A TRANSECT IN SOUTHERN TUSCANY, FROM THE BACCINELLO BASIN TO THE CETONA RIDGE

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INTRODUCTION AND PURPOSE OF THE EXCURSION

The Northern Apennines (NA) is a NE-verging thrust and fold belt (Fig. 1) produced by the Cenozoic collision between the Corso-Sardinian block and the Adria Plate (Boccaletti and Guazzone, 1972; 1974; Principi and Treves, 1984; Malinverno and Ryan, 1986, among others). The NA thrust-nappe pile consists of sequences deposited on the Adria Plate continental margin (Tuscan and Umbria-Marche Units) which were overthrust by the Ligurian Units during continental collision. The Ligurian Units, which consist of ophiolites and their sedimentary covers, represent the remnants of the Ligurian-Piedmont paleo-ocean (Abbate et al., 1970). The NA evolution, after the Oligocene continental collisional phase, has been referred to two different models. In the first one, the development of an external thrust belt shifting eastwards, coupled with an internal extensional area is envisaged. In this process both the crust and the lithosphere would be involved (Merla, 1951; Boccaletti and Guazzone, 1974; Elter et al., 1975; Carmignani et al., 1980; Boccaletti et al., 1990; Patacca et al., 1990). In front of the migrating chain a foredeep basin developed during Late Oligocene-Miocene, whose deposits were progressively annexed to the chain (Ricci Lucchi, 1986; Boccaletti et al., 1990). In the second model, the accretionary prism, thickened by crustal collision, would collapse to recover its equilibrium conditions (Carmignani and Kligfield, 1990). As a consequence of the gravitational collapse, the development of core complex structures and of extensional tectonics has taken place since Burdigalian-Langhian (Carmignani et al., 1994). In this model, the Northern Apennines thrust belt is explained as due to gravitational tectonics active since the Early Miocene (Decandia et al., 1993; Carmignani et al., 1995).

Starting in late Tortonian, the internal area (hinterland) of NA was characterized by the development of continental and marine basins, mostly striking from NW-SE to N-S, and subparallel to the main thrust fronts of the chain. Their formation has been commonly referred to the extensional processes related to the opening of the Tyrrhenian Basin, either in a back-arc regime (Boccaletti and Guazzone, 1972; 1974; Malinverno and Ryan, 1986; Royden et al., 1987; Boccaletti et al., 1990; Patacca et al., 1990), or as due to late orogenic gravity collapse (Carmignani and Kligfield, 1990; Cameli et al., 1993; Carmignani et al., 1994; Keller et al.,

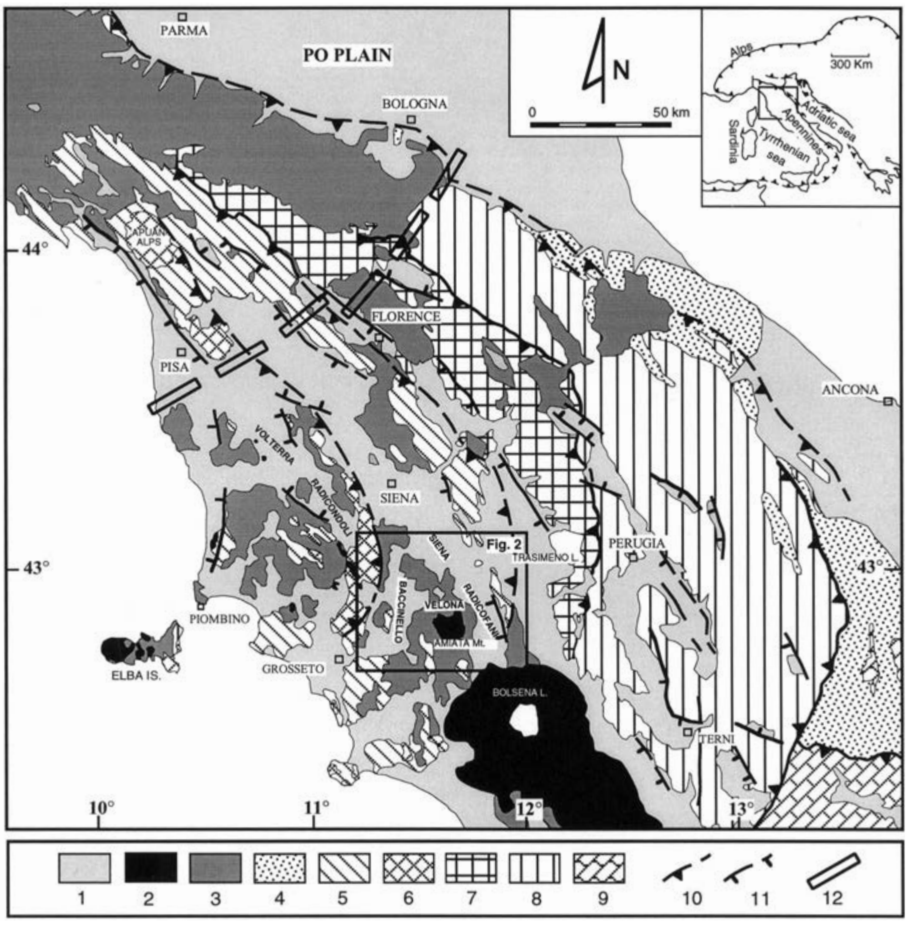


Fig. 1 - Geological map of Northern Apennines. 1- Neogene-Quaternary deposits; 2- Magmatic rocks; 3- Ligurian, Subligurian and Epiligurian Units; 4- Tortonian "Molasse", Laga Formation and Pliocene external sediments; 5- Tuscan Unit; 6- Tuscan Metamorphic Unit; 7- Cervarola-Falterona and Castel Guerrino Units; 8- Umbro-Marchean Units; 9- Abruzzi-Latium platform; 10- Main thrust fronts (triangles on the hangingwall); 11- Main normal faults (barbs on the downthrown side); 12- Livorno-Sillaro line. Location of Fig. 2 is shown.

1994). The eastward younging trend of the hinterland basins has been related to the eastward shifting of the extensional front, which followed the migration of the thrust front (Merla 1951; Elter et al., 1975).

However, in the last two decades structural studies have shown that the deposits of the hinterland basins have been affected by widespread compressional deformations and by major angular unconformities (Boccaletti et al., 1995, and references therein) that allow to subdivide the entire succession into five Unconformity Bounded Stratigraphic Units (UBSUs, Salvador, 1987).) since the unconformities that limited each UBSU have been correlated on a regional scale, (Boccaletti et al., 1994; 1995). The deformations affecting the basin fill, their architecture, the presence of regional unconformities strongly suggest that they have mostly developed under a compressional tectonic regime, tied to reactivation of thrust faults affecting the pre-Neogene substrate (Boccaletti et al., 1995; 1997; Bonini and Moratti, 1995; Landi et al., 1995).

The objective of this excursion, whose road log is reported in Fig. 2, is to illustrate the relationships between tectonics and sedimentation in the hinterland basins along a transect across Southern Tuscany including the Baccinello-Cinigiano, Velona and Siena-Radicofani Basins. In this area, basin development has been mainly related to the activity of two crustal thrusts: the Mid-Tuscany Metamorphic Ridge and the Cetona Mountain thrusts (Fig. 3).

FIELD TRIP

FIRST DAY

The Baccinello-Cinigiano Basin

The Baccinello-Cinigiano Basin is located in Southern Tuscany and it is limited by the Mid-Tuscany Metamorphic Ridge (MTMR) on the western side, and by the Montalcino-Monte Amiata-Monte Labbro alignment on the eastern side (Fig. 3).

The Neogene-Quaternary succession of this basin includes four main cycles limited by angular unconformities, described as UBSUs, three of which are shown in Fig. 4.

The 1st UBSU formed during middle Tortonian-early Messinian and consists of (from bottom to top): polymictic conglomerates constituted by disorganized, matrix-supported angular pebbles which mainly crop out on the eastern margin of the basin; lacustrine sands, clays and clayey silts with sandy limestone beds rich in organic material which discontinuously crop out in the central-southern part of the basin; lacustrine clays and silts containing lignite layers which unconformably overlie older sediments of the basin and widely crop out in the whole basin; lacustrine sands, carbonates and gypsum include various lithofacies each of them prevailing in different areas.

The sediments of the 2nd UBSU are late Messinan-Early Pliocene in age and crop out in the whole basin. They include polymictic conglomerates constituted by rounded pebbles in a sandy-clayey, strongly reddened matrix. These conglomerates can be correlated (Pasquarè et al., 1983) with the Montebamboli Conglomerate (Lazzarotto et al., 1969) that crops out west of the MTMR. These conglomerates are unconformably overlain by the Lower Pliocene marine clays and sandy clays that mainly crop out near the Orcia River and W of Baccinello. They include clays, sandy clays and sands rich in marine micro- and macro-fossils.

The 3rd UBSU is constituted only by marine sands of Middle-Late Pliocene age. They crop out in the northern and southern portions of the basin and rest unconformably on the other Neogene sediments (1st and 2nd UBSUs). They consist of yellow sands interbedded with conglomerate and shelly limestone layers. In the Civitella Marittima area and in the Mt. Faete area (i.e. western margin of the basin) these sediments are laterally heteropic with polymictic conglomerates constituted by rounded pebbles in a dark-brown sandy matrix.

The sediments of the 4th UBSU of late Villafranchian age are represented by fluvio-lacustrine conglomerates scattered cropping out in the central-southern part of the basin. They are constituted by rounded pebbles in a sandy-clayey dark-red matrix.

The geological study has revealed some important aspects that lead to a new hypothesis regarding the tectonic evolution of the basin. Some reverse faults have been

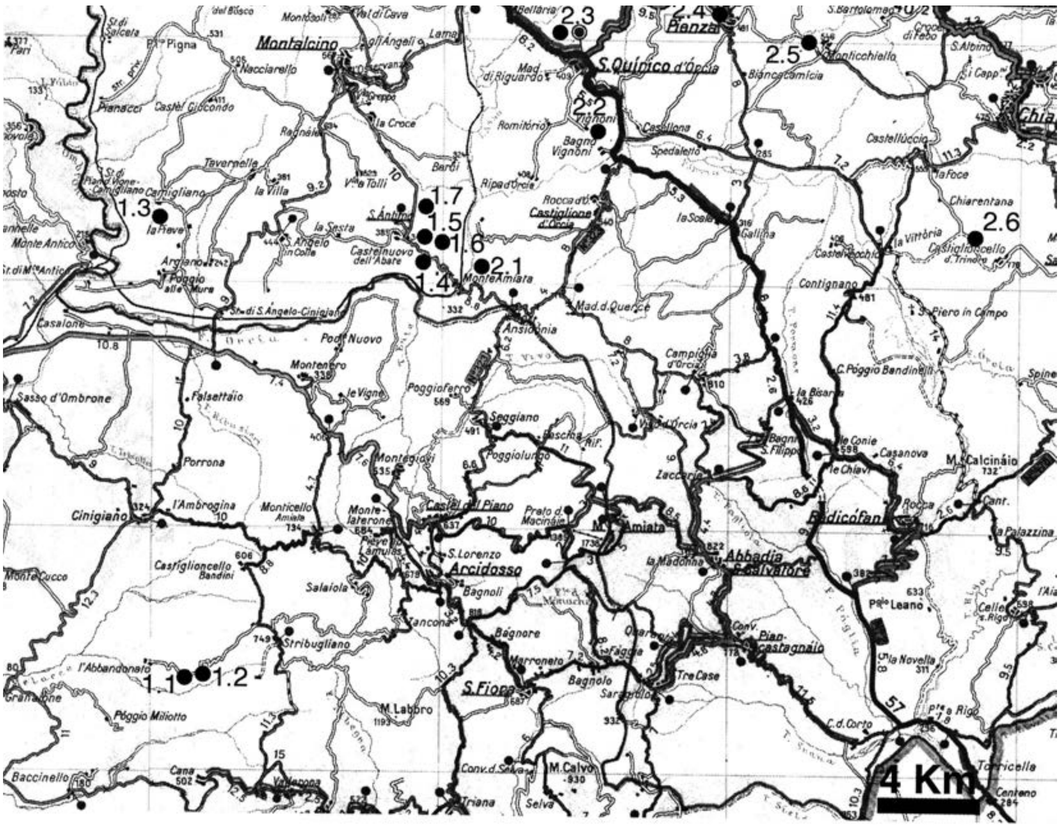


Fig. 2 - Road log of the excursion (modified after “Atlante stradale d’Italia” of the Italian Touring Club, 5th edition, 1980).

found both at the mesoscale and macroscale, mostly on the eastern side of the basin. Some normal faults have cut the whole Neogene and are mostly located in the southern part of the Cinigiano-Baccinello basin. They obliquely crosscut the N-S trend of the basin (Fig. 4). The normal faults did not control location and shape of the basin.

Along the eastern margin of the basin, progressive unconformities (*sensu* Riba, 1976) becoming paraconformities toward the centre of the basin have been observed (see "Schema Stratigrafico" in "Carta Geologica del Bacino Cinigiano-Baccinello", Carobbi et al., 1996). In particular, the deposits of the 1st and 2nd UBSUs are folded (somewhere reaching vertical dips), whereas the 3rd UBSU deposits are only slightly deformed. Vertical strata in the 1st UBSU deposits are also present near the western margin of the basin.

These overall characteristics of the deposits, the relationships among the three UBSUs and the compressional deformations affecting the basin fill, allow the formation and evolution of this basin to be associated with a compressional rather than an extensional regime, as it was previously interpreted (Boccaletti et al., 1995; Landi et al., 1995).

The itinerary ideally starts from Cinigiano (Fig.2). Eastwards, after about 7 km, a deviation on the right (southwards) leads to Castiglioncello Bandini and to Stribugliano; 1.5 km before this village a further deviation to the left to L'Abbandonato leads, after 5 km, to the stops 1.1 and 1.2, located in the same area.

Stop 1.1 - *First-order angular unconformity between 1st and 2nd UBSUs (Figs. 2 and 3).*

A good exposure exists of the unconformity separating the sediments of the 1st UBSU from those of the 2nd UBSU (Fig. 5). The unconformity separates the basal conglomerates, constituting the first term deposited in the basin, unconformably overlying the pre-Neogene substratum, from the upper Messinian conglomerates. The basal conglomerates are assigned, on the basis of their stratigraphic position, to the middle Tortonian.

The strongly erosional contact between the basal conglomerates and the upper Messinian conglomerates is quite evident because of the difference in colour between the two terms. The 1st UBSU conglomerates plunge westwards towards the centre of the basin with progressively steeper dips approaching the eastern border, whereas the 2nd UBSU conglomerates display a gentler dip of 10-20° westward (Fig. 5).

Stop 1.2 - *Second-order angular unconformity within the 1st UBSU (Figs. 2 and 3).*

Here we can observe the oldest lithological units cropping out in the basin, both belonging to the 1st UBSU. In the first outcrop the lacustrine sands and carbonates and the upper lacustrine clays are well exposed. The carbonates show a brackish molluscan assemblage mainly consisting of *Dreissena* and *Limnocardium* (level F1, Gillet et al., 1965); these carbonates can be correlated with the lignite-bearing lacustrine clays cropping out along the Trasubbie Creek (Landi et al., 1995; Benvenuti et al., 1997). Within this formation two different layers have been recognized containing mammal fauna assemblages (V_0-V_1) (Lorenz, 1968; Hurzeler and Engesser, 1976) of middle Tortonian age.

The upper clays are up to 180 m thick and widely crop out in the whole basin. They are interbedded, in this area, with centimetric-thick brown marly layers. The discovery of two mammal levels (V^2-V^3) in these sediments, allow to ascribe them to the late Tortonian-early Messinian age (MN13) (Lorenz, 1968; Hurzeler and Engesser, 1976).

The passage from lacustrine sands and carbonates to lacustrine clays occurs through an angular unconformity, evidenced by subvertical carbonates underlying subhorizontal lacustrine clays (Fig. 6). The same angular unconformity is also well recognizable on the right side of the Trasubbie Creek, in the Baccinello area.

The lacustrine clays are also affected by several NE-dipping mesoscopic reverse faults (Fig. 7).

We came back to Cinigiano and take the road northwards, for reaching, after about 10 km, the main road to Mt. Amiata. After 1.5 km, a deviation on the left leads to St. Angelo Scalo and to Cinigiano. The stop 1.3 is located 700 m SW of Camigliano (Fig. 2).

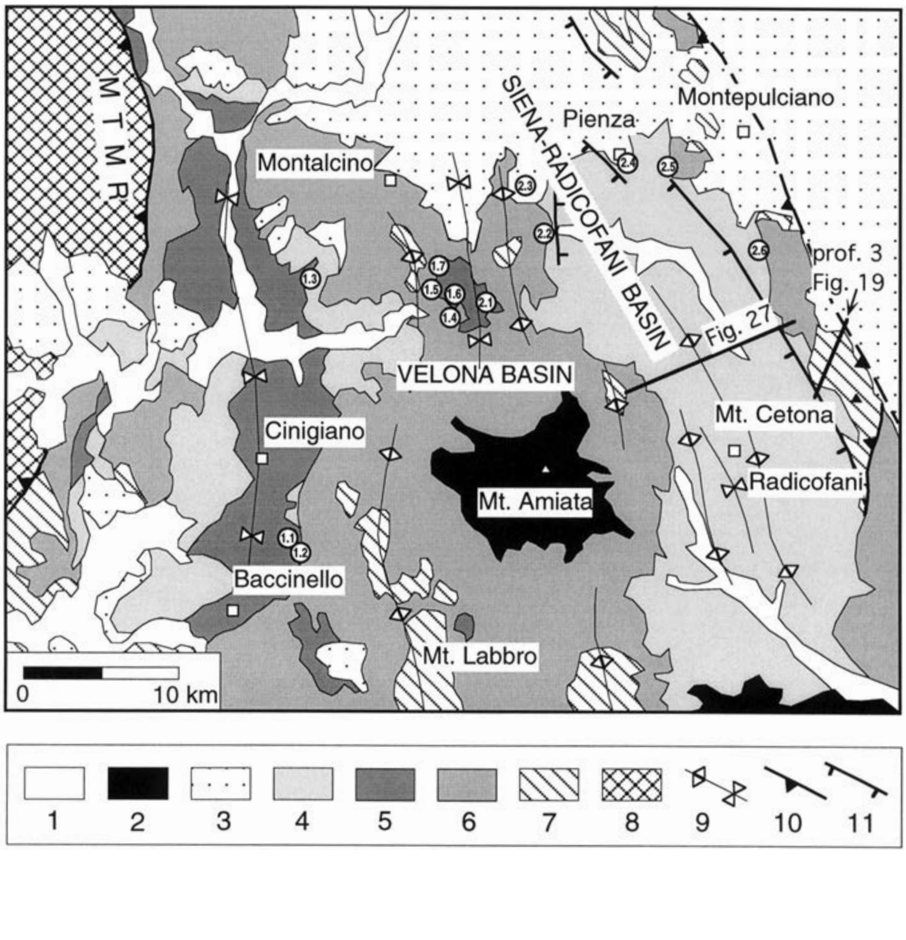


Fig. 3 - Schematic geological map of Southern Tuscany, including Cinigiano-Baccinello, Velona and Siena-Radicofani Basins, and the locations of the stops (numbers 1.1-2.6). MTMR = Mid-Tuscany metamorphic Ridge. 1- Recent alluvial deposits; 2- Volcanic rocks; 3- 3rd UBSU deposits; 4- 2nd UBSU deposits; 5- 1st UBSU deposits; 6- Ligurian Units s. l.; 7- Tuscan Unit; 8- Tuscan Metamorphic Units; 9- Anticline and syncline; 10- Thrust fault; 11- Active normal fault. See Fig. 1 for location.

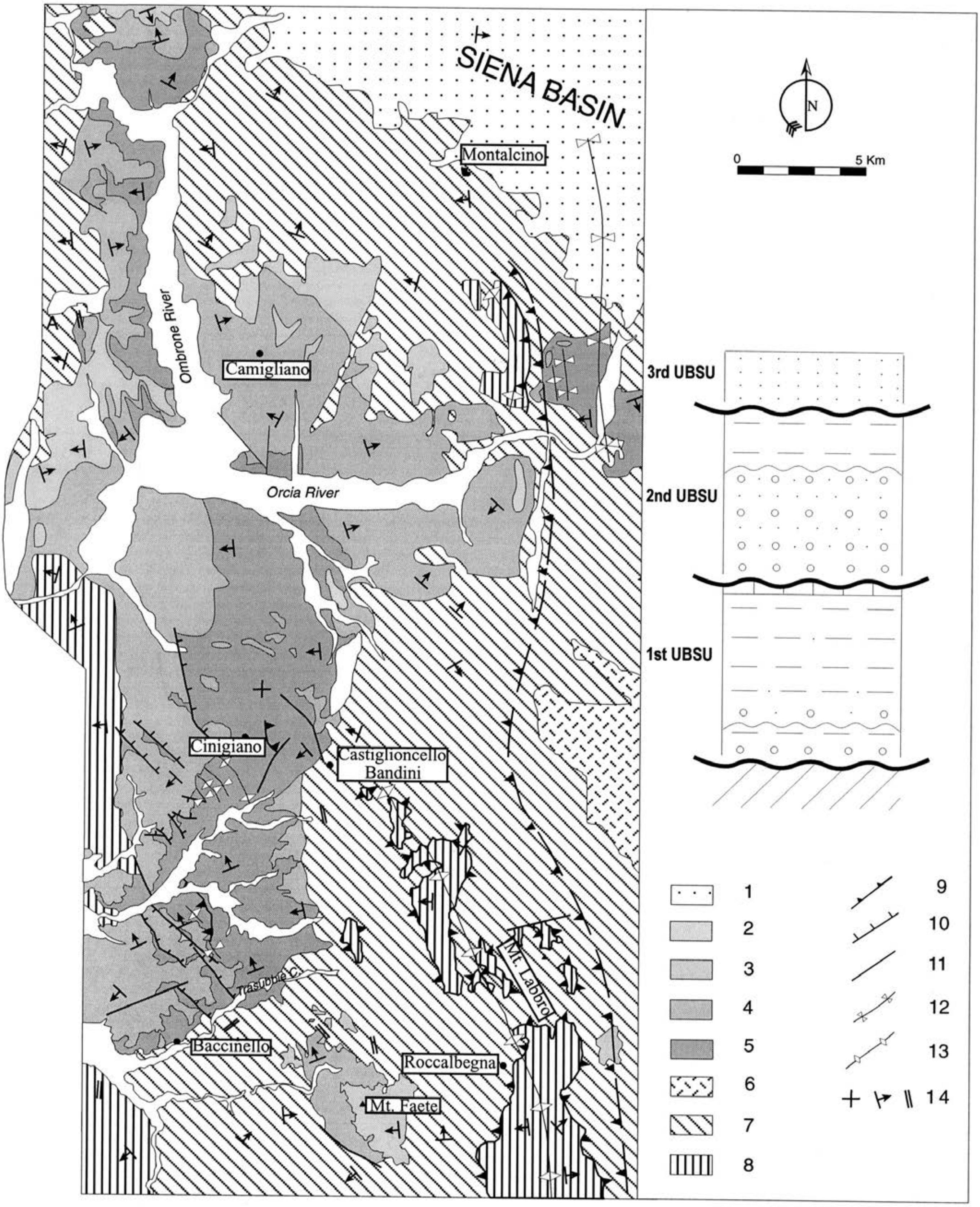


Fig. 4 - Schematic geologic map and schematic stratigraphic succession of the eastern part of the Cinigiano-Baccinello Basin. 1- Siena Basin deposits (2nd and 3rd UBSUs); 2- 4th UBSU deposits; 3- 3rd UBSU deposits; 4- 2nd UBSU deposits; 5- 1st UBSU deposits; 6- Magmatic rocks; 7- Ligurian Units s.l. (LU); 8- Tuscan Unit (TU); 9- Thrusts and reverse faults (triangles on the hangingwall); 10- Normal faults (barbs on the downthrown side); 11- Faults; 12- Synclines; 13- Anticlines; 14- Strike and dip of the beds: sub-horizontal, normal, vertical.

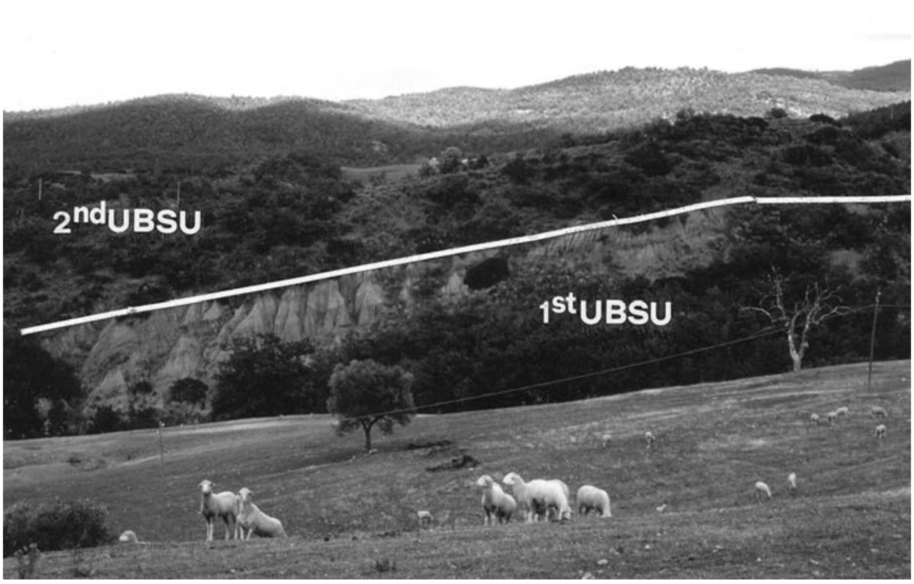


Fig. 5 - Angular unconformity between 1st UBSU and 2nd UBSU at Pod. Passonaio, near l'Abbandonato (Stop 1.1).

Stop 1.3 - *Angular unconformities affecting the 2nd and 3rd UBSUs (Figs. 2 and 3).*

The outcrop is located near the northeastern margin of the Cinigiano-Baccinello Basin, where it is possible to observe the unconformities affecting the 2nd and 3rd UBSUs.

The second-order unconformity within the 2nd UBSU, between the upper Messinian conglomerates and the Lower Pliocene marine sands is well exposed (Fig. 8). The conglomerates plunge toward the west, with dip of about 20° and are in contact with the overlying Lower Pliocene marine sands through a planar surface slightly dipping (about 10°) eastwards. This unconformity is only locally present in Southern Tuscany and not sufficiently widespread to define another UBSU.

In the upper part of the outcrop, it is possible to observe the regional first-order unconformity separating the 2nd and 3rd UBSUs, which is present in the whole Southern Tuscany (Fig. 8). This angular unconformity separates through a subhorizontal surface the Lower Pliocene east-dipping marine sands from the overlying Middle Pliocene conglomerates.

The geometrical relationships among the various angular unconformities shown at Stops 1.1, 1.2 and 1.3 along the eastern margin of the basin (Figs. 2 and 3), indicate a synsedimentary uplifting of this margin which caused a progressive tilting of the unconformities basinward.

This process, that acted from middle Tortonian to Pliocene, has been related to the activity of the Mt. Labbro-Montalcino thrust bounding the basin to the east (Fig. 2). This structure also affects, at depth, the Tuscan basement (Bally et al., 1986; Boccaletti et al., 1995).

Fig. 6 - Second-order angular unconformity within 1st UBSU's sediments at Stop 1.2.

Fig. 7 - Mesoscopic southwest-verging reverse faults within 1st UBSU's deposits at Stop 1.2.

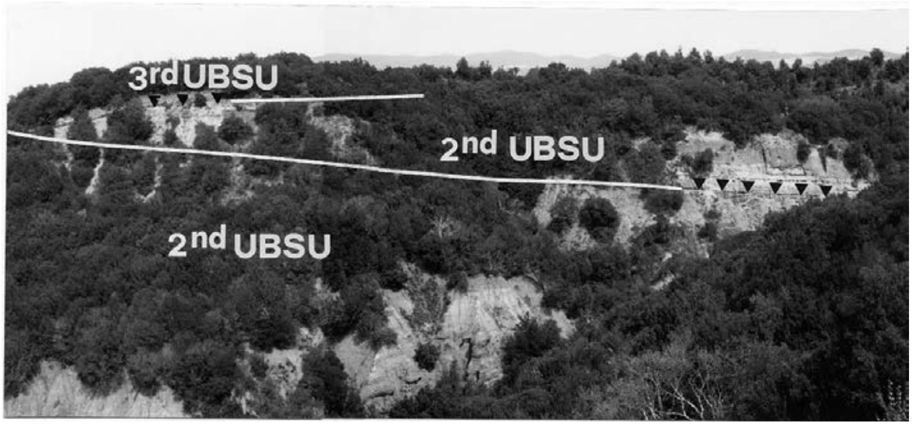


Fig. 8 - Main unconformity between nd and 3rd UBSUs, and second-order angular unconformity within 2nd UBSU's deposits at Stop 1.3.

The excursion continues in the Velona Basin.

The Velona Basin

The Velona Basin (VB) is a NNW-SSE oriented small continental basin located between two main ridges, the Ripa d'Orcia and the Montalcino-Castelnuovo dell'Abate ridges (Fig. 9). These ridges correspond to E-verging thrust anticlines involving both the Ligurian Units and the underlying Tuscan Succession. The thrust anticlines separate this basin from the Baccinello-Cinigiano one to the west and from the Siena-Radicofani basin to the east (Figs. 2 and 9).

The continental succession of the VB, previously described by Damiani et al. (1980) and by Martini and Sagri (1993), and Rook and Ghetti (1997), consists of alternating Upper Miocene conglomerates, sands and clays. Field mapping allowed us to recognize three main depositional cycles separated by syntectonic angular unconformities (Fig. 9). First and second cycles together constitute the 1st UBSU, while the third cycle corresponds to the 2nd UBSU.

The first cycle, about 140 m thick, crops out in the central-eastern part of the basin and onlaps the folded substrate. It consists of a basal, often reddish, conglomerate with alternating sandy beds cropping out along the eastern margin of the basin. Sands increase upwards and pass to lignite bearing clays either towards the centre of the basin or towards the top of the succession. The cycle ends with a top sandy level indicating a coarsening upwards trend (Fig. 9).

The second cycle crops out in the western side of the VB and it is about 70-80 m thick. The basal portion of this cycle consists mainly of conglomerates unconformably overlying the first cycle deposits and the substratum. Upwards, the deposits continue with a thick sandy layer passing towards the centre of the basin (eastwards) to clays and silty-clays (Fig. 9).

The third cycle sediments crop out along the western margin of the VB and are composed of reddish, up to 30 m thick conglomerates unconformably overlying both the substratum and the previous cycles deposits (Fig. 9).

The VB has been interpreted by Martini and Sagri (1993) and Rook and Ghetti (1997) as a half-graben; the master fault, controlling the sedimentation, would be located along its western margin. The general setting of the VB deposits is a gentle syncline and no large normal faults have been observed within the basin. The main structure is complicated by the occurrence of folds affecting both the sediments of the 1st UBSU and the substrate. Also mesoscopic compressional structures, such as folds, reverse faults and stylolitic pits on conglomerates, that appear to mainly concentrate near the basin margins, are well developed both in the first and in the second cycle deposits. An E-W to ESE-WNW trending direction of compression has been determined in all sites of measurement, both in the first and in the second cycle deposits, and it is coherent with the trend of the major folds affecting the basin (St. Giorgio anticline and Ripi syncline in the second cycle sediments, Piane anticline in the first cycle sediments, Fig. 9). The third cycle deposits are not affected by folding as they blanket the older deposits through a nearly horizontal surface.

To evaluate the paleostress field and to better kinematically constrain the main structures affecting the VB deposits, mesoscopic fault-slip data, folds and stylolitic pits on the calcareous pebbles surfaces have been collected at 11 sites. The principal stress axes have been computed from the fault-slip data using the inversion method of Carey (1976; 1979). The orientation of the stylolitic columns on calcareous pebbles surface have been used to obtain the local direction of maximum compression (Figs. 9 and 14).

We came back to St. Angelo Scalo and we go northwards. After about 8 km a deviation on the right leads to Castelnuovo dell'Abate (Fig. 2); 2 km passed Castelnuovo dell'Abate, towards Mt. Amiata Scalo, near the Velona Castle we stop.

Stop 1.4 - *General view of the Velona basin toward NE (Fig. 2 and 3).*

The deposits of the basin are visible between the Ripa d'Orcia ridge to the east and the Montalcino-Castelnuovo dell'Abate ridge to the west (Figs. 9 and 10). In the foreground (Fig. 10) the second cycle deposits, unconformably overlain by the third cycle ones, crop out. They consist mainly of clays, silty clays and sandy levels; some conglomeratic levels are also visible in the lower part of the succession. The general structure of the basin is referable to a NNW-SSE trending gentle syncline. This setting is complicated by the occurrence of basin-wide, as well as outcrop-scale deformations, mainly located near the western margin of the basin (Ripi syncline and St. Giorgio and Piane anticlines; Fig. 9).

Eastwards (towards the Orcia R.), the first cycle deposits crop out extensively, generally dipping about 20-25° towards WSW. To the east, the basin is delimited by the Ripa

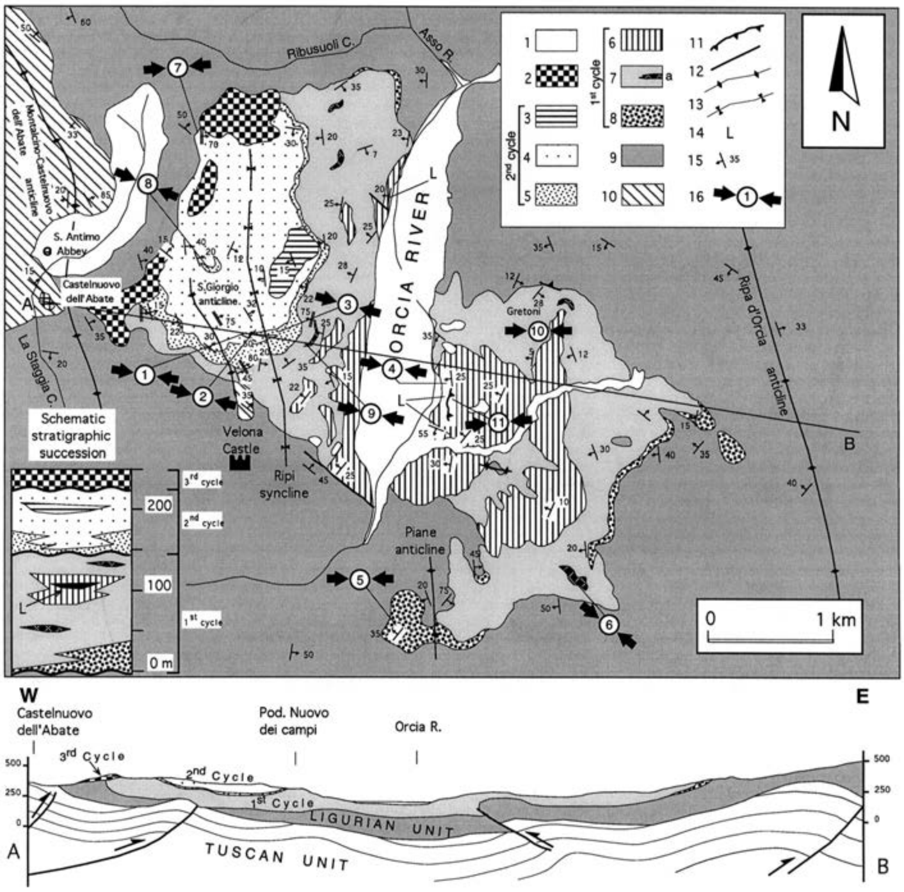


Fig. 9 - Structural-geological map of the Velona Basin and schematic stratigraphic succession (From Bonini et al., 1997). 1- Alluvial and terraced deposits; 2- 3rd cycle conglomerates (Montebamboli Conglomerates); 2nd cycle deposits: 3- Clays and silty clays; 4- Sands; 5- Conglomerates; 1st cycle deposits: 6- Lignite-bearing clays; 7- Sands with lenticular conglomeratic bodies (a); 8- Basal conglomerates; 9- Ligurian Units s.l.; 10- Tuscan Unit; 11- Thrust faults; 12- Faults; 13- Anticline and syncline axes; 14- Lignitiferous levels; 15- Strike and dip of beds; 16- Sites of structural measurements and paleo-stress orientation (convergent arrows indicate the shortening direction). A-B: trace of the geological cross section.

d'Orcia ridge (Fig. 9). Here, the Tuscan Unit (in particular the "Macigno" sandstones), tectonically overlain by the Ligurian Units, crops out along the Ripa d'Orcia gorge.

We come back towards Castelnuovo dell'Abate and, 1 km before the village, a small country road to the right leads to Podere Poggio di Sotto.

Stop 1.5 - *T-shaped angular unconformity between the first and second cycle deposits (Figs. 2 and 3).*

Vertical strata in the conglomerates of the first cycle, unconformably overlain by the second cycle deposits, are exposed along the western margin of the basin (Fig. 11). The syntectonic deposition of the second cycle sediments near this margin testifies the activity of the Montalcino-Castelnuovo dell'Abate thrust (Bonini et al., 2000, this issue). The pre-Neogene substrate consists of Ligurian Units.

The same country road as Stop 1.5, leading to Podere Novo dei Campi.

Stop 1.6 - *Outcrop-scale compressional structures (Figs. 2 and 3).*

Outcrop-scale well developed compressional structures affect the second cycle sediments, and consist of sandy-clayish deposits overlain by conglomerates. An E-verging reverse fault affects the sandy levels alternating with claystone (Fig. 12) and mesoscopic overturned folds are also visible (Fig. 13). The overlying conglomerates are widely affected by stylolitic pits and striae on the calcareous pebbles (Fig. 14). The E-W/ESE-WNW orientation of the shortening directions obtained by mesoscopic structural analysis is coherent with the orientation of the major structures affecting the second cycle deposits (Figs. 9 and 15). The mesoscopic structures are likely associated with the compressional event that gave rise to the St. Giorgio anticline and Ripi syncline.

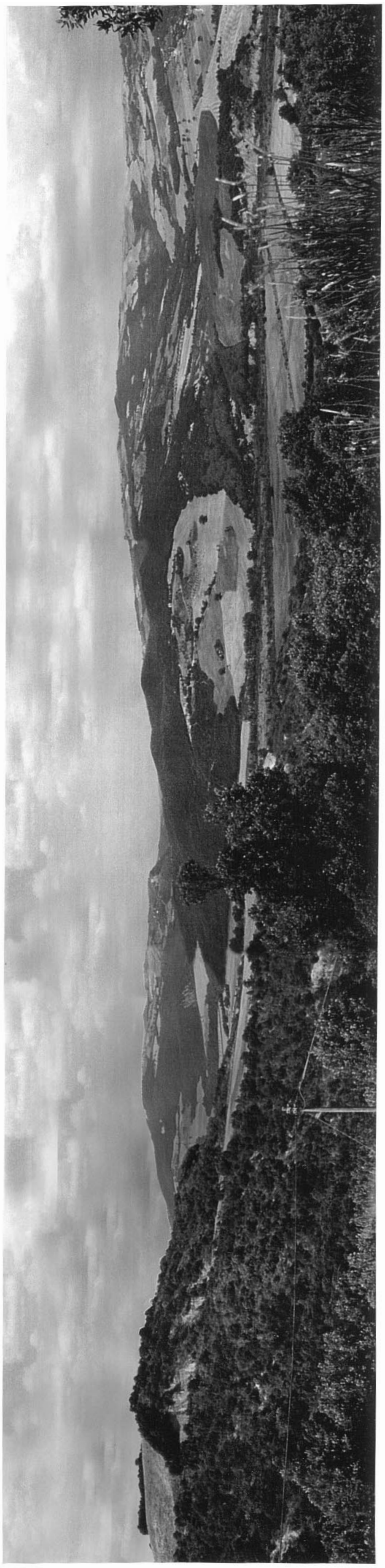
Road between Castelnuovo dell'Abate and Podere La Fornace. Locality Podere Poderina.

Stop 1.7 - *Mesoscopic reverse fault and folds (Figs. 2 and 3).*

This locality shows fault-related E-verging folds affecting the second cycle sediments near the Ligurian substrate (Fig. 16). The alternating sandy and sandy-clayish levels are offset by a reverse fault and folded according to an E-W direction of maximum shortening In this case, too, the syntectonic deformation of the second cycle sediments near the western margin has been interpreted to indicate activity of the Montalcino-Castelnuovo dell'Abate thrust.

Active tectonics in the Sant'Antimo area

From La Poderina a small country road leads to the main road to Montalcino. Looking to the left we have a sight on a small valley. The Sant'Antimo Abbey is located in the part of the La Staggia creek where the stream carves deeply into upper Pleistocene alluvial deposits (Fig. 9). The extension of these alluvial deposits, and the tilting towards the S of their upper paleosurface, suggest that this part of the valley belonged to a greater water course than the present La Staggia Creek. The La Staggia valley is in fact aligned with the upper part of the Ribusuoli Creek, which is presently set in a deep canyon, so that it results in hanging position with respect to the base level of this latter. The described features indicate that a former roughly N-S trending main stream was captured by the regressive erosion of a smaller tributary



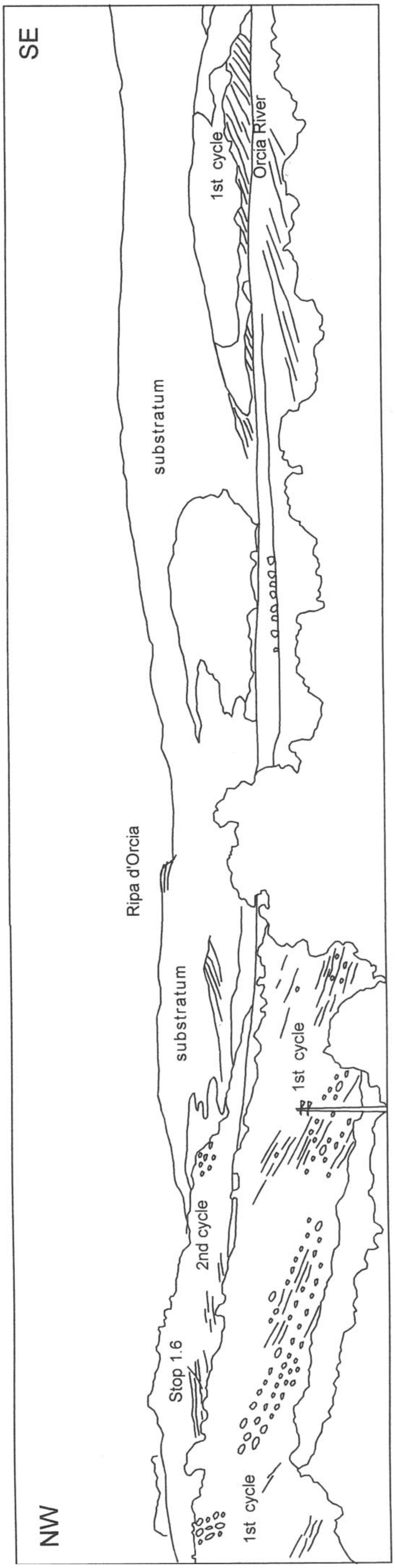


Fig. 10 - General view of the Velona Basin looking to the NE.

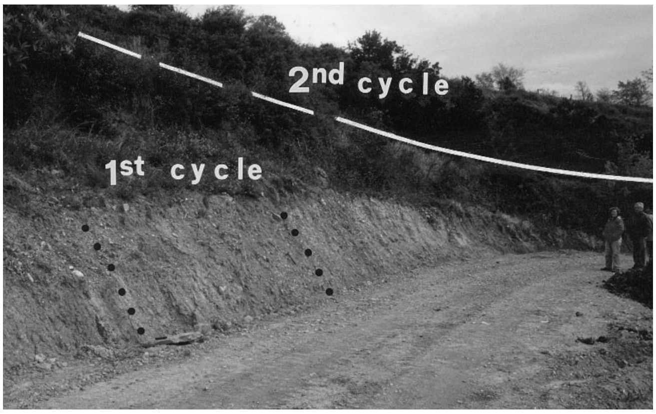


Fig. 11 - Vertical strata of the 1st cycle deposits overlain by the second cycle deposits along the western margin of the basin.

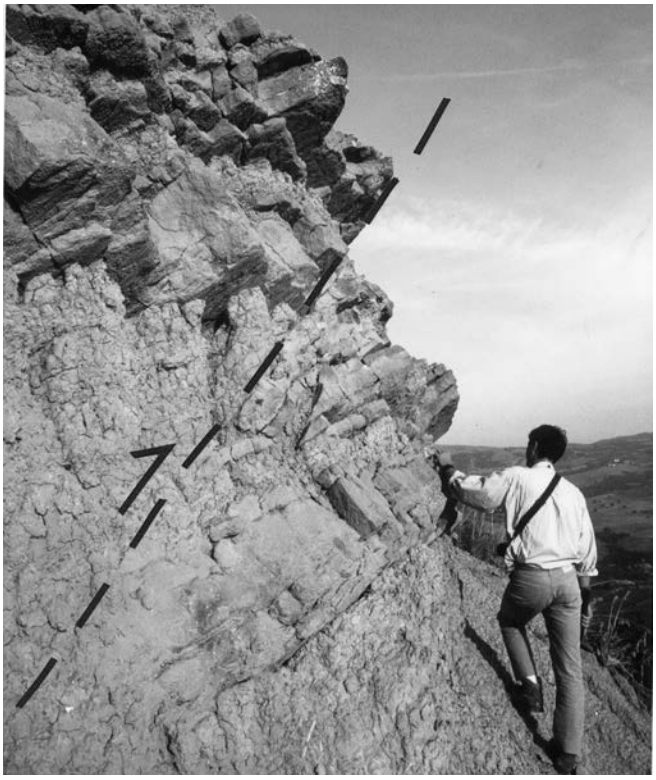


Fig. 12- E-verging reverse fault in 2nd UBSU deposits, consisting of sandy levels alternating with clays. Marco Bonini for scale.

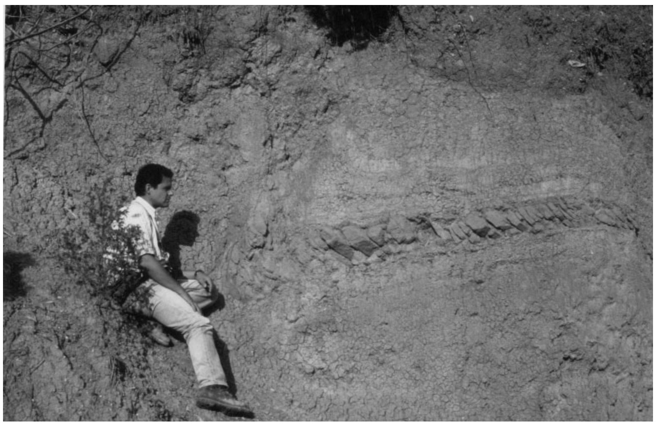


Fig. 13 - Mesoscopic overturned fold marked by a sandy layer in the 2nd UBSU deposits. The sandy layer is also affected by intense jointing. Federico Sani for scale.

Fig. 14 - Stylolitic pits and striae affecting the calcareous pebbles of the 2nd UBSU conglomerates. The black arrow indicates the sense of movement of the missing block.

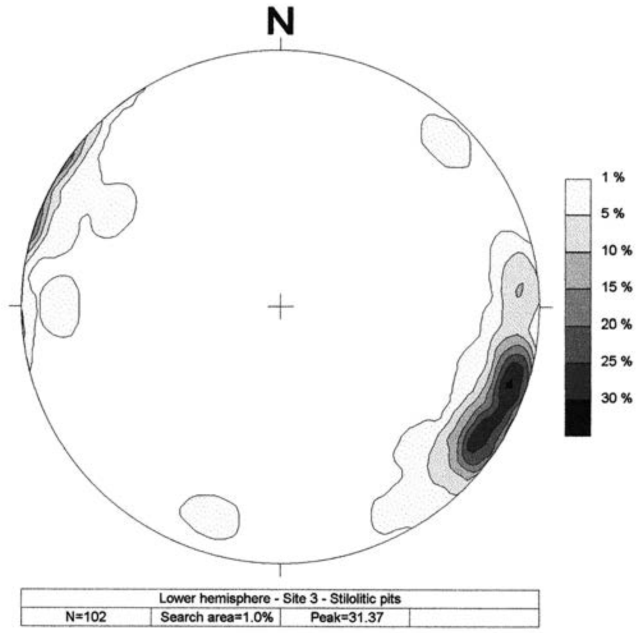


Fig. 15 - Stereonets showing the mean σ_1 axis directions obtained plotting stylolitic pits and striae collected at Stop 1.6.

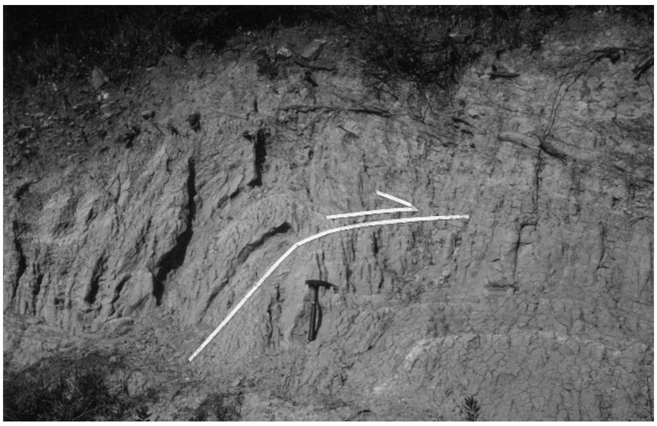


Fig. 16 - Fault-related E-verging fold in the 2nd UBSU sandy and sandy-clayish levels, near the western margin of the Velona Basin (Stop 1.7).

of the Orcia River, corresponding to the present lower course of the Ribusuoli Creek (Fig. 9). This rejuvenation, with increase in stream erosion, may be due to the tectonic uplift of the Monte Labbro-Montalcino ridge in the Castelnuovo dell'Abate area (Figs. 2 and 9). In fact morphologic features possibly related to recent tectonic activity are visible along the N-S trending Asso-Orcia valley. They are much more evident along the western side of the valley than along the eastern side. We therefore hypothesize that vertical movements occurred after the late Pleistocene along this side of the valley, causing uplift to the west and downthrow to the east. More detailed research is necessary to assess whether the vertical movement was induced by thrusting or by normal faulting.

We go ahead to Bagno Vignoni for the night.

SECOND DAY

We come back to Castelnuovo dell'Abbate. From here we keep up the road to Arcidosso and Mt. Amiata. About 1 km after Mt. Amiata Scalo (Fig. 2), about 1 km after Mt. Amiata Scalo, a small country road on the left leading to the Orcia River.

Stop 2.1 - *West-verging fault-related folds affecting the first cycle deposits of the Velona Basin (Figs. 2 and 3).*

This locality shows well developed W-verging fault-related folds in the first cycle deposits cropping out towards the centre of the basin, near the Orcia River (Fig. 17). They are interpreted as related to a minor backthrust related to the activity of the Ripa d'Orcia thrust during the deposition of the first cycle sediments.

Minor reverse faults and folds also occur in the sandy and/or in the lignite-bearing levels alternating to the clays. The shortening direction obtained from the fault slip data, and elaborated using the inversion method of Carey (1976; 1979), is coherent with the major structures affecting the basin fills (Fig. 9).

On the basis of the geometrical relationships among the various cycles and the compressional deformations affecting the basin fill, the evolution of the Velona Basin has been referred to the activity of the Ripa d'Orcia and Montalcino-Castelnuovo dell'Abate thrusts (Bonini et al., 2000, this issue).

The itinerary continues in the Siena-Radicofani Basin.

The Siena-Radicofani Basin

The Siena-Radicofani Basin develops for a length of almost 90 km, trending NNW-SSE between the MTMR to the West and the Chianti Mts.-Mt. Cetona Ridge to the East, both constituting main thrust-fault anticlines (Fig. 2). Because of its extension and of the thickness of the sedimentary succession filling the basin, the Siena-Radicofani Basin is one of the most important episutural basins of the Northern Apennines. Longitudinally, it may be subdivided into two parts: the Siena Basin to the North and the Radicofani Basin to the South of Pienza, which is located on a substrate high. Highs of pre-Neogene substrate, forming thrust-related anticlines whose activity influenced the sedimentation, crop out as windows within the basin fill. One of these is the Monticchiello high, whose flank will be shown in Stop 2.5 (Fig. 3).

The sedimentary successions of these basins consist of Upper Miocene to Upper Pliocene conglomerates, sands and clays variously alternating and heteropically interfingering.

The succession of the Radicofani Basin, visible during the trip, developed entirely during the Pliocene and is subdivided into two cycles, corresponding to the 2nd and 3rd UBSUs.

The 2nd UBSU starts with basal polygenic conglomerates, sometimes matrix-supported, with alternating sandy levels, passing upwards to reddish sands. Their thickness may attain 100-150 m. They are conformably overlain by the so-called "grey-blue clays", extensively cropping out in the whole Radicofani Basin. They consist of deep marine grey-blue clays and silty clays with alternating thin sandy or conglomeratic levels; in the southern part of the basin, near the eastern margin, they pass upwards to sands and conglomerates, showing a regressive trend. Their thickness in the central part of the basin reaches 1000 m, but it decreases towards the margins. Their age is progressively younger from west to east, varying from the *G. margaritae* to the *G. margaritae-puncticulata* zone (Early Pliocene; Iaccarino et al., 1994; Liotta 1996).

The 3rd UBSU, unconformably overlying both the substratum and the 2nd UBSU deposits, starts with ocra sands with alternated clayey, carbonatic and conglomeratic levels and lenses, which testify a shallow marine to transitional environment. In particular, between Pienza and St. Quirico d'Orcia, lacustrine lignite-bearing levels have been found intercalated in the sands. The town of Pienza, moreover, is built on a 10 m thick level of bioclastic limestones, alternated to the sands. The age of the sands has been referred to the Late Pliocene, as they contain *Globorotalia puncticulata* (Gandin, 1967; 1982).

Upwards, the 3rd UBSU continues in the southern area with *Amphistegina*-bearing limestones (Conti et al., 1983), which crop out in correspondence of the Mesozoic basement highs, in particular near the Mt. Cetona, directly lying on the substrate. These are shallow marine deposits containing *Pecten, Ostreae* and macroforaminifera of Late Pliocene (*Gt. aemiliana* zone, Iaccarino et al., 1994). Near the Mt. Cetona at places they pass laterally to calcareous breccias and conglomerates deriving from the erosion of the Pliocene coastline (Passerini, 1964). The total thickness of the 3rd UBSU deposits, as calculated from the outcrops, may attain 100-150 m.

Fig. 17 - Well developed W-verging fault-related folds in the 2nd UBSU deposits, near the Orcia River, representing a minor backthrust. F.S. and M.B. for scale.

Several Quaternary travertines crop out in the basin, the most well known being the ones of Bagno Vignoni (still in deposition) (Fig. 18b), Rapolano, Cetona-Sarteano and St. Casciano dei Bagni.

Active tectonics in the Siena-Radicofani Basin

The Siena-Radicofani Basin is bound by mainly NNW-SSE to NW-SE trending active normal faults on its eastern margin and by N-S trending faults along its western margin. These faults have been studied in more detail in the northern sector of the basin (Fig. 2).

In a few favourable cases, it was possible to quantify the movement rates on these faults (see below Stop 2.2). In particular, this was possible for the fault that borders the western side of the Mt. Cetona between Bacchianello and la Mea (Fig. 19a) and for the fault which borders the Pienza *plateau* (Figs. 18b and 24).

From the Stop 2.1 we reach Castiglione d'Orcia and Bagno Vignoni. Approximately 15 km northwards we reach Bagno Vignoni (Fig. 2).

Stop 2.2 - *View of the Cetona-Pienza fault from Bagno Vignoni (Figs. 2 and 3).*

The fault that bounds to the west the Mt. Cetona shows both morphological and structural-geological evidence of recent tectonic activity, and it is one of the most important structures of the Quaternary tectonics of the area. The fault, composed by WNW-ESE to NW-SE trending segments (Fig. 2), is rather continuous and clearly visible both on satellite images (Landsat, Spot, X-sar; Fig. 18a) and aerial photographs. The fault trace is marked by a morphological scarp of constant height (Fig. 19).

From profile 3 (Figs. 2 and 20) an evident paleosurface is recognizable east of the fault, correlated to that of the Sarteano travertines, which is middle-late Pleistocene in age. Integrating the results obtained analysing the different profiles (profiles 1, 2, 3, DD' and CC'; Figs. 2, 19a and 20) and assuming that the paleosurface corresponds to the equilibrium profile shown also by the the creek of profile 1, it was possible to determine an average vertical movement on the fault of about 85 m after middle-late Pleistocene, which leads to a slip-rate of 0,68 mm/year.

Coming back along the national road n. 2 (SS 2-Cassia), we go northwards until St. Quirico d'Orcia. The Stop 2.3 is located north of the village in a quarry close to the cemetery.

Stop 2.3. *Mesoscopic compressional deformations at the northern periclinal termination of the Ripa d'Orcia anticline (Figs. 2 and 3).*

This locality shows a W-verging reverse fault affecting the 3rd UBSU deposits of the Siena-Radicofani Basin. Sands of the 3rd UBSU overthrust a conglomeratic level (Fig. 21). The fault plane is well exposed and it is marked by a thin (5 to 10 cm) layer, of tectonized grey-greenish clays squeezed between sands and conglomerates. The reverse sense of movement, nearly dip-slip, is indicated both by the development of incongruous steps in the rock and by downward-thickening striated oxides patinae (Figs. 22 and 23).

Coming back to St. Quirico d'Orcia a deviation to the right leads to Pienza.

Stop 2.4. *The active tectonics of the Pienza fault, Pienza (Figs. 2 and 3).*

The town of Pienza is located in the central-western part of the Siena-Radicofani Basin, on a roughly-horizontal paleosurface bounded to the SE by a WNW-ESE trending, subvertical normal fault, belonging to the fault system of the Mt. Cetona (Fig. 2).

Pienza is built on *Amphistegina and Lithotanmium* bearing limestones (Figs. 18b and 24) that have a thickness minor than 10 m, overlying sands and sandstones of the 3rd UBSU of thickness variable between 10 and 40 m. Underlying there are the clays of the 2nd UBSU with a thickness of about 100 m. The *Amphistegina and Lithotanmium* bearing limestones laterally pass into the clays of the 3rd UBSU (Fig. 24). Several profiles (obtained from 1:10,000 maps) illustrate the morphology and the geology of the investigated area (Fig. 24).

Historical earthquakes on the Pienza fault

The Cathedral of Pienza, built between 1459 and 1462, together with the Piccolomini Palace and Pio II Square, is located on the southwestern side of the arenaceous-limestone *plateau*, near the scarp of the WNW-ESE trending main fault (Figs. 18b and 25a). The hangingwall of this fault, historically known to subside at least since 1459, is still presently lowering, as calculated by Calabresi et al. (1995) and AA.VV (1992). The central and southern parts of the Cathedral present a few fractures, parallel to the fault and with lowering of the SW side (Fig. 25).

From the parking lot under the Cathedral the dislocation of the apse with respect to the transept is clearly visible (Fig. 25b). Cracks are visible both in the external walls and inside the church (Figs. 25b and 25c), and they are surveyed by means of glass-spies which show normal movements still going on.

According to some manuscripts preserved in the Bishop's Curia (see AA. VV., 1992; Calabresi et al., 1995), in 1545 and in 1679 Pienza was the epicentre of two strong earthquakes that are not reported in the official seismic catalogues. In particular, during the first earthquake a crack ("*cretto*") extending from Porta al Ciglio to Santa Caterina developed (Fig. 25a). Other sure seismic events with epicentre in Pienza, abstracted from the "Strong Italian Earthquakes Catalogue" (Boschi et al., 1995), are those of 1897 and between 1920 and 1926, which mostly affected the southern and western areas of Pienza.

Also the walls of other buildings show the same kind of cracks, which are aligned with the ones affecting the Cathedral (Fig. 25d).

Slightly to the NW of Pienza, one can see the fault plane cropping out. Here it is possible to observe the upper part of the fault's footwall, made of sands and sandstones of the 3rd UBSU with a thickness of about 10 m, over which there are the *Amphistegina* and *Lithotanmium* bearing limestones that here have a thickness of 2 m. In this point Bartolini et al. (1982) have calculated a throw of 12 m.

View of the Rigo fault from Pienza

From the panoramic street behind Pienza Cathedral, looking towards the SW (Fig. 18), the alignment of the faceted spurs of the Rigo Creek fault is visible.

The Rigo fault is marked by some morphological features:

- the alignment of the Rigo Creek in a N-S direction;
- the presence of triangular facets along the Rigo Creek, incised in the 2nd UBSU sediments and in the pre-Neogene substrate. On their summits lie the villages of St. Quirico d'Orcia, Vignoni and Rocca d'Orcia (Fig. 18b). In particular, on the triangular facet of St. Quirico d'Orcia, at the base of the bigger faceted spur, smaller and more recent facets can be seen (Fig. 18b).
- a morphological scarp is present under theVignoni village along the road between Bagno Vignoni and St. Quirico d'Orcia.
- where the Orcia River crosses the fault, next to Bagno Vignoni, the river running from W to E carves a narrow canyon in the footwall;

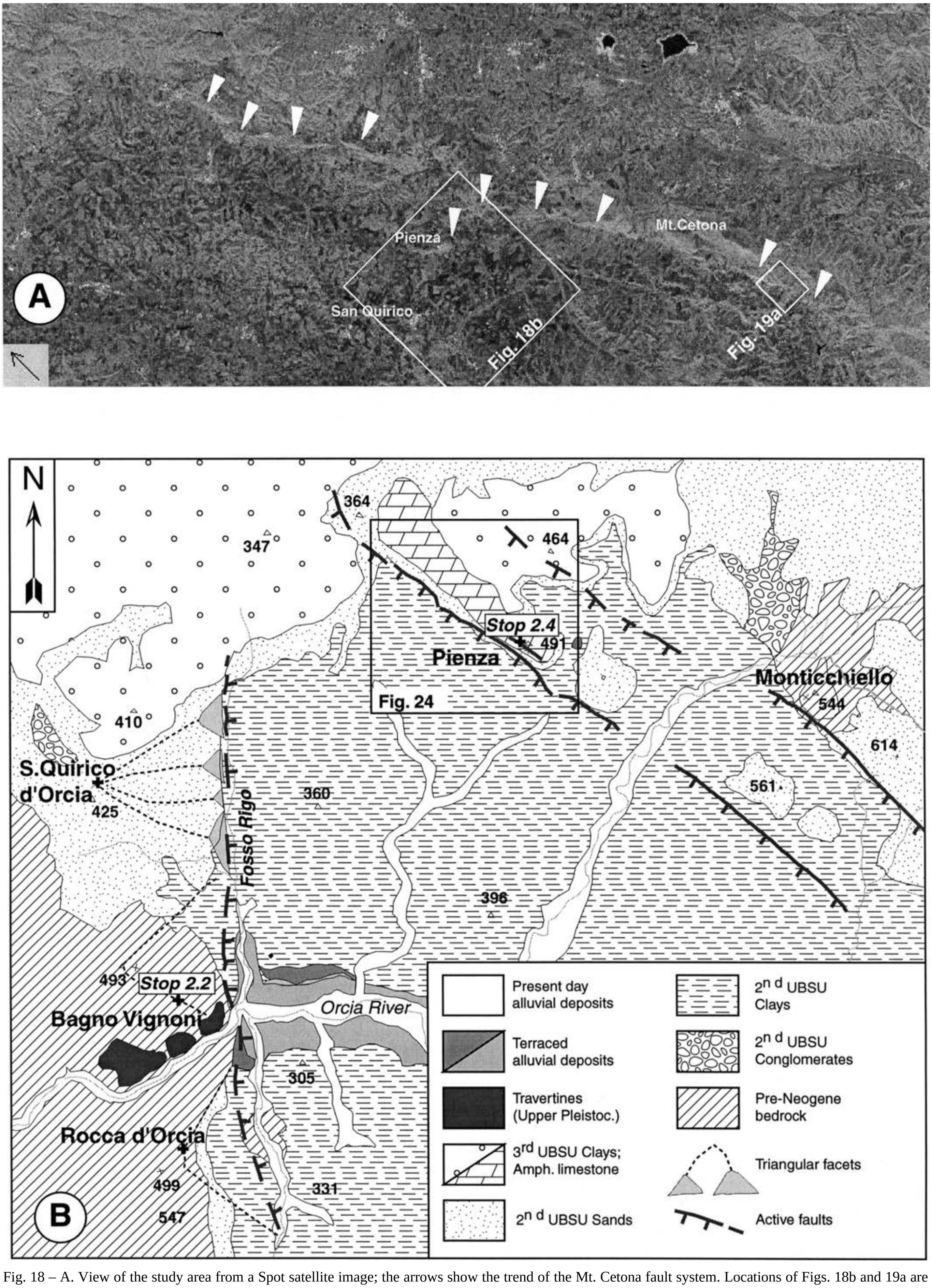


Fig. 18 – A. View of the study area from a Spot satellite image; the arrows show the trend of the Mt. Cetona fault system. Locations of Figs. 18b and 19a are indicated. B. Geological and morphotectonic map of the study area, with indication of the two stops.

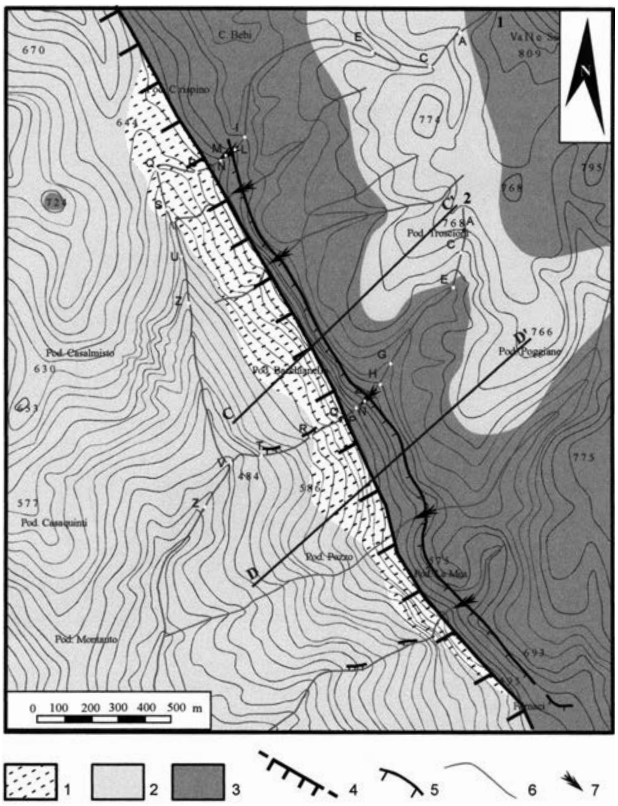


Fig. 19 – a. Geological and morphotectonic map of the Mt. Cetona fault between Podere Bacchianello and Podere La Mea. Legend: 1- Debris; 2- Middle-Upper Pliocene sands of the 2nd UBSU; 3- Mesozoic substrate; 4 Mt. Cetona active fault; 5- Terrace edge; 6- Streams; 7- Strongly eroded stream bed. B. The Mt. Cetona fault: morphological scarp looking to the North (St. Casciano dei Bagni).

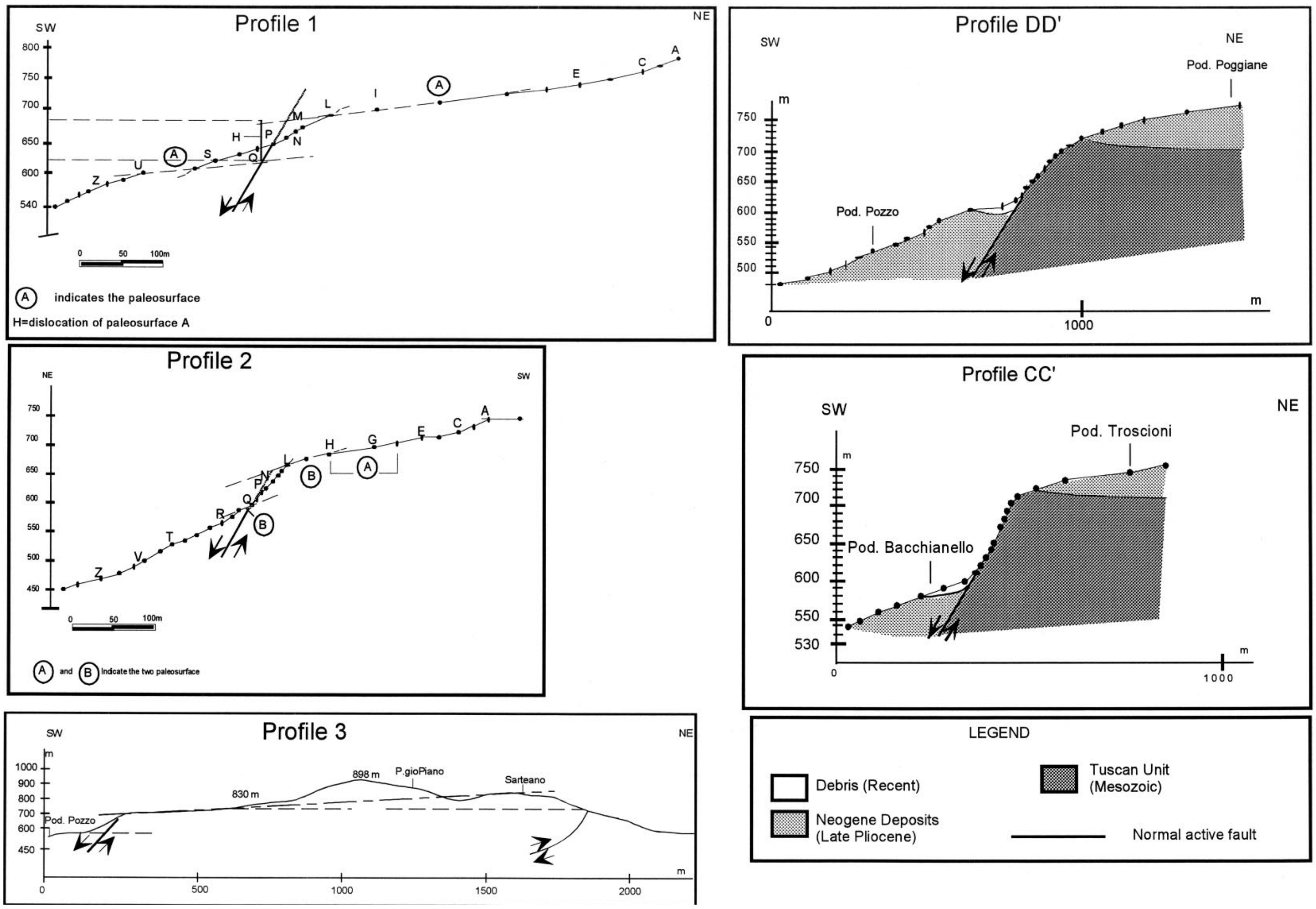


Fig. 20 - Topographic and geological profiles of the Mt. Cetona fault (locations are shown in Figs. 2 and 19a). Profiles 1, 2, CC' and DD' have been drawn on 1:10,000 scale maps.

Fig. 21 - W-verging reverse fault affecting the 3rd UBSU deposits near St. Quirico d'Orcia. Sands overthrust a conglomeratic level with interposed a fault gouge made of a thin layer of grey-greenish clays.

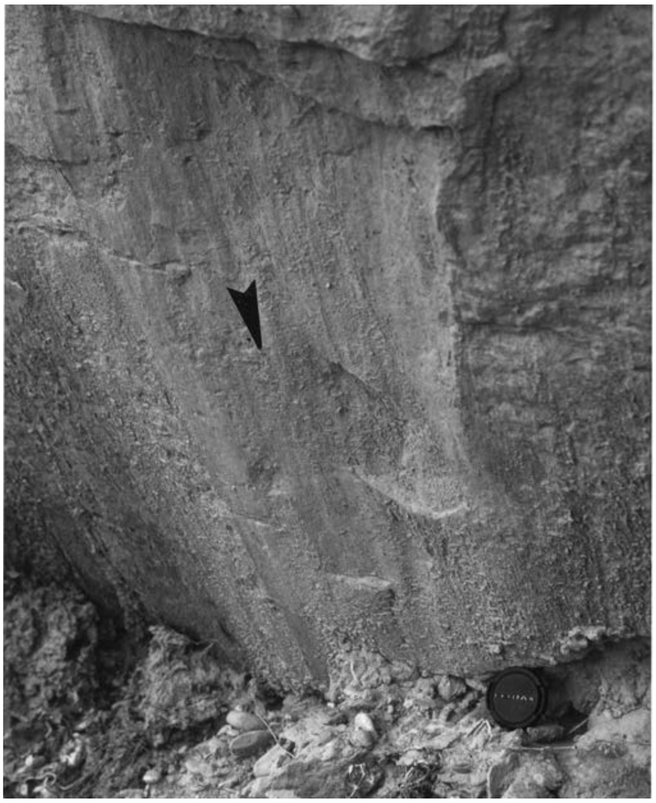


Fig. 22 - Incongruous steps in the rock of the hanging wall of the fault shown on Fig. 21, indicating a reverse sense of movement. The black arrow indicates the sense of movement of the missing block.

– on the hangingwall of the Rigo Creek fault, the Orcia River incises deeply into the 2nd UBSU clays creating scarps of about 15 m height near the Bagno Vignoni threshold; and also the recent alluvial deposits show at least two different orders of reincised terraces (Fig. 18b).

Field work and morphological studies allowed to correlate the uppermost paleosurface of the 2nd UBSU clays with the one of Pienza and with the summits of the hills to the east of Fosso Rigo. Such paleosurface, therefore, would have been displaced by the two faults described above (Pienza and Rigo faults).

Fig. 23 - Dip-slip striae in downward-thickening oxides patinae growing on the hanging wall of the fault shown on Fig. 21, indicating a reverse sense of movement. The black arrow indicates the sense of movement of the missing block.

From Pienza a road leads to Monticchiello; 0.5 km before Monticchiello, we follow a country road on the left, leading to Podere La Costarella.

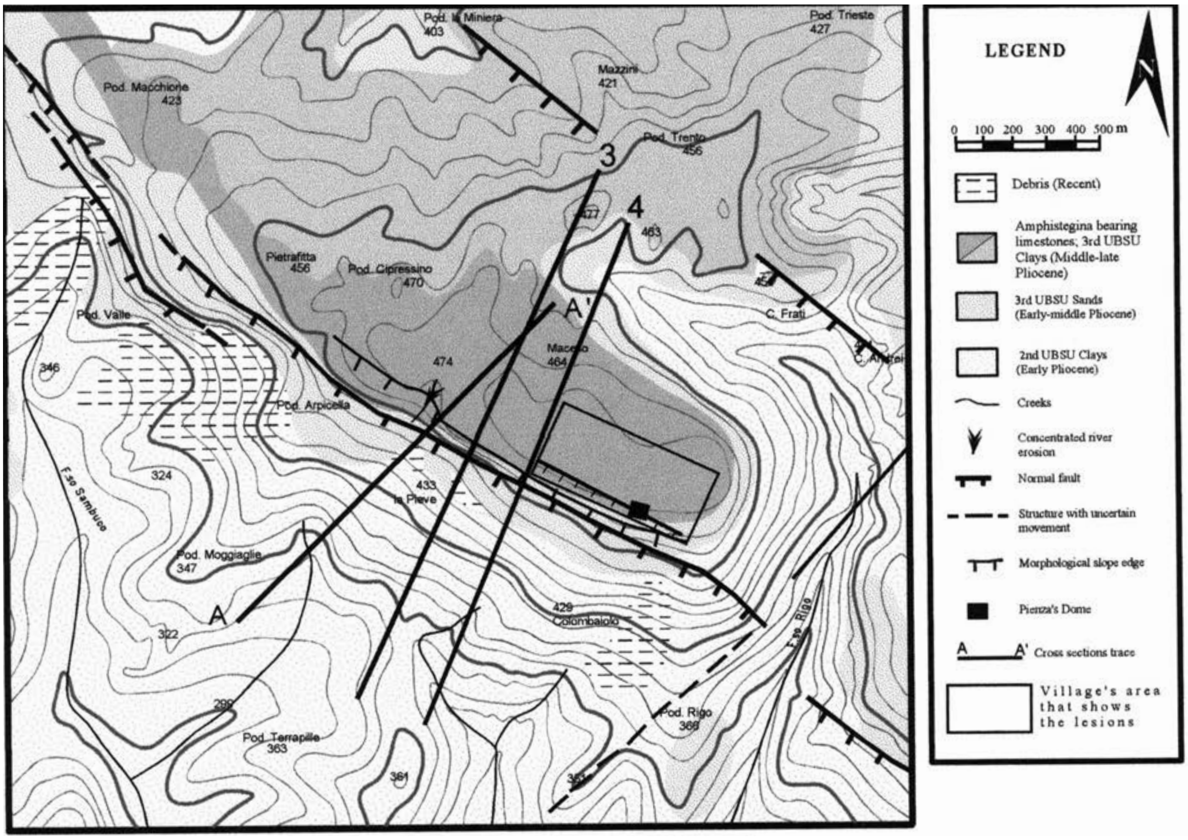
Stop 2.5. *Angular unconformity along the eastern margin of the Radicofani Basin (Figs. 2 and 3).*

From W to E the clays and basal conglomerates of the 2nd UBSU, Early Pliocene in age, dipping from 10 to 40 degrees to the W and unconformably overlying the pre-Neogene substrate of the Monticchiello Mesozoic high are visible. They are unconformably overlain by the subhorizontal sands of the 3rd UBSU, Late Pliocene in age, visible under Podere Fabbrica (Fig. 26). The Mesozoic substrate is folded in an anticline and no normal faults have been found in the field. The tilting of the 2nd UBSU deposits is therefore related to the progressive tilting of the backlimb anticline of the Monticchiello thrust. The timing of thrust activity is constrained by the age of the angular unconformity between the 2nd and 3rd UBSU deposits, which, on the basis of the foraminiferal content of the deposits, has been assigned to the upper part of the *G. puncticulata* zone.

Coming back towards Monticchiello we go on to the south along unasphalted roads reaching La Foce (Fig. 2) and Castiglioncello sul Trinoro. About 0.5 km north of the village we stop.

Stop 2.6. *Vertical strata along the eastern margin of the Radicofani Basin ((Fig. 3).*

Vertical to overturned and steeply dipping conglomerates of the 2nd UBSU, near the pre-Neogene substrate of



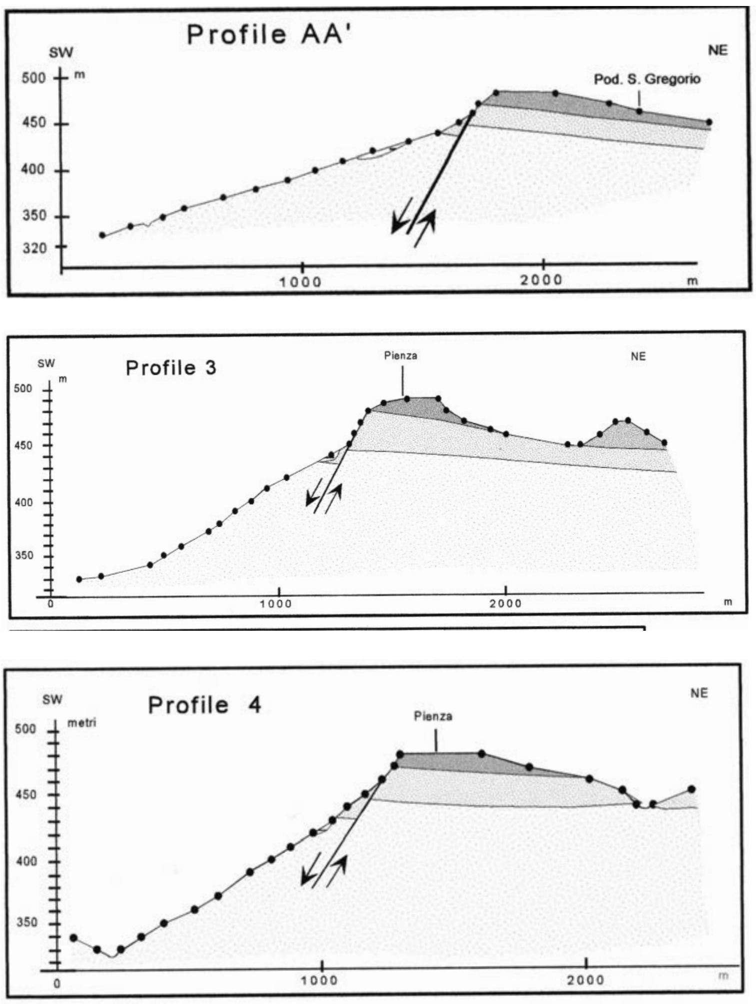


Fig. 24 - Geological-morphotectonic map and geological profiles of the Pienza fault.

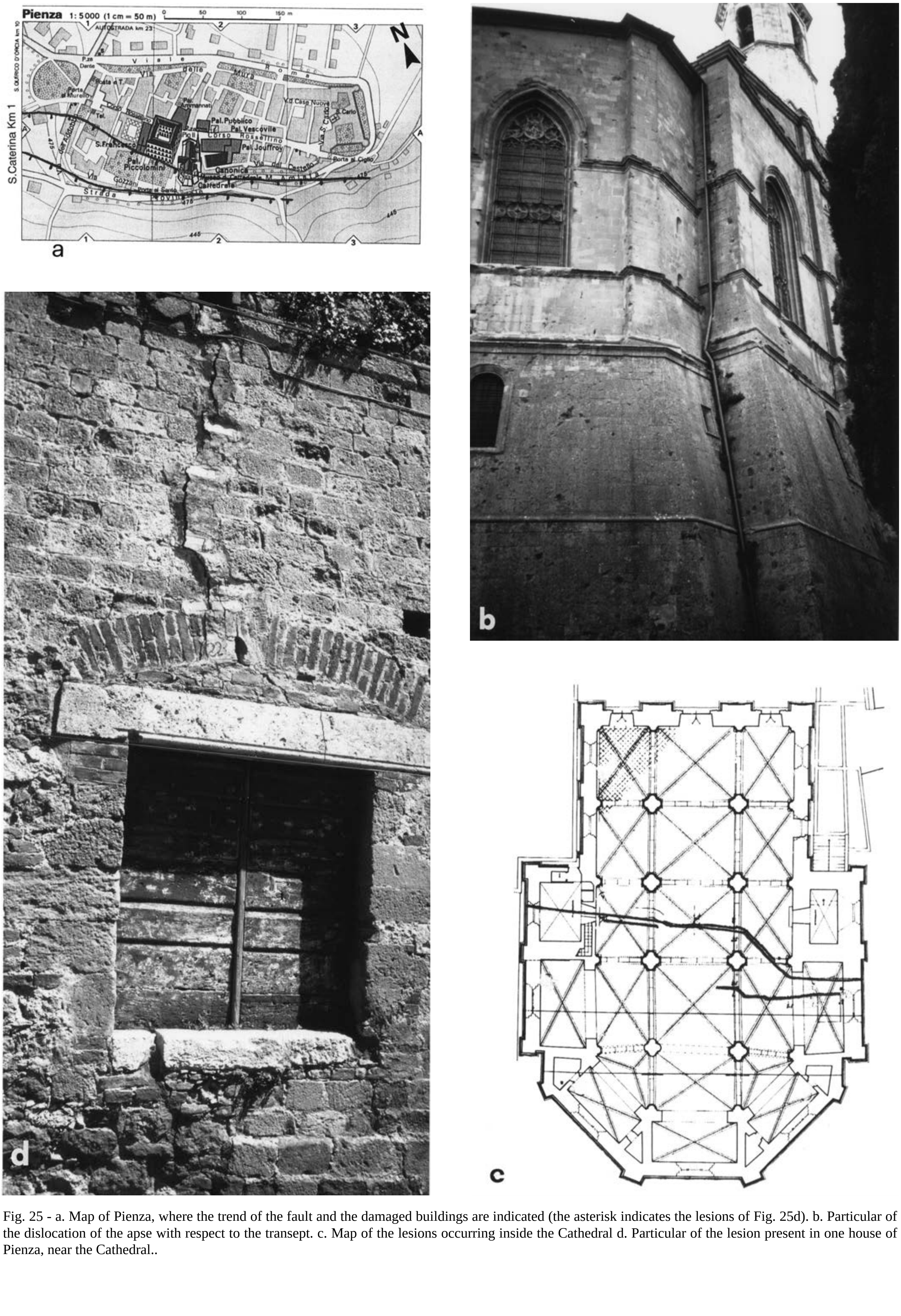


Fig. 25 - a. Map of Pienza, where the trend of the fault and the damaged buildings are indicated (the asterisk indicates the lesions of Fig. 25d). b. Particular of the dislocation of the apse with respect to the transept. c. Map of the lesions occurring inside the Cathedral d. Particular of the lesion present in one house of Pienza, near the Cathedral..

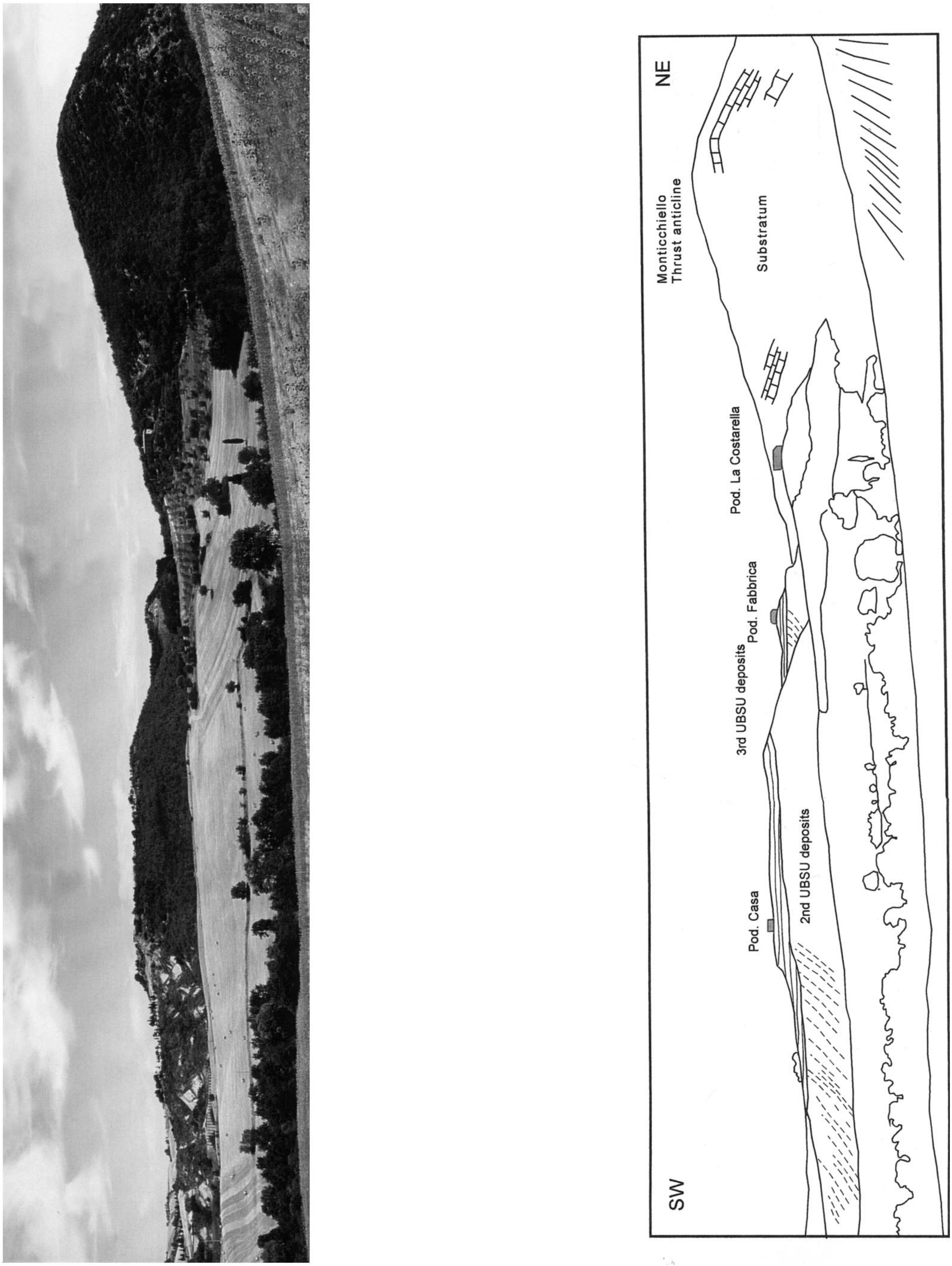


Fig. 26 - General view and line drawing from S to N of the angular unconformity between 2nd and 3rd UBSU deposits of the Radicofani Basin near Monticchiello. The flat-lying 3rd UBSU sands unconformably overlie the 2nd UBSU clays and basal conglomerates, dipping from 10 to 30-40 degrees to the W. These latter, in turn, unconformably overlie the thrust-related backlimb anticline of the Monticchiello Mesozoic high.

Fig. 27 - Vertical to overturned basal conglomerates of the 2nd UBSU, near the pre-Neogene substrate of Mt. Cetona. People for scale.

the Mt. Cetona are here visible (Fig. 27). In the alternating conglomeratic and sandy levels minor normal faults, rotated with the beds, may indicate a collapse episode within the basin during the syntectonic deposition of the 2nd UBSU basal conglomerates, whose attitude is due to the uplift of the margin.

On the basis of the geometrical relationships between the 2nd and 3rd UBSU deposits and of the compressional deformations affecting the basin fill, the Pliocene evolution of the Siena-Radicofani Basin has been referred to the activity of the Cetona ridge thrust. More indications about the evolution of this basin can be inferred from the analysis of seismic profiles; the line drawing of one of them is illustrated in Fig. 28. Three main sequences have been identified: 1) Middle-Upper Miocene deposits (probably referable to the Ponsano Sandstones; Giannini and Tongiorgi, 1959; Mazzei et al., 1980; Mazzanti et al., 1981); 2) Upper Miocene sediments (probably referable to the 1st UBSU deposits); 3) Lower Pliocene 2nd UBSU deposits cropping out in the field. The analysis of this seismic line allows the reconstruction of the following tectono-sedimentary evolution:

a) deposition of sequence n. 1 in an apparently bowl shaped basin;
b) deposition of sequence n. 2 (1st UBSU) controlled by the normal fault located to the east (on the western side of the Cetona ridge). This normal fault (see Fig. 28) does not continue northwards nor southwards, as observed in other seismic profiles; therefore, we interpret it as a second-order structure accommodating the uplift of the eastern margin related to the Cetona ridge thrusting during Late Miocene-Pliocene times;
c) a compressional phase that shortened the basin during the latest Miocene; this phase is documented by the anticline that affects the sequence n. 2 deposits (1st UBSU) and uplifts the central part of the basin;
d) unconformable deposition of sequence n. 3 (2nd UBSU) onlapping on the deformed sequence n. 2;
e) uplift and shortening of sequence n. 3 deposits (2nd UBSU), due to an Upper Pliocene compressional phase (post -*G. puncticulata* zone);
f) formation of the normal faults, still active, during the Quaternary, mainly developed along the western side of the Mt. Cetona ridge.

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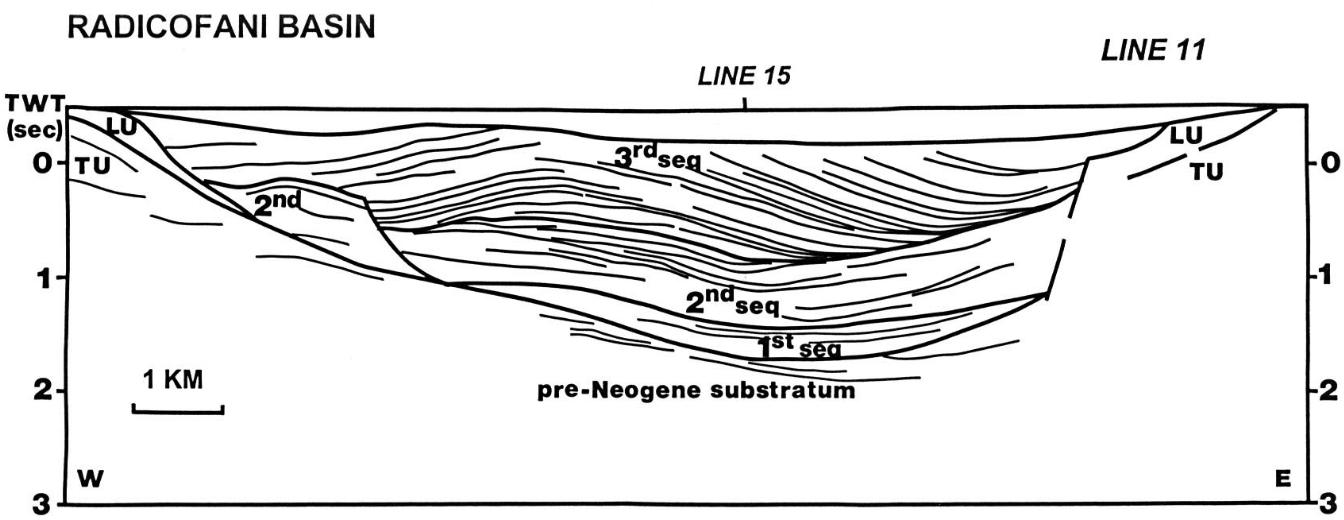

Fig. 28 - Line-drawing of seismic line A-B. See location in Fig. 2 - 1st sequence = Early-Middle Miocene; 2nd sequence = Late Miocene (probably corresponding to the 1st UBSU, late Tortonian-Messinian in age); 3rd sequence = Early Pliocene (*Sphaeroidinellopsis seminulina-Gt. puncticulata* zones, corresponding to the 3rd UBSU); LU = Ligurian Units s. l.; TU = Tuscan Unit.

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