is due to the fact that such an event has been generated by a strain regime (NW-SE to N-S extension) significantly different from the one that dominated the evolution of the inner part of Northern Apennines (NE-SW extension).

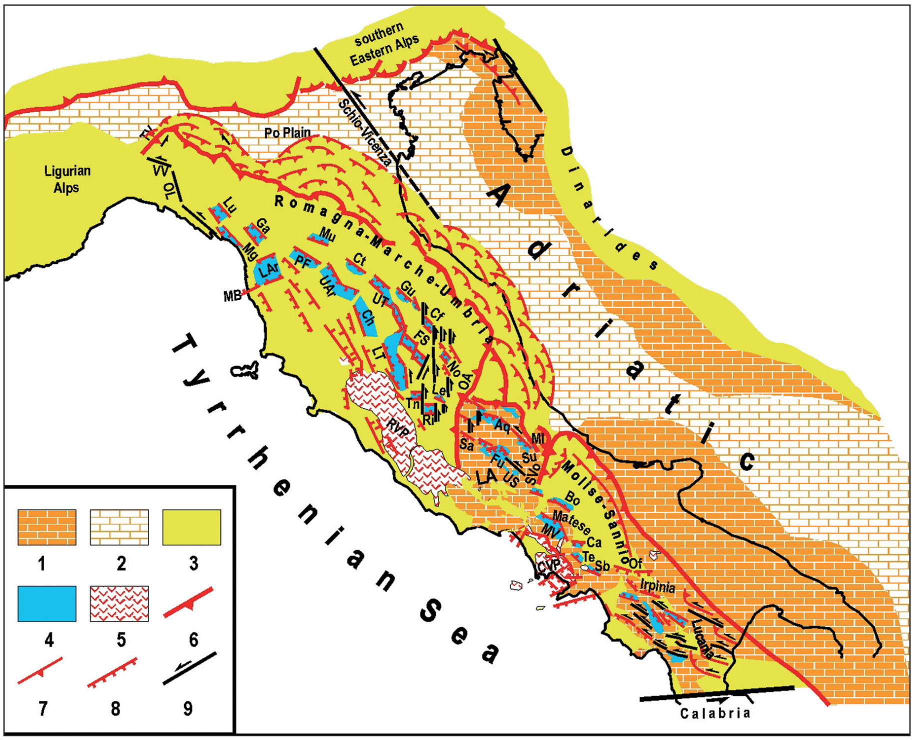

Fig.1. - Tectonic sketch of the Apennine belt. 1) Carbonate platforms 2) Thinned continental Adriatic domain 3) Orogenic units 4) Extensional troughs with Quaternary activity 5) Quaternary volcanic zones 6) Outer thrust fronts 7,8,9) Main compressional, extensional and transcurrent features. LA=Latium-Abruzzi platform; MI=Maiella structural high; CVP=Campanian volcanic province; RVP=Roman volcanic province. Main fault systems: MB=Meloria-Bientina; OA=Olevano-Antrodoco; Of=Ofanto; OL=Ottone-Levanto; SVo=Sangro-Volturno; TV=Tortona-Voghera; VV=Villavernia-Varzi. Main troughs with Quaternary activity: Aq=Aquila; Bo=Boiano; Ca=Calore; Cf=Colfiorito; Ch=Chiana; Ct=Casentino; FS=Foligno-Spoleto; Fu=Fucino; Ga=Garfagnana; Gu=Gubbio; LAr=Lower Arno; Le=Leonessa; LT=Lower Tiber; Lu=Lunigiana; Mg=Magra; Mu=Mugello; MV=Middle Volturno; No=Norcia; PF=Pistoia-Firenze; Ri=Rieti; Sa=Salto; Sb=Sabato; Su=Sulmona; Te=Tesa; Tn=Terni; UAr=Upper Arno; US=Upper Sangro; UT=Upper Tiber.

Schema tettonico della catena appenninica. 1) Piattaforme carbonatiche 2) Dominio adriatico continentale assottigliato 3) Unità orogeniche 4) Fosse estensionali attive nel Quaternario 5) Zone vulcaniche quaternarie 6) Fronti esterni di sovrascorrimento 7,8,9) Principali strutture compressive, distensive e trascorrenti. CVP=Provincia vulcanica campana; LA=Piattaforma laziale-abruzzese; MI= Alto strutturale della Maiella; RVP=Provincia vulcanica romana. Principali sistemi di faglie: MB=Meloria-Bientina; OA=Olevano-Antrodoco; Of=Ofanto; OL=Ottone-Levanto; SVo=Sangro-Volturno; TV=Tortona-Voghera; VV=Villavernia-Varzi. Fosse ancora attive: Aq=Aquila; Bo=Boiano; Ca=Calore; Cf=Colfiorito; Ch=Chiana; Ct=Casentino; FS=Foligno-Spoleto; Fu=Fucino; Ga=Garfagnana; Gu=Gubbio; LAr=Basso Arno; Le=Leonessa; LT=Basso Tevere; Lu=Lunigiana; Mg=Magra; Mu=Mugello; MV=Medio Volturno; No=Norcia; PF=Pistoia-Firenze; Ri=Rieti; Sa=Salto; Sb=Sabato; Su=Sulmona; Te=Tesa; Tn=Terni; UAr=Alto Arno; US=Alto Sangro; UT=Alto Tevere.

2. MIDDLE PLEISTOCENE TECTONIC REORGANIZATION OF THE APENNINE BELT: MAJOR EVIDENCE

Southern Apennines

Since the middle Pleistocene, the deformation pattern of this belt sector has undergone a considerable change. The Lucanian Apennines (Fig.1) have been dissected by a system of NW-SE sinistral strike-slip faults, associated with compressional and extensional features at restraining and releasing stepovers respectively, and have undergone considerable uplift (e.g., SCHIATTARELLA *et al*., 2003; CATALANO *et al*., 2004). In the northern sector of the Southern Apennines, from the Matese to Irpinia zones (Fig.1), normal faults trending from NW-SE to E-W, have developed along the inner side of the Molise-Sannio wedge (e.g., ORTOLANI & TORRE, 1981; CINQUE *et al*., 2000; BROZZETTI & SALVATORE, 2005; ASCIONE *et al*., 2007), forming several troughs, such as the Middle Volturno, Calore and Boiano. The above extensional border prosecutes toward south with the NW-SE Tesa and Sabato troughs, up to reaching a complex of E-W trending normal faults in the Ofanto zone. In the Irpinia sector of such border, both E-W and NW-SE active normal faults are recognized.

Since the middle Pleistocene, a large amount of volcanic products has erupted along the inner extensional border of the Molise-Sannio wedge (e.g., PECCERILLO, 2003 and references therein), generating the Campanian volcanism (Fig.1).

Central Apennines

This zone, confined to South and North by the Sangro-Volturno and the Olevano-Antrodoco thrust fronts respectively (Fig.1), has been affected by sinistral transtensional tectonics since the middle Pleistocene. This deformation is suggested by several observed features, such as NW-SE sinistral and conjugate dextral normal-oblique faults, en-echelon fracture arrays, block rotations about vertical axes (e.g., GALADINI, 1999; PICCARDI *et al*., 1999, 2006) and the focal mechanism of the large Avezzano earthquake (1915, M=6.9), which occurred in the Fucino trough (e.g., AMORUSO *et al*., 1998). Two main NW-SE transtensional fault systems can be recognized. The southwestern system encompasses the Upper Sangro, Fucino and Salto basins, while the northeastern system crosses the Sulmona and Aquila troughs (e.g., GALADINI & GALLI, 2000; PACE *et al*., 2002). For simplicity, hereafter these two major seismotectonic belts will be recalled as Fucino and Aquila fault systems.

Late Quaternary transpressional deformation and uplift are recognized in the Sangro-Volturno and Maiella structures, located at the boundary with the Southern Apennines (e.g., PIZZI, 2003; ESESTIME *et al*., 2006; ASCIONE *et al*., 2008). In the axial sector of the Central Apennines, the rapid uplift of the belt has determined the depletion of lakes in most intermontane basins, such as Fucino and Aquila (Fig.1), followed by erosion of fluvio-lacustrine sediments and deposition of alluvial fans (e.g., D'AGOSTINO *et al*., 2001).

Northern-Apennines

In the Umbria-Marche Apennines (Fig.1), old Miocene-Pliocene structures, as the Olevano-Antrodoco thrust front, have been dissected by a system of sinistral transtensional faults since the middle Pleistocene (e.g., CELLO *et al*., 1997, 1998; PICCARDI *et al*., 2006). This fault system, associated with significant seismic activity (e.g., CALAMITA *et al*., 1994, BONCIO & LAVECCHIA, 2000), is formed by NW-SE normal and oblique faults bounding fluvial-lacustrine basins, such as the Leonessa, Rieti, Terni, Norcia, Colfiorito, Gubbio, Upper and Lower Tiber and Foligno-Spoleto, connected by N-S sinistral strike-slip faults (e.g., TONDI & CELLO, 2003). Such fault system has been interpreted by CELLO *et al*. (1997) as a negative flower structure, representing the shallow expression of a N-S trending deep sinistral shear zone, located below the brittle-ductile transition zone. North of the Umbria-Marche sector (Fig.1), roughly NE-SW extension has accelerated since the middle Pleistocene in the intermontane troughs, such the Chiana, Casentino, Upper Arno, Pistoia-Firenze, Mugello, Garfagnana, Lunigiana and Magra, most of them seismically active (e.g. BONCIO & LAVECCHIA, 2000; MARTINI *et al*., 2001; BERNINI & PAPANI, 2002; BRIGANTI *et al*., 2003; MANTOVANI *et al*., 2008b).

During the Quaternary, N-S to NW-SE extension has also occurred in the Lower Arno basin (e.g., BOSI, 2004), as suggested by the formation of E-W normal faults, such as the Meloria-Bientina (CANTINI *et al*., 2001). It is worth noting that the roughly N-S extensional axis in that relatively large basin is significantly different from the NE-SW axis that characterized extension throughout the inner part of the Northern Apennines.

Seismicity distribution and geomorphologic indicators (e.g., TOMASELLI *et al*., 1992; BENEDETTI *et al*., 2003; MEISINA & PICCIO, 2003) suggest that seismotectonic activity occurs in the relatively narrow zone running from the Lunigiana basin to the Tortona-Voghera thrust front (Fig.1). Such activity could be due to the reactivation of old transpressive faults, such as the Villalvernia-Varzi and Ottone-Levanto (e.g., CERRINA FERONI *et al*., 2004), which would now act as NW-SE sinistral decoupling zones between the mobile part of the Ligurian units and the more inner fixed belt. This hypothesis is consistent with the fact that NW-SE sinistral strike-slip faulting, presumably active since the Quaternary, has been recognized west of the Magra basin (e.g., STORTI, 1995).

Acceleration of uplift in the axial sector of the Northern Apennines since the middle Pleistocene is documented by various geomorphological indicators, such as displacement of fluvial terraces and landsurfaces, modification of fluvial drainage and changes in sedimentation rate within intermontane troughs, and by the fact that the Ligurian units (which lay at the top of the Apenninic thrust sheets) have been completely eroded in a large zone lying between the Umbria-Marche Apennines and the Latium-Abruzzi platform (e.g., BARTOLINI, 1999, 2003; ARGNANI *et al*., 2003; BOSI, 2004; BOCCALETTI & MARTELLI, 2004).

Since the middle Pleistocene, a large amount of volcanic products erupted along the inner side of the Romagna-Marche-Umbria units (e.g., PECCERILLO, 2003), building up the Roman volcanic province (Fig.1). The generation of such volcanism has been interpreted as an effect of transtensional tectonics (e.g., MARRA, 2001; ACOCELLA & FUNICIELLO, 2002).

Some authors (e.g., DI BUCCI & MAZZOLI, 2002) suggest that the deformation of the Northern Apennines arc has slowed down up to ceasing around the upper Pliocene-lower Pleistocene, when the most external thrust front reached its current position. However, as extensively discussed by VITI *et al*. (2006), this hypothesis is not easily reconcilable with seismotectonic evidence, which rather suggests that tectonic activity is still going on in those zones (e.g., BOCCALETTI & MARTELLI, 2004 and references therein).

3. PROPOSED DRIVING MECHANISM

Middle Pleistocene acceleration of the Adriatic plate

Several features of the Quaternary deformation pattern in the Central Mediterranean region suggest that since the middle Pleistocene the Adriatic plate has accelerated, after a period of minor mobility in the early Pleistocene (VITI *et al*., 2006; MANTOVANI *et al*, 2007a, 2008a). The time of that acceleration, driven by the convergence of the confining plates (Africa, Eurasia and the Anatolian-Aegean system), has been determined by the reactivation of underthrusting of the southeastern Adriatic margin beneath the adjacent orogenic belts (MERCIER *et al*., 1987; SOREL *et al*., 1992; ALIAJ, 2006). The supposed Adriatic acceleration is consistent with the fact that since the middle Pleistocene deformation and uplift at the northern front of that plate, the southern Eastern Alps and northernmost Dinarides, has significantly strengthened. Roughly NNW-SSE shortening, associated with historical large earthquakes, is recognized at the Aviano compressional front shown in figure 2 (e.g., BENEDETTI *et al*., 2000; GALADINI *et al*., 2005). Acceleration of uplift is suggested by the changes in sedimentation rate recognized in the Venetian plain (e.g., STEFANI, 2002).

Neotectonic deformation and seismic activity is also recognized in other peri-Adriatic decoupling shear zones: in the northernmost Dinarides, at the system of dextral NW-SE strike-slip faults, such as the Rijeka and Idrija, in the Central Alps, at the Schio-Vicenza fault system, and in the central Dinarides (e.g., Markusic & Herak, 1999; Poljak *et al*., 2000; Sauro & Zampieri, 2001).

Compressional and transpressional seismotectonic activity is recognized at the southeastern border of the Adriatic plate (e.g., Louvari *et al*., 2001). In the Northern Hellenides thrusting accommodates the convergence between the Aegean wedge and the southern part of the Adriatic plate (e.g., Mantovani *et al*., 2006, 2007a, 2008a). Transpressional deformation at the Cephalonia fault system (e.g., Louvari *et al*., 1999) accommodates the dextral relative motion between the northern Hellenic Arc and the southernmost Adriatic continental domain.

The evidence and arguments that support the motion of the African and Adriatic domains shown in figure 2 are described by Mantovani *et al*. (2007b).

Short-term (geodetic) and long-term (geological) kinematics

It is well known (e.g., Pollitz, 2003) that the short-term kinematics in tectonic zones, such as the Mediterranean region, is controlled by the effects of post-seismic relaxation induced by strong earthquakes wich recently occurred (from years to tens of years, depending on the magnitude and nature of seismic sources) in the surrounding zones. Thus, one must be aware that such kinematics, estimated by geodetic measurements, cannot easily be taken as representative of the long-term geological behaviour of plates and crustal wedges. For instance, considerable discrepancies between the strain field implied by the geodetic data given by Serpelloni *et al*. (2005) for the central Mediterranean region and the strain regimes inferred from neotectonic information have been pointed out by Viti *et al*. (2006). Other macroscopic differences between geodetically determined strain fields and the observed neotectonic deformation have been pointed out for the Atlantic zone by Merkouriev & De Mets (2008).

Anyway, comparing the most recent geodetic velocities (Fig. 3) with the Adria kinematics inferred from

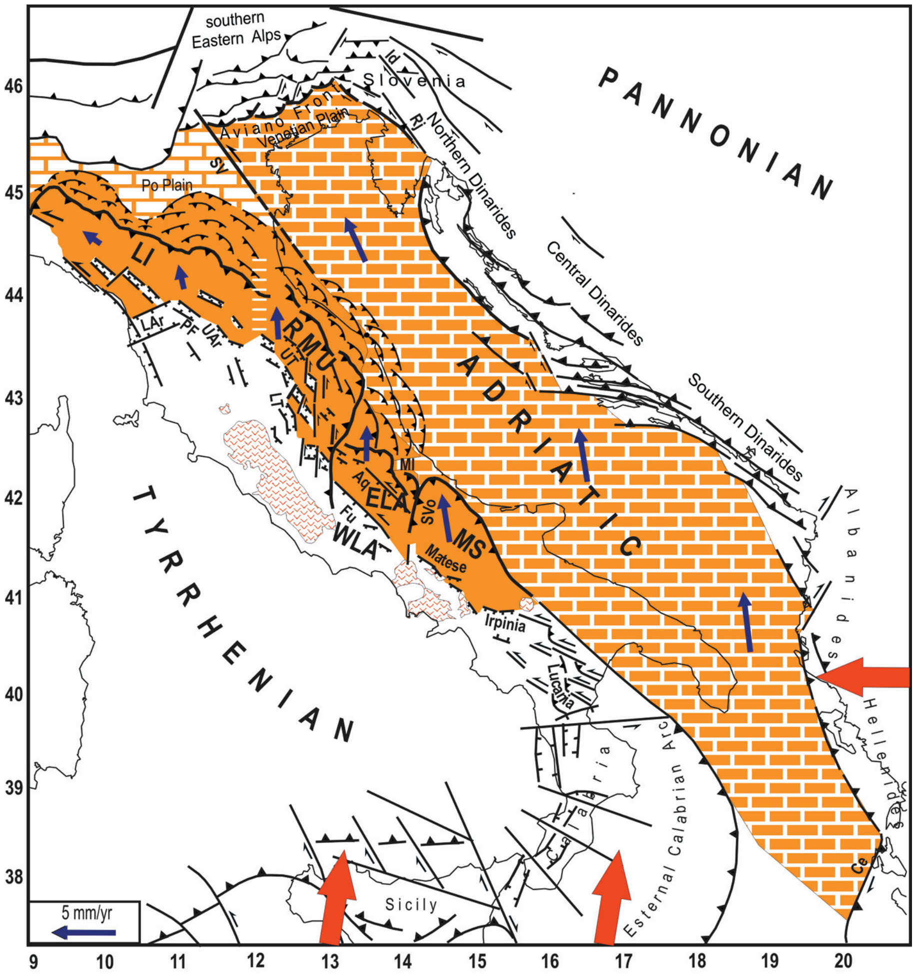

Fig.2 - Kinematic/tectonic sketch of the Adriatic-Apennines system, evidencing the Apennine units (brown) that move in connection with the Adriatic plate, with respect to almost fixed inner belt. Aq=Aquila fault zone; ELA=Eastern (mobile) part of the Latium Abruzzi platform; Fu=Fucino fault zone; Id=Idrija fault; LAr=Lower Arno trough; LI=Ligurian units; LT=Lower Tiber trough; MI=Maiella structural high; MS=Molise-Sannio units; Rj=Rijeka fault; RMU=Romagna-Marche-Umbria units; PF=Pistoia-Firenze trough; SV =Schio-Vicenza fault system; SVo =Sangro-Volturno thrust front; UAr=Upper Arno trough; UT=Upper Tiber trough; WLA=Western (fixed) part of the Latium-Abruzzi platform. The white-banded strip near RMU indicates the Romagna transpressional zone (Costa, 2003), possibly decoupling the RMU from the Ligurian wedges. Blue arrows show the presumed kinematics (scale in the inset) of the Adriatic plate and the mobile Apennine orogenic wedges with respect to Eurasia. Large red arrows indicate the presumed pushes of the confining plates (Africa and Aegean-Anatolian system) on the Central Mediterranean region (e.g., Mantovani *et al*., 2007b, 2008a). Symbols and abbreviations as in figure 1.

Schema cinematico/tettonico del sistema Adriatico-Appennini, con evidenziate le Unità appenniniche (in marrone) che si muovono in connessione con la placca adriatica, rispetto alla catena interna pressoché immobile. Aq= faglia dell'Aquila; ELA= parte orientale (mobile) della Piattaforma laziale-abruzzese; Fu= faglia del Fucino; Id= faglia di Idrija; LAr=Fossa del basso Arno; LI=Unità liguri; LT=Fossa del basso Tevere; MI=Alto strutturale della Maiella; MS=Unità Molise-Sannio; Rj= faglia di Rijeka; RMU=Unità romagnole-marchigiane-umbre; PF=Fossa di Pistoia-Firenze; SV=Sistema di faglie Schio-Vicenza; SVo =Fronte di sovrascorrimento Sangro-Volturno; UAr=Fossa dell'alto Arno; UT=Fossa dell'Alto Tevere; WLA=Parte occidentale (fissa) della Piattaforma laziale-abruzzese. La banda con strisce bianche presso la sigla RMU corrisponde alla zona transpressiva della Romagna (Costa, 2003), che viene interpretata come un possibile svincolo tra le Unità liguri e le RMU. Le frecce blu indicano la cinematica presunta, rispetto all'Eurasia, della placca adriatica e dei cunei appenninici (scala nel riquadro). Le frecce rosse più grandi in Africa e nel blocco egeo indicano l'orientazione delle spinte di tali blocchi sulla regione considerata (e.g., Mantovani et al*., 2007b, 2008a). Simboli e sigle come in figura 1.*

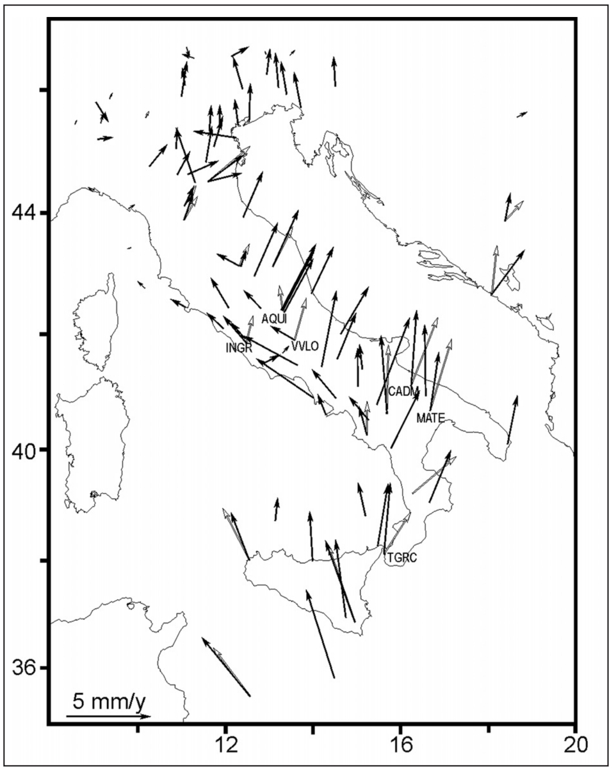

Fig.3 - Residual velocities with respect to Eurasia deduced by continuous GPS measurements. Black arrows indicate the velocities provided by DEVOTI *et al.* (2008), with absolute Eurasia Euler pole at 55.85°N, 95.72°W, ω=0.266 °/My. Empty arrows indicate the vectors provided by SERPELLONI *et al*. (2007), with Eurasia Euler pole at 52.92°N, 105.66°W, ω =0.246 °/My.

Velocità residue rispetto all'Eurasia ottenute da misure GPS continue. Le frecce nere indicano le velocità prese da DEVOTI et al. (2008), *con il polo euleriano dell'Eurasia situato a 55.85°N, 95.72°W, ω =0.266 °/My. Le frecce vuote indicano le velocità prese da* SERPELLONI et al. (2007), *con polo euleriano dell'Eurasia posto a 52.92°N, 105.66°W, ω =0.246 °/My.*

Pleistocene deformation (Fig. 2) could provide insights into the eventual differences between short and long-term kinematic patterns in the study area. In the southern Adriatic, geodetic vectors have a dominant orientation from S-N to SSW-NNE, which is similar to the long-term motion trend predicted in figure 2. In this regard, one could point out that the quantification of the effects of the post-seismic relaxation induced by the 1979 strong (M=6.7) Montenegro earthquake (VITI *et al*., 2003) provides an increase of about 2 mm/y in the NE direction of present motion rates in the southern Adriatic and Apennine zones. In the central and northern Apennines, the dominant NNE to NE ward trend of geodetic vectors is compatible with the extrusion pattern of that belt sector (Fig. 2) implied by our evolutionary reconstruction (VITI *et al*., 2006; MANTOVANI *et al*., 2007a, 2008a). In the southern Eastern Alps, the dominant Northward trend of geodetic vectors is slightly different from the NNW ward motion proposed in figure 2. Since this difference is presumably comparable to the uncertainty associated with the motion trend inferred from Pleistocene deformation, recognizing whether effects of post seismic relaxation are present in that zone is not easy.

Another major feature of the geodetic velocities is the significant difference, both concerning amplitude and trend of vectors, between the velocities in axial-outer sector of the Apennines and those in the inner belt. This evidence, already pointed out by CENNI *et al*. (2008), is compatible with the hypothesis that the axial-outer belt (carried by the Adriatic plate) moves faster than the inner belt (VITI *et al*., 2006; MANTOVANI *et al*., 2008a), as discussed in the following section.

Finally, one could note that some significant differences between the velocities provided by the two different authors in figure 3, especially those of the Reggio Calabria (TGRC), Matera (MATE), Castel del Monte (CADM), Villavallelonga (VVLO), Roma (INGR) and Aquila (AQUI) stations, cannot easily be explained, even if one takes into account that the absolute velocities are related with different reference models (ITRF2000 and ITRF2005) and that different Eurasian Euler poles have been adopted to derive residual velocities.

Geodynamics of the Southern and Central Apennines

The connection between the acceleration of the Adriatic plate and the tectonic reorganization of the Apennine belt is due to the fact that since the middle Pleistocene the outer sectors of the Apennines have been carried by the Adriatic plate (VITI *et al*., 2006; MANTOVANI *et al*., 2008a). The consequent oblique separation between such mobile orogenic units and the inner almost fixed belt (Fig.2) has induced transtensional deformation in the axial belt, while the mobile units, under the push of the Adriatic, has undergone a significant acceleration of uplift.

In the Southern Apennines, the mobile belt is mainly formed by the Molise-Sannio (MS) wedge. The extensional decoupling zone between this wedge and the inner belt is formed by a system of normal faults running from the Matese to the Irpinia zones, as described earlier (Figs.1 and 2). The transmission of compressional stress from the MS wedge to the Latium-Abruzzi (LA) platform involves oblique thrusting and strong seismicity at the border between those two blocks, as recognized in the Maiella and Sangro-Volturno zones (Fig.2). The fact that the push of the MS wedge is mainly applied to the eastern sector of the Latium-Abruzzi platform (ELA) has induced sinistral shear stress in that platform, with the consequent formation of NW-SE transtensional fault systems, such as the Aquila and Fucino.

The decoupling between the Adriatic-Apennine mobile system and the extruding Calabrian wedge is accommodated by NW-SE sinistral strike-slip faults recognized in the Lucanian Apennines (e.g., VITI *et al*., 2006; MANTOVANI *et al*., 2008a).

Geodynamics of the Northern Apennines

The recent deformation pattern of the Northern Apennine arc may be plausibly explained as an effect of the indentation of ELA (VITI *et al*., 2006; MANTOVANI *et al*., 2008a,b). A tentative reconstruction of the proposed driving mechanism and tectonic evolution is shown in figure 4. The most mobile sector of the above arc is the Romagna-Marche-Umbria (RMU) wedge. Under the push of ELA, this arc has undergone outward bending and extrusion, accommodated by folding and thrusting at the outer front and extension in the inner side, both associated with high seismic activity (e.g., Viti *et al.*, 2006; Cenni *et al.*, 2008; Mantovani *et al.*, 2008b). The information provided by seismic soundings (Finetti *et al.*, 2005) indicates that the extruding orogenic wedge is formed by the uppermost crustal units overlying the Triassic evaporitic layer, which acts as decoupling zone. This wedge moves eastward sliding over the main Tiber fault (e.g., Boncio *et al.*, 2000; Finetti *et al.*, 2005; Cenni *et al.*, 2008). The extensional separation between the migrating wedge and the inner belt has formed the Upper Tiber trough (Fig. 4). On the other side, the convergence of that wedge with the Adriatic domain has generated the compressional features recognized at the outer Apennine thrust front (e.g., Lavecchia *et al.*, 2003a). It must be pointed out that the lateral escape of the above wedge has occurred while the Adriatic lithosphere, driven by the convergence of the confining plates (Africa, Eurasia and Aegean), was underthrusting the Apennine belt (Cenni *et al.*, 2008).

Support to the hypothesis that the deformation of Northern Apennines is connected with the indentation of ELA is provided by the distribution of major earthquakes in these regions. For instance, a discussion about the influence that the strongest historical decoupling earthquakes in the LA fault systems (Aquila and Fucino) may have had on the seismic activity of the Northern Apennines is given by Mantovani *et al.* (2008b).

The fact that the Roman volcanic province (Fig.4) is located along the inner boundary of the RMU wedge corroborates the hypothesis that such volcanism was connected with the transtensional regime that developed in the wake of that migrating wedge (e.g., Tamburelli *et al.*, 2000; Viti *et al.*, 2006).

While extruding outward, the RMU wedge has transmitted stress to the Ligurian units and adjacent structures, causing their counterclockwise rotation and NW ward translation. This kinematics can account for the compressional deformation recognized at the Padanian margin of the above units and the extensional seismotectonic activity observed at their inner boundary (Pistoia-Firenze, Garfagnana and Lunigiana troughs), described in section 2. The decoupling of the Ligurian wedge from the westernmost part of the Apennines is accommodated by a sinistral transpressional fault system running from the Lunigiana trough to the Tortona-Voghera thrust front (Fig.4). Seismic soundings and spatial distribution of earthquakes in the Romagna Apennines might indicate the presence of a roughly N-S transpressional decoupling zone between the RMU and Ligurian wedges (Costa, 2003), as tentati-

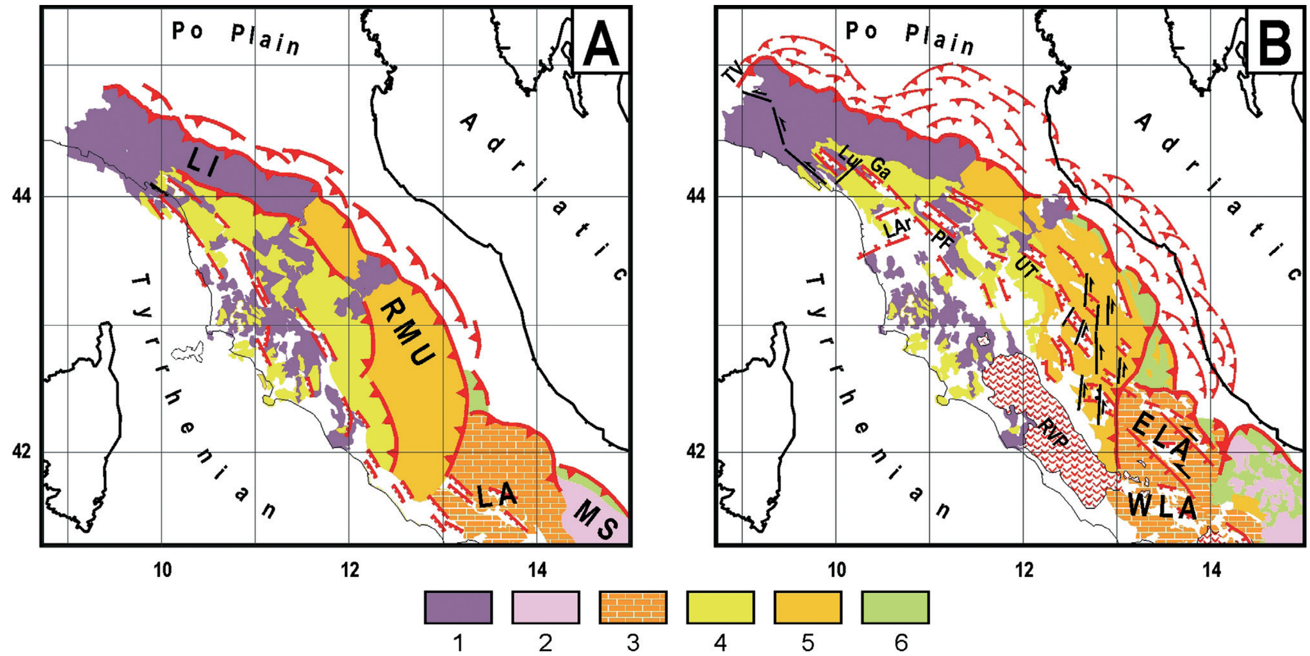

Fig.4 - Tentative reconstruction of the Late Pliocene configuration of major structural units in the Central and Northern Apennines (**a**), compared with the present setting (**b**). Comments in the text. 1) Ligurian units 2) Southern Apennine pelagic units 3) Carbonate platforms 4) Northern Apennine internal units 5) Northern Apennine external units 6) Laga turbidites and similar units. ELA=Eastern (mobile) part of the Latium-Abruzzi platform (LA); LI=Ligurian units; LAr=Lower Arno trough; MS=Molise-Sannio units; RMU=Romagna-Marche-Umbria units; RVP =Roman Volcanic Province; WLA=Western (fixed) part of the Latium-Abruzzi platform. The distribution of structural units in b) is taken from the Tectonic Map of Italy (Funiciello *et al.*, 1981). Other symbols and abbreviations as in figure 1.

Ricostruzione della configurazione delle principali unità strutturali nel tardo Pliocene (a), confrontata con l'assetto attuale (b), preso dalla Carta Tettonica d'Italia (Funiciello et al., *1981). Commenti nel testo. 1) Unità liguri 2) Unità pelagiche dell'Appennino meridionale 3) Piattaforme carbonatiche 4) Unità interne dell'Appenino settentrionale 5) Unità esterne dell'Appennino settentrionale 6) Unità torbiditiche della Laga ed affini. ELA=Parte orientale (mobile) della Piattaforma laziale-abruzzese; MS=Unità Molise-Sannio; LA=Piattaforma Laziale-Abruzzese; RMU=Unità Romagnole-Marchigiane-Umbre; RVP=Provincia vulcanica romana; WLA=Parte occidentale (fissa) della piattaforma laziale-abruzzese. Altri simboli e sigle come in figura 1.*

vely sketched in figure 2.

The divergence between the migrating Ligurian wedge, encompassing the Apuane metamorphic complex, and the almost fixed Southern Tuscany zone, might explain the N-S to NW-SE extension that formed the Lower Arno trough (Fig. 4). It must be pointed out that the occurrence of such tectonic event, being characterized by a deformation style rather different from the one that dominated the formation of the inner side of the Northern Apennines (NE-SW extension), provides a very important constraint on the driving mechanism of this belt sector, as discussed in the next section.

4. ALTERNATIVE GEODYNAMIC INTERPRETATIONS

Various hypotheses have been advanced about the geodynamic setting responsible for the middle Pleistocene tectonic reorganization of the Apennines. In the following, we make some remarks about the plausibility of the most cited interpretations and their consistency with the observed deformation pattern.

Slab detachment

This hypothesis suggests that the acceleration of uplift in the Apennines since the middle Pleistocene has occurred as a sort of lithospheric rebound, in response to the break of the underlying slab (e.g., CINQUE *et al*., 1993; WESTAWAY, 1993; BERTOTTI *et al*., 1997).

In our opinion, this interpretation presents major weak points. In the Northern Apennines, tomographic investigations delineate a continuous westward dipping slab down to several hundreds of km (e.g., PIROMALLO & MORELLI, 2003), which is evidently incompatible with the slab detachment model. Alternatively, the structural images provided by CROP deep seismic soundings (FINETTI *et al*., 2005) exclude the presence of a well-developed slab beneath the Northern Apennines and rather suggest that the underlying lithospheric body is formed by relatively short continental slivers only reaching a moderate depth (less than 100 km). This reconstruction is compatible with the distribution of subcrustal earthquakes in the Northern Apennines, in particular with the lack of events deeper than 70-80 km (e.g., CHIARABBA *et al*., 2005), and with the recognized continental nature of the Adriatic lithosphere that lay in front of the advancing arc since the Miocene (e.g., SERRI *et al*., 1993). Even considering this alternative view of the deep structural setting, the slab detachment model cannot be invoked as the driving mechanism of crustal uplift in the Northern Apennines.

In the Southern Apennines, some tomographic investigations suggest the presence of a gap in the subducted lithosphere (e.g., LUCENTE & SPERANZA, 2001). Thus, the slab detachment model could be applied to that Apennine segment. However, other considerations do not support the reliability of that interpretation:

- The feasibility of the proposed physical mechanism is not demonstrated. For instance, some numerical simulations of that phenomenon (e.g., GIUNCHI *et al*., 1996) predict subsidence instead of uplift of the lithosphere overlying the broken slab.
- The slab detachment model could account for the timing of the observed acceleration of uplift in the Apennines only if the presumed break had occurred around the middle Pleistocene. However, there is no evidence of such timing.
- The strain regimes recognized in the Matese-Irpinia and Lucanian sectors of the Southern Apennines are rather different, as mentioned earlier. Explaining why two adjacent crustal structures have reacted in such different ways to the detachment of the underlying slab is not easy.
- One should also consider that in the Calabrian Arc, where strong Quaternary uplift is clearly documented (e.g., WESTAWAY, 1993), any significant interruption of the slab is ruled out by seismic tomography (e.g., PIROMALLO & MORELLI, 2003), deep seismic soundings (FINETTI, 2005) and studies of seismic wave propagation from deep earthquakes (MELE, 1998).

Mantle upwelling

Some authors (e.g., D'AGOSTINO *et al*., 2001; LAVECCHIA *et al*., 2003b) suggest that this phenomenon is taking place under the Apennines belt and that it could be responsible for the observed Quaternary deformation, in particular volcanism and coeval occurrence of uplift and crustal extension. D'AGOSTINO *et al*. (2001) even advance the hypothesis that the spreading induced by the mantle-supported uplift in the Apennines forces the Adriatic lithosphere to move NE ward with respect to Eurasia.

In the following, we argue that the occurrence of active rifting beneath the Apennines belt cannot easily be reconciled with major evidence.

- One can hardly understand why mantle upwelling would have caused the NE ward displacement of the Adriatic block, whereas the domains lying on the other side of the presumed rifting process (Tyrrhenian region and Corsica-Sardinia block) have not undergone any westward migration. In our opinion, this strong asymmetry in the effect of the presumed rifting is a major problem for the mantle upwelling model, especially if one considers that pushing away a relatively small block suck as Corsica-Sardinia would have been much easier than displacing the large Adria plate. Until a plausible explanation is found for this difficulty, mantle upwelling can hardly be claimed to be a feasible driving mechanism.
- Time space distribution and petrological features of Quaternary volcanism in the Apennine belt is considerably different from that observed in active rifting zones (e.g., PECCERILLO, 2003, 2006). In particular, one should explain why volcanic activity has mainly developed in two limited zones of the inner belt (Figs. 1 and 4).
- Mantle convection and related rifting appear to be large-scale phenomena that involve wide spaces (much more than the Central Apennines) and requires millions of years to fully develop (e.g., ZIEGLER & CLOETINGH, 2004). Thus, one could wonder why such processes had a relatively fast development around the middle Pleistocene and such a limited spatial effect.
- The occurrence of some peculiar tectonic events, such as for instance the formation of the Lower Arno basin (Fig. 4), can hardly be interpreted as an effect of active rifting under the belt.
- Considering that in the Lucanian Apennines, uplift is

associated with strike-slip tectonic, instead of crustal extension, and that an even more complex tectonic pattern is recognized in Calabria (FINETTI, 2005), one could wonder why the presumed effects of active rifting only occur along a limited sector of the Apennines. In this regard, one should also explain other important differences in the tectonic evolution of the Apennines, for instance the fact that in the Quaternary thrusting stopped in the Southern Apennines and continued to develop in the outer belt of the Northern Apennines.

- The dynamic/kinematic scheme proposed by D'AGOSTINO *et al*. (2001) requires a zone of decoupling between the Adriatic (moving NE ward in the above view) and Africa (moving NNW ward in the NUVEL1 kinematic model), which is not supported by any significant evidence. A detailed discussion about this problem is given by BABBUCCI *et al*. (2004) and MANTOVANI *et al*. (2007b).

Multiple driving mechanisms

Some authors have tried to overcome the difficulties of the above interpretations by invoking the contemporaneous action of more than one driving mechanism. A significant example of this kind of interpretation is the one proposed by MELETTI *et al*. (2000), who suggest that the Quaternary deformation pattern recognized in the Tyrrhenian-Apennines system may be explained as an effect of a complex of driving mechanisms. In that view, the Adriatic counterclockwise rotation would cause compressional deformation in the southern Eastern Alps and Northern Dinarides and extensional tectonics in the Southern Apennines. Slab roll back would be responsible for the development of arc-back arc tectonics (arc migration, trench retreat and back arc opening) in the Northern Apennines and Calabrian arc. Slab detachment is invoked to explain the uplift of the Apennine belt, while pushing of asthenospheric wedges would be responsible for the compressional deformation observed at the external fronts of the Northern Apennines and Calabrian arcs. The Africa-Eurasia convergence would explain the compressional deformation observed along the Maghrebian chain in Northern Sicily and the adjacent Tyrrhenian area.

In general, invoking so many driving mechanisms for a relatively limited region as the Central Mediterranean appears to be mainly speculative. To check the plausibility of that model one should compare the observed features with the deformation resulting from the combined effects of all presumed driving mechanisms.

CONCLUSIONS

Around the middle Pleistocene, the resuming of the underthrusting process at the south eastern Adriatic collisional border has allowed the Adriatic plate to accelerate its motion towards Eurasia. That tectonic event has deeply influenced the deformation pattern of the Apennine belt, since the above acceleration has also involved the outer part of the Apennines (Molise-Sannio, Eastern Latium-Abruzzi platform, Romagna-Marche-Umbria and Ligurian units), causing its oblique separation from the inner belt, almost fixed. Such divergence has been accommodated by transtensional deformation in the axial part of the chain, while the belt-parallel push of the Adriatic has caused acceleration of uplift in the mobile units. The compatibility of the proposed geodynamic interpretation with the Quaternary deformation pattern in the Apennine belt, with particular regard to the Northern Apennines, is discussed. On the other hand, it is argued that the implications of the alternative driving mechanisms so far proposed can hardly be reconciled with the available evidence.

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