NEOGENE CRUSTAL SHORTENING AND BASIN EVOLUTION IN TUSCANY (NORTHERN APENNINES)

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ABSTRACT

The structural studies carried out in the Northern Apennines during the last decade show that the Neogene tectonic evolution of this area is much more complex than the classical model which proposed a NE-directed shifting of the compressive front followed by lateral extension in the internal zone tied to the development of the Tyrrhenian basin.

Recent structural data systematically collected both in the chain and in the sedimentary fill of the hinterland basins, allow us to propose an alternative model for the development of the basins and for the Neogene evolution of the whole Northern Apennines sector. In the central sector of the chain (Tuscan-Romagna Apennines), there is evidence of polyphase thrust reactivations and out-of-sequence thrusting. In the hinterland basins, compressive deformations usually occur in correspondence of thrust ramps and regional unconformities have been found. The timing of both thrust reactivations in the chain and of the major compressive phases affecting the hinterland basins (Radicondoli-Volterra, Baccinello, Velona and Siena-Radicofani basins) well correlates with the periods of magmatic quiescence and with the compressive phases detected in the external sector of the Northern Apennines (Padan-Adriatic foredeep).

The presented data allow us to propose that compressive tectonics played a major role in the recent evolution of the Northern Apennines. The mechanism envisaged to explain this tectonic framework has been related to the piggyback emplacement (from the internal toward the external areas) of basement thrusts, that occurred since Miocene. The emplacement of basement thrusts likely caused the reactivation of cover thrusts, giving rise to out-of-sequence thrusting and affecting the development and/or deformation of the hinterland basins.

This tectono-sedimentary evolution based on field analysis fits well with the recent reinterpretations of a deep seismic profile (CROP 03 line) hypothesising that basin development was strictly related to crustal shortening. In this frame, the extensional structures have been interpreted either as second-order features accommodating thrusting or as related to the Middle Pliocene and Quaternary extensional phases during which fault-controlled basins locally developed.

INTRODUCTION

The Northern Apennines (NA) is a NNW-trending arcuate fold and thrust belt that derived from the collision between the Corso-Sardinian block and the Adriatic Plate. The Apennine chain is made up by E-verging tectonic units, the uppermost of which are the ocean-derived Ligurian Units (Fig. 1). The NA have been commonly subdivided into two sectors, an internal sector mainly characterised by extensional tectonics since Late Miocene and an external sector where thrusting processes are still active. The internal side of the NA (mainly in the Tuscany, Latium and Umbria regions) is characterised by the occurrence of marine and continental Late Miocene to Quaternary hinterland basins that have been classically considered of extensional type, being their structure interpreted either as graben or half-graben. According to this model, extension is connected to the back arc-related Tyrrhenian basin opening that progressively followed the shifting of the thrust fronts to the east (e.g. Merla, 1951; Trevisan, 1951; Giannini and Tongiorgi, 1958; Mazzanti et al., 1963; Sestini, 1970; Elter et al., 1975; Lazzarotto and Mazzanti, 1976; Boccaletti et al., 1985; 1990; Malinverno and Ryan, 1986; Royden et al., 1987; Patacca et al., 1990; Martini and Sagri, 1993; Bossio et al., 1997; Pascucci, 1997). During continental collision Late Oligocene to Miocene foredeep basins mainly filled by siliciclastic turbidite sediments formed at the front of the migrating chain. Their sediments conformably overlie the Upper Triassic-Eocene carbonate margin sequence of the Adriatic margin (Tuscan and Umbria-Marchean domains). Successively, the foredeep deposits were progressively (from W to E) involved in thrusting and annexed to the chain (e.g. Bortolotti et al., 1970; Ricci Lucchi, 1986a, and ref. therein).

During the last decade, the evolution of the NA has been also interpreted as post orogenic gravity collapse of an overthickened accretionary prism, with the development of core complex structures associated with low-angle normal faulting. This process would have been affecting the Apennine chain since Early Miocene (Carmignani and Kligfield, 1990; Bertini et al., 1991; Cameli et al., 1993; Decandia et al., 1993; Carmignani et al., 1994; Keller et al., 1994).

However, the occurrence of widespread mesoscopic compressive deformations affecting the deposits of the hinterland basins has been pointed out since the seventies (e.g. Pertusati et al., 1977; 1978; 1980; Plesi and Cerrina Feroni, 1979; Cerrina Feroni et al., 1989). Successively, a correlation between these compressive deformations and the unconformities within the sediments of both the hinterland basins and the Padan-Adriatic margin has been proposed (Bernini et al., 1990; Boccaletti et al., 1992; 1994; Bonini and Sani, 1993). Accordingly, the stratigraphic successions of the internal basins have been subdivided into five unconformity-bounded stratigraphic units (the so called UBSUs according to Salvador's (1987) definition): 1st UBSU (middle-late Tortonian-Messinian); 2nd UBSU (Messinian p.p.-Early Pliocene); 3rd UBSU (Early Pliocene p.p.-Middle Pliocene); 4th UBSU (Late Pliocene p.p.-early Pleistocene); 5th UBSU (middle-late Pleistocene) (Boccaletti et al., 1995a; 1995b). UBSUs are bounded by regional unconformities that are correlatable basin to basin; however, minor unconformities may locally occur within UBSUs.

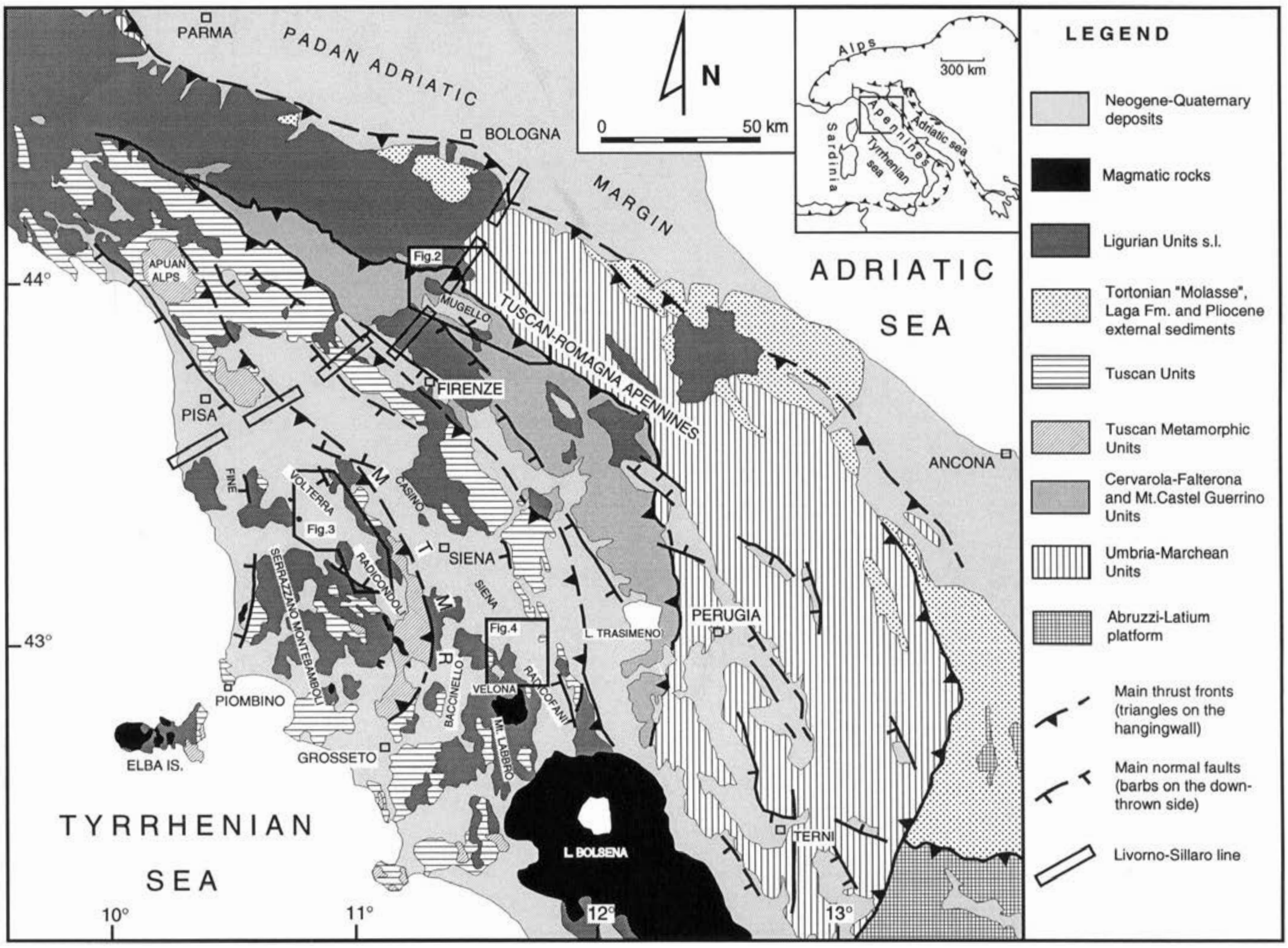

Fig. 1 - Sketch map of the Northern Apennine fold and thrust belt; The hinterland basins described in the text are indicated by the boxes. MTMR: Mid-Tuscany Metamorphic Ridge.

The hinterland area in NA extends onshore from the Tuscan coastline up to the Tuscan-Romagna watershed to the east. The hinterland area can be broadly subdivided into two parts: an eastern sector where continental intermontane basins occur and a western sector where Tuscan metamorphic units crop out along the Mid-Tuscany Metamorphic Ridge (MTMR), a major crustal thrust that is well evident in geophysical data (Arisi Rota and Fichera, 1985; Ponziani et al., 1995; Finetti et al., 1997b). The MTMR delimits on both sides the oldest hinterland basins and played an important paleogeographic role during Messinian, as it separated basins with evaporitic sedimentation to the west (i.e. Radicondoli-Volterra, Fine, Serrazzano-Montebamboli) from basins with a predominant continental sedimentation to the east (Fig.1; Baccinello, Casino, Siena-Radicofani) (e.g. Bossio et al., 1992).

Geological-structural studies have been carried out both in the hinterland area and in the Tuscan-Romagna Apennines (the central sector of the chain) evidencing a complex and polyphase Neogene tectonic evolution of this area. In general, the sedimentary filling of the hinterland basins have been affected by both compressional and extensional deformations. Compressional deformations are often predominant and consist of reverse faults, folds, joint systems and solution pits on calcareous pebbles surfaces. Where chronological relationships are available, extensional deformations generally post-date the compressional ones (e.g. Boccaletti et al., 1995a; 1995b; Bonini and Moratti, 1995; Landi et al., 1995; Bonini, 1997).

The complex evolution of the NA thrust-belt is illustrated by the structural setting of the Tuscan-Romagna Apennines, where thrust reactivations and out-of-sequence thrusting evidence polyphase compressional tectonics (e.g. Bendkik et al., 1994). However, the age of these thrusting phases is poorly constrained, on the basis only of the age of the younger sediments involved in thrusting, generally the siliciclastic Lower-Middle Miocene foredeep sediments. This is the main reason why we have also focused our work on the hinterland basins, that represent a powerful tool to date the Upper Miocene to Pleistocene deformative phases that affected the NA. Our approach was to combine field mapping of the basins with structural analysis of both deformations affecting syntectonic strata and structures affecting the substratum surrounding the basins. The relationships of these structures with basin development have been obviously investigated as well.

The present work briefly illustrates a summary of the studies carried out on the NA hinterland basins at the Florence University over the last 10 years. Structural data systematically collected both in the hinterland basins and in the chain allow us to propose an alternative model for basin evolution that involves some important implications for the Neogene tectonic evolution of the NA. Our principal hypothesis is that hinterland basins developed in a compressional setting related to thrust activity. Examples of basins located in various structural settings of the hinterland area are illustrated below: first, the intermontane Mugello Basin, second the Radicondoli-Volterra and Velona Basins that developed east and west of the MTMR respectively (Fig. 1). This paper is integrated by the post-congress field-trip guide (C2) across Southern Tuscany (Sani et al., 2000, this issue).

THE INTERMONTANE MUGELLO BASIN

The intermontane Mugello Basin is located within the Tuscan-Romagna fold and thrust belt and represents one of the easternmost hinterland basins of Tuscany. The Tuscan-Romagna fold-thrust belt mainly consists of NE-verging thrust sheets made up by Lower-Middle Miocene siliciclastic foredeep sediments that are frequently detached from their carbonate substratum (Tuscan and Umbria-Marchean margin successions). Reactivation episodes along these thrusts are apparent from cross-cutting relationships between thrust faults and the occurrence of different orientations of the stress field associated with the various thrusting phases (Bendkik et al., 1994). This structural frame is particularly evident along the Cervarola-Falterona (CF) and Mt. Castel Guerrino (MCG) thrusts, that delimit the Mugello Basin to the northeast (Fig. 2). In particular, the MCG thrust displays a clear out-of-sequence geometry because in the Mt. Castel Guerrino area this unit overthrusts along a flat tectonic contact the Ligurian Units s.l., cutting older thrusts (cross section CD in Fig. 2). Along its southwestern margin the Mugello Basin is affected by NW-SE-trending normal faults (Benvenuti, 1996). These faults show well developed morphostructural features (like triangular facets and scarps) and are oblique to the WNW trend of the basin.

The continental fill of the Mugello Basin mainly consists of a ≈600 m thick Upper Pliocene(?)-lower Pleistocene fluvio-lacustrine succession (corresponding to the 4th UBSU), unconformably overlain by middle Pleistocene fluviatile deposits (corresponding to the 5th UBSU) (Sanesi, 1965; Sagri et al., 1994; Benvenuti, 1995).

The WNW-trending axis of the Mugello Basin strikes parallel to the MCG thrust and this basin shows a general

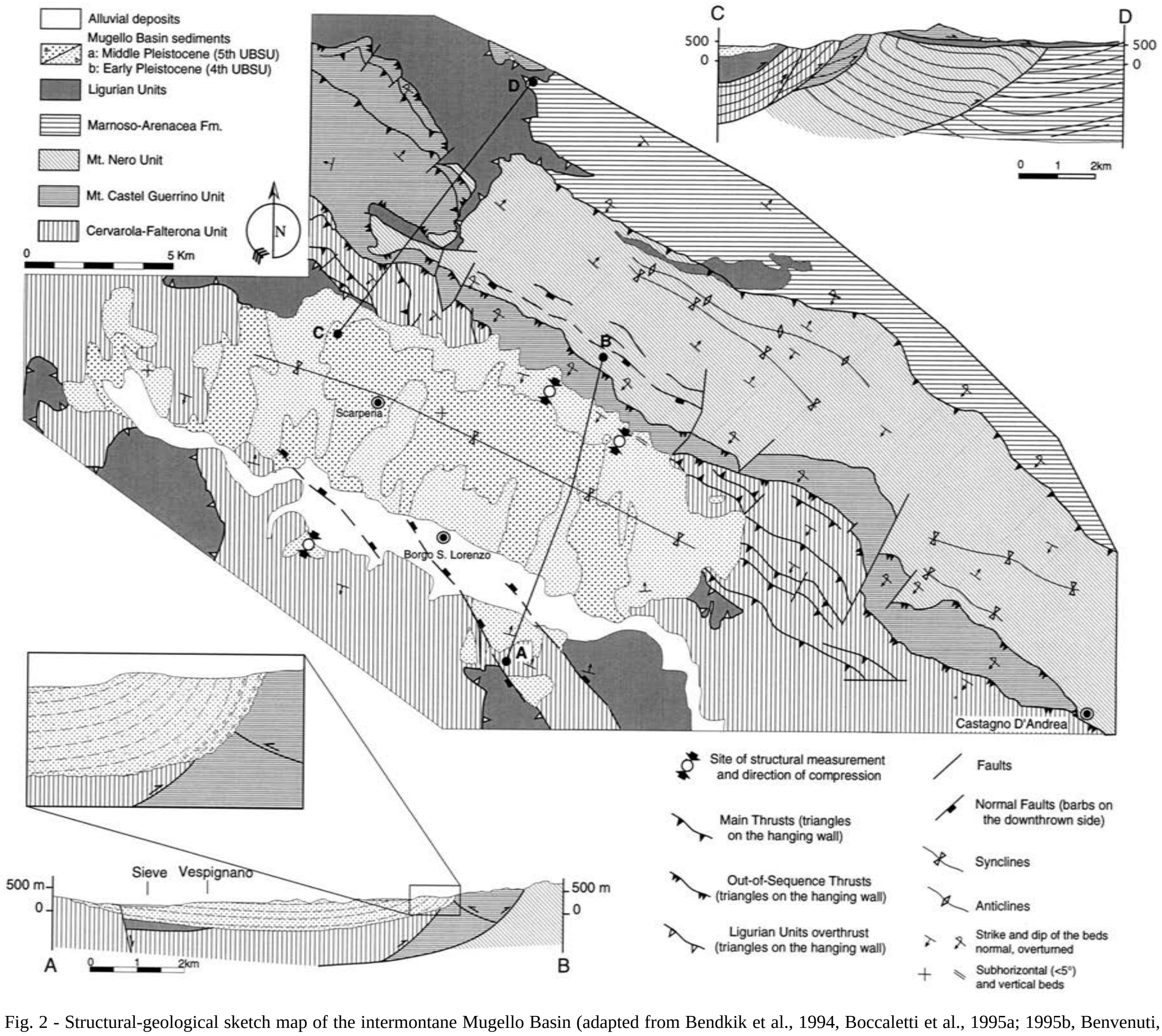

Fig. 2 - Structural-geological sketch map of the intermontane Mugello Basin (adapted from Bendkik et al., 1994, Boccaletti et al., 1995a; 1995b, Benvenuti, 1996). Top of the pre-lacustrine formations as in Gemina (1963).

synformal structure, as shown in the drills for lignite exploration performed by Gemina (1963) (Fig. 2). Along the northeastern margin of the basin, 4th UBSU continental deposits steeply dip southwestward overstepping the pre-Pliocene substratum. Locally, these beds show a vertical setting while basinwards the dip of the beds progressively decreases. Progressive syntectonic unconformities (e.g. Riba, 1976) have been recognized within the Upper Pliocene(?)-lower Pleistocene continental succession exposed along the northeastern margin (Benvenuti, 1995), indicating a synsedimentary uplift of this margin.

In this context, we interpret the Mugello as a thrust-top basin that developed following the reactivation of the MCG thrust during Late Pliocene-early Pleistocene times (Boccaletti et al., 1995a; 1995b). Syntectonic progressive unconformities developed within the continental succession along the northeastern margin of the basin related to the uplifting of the margin produced by the thrusting above the frontal ramp of the MCG thrust. This hypothesis rejuvenates the age of thrusting of this sector of the Apennines, as it implies that thrust reactivation phases occurred during Late Pliocene-early Pleistocene. Mesoscopic compressive deformations, mainly stylolitic pits, fit in the above depicted scenario, being the NNE directions of compression nearly orthogonal to both the MCG thrust and the Mugello Basin trend (Fig. 2). Successively, during middle Pleistocene-Holocene times the Mugello Basin experienced normal faulting related to the NW-SE-trending faults dissecting its original synformal structure at the southwestern margin (Fig.2 and cross section AB). From this frame we infer a chronology of faulting because these normal faults post-date the Mugello development, as they obliquely displace the initial synformal structure of the basin (Fig. 2).

THE RADICONDOLI-VOLTERRA BASIN

The Radicondoli-Volterra Basin is located west of the MTMR and extends in a NNW direction over a length of about 50 km, representing one of the most important hinterland basins of the NA (Fig. 1).

Three unconformity-bounded units have been distinguished in the basin fill (from the bottom): an upper Tortonian-Messinian unit (1st UBSU), a Messinian-Lower Pliocene unit (2nd UBSU) and Lower Pliocene p.p.-Middle Pliocene unit (3rd UBSU) (Fig. 3). The 1st UBSU is about 1000 m thick and consists of a basal continental succession grading upwards to a shallow-marine succession characterised by episodes of evaporitic deposition (Lazzarotto and Mazzanti, 1976; Bossio et al., 1981; Bonini et al., 1994). The following 2nd UBSU consists of a basal shallow-marine and marine-lagoonal sediments marked by the occurrence of evaporites. These at the beginning of Pliocene, grade upwards to a mainly clayey succession indicating a deeper marine environment (Bossio et al., 1978; 1991; 1992; Bonini and Moratti, 1995, and references therein). Finally, the 3rd UBSU is mainly composed of marine clays and sands, whose thickness increases northwestwards.

The Radicondoli-Volterra Basin displays a general syncline structure as the older sediments generally onlap the pre-Neogene substratum along both margins and strongly dip toward the centre of the basin (Fig. 3). Thought normal faulting has been invoked to explain the origin of the basin (i.e. Lazzarotto and Mazzanti, 1976; Martini and Sagri, 1993; Pascucci, 1997) only locally normal faults affect the basin margins (Fig. 3). This major syncline is open in the Volterra area and becomes very pronounced southward, in the Radicondoli area, defining the so-called “Radicondoli syncline” (Lazzarotto and Mazzanti, 1976; Bonini et al., 1994; Bonini and Moratti, 1995). Here its eastern limb is affected by a ENE-dipping NNW/SSE trending reverse fault that in outcrop can be followed for some kilometres; vertical to overturned beds, cataclasites as well as minor reverse faults and folds are often developed in correspondence of this structure (Bonini and Moratti, 1995). However, outcrop-scale compressive structures are well developed in the whole Radicondoli-Volterra Basin, and mostly indicate a NE to ENE direction of compression that is orthogonal to the basin trend (Fig. 3). Northward, in the Volterra area, a similar major ENE-dipping reverse fault striking parallel to the previous one has been detected through seismic profile interpretation by Del Campana (1993). This fault is buried beneath Pliocene sediments and affects the substratum as well as the 1st and 2nd UBSUs deposits, displaying a well developed west-verging ramp anticline (Fig. 3). Together with the E-dipping reverse fault of the Radicondoli area they constitute back-thrust structures. In previous papers we have interpreted the back thrusts affecting the Radicondoli-Volterra Basin fill as related to a strong reactivation of the MTMR thrust during Messinian. This deformative phase shortened the basin and caused the unconformity between the 1st and the 2nd UBSUs (Bonini et al., 1994; Bonini and Moratti, 1995). Similarly, we hypothesise that also the formation of the basin occurred in a compressional setting related to the activity of the MTMR thrust. In this context, we propose that the first syntectonic deposit within the Radicondoli-Volterra Basin is represented by the neritic upper Serravallian-lower Tortonian “Ponsano Sandstones”, whose outcrops are exposed at the Ponsano village, along the eastern margin of the basin (Boccaletti et al., 1995b) (Fig. 3). During the last years, tectonic setting in which sedimentation of the Ponsano Sandstones occurred has represented a matter of debate. Deposition of Ponsano Sandstones, in fact, has been related either to satellite basins passively carried up by thrusts within the Ligurian Units (Boccaletti et al., 1990) or to an extensional regime (Giannini and Tongiorgi, 1958; Elter and Sandrelli, 1995). Recently, Foresi et al. (1997) on the basis of the sedimentation rate determined for the Ponsano Sandstones (300 m/Ma) have favoured the extensional setting. However, care should be taken in assuming sedimentation rate as diagnostic for the tectonic regime, as sedimentation rates of the hinterland basins of Tuscany (350-1000 m/Ma; Foresi et al., 1997 and references therein) strikingly match those determined in the Northern Apennines Lower-Upper Miocene foredeep basins (150-600 m/Ma; Sagri, 1973; Ricci Lucchi, 1986b) as well as that of the Pliocene piggy back basins of the Padan-Adriatic margin (500-1500 m/Ma; Zoetemeijer et al., 1993).

The Radicondoli-Volterra Basin was successively affected by NW-SE-trending normal faults associated with the Early Pliocene Anqua Basin (Bonini and Moratti, 1995). Finally, during Late Pliocene this basin experienced a further (and the last) contraction episode that lifted the central part of the basin, as indicated by the NNW-trending anticline affecting the 3rd UBSU sediments north of Volterra (Fig. 3).

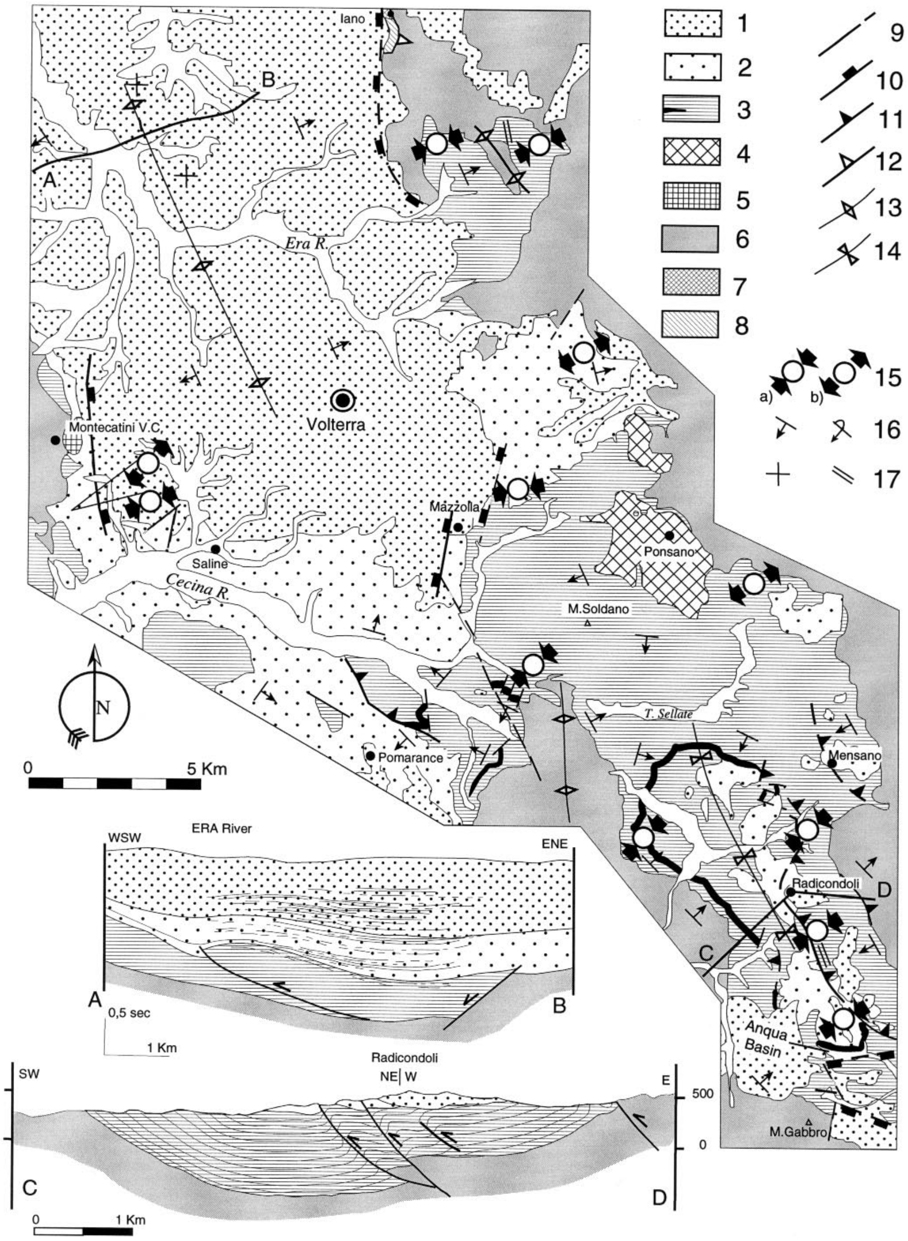

Fig. 3 - Structural-geological sketch map of the Radicondoli-Volterra Basin (adapted from Bonini and Moratti, 1995; Moratti and Bonini, 1998); interpretative seismic line drawing AB redrawn from Del Campana (1993). 1- 3rd UB-SU sediments; 2- 2nd UBSU sediments; 3- 1st UBSU sediments (in black are represented the interbedded evaporites that define the "Radicondoli syncline"); 4- Ponsano Sandstones; 5- magmatic rocks; 6- Ligurian Units s.l.; 7- Tuscan Units; 8- Tuscan Metamorphic Units; 9- fault; 10- normal fault (rectangles on the downthrown side); 11- reverse fault (triangle on the hangingwall); 12- Ligurian Units overthrust (triangle on the hangingwall); 13- anticline; 14- syncline; 15- site of structural measurement and deduced direction of compression (a) or extension (b); 16- strike and dip of the beds, normal, overturned; 17- subhorizontal (dip <5°) and subvertical beds.

THE VELONA BASIN AND THE ADJOINING SIENA-RADICOFANI BASIN

The Velona Basin is a small continental basin located to the east of the MTMR (Fig. 1). This basin lies between two N-S-trending ridges, the Montalcino-Castelnuovo dell'Abate ridge to the W and the Ripa d'Orcia ridge to the E, that correspond to E-verging thrust anticlines where the siliciclastic "Macigno" sandstones of the Tuscan sequence outcrop at the core (Fig. 4; see also cross section in Servizio Geologico d'Italia, 1968). The Montalcino-Castelnuovo dell'Abate ridge continues southward with the Mt. Labbro ridge (Fig. 1) that corresponds to a thrust anticlines involving at depth the Tuscan units as well (Bally et al., 1986; Boccaletti et al., 1995a; 1995b). The Velona Basin is separated from the broader marine Siena-Radicofani Basin extending to the east by the Ripa d'Orcia anticline (Fig. 4).

Three unconformity-bounded units have been distinguished within the basin fill (Fig. 4; Sani et al, 2000, this issue) Recent mammal fauna discovery allowed to date the lower portion of the Velona Basin fill (the 1st unit in Fig. 4) to the early Messinian (Rook and Ghetti, 1997), such that all the sedimentary fill of the basin is Messinian in age, being the upper reddish conglomeratic deposits of the 3rd unit likely correlatable to the upper Messinian Montebamboli Conglomerate. Following the subdivision of the hinterland basin successions proposed in Boccaletti et al. (1995a; 1995b), the 1st and 2nd units of the Velona Basin are correlatable to the 1st UBSU, and the 3rd unit to the 2nd UBSU (Fig. 4). The deposits of the adjoining Siena-Radicofani Basin have been distinguished into two unconformity-bounded units; the lower is Early Pliocene in age while the upper unit is Early-Middle Pliocene and correspond to the 2nd and 3rd UBSU respectively (Sani et al., 2000, this issue).

The large-scale structure of the Velona Basin substratum is a roughly N-S-striking synform that developed in between the two N-S anticlines; the Pliocene sediments of the Siena-Radicofani Basin penetrate southwards along this structure, defining the "Asso-Velona synform" (Fig. 4). The geometry at depth of the Siena-Radicofani Basin sediments is shown by the NE-SW-oriented commercial seismic profile A-A' that crosses this basin between Torrenieri and St. Quirico d'Orcia villages (Fig. 4). The seismic profile evidences both the unconformity between the 2nd and 3rd UBSUs and the prosecution of the Ripa d'Orcia anticline to the north beneath the deposits of the Siena-Radicofani Basin (Fig. 5). This thrust anticline isolated two synformal sub-basins during 2nd UBSU sedimentation (the Asso-Velona synform is to the west in the profile), while the 3rd UBSU deposits filled these basins onlapping the limbs of the Ripa d'Orcia anticline (Fig. 5).

Roughly N-S-trending map-scale folds affect the basin fill close to the western margin and are likely related to the thrust activity of the Montalcino-Castelnuovo dell'Abate anticline during basin evolution. Outcrop-scale compressive structures affecting the basin fill are well developed in the whole basin, while extensional structures were observed very rarely. Both major folds and mesoscopic structures indicate a shortening direction trending around E-W, orthogonal to the thrust anticlines (Fig. 4). For these reasons, we relate the development of the Velona Basin to the activity of the thrusts bounding the basin and we consider it as a thrust-top basin. In particular, the basin fill architecture allows to reconstruct the thrust kinematics. First cycle deposits display a strong asymmetrical setting with respect to the synform basin axis, as the deposits are dominantly dipping to the west suggesting the occurrence of down-lap relationships of the deposits with the basin substratum. This setting is markedly similar to that of some piggy back basins of Southern Apennines where both tilting of the syntectonic strata and migration of the basin depocenter occur in a direction opposite to the direction of thrusting (e.g. Hippolyte et al., 1994). On these bases we hypothesise that deposition within the Velona Basin was mainly controlled by the Ripa d'Orcia thrust. The synsedimentary tilting to the west of the Ripa d'Orcia backlimb anticline during thrusting caused the westward migration of the Velona depocenter, as proposed in the models by Roure et al. (1990) and Hippolyte et al. (1994).

The Velona Basin, thus, evolved between two competing thrust anticlines whose activity is evidenced by outcrop-scale compressive structures affecting the near Messinian-Pliocene sediments (Fig. 6). This setting is illustrated by the key points labelled A, B and C in Fig. 4. Site A (Figs. 4 and 6a) is located in front of the Montalcino-Castelnuovo dell'Abate thrust anticline and evidences the compression suffered by the basin fill in front of this structure. Sites B and C are located on the backlimb and on the forelimb of the Ripa d'Orcia anticline respectively (Fig. 4). These deformations allow to infer a rather long time of activity of this structure, as mesoscopic deformations in B (Fig. 6b) are associated with the Messinian development of the Velona thrust-top Basin, while site C (Figs. 6c, d) demonstrates the activity of the Ripa d'Orcia anticline during the Early-Middle Pliocene, being this a synsedimentary deformation (I.P. Martini, personal communication, 1997).

Finally, field mapping of the Velona Basin has also revealed the existence of E-W-trending gentle folds superimposed onto the synformal basin structure, resulting in a smooth undulation of the former N-S-trending fold axes. However, E-W folds occur only as local features and might have developed in relation to a minor shortening event characterised by a N-S to N20°-oriented shortening direction that affected this region around the end of Messinan (Boccaletti et al., 1992; 1994).

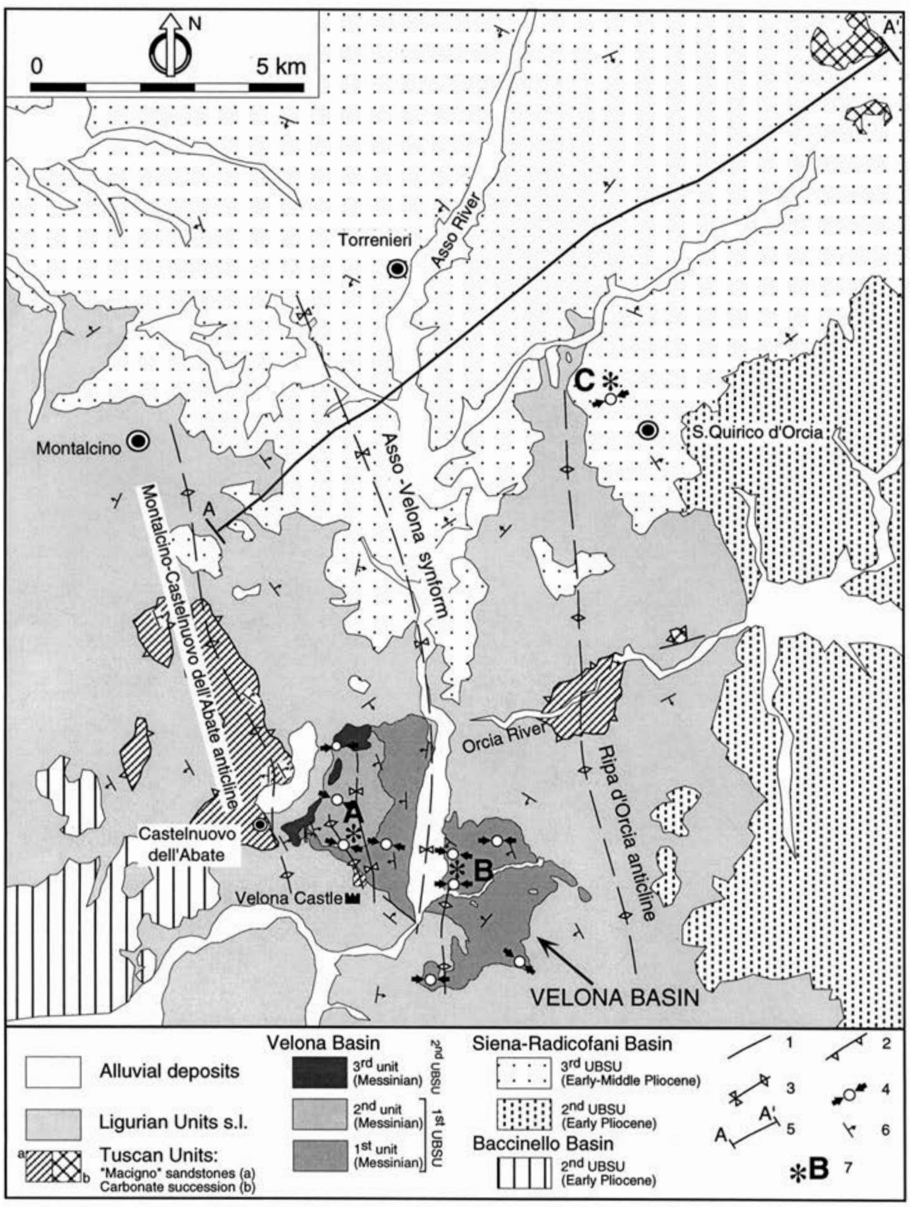

Fig. 4. Structural-geological sketch map of the Velona Basin and the adjoining Siena-Radicofani Basin. 1- fault; 2- Ligurian Units overthrust (triangles on the hanginwall); 3- syncline and anticline; 4- site of structural measurement and deduced direction of compression; 5- trace of the seismic line shown in Fig. 5; 6- strike and dip of the beds; 7- Key outcrop-scale structures described in the text and shown in Fig. 6.

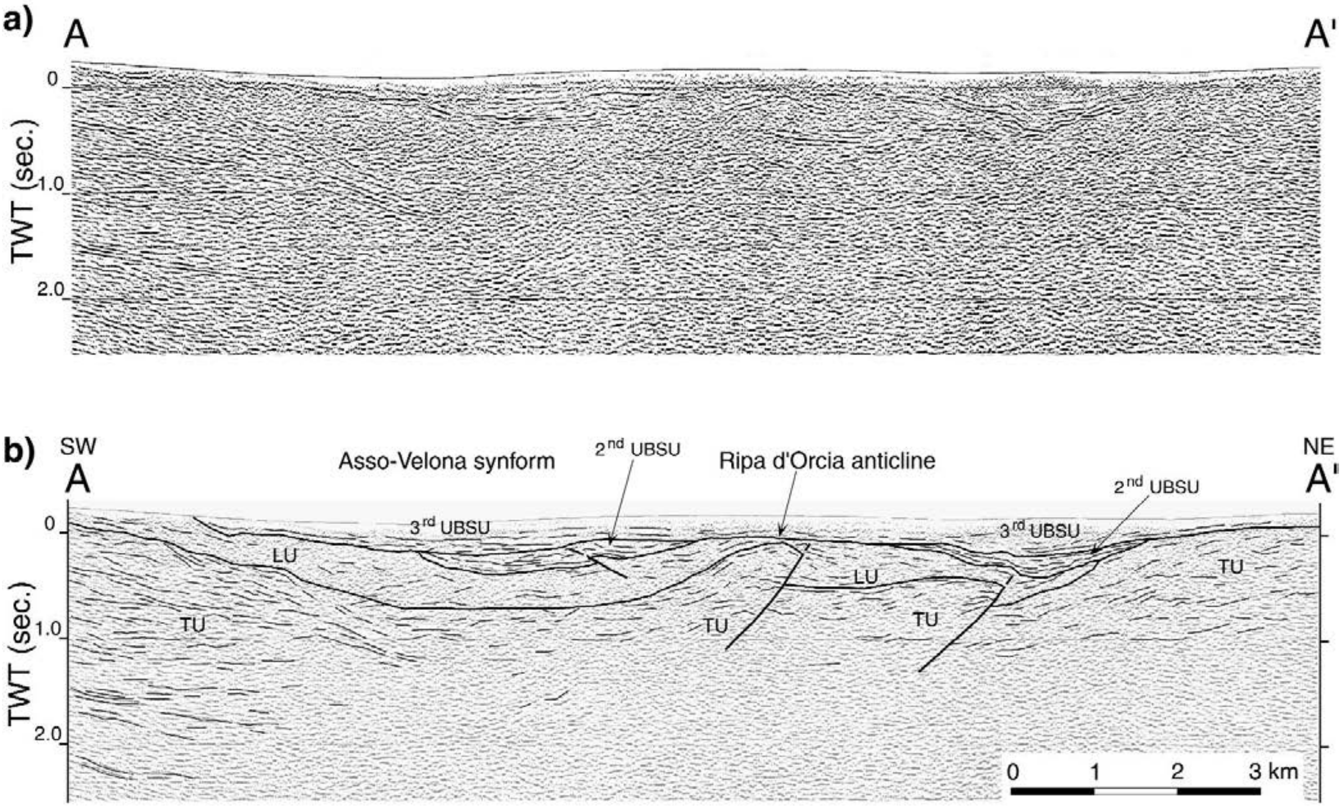

Fig. 5 - a- Uninterpreted and b- interpretative line-drawing of the seismic line A-A’, whose trace is indicated in Fig. 4 (seismic line by courtesy of FINA Italiana S.p.A.). The ages of the 2nd and 3rd UBSUs are reported in Fig. 4. TU- Tuscan Units; LU- Ligurian Units s.l.

A PROPOSAL FOR THE HINTERLAND BASINS EVOLUTION

Summarising the results of the studies carried out on the NA hinterland basins (Boccaletti et al., 1995a; 1995b; 1996; Bonini and Moratti, 1995; Landi et al., 1995; Bonini, 1997), some general common features to the investigated basins can be pointed out as follows:

– an initial synformal-shaped structure of the basins;
– basins generally develop between thrust-faults or thrust anticlines;
– unconformities distinguished within the stratigraphic succession of the basins are commonly strongly tilted basinward, displaying gentler inclination proceeding from the basin margin to the centre of the basin and from older to younger sediments; locally progressive unconformities developed, indicating a synsedimentary margin uplift;
– both compressional and extensional deformations affect the basin fill, but usually extension post-dates compressive deformations;
– compressive deformations are well developed and *palaeo*-stress determinations indicate that the trajectories of the shortening directions are generally orthogonal to both the trend of the basins and the thrust-anticlines bounding the basins.

Considering the above data and that sediments of the basins are commonly affected by compressive deformations, both in front and back of the thrust anticlines, we hypothesise that the studied Neogene to Pleistocene hinterland basins of the Northern Apennines developed in a compressive tectonic regime related to thrusting (e.g. Boccaletti et al., 1995a; 1995b). We have also attempted to correlate the thrust activity along the thrusts bounding the basins to the main unconformities within the basin fills, proposing a timing of deformation for the internal side of the chain during the Neogene-Pleistocene interval. In this frame, we propose that the main compressive phases and thrust reactivations are identifiable by the main unconformity-bound stratigraphic units that are well correlatable basin to basin and that thus represent regional unconformities (UBSUs). The successions of the hinterland basins have been subdivided into five UBSUs bounded by roughly synchronous angular unconformities, that are thought to be associated with the main shortening episodes (Boccaletti et al., 1992; 1994; 1997; Fig. 7). Likely, the whole chain was affected by those shortening phases, as similar stress field orientations and unconformities occurr nearly simultaneously both in the central-external sector and in the internal sector of the chain (Boccaletti and Sani, 1998, and ref. therein; Fig. 7). Probably, these main phases of shortening, had also an important influence on the magmatism of the area. Periods of quiescence in the magmatic activity, in fact, fit well with the timing of the main compressive phases recorded by the UBSUs (Fig. 7). In other words, we suggest that the main phases of shortening interrupted the magmatic activity in the hinterland area.

The depicted structural scenario, fits well with the reinterpretation of the crustal profile CROP 03 running across the whole Northern Apennines chain (Finetti et al., 1997a; 1997b). In this interpretation, the crustal structure of the Northern Apennines is dominated by W-dipping thrust faults involving the basement, defining a thick-skinned tectonic style. Typically, the wavelength of the basement thrusts is around 30-40 km, that is comparable with the numerical modelling for the brittle upper crust by Martinod and Davy (1992). Conversely, the wavelength of the thrusts in the cover is much smaller, and a thin-skinned tectonics has been as-

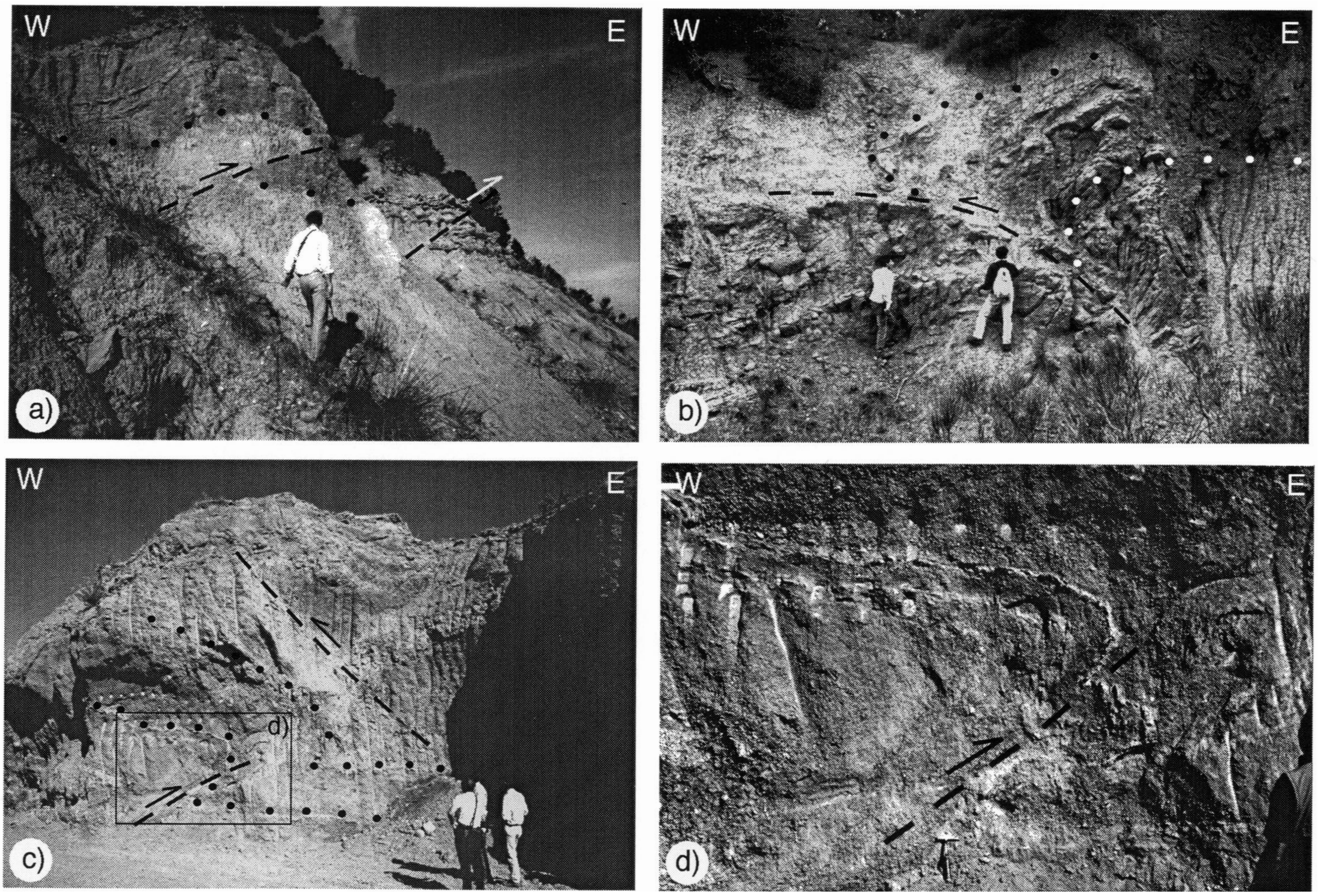

Fig. 6 - Key outcrop-scale structures evidencing the activity of the thrust anticlines bounding the Velona Basin during its evolution. a) SW-dipping reverse fault affecting the lower Messinian sediments (1st UBSU) of the Velona Basin east of the Montalcino-Castelnuovo dell'Abate anticline (outcrop labelled A in Fig. 4; Podere Nuovo dei Campi area); b) E-dipping reverse fault and fault-related fold affecting the lower Messinian continental sediments (1st UBSU) of the Velona Basin on the Ripa d'Orcia anticline backlimb (outcrop labelled B in Fig. 4; Orcia River area); c) E-verging overturned thrust-related fold and E-dipping reverse fault (defining a triangle zone) affecting the Lower-Middle Pliocene marine sediments (3rd UBSU) on the Ripa d'Orcia anticline forelimb (outcrop labelled C in Fig. 4; quarry near St. Quirico d'Orcia Village); d) close-up of the E-verging fault-related fold.

sumed due to the presence of the basal *décollement* horizon constituted by the Upper Triassic evaporites (Burano Fm.). In this frame, Boccaletti and Sani (1998) propose a piggy-back sense of emplacement, from W to E, for the basement thrusts. In their model, thrusts in the cover have been repeatedly reactivated by the basement thrusts, that in turn have been reactivated during the main Neogene shortening phases. The basement thrusts are inferred to have reactivated the thin-skinned thrusts lying in front of them, originating thrust-top basins like the Mugello and the Velona ones. Normal faults would then represent second-order structures accommodating uplifting related to thrusting. In some cases, like the Mid-Tuscany Metamorphic Ridge, W-dipping normal faults are associated with W-dipping thrusts, defining a "composite wedge" geometry (see Migliorini's 1948 model).

In conclusion, on the basis of both the deformations affecting the hinterland basins and the interpretation of geophysical data (Arisi Rota and Fichera, 1985; Ponziani et al., 1995; Finetti et al., 1997b), we suggest that crustal shortening in the hinterland area continued until Pliocene times and involved thrusting associated with basin development. In this model, normal faults either post-date basin formation (e.g. Bonini, 1997; 1998; Piccardi et al., 1997; Sani et al., 2000, this issue) or accommodate thrusting processes (Finetti et al., 1997a; 1997b). We also propose that the regional angular unconformities limiting the UBSUs of the hinterland basins roughly indicate the timing of the main crustal shortening phases.

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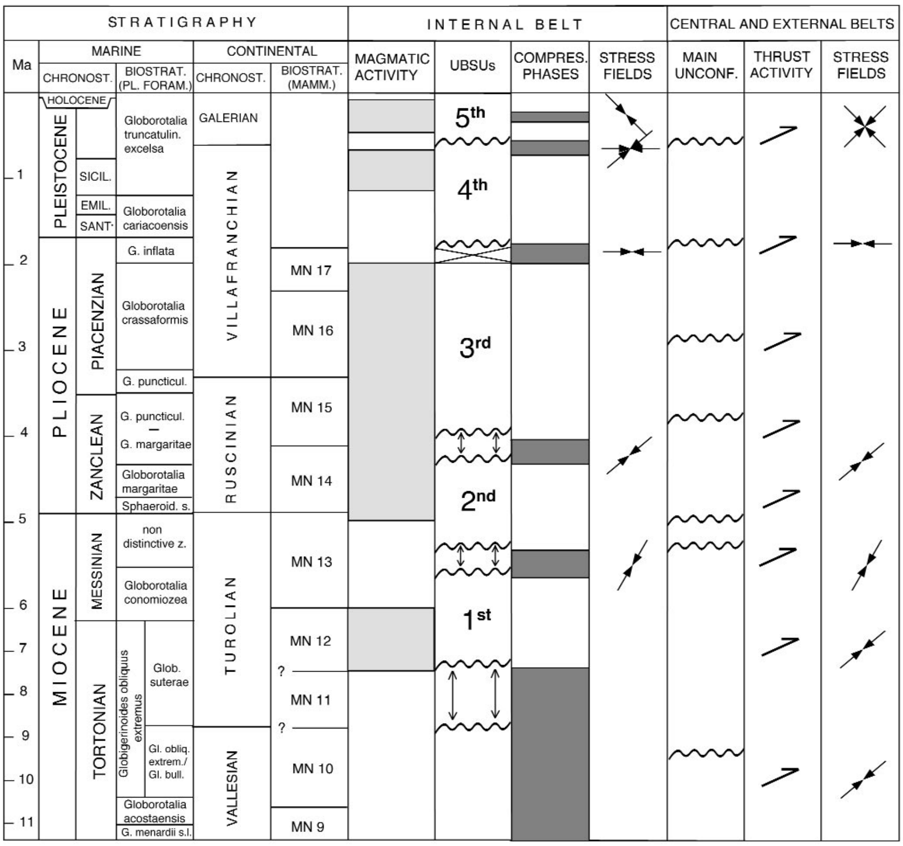

Fig.7 - Comparison of the structural data and magmatic activity in the hinterland area with the structural data and thrust activity in the central and external side of the Northern Apennines (after Boccaletti and Sani, 1998). The main phases of magmatic activity are from Serri et al. (1993) and Barberi et al. (1994).

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