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UPPER MIOCENE EXTENSIONAL TECTONICS AND SYN-RIFT SEDIMENTATION IN THE WESTERN SECTOR OF THE VOLTERRA BASIN (TUSCANY, ITALY)

CONTENTS

ABSTRACT

This paper analyses the tectonic-sedimentary evolution of the northwestern portion of the upper Miocene - middle Pliocene Volterra basin. The studied area lies between Chianni and Orciatico villages, along the Sterza valley. The upper Tortonian - lower Pliocene succession consists of two unconformity bounded stratigraphic units (UBSU). The first, upper Tortonian - lower Messinian, is made up of continental to transitional environment clastic deposits. The second UBSU, upper Messinian - lower Pliocene, features continental clastic deposits in the lower portion, and lower Pliocene marine clastic sediments in the upper one. The lower UBSU represents a syn-rift wedge, filling a NNE-SSW half graben. A late Messinian uplift stopped the sedimentation and caused erosion. Immediately after, another half graben was opened, along a new master fault parallel to the first one, few kilometers west, that tilted the lower UBSU. An attempt to reconstruct the lower UBSU master fault is made, through a dip domain analysis, adopting a multiple bend fault model. The reconstructed cross section allows to evaluate an extension of 1025 m on a section of 3475 m, during the late Tortonian - early Messinian interval, and a 0.6 mm y^{-1} sedimentation rate.

RIASSUNTO

La Val di Sterza costituisce un'appendice del bacino miocenico superiore - pliocenico medio di Volterra. Lo studio stratigrafico e strutturale dei depositi in essa affioranti ha permesso di ricostruire l'evoluzione tettonica dell'area, dal Tortoniano superiore al Pliocene inferiore. Un tentativo di modelizzazione delle strutture tettoniche in profondità, basato sull'analisi dei dip domain, fornisce inoltre una approssimativa quantificazione di alcuni parametri geometrici delle strutture stesse.

La successione neogenica della Val di Sterza è suddivisibile in due *unconformity bounded stratigraphic unit* (UBSU). La piú bassa giace in discordanza sul substrato costituito da unità liguri, è di età Tortoniano superiore - Messiniano inferiore, ed è costituita principalmente da argille sabbiose con intercalazioni di conglomerati d'ambiente lacustre nella parte bassa e transizionale nella parte alta. Al tetto è sovrastata in discordanza dalla UBSU superiore che è di età Messiniano superiore - Pliocene inferiore, ed è costituita da conglomerati rossi, calcareniti e argille d'ambiente continentale del Messiniano superiore, sovrastati in concordanza da argille, sabbie e conglomerati marini del Pliocene basale.

La UBSU inferiore si presenta suborizzontale nel settore orientale dell'area rilevata, mentre in Val di Sterza è strutturata secondo una monoclinale immergente verso ONO, con inclinazioni decrescenti dal basso verso l'alto, contro una faglia normale orientata N10° e immergente verso ESE. Sulla base dell'esistenza di analogie strutturali alla scala dell'affioramento, tale strutturazione viene interpretata come un semi-*graben* apertosi lungo una faglia listrica e riempito da depositi sintettonici. Al Messiniano superiore l'area esaminata, subisce un sollevamento, che interrompe la sedimentazione della UBSU inferiore e provoca erosione. Immediatamente dopo, una nuova faglia N10° si apre ad ovest della precedente, e lungo di essa si forma un nuovo semi-*graben*, nel quale si accumula la UBSU superiore. Questo nuovo evento distensivo provoca il basculamento delle vecchie strutture verso ovest. Restaurando palinspasticamente la sezione piú significativa alla fine del Messiniano inferiore, e,sfruttando l'analisi dei *dip domain* la faglia sinsedimentaria rispetto alla UBSU inferiore viene modellizzata come una faglia ad angoli multipli (*multiple bend fault*), secondo il metodo di Xiao & Suppe (1992). Ciò permette di valutare un'estensione tra il Tortoniano superiore e il Messiniano inferiore di 1025 m su una sezione di 3475 m. L'evoluzione tettonica di quest'area al Miocene superiore presenta forti analogie con quella di altri settori del bacino di Volterra, per i quali è stata accertata la presenza in profondità di corpi magmatici intrusivi a partire almeno dal Pliocene inferiore. Viene qui suggerito che anche la zona in esame sia interessata da un corpo plutonico non ancora identificato, e che la formazione dei magmi sia da mettere in relazione alla forte estensione subita dall'area in precedenza.

KEY WORDS: Tuscany, Upper Miocene, Tectonic evolution, Rift-basin, Structural modelling.

PAROLE CHIAVE: Toscana, Miocene superiore, Evoluzione tettonica, Bacini di *rift*, Modellizzazione strutturale.

INTRODUCTION

This paper presents the results of stratigraphic and structural investigations conducted on the upper Tortonian - Lower Pliocene stratigraphic succession of the Sterza valley (Pisa, Italy).

The Sterza creek is a left tributary of the Era river which, at its turn, is a left tributary of the Arno river. The Era river, like most of the other left tributaries of the Arno river, flows northeastward along a NW-SE trending graben. This graben, as well as the others (Elsa

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valley and Fine valley, Fig. 1), is filled with upper Miocene to Pleistocene deposits and represents one of the most recognizable extensional structures in central Tuscany (MAZZANTI, 1961; LAZZAROTTO & MAZZANTI, 1978), being bordered on both sides by NW-SE trending normal faults (as is clearly visible in the seismic sections issued by MARIANI & PRATO, 1988) and being separated by horsts of the same orientation, and constituted by pre-upper Miocene folded units mainly belonging to the ligurian and tuscan nappes (Fig. 1). Until the late seventies the formation of these grabens had been dated, as the lowest unfolded sediments, late Tortonian, and the bordering normal faults had been considered active since then. LAZZAROTTO & MAZZANTI (1978) first noted that the NW-SE fault system cut Pliocene, and in one case Pleistocene deposits, whereas N-S faults don't cut sediments younger than upper Miocene, thus hypothesising that brittle extensional tectonics started cutting the Tyrrhenian margin of the Apennines during upper Miocene along a N-S direction, and later (Pliocene) the strain field switched to a NW-SE direction.

That was just a working hypothesis based on few data obtained by the examination of a structural sketch.

This paper is an attempt to unravel the problem of the tectonic evolution of central Tuscany from upper Miocene on, by examining in detail a peculiar area where cross cutting relationships between Pliocene and previous tectonic structures are evident. This will bring further constraints to the reconstruction of the palaeogeography of the Volterra basin during upper Miocene.

STRATIGRAPHY

The upper Miocene - lower Pliocene stratigraphic succession of the Sterza valley can be subdivided in two major UBSU (*unconformity bounded stratigraphic unit*). The upper one, latest Messinian - middle Pliocene in age (SARTI & TESTA, 1994), is unconformably overlain, few kilometers north of the examined area, by lower Pleistocene marine deposits, and rests unconformably on the lower UBSU and the cretaceous "*Argille a palombini*" formation belonging to the internal ligurian nappe (Tav. 1). The lower UBSU is upper Tortonian - lower Messinan and lies unconformably on the "*Argille a palombini*" formation.

Lower UBSU

It has been subdivided from the bottom to the top into three lithostratigraphic units: "*Conglomerato basale*" and "*Argille sabbiose e conglomerati della Sterza*"; eastward the former pinches out, whereas the latter passes laterally into the "*Argille e calcari dolomitici di Podere il Casino*".

Conglomerati basali

This unit outcrops at the southernmost edge of the mapped area - Podere Le Marie, Sterzuola creek- and near Podere Cialambrone (eastern part of the map). This unit is approximately 20 m thick. In each of these areas it unconformably covers the "*Argille a palombini*". Eastward from Podere Cialambrone it pinches out. At the top it gradually passes into the "*Argille sabbiose e conglomerati della Sterza*". It is a massive, polygenic, coarse to medium sized conglomerate mainly composed by grey calcilutites and quartzose-felspatic sandstone clasts. Clasts are subrounded - subangular. This unit is interpreted as an alluvial fan facies.

Argille sabbiose e conglomerati della Sterza

This unit represents most of the lower UBSU, spanning the entire stratigraphic interval between the "*Conglomerati basali*" and the upper UBSU. Its thickness varies from about 1200 m along a WNW-ESE section across the Sterza valley (see "Tectonics" paragraph for discussion), to 0 m in the esternmost part of the mapped area. It is composed of an alternation of clay and conglomerate. The conglomerate prevail in the southern part of the mapped area, whereas the clay in the northern. Clay is sandy-silty, often laminated with lignitic plant debris interlaminae, frequent intercalation of graded sand beds with erosional bottom and less frequent intercalations of fine conglomerate lenses (Fig. 2). All these intercalations thin eastward. Conglomerate is medium to fine grained, moderately to poorly sorted, mostly matrix supported. It forms levels hundreds of meters thick in the southern part and tens of meters thick in the northern. These levels are made up of beds and lenses one to several m thick, with minor clayey, silty sand intercalations (Fig. 3). Clasts are generally embricated with a transport direction constantly ranging around east (Fig. 4). Conglomerate beds are prevailingly normally graded with undulate erosional bottom in the western outcrops, and reversely graded with even bottom in the eastern ones (Fig. 5). They are distributed at two levels (Tav. 1) that roughly divide the succession in three equal parts (Tav. 1).

The lower two thirds of this unit (below the upper conglomerate level) contain a microfossil assemblage made up of the Ostracods: *Cyprideis* sp., *Candona angulata*, *Cypria candonaeformis*, *Tavanicythere* sp. and the gastropod *Bithynia*, which testify for a fresh water lacustrine environment.

The upper third instead contains a brackish water microfossil assemblage: *Cyprideis* gr. *torosa*, *Loxoconcha* spp., *Carthocythere* sp. and *Ammonia beccari tepida*. The passage from fresh to brackish water fossil assemblage is typical of the top of the fluvio-lacustrine pre-evaporitic upper Miocene succession of the Volterra basin (BOSSIO *et alii*, 1978; 1981; 1994).

Although there is a change in the biofacies throughout this unit, the lithofacies, hence the depositional processes responsible for their sedimentation, remain the same. The most probable environmental setting of this unit is a lacustrine basin in which, due to tectonic pulses and/or climatic changes, a fine grained pelagic to distal turbiditic was alternated with coarse grained deltaic to fluvial sedimentation both being supplied from west, by eastward flowing streams. At a certain moment of basin's history, sea water overpassed the threshold separating it from the sea, and mixed with fresh waters, without changing the operating depositional processes.

Argille e calcari dolomitici di Podere il Casino

This unit has been distiguished and described for the first time by SARTI & TESTA (1994). It outcrops in the far eastern sector of the mapped area, where it takes laterally the place of the *Argille sabbiose e conglomerati della Sterza*. It lies unconformably on the "*Argille a palombini*" formation, and is unconformably overlain by the upper UBSU. Its maximum thickness is

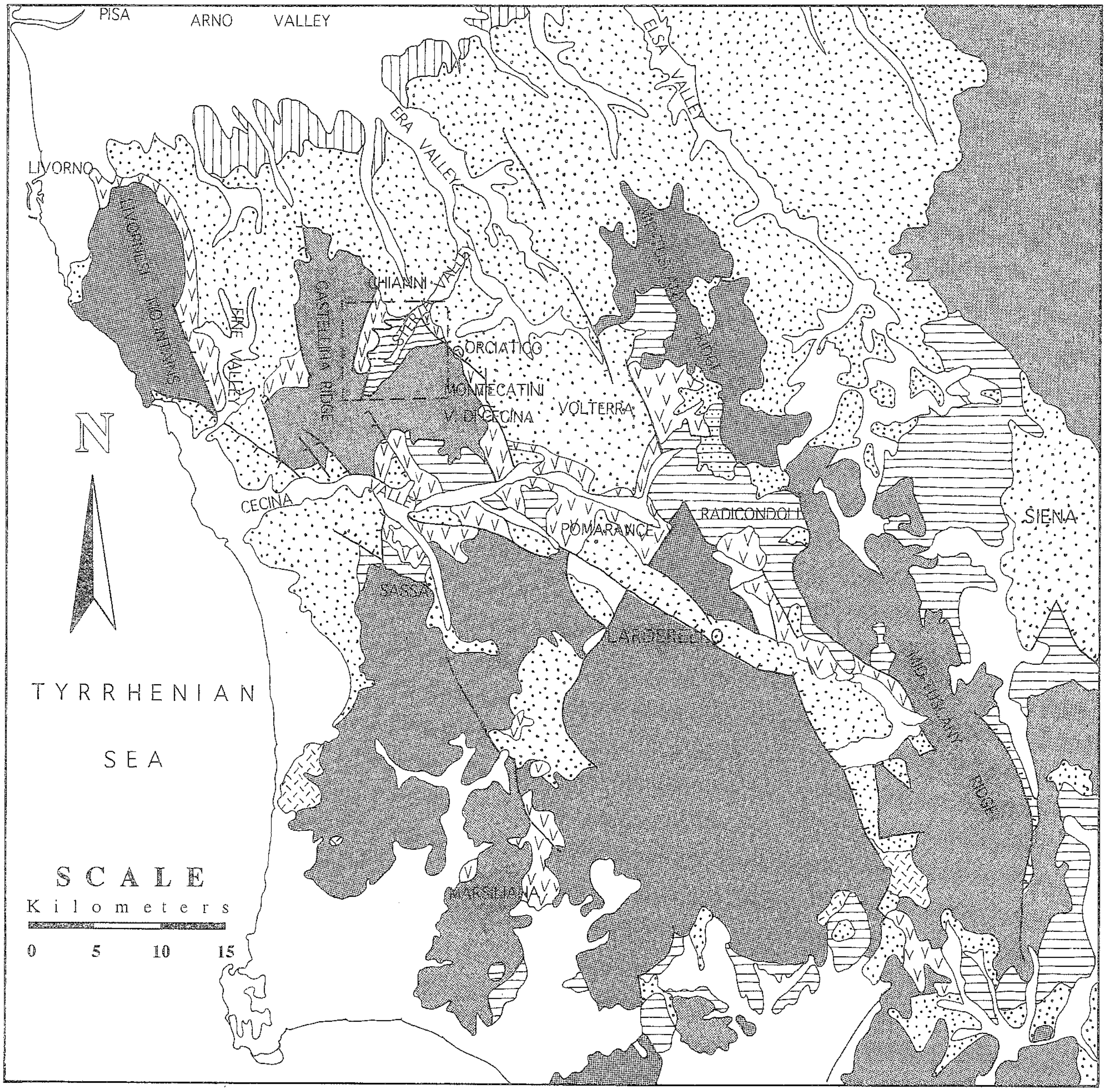

fig. 1 - Structural sketch of the Neogene basins of Tuscany. From Bigi et alii (1992) modified. The mapped area is contoured with a dashed line.

LEGEND: ☐ Recent alluvial deposits, mid-upper Pleistocene marine and continental deposits; ▨ Neogene igneous rocks; ▥ Upper Villafranchian continental deposits; ▒ Lower Pliocene-Lower Pleistocene marine deposits; VVV Mid-upper Messinian marine, evaporitic and continental deposits; ▤ Fluvio-lacustrine deposits (upper Tortonian-lower Messinian, west of the Mid-Tuscany ridge; upper Tortonian-upper Messinian, east of the Mid-Tuscany ridge); ▤ Lower Tortonian marine deposits (Ponsano Sandstone); ▓ Pre-Neogene substrate; ⊥⊥⊥ Normal faults; ╲ Faults of uncertain origin.

about 100 m. It is made up of gray massive clays with intercalations of beige to ochre, well lithified, finely grained carbonate beds (Fig. 6) that react weakly to diluted hydrochloric acid. Most of these beds display desiccation structures. This unit contains, for almost its entireness the same fresh water ostracod assemblage as the lower part of the "*Argille sabbiose e conglomerati della Sterza*". Just a very thin level at the top contains a brackish water assemblage.

All the fossils, both of the fresh and brackish water assemblages are just facies fossils, and have no biostratigraphic value; furthermore these deposits cannot be physically correlated (at least through surface data) with other fluvio-lacustrine successions - e.g. the well studied fluvio-lacustrine succession of the Radicondoli area (Bossio *et alii*, 1978 and 1981) - whose age is better constrained because it rests on the lower Tortonian Ponsano Formation (Fig. 1) and is overlain by the lower Messinian marine deposits (Lazzarotto & Mazzanti, 1978; Bossio *et alii*, 1981) and has recently been

Fig. 2 - "*Argille sabbiose e conglomerati della Sterza*": laminated silty clay with a fine conglomerate interbed.

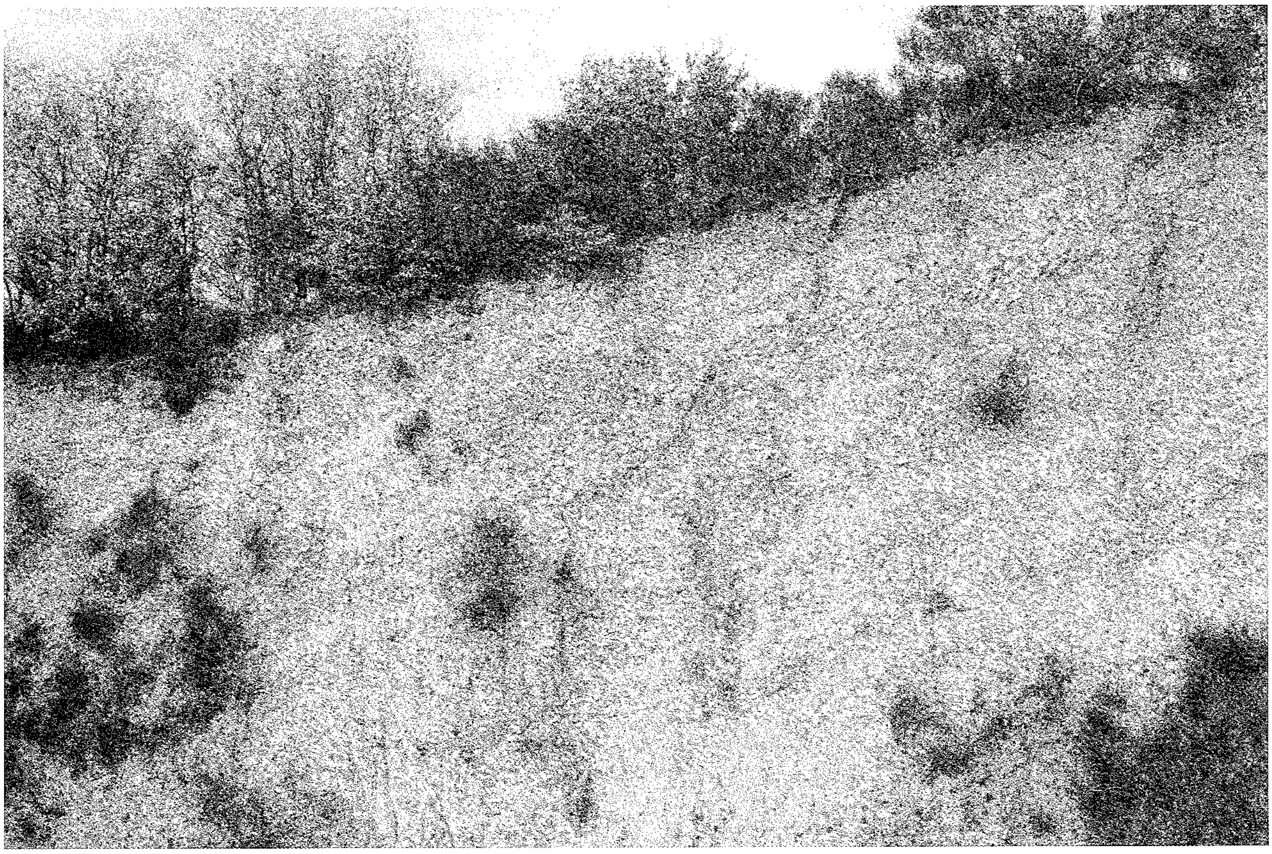

Fig. 3 - "*Argille sabbiose e conglomerati della Sterza*": conglomerate beds and lenses with minor intercalations of silty sands. "*Grotte di Strido*", southern part of the mapped area.

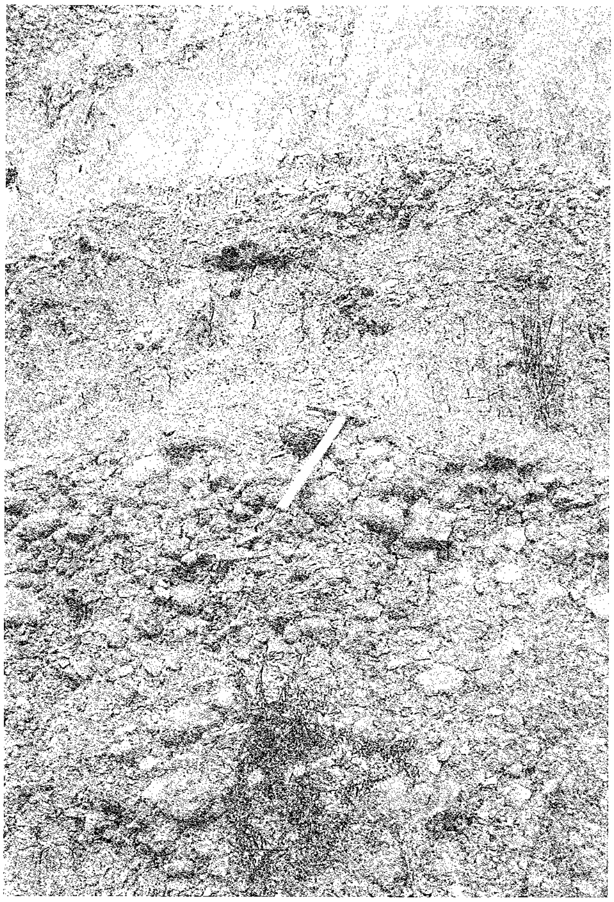

Fig. 4 - "*Argille sabbiose e conglomerati della Sterza*": conglomerate beds with a high clast-versus-bed thickness ratio, and clast embrication. East is on the right side of the photograph.

confirmed by the radiometric age of an intercalated tuff layer (D'Orazio *et alii*, this volume). Nontheless the environmental setting and evolution of this UBSU are typical, in Tuscany, of the late Tortonian - early Messinian time interval.

Upper UBSU

In this paragraph only latest Messinian and early Pliocene units will be considered, as middle Pliocene units outcrop out of the mapped area. From the bottom to the top the following units have been distinguished:

1 - red massive, coarse to medium grained, poorly sorted conglomerate ("*Conglomerato di Poggio rosso*" of Sarti & Testa, 1994; Fig. 7) whose thickness decreases from 50 to 0 m from the western to the eastern edge of the mapped area, where it passes laterally into a gypsum level;

2 - allochemical, coarse grained calcarenite with grey and red shale intercalations ("*Calcareniti di Poggio Riparossa*" of Sarti & Testa, 1994); southward they laterally pass into grey clay; this unit contains a peculiar fresh water ostracod assem-

Fig. 5 - "*Argille sabbiose e conglomerati della Sterza*": conglomerate bed approximately 3 m thick with reverse grading. Southern Sterza valley, by the bridge on the Sterza river.

Fig. 6 - "*Argille e calcari dolomitici di Podere il Casino*": grey massive marly clay, with ochre interbeds of finely grained dolomitic limestone. Podere il Casino, eastern sector of the mapped area.

Fig. 7 - "*Conglomerato di Poggo rosso*": red massive, coarse to medium, poorly sorted conglomerate. See the glove in the lower right for scale. Botro al Noce, southern Sterza valley.

blage typical of uppermost Messinian: *Loxoconcha* sp., *L. djaffarovi*, *Amnicythere* sp., *Euxinocythere praebaquana*, *Tyrrhenocythere pontica*.

3 - red, coarse, massive, poorly sorted conglomerate;

4 - fossiliferous calcarenite, clayey sand and blue clay, bearing an abundant benthic and planktonic foraminifer assemblage of early Pliocene age.

For further details on lithostratigraphy, petrography and biostratigraphy of these units see SARTI & TESTA (1994).

Stratigraphic interpretation

The two UBSU can be sequentially interpreted as follows.

The transition from fresh to brackish water in the lower UBSU, has been correlated by SARTI & TESTA (1994) to the one recorded in other sectors of the Volterra basin between the fluvio-lacustrine and the brackish deposits underlying the messinian marine deposits (BOSSIO *et alii*, 1978; 1981). It could be argued that this is just a facies transition with no biostratigraphic constraint, and could be related to any combination of sea level rise with subsidence. Yet SARTI & TESTA (1994) suggested that the brackish interval in this area could be equivalent to the brackish plus the marine intervals of the rest of the Volterra basin.

An important point to make, is that two main transgressive episodes are present in the Volterra basin. The first has been considered earliest Messinian by Bossio *et alii* (1994), it causes the passage from a continental to a transitional environment, and locally the onlap on pre-Neogene units (Bossio *et alii*, 1994), and has been correlated by Bossio *et alii* (in press) to the "*Calcare dell'Acquabona*" (lower member of the "*Calcare di Rosignano*" formation), in the Fine basin. The second is early Messinian (Bossio *et alii*, 1994), causes the onset of open marine on brackish transitional sedimentation, and the onlap on pre-Neogene units of the Castellina ridge (western margin of the Volterra basin), and has been correlated (Bossio *et alii*, in press) to the "*Calcare di Castelnuovo*" (upper member of the "*Calcare di Rosignano*" formation, Bartoletti *et alii*, 1985) of the Fine basin.

In the first transgressive event, the sea ingression is from south to north (Sarti & Testa, 1994); recent investigations of the author brought evidence that, in the fluvio-lacustrine deposits of the western Volterra basin the sediment supply was from south to north too. These two facts can fit together only assuming a tectonic event between the two units. For the second transgressive event, there are no clear evidences of a renewal of subsidence. However the sequential trend in many lower Messinian open marine succession, all around the Mediterranean, is regressive, thus excluding a sea-level rise as a possible cause of the transgression.

The trangressive event recorded in the upper Miocene succession of the Sterza valley can be related to either the first or the second transgressive events of the Volterra basin.

The angular unconformity separating the two UBSU is well described by Squarci & Taffi (1963) and Sarti & Testa (1994). They correlated it to the one recognized by Mazzanti (1966) at the base of the "*Conglomerati a ciottoli di eurite*" in the Pomarance area (Fig. 1), and considered it as the product of tectonic activity in uppermost Messinian. The lower Pliocene transgression has always been considered an eustatic event for the whole Mediterranean, being due to the restoration of the connections between the Mediterranean and the Atlantic ocean.

TECTONICS

In the Sterza valley, the lower UBSU is structured along a monoclinal dipping WNW against a NNE-SSW trending fault, which outcrops in the southern portion of the mapped area, whereas in the northern it is sutured by the upper UBSU (tav. 1). Going eastward from the Sterza valley, the beds gradually turn, from a WNW, to a NE dip. In the southern area the upper UBSU dips gently WNW against a NNE-SSE trending, ESE dipping normal fault; whereas it is roughly horizontal in the northwestern area, and it gently dips ENE in the eastern area, against a system of contrary normal faults, with a strike dispersal from N-S to NW-SE. Several NW-SE striking normal faults are present, in the southern portion of the examined area, many of which dip northeastward. Some of them stop against the NNE-SSW major fault, and cut only the lower UBSU; others cut both the lower and the upper UBSU. Some from the first group are clearly listric and display a syntectonic hanging wall sedimentary wedge (Fig. 8a and b). Both the two systems contribute to form a tectonic staircase that lowers northeastward the whole succession. The lower UBSU beds dip mainly WNW in the northern and central sectors of the mapped area, whereas they display sudden changes of dip direction (from WNW to SW) in the southern sector. Summarizing there are at least 6 systems of faults:

1) N10°(1), normal faults; 2) and 3) N130° and N310° normal faults, syndepositional with the lower UBSU; 4) and 5) N130° and N310° postdepositional normal faults; 6) N150° to N180° normal faults. System 4, 5 and 6 are the youngest, being not earlier than lower Pliocene. The easternmost N10° fault is late Messinian, cutting the lower, and being sutured by the upper. Systems 2 and 3 are conjugated and late Tortonian - early Messinian in age, being syndepositional with the lower, and being sutured by the upper UBSU. The easternmost N10° fault is here considered to continue northward underneath the upper UBSU. In the central part of the mapped area, the beds have the same strike as this fault, they dip against it, and their attitudes decrease from the bottom to the top. All these data are consistent with a rollover fault growth model for the sedimentary succession of the lower UBSU, as suggested by the outcropping structural analog of Fig. 8. Then also the easternmost N10° fault may be considered syndepositional with the lower UBSU, and thus late Tortonian - early Messinian.

Tectonics interpretation

From these data we can try to carry out the tectonic evolution of the area. Extensional movements with an horizontal σ_2 roughly oriented N10°, started to dissect the area in upper Tortonian. An ESE dipping listric fault formed, on the hanging wall of which the fluvio-lacustrine deposits of the lower UBSU began to be accumulated. There are no sediments left on the footwall; perhaps they've been eroded before the deposition of the upper UBSU. However they didn't have to extend a long way westward; infact the Fine basin (Fig. 1) is considered to be opened later, displaying almost no upper Tortonian fluvio-lacustrine deposits at the base of its sedimentary succession (Bartoletti *et alii*, 1985).

Furthermore, the distribution of the sedimentary facies and the paleocurrent indicators suggest that the Sterza valley master fault represented a segment of the western border of the fluvio-lacustrine basin. Another segment is recognizable south of the Cecina river (Fig. 1), in the Sassa area, where the base of the fluvio-lacustrine succession is represented by alluvial-fan deposits (D'Orazio *et alii*, 1995), which can be related to a tectonically active basin margin. These two segments form an en echelon-style setting with an overstep area striking roughly N 130°.

This geometry must have been syndepositional, since these sub-basins tend to thin out along strike in the overstep areas (e.g. the Sassa sub-basin, Bossio *et alii*, 1994). Furthermore, the presence of N130° listric synsedimentary normal faults, at the southwestern edge of the Sterza basin suggests that the overstep area in this case was a weakness band probably related to a

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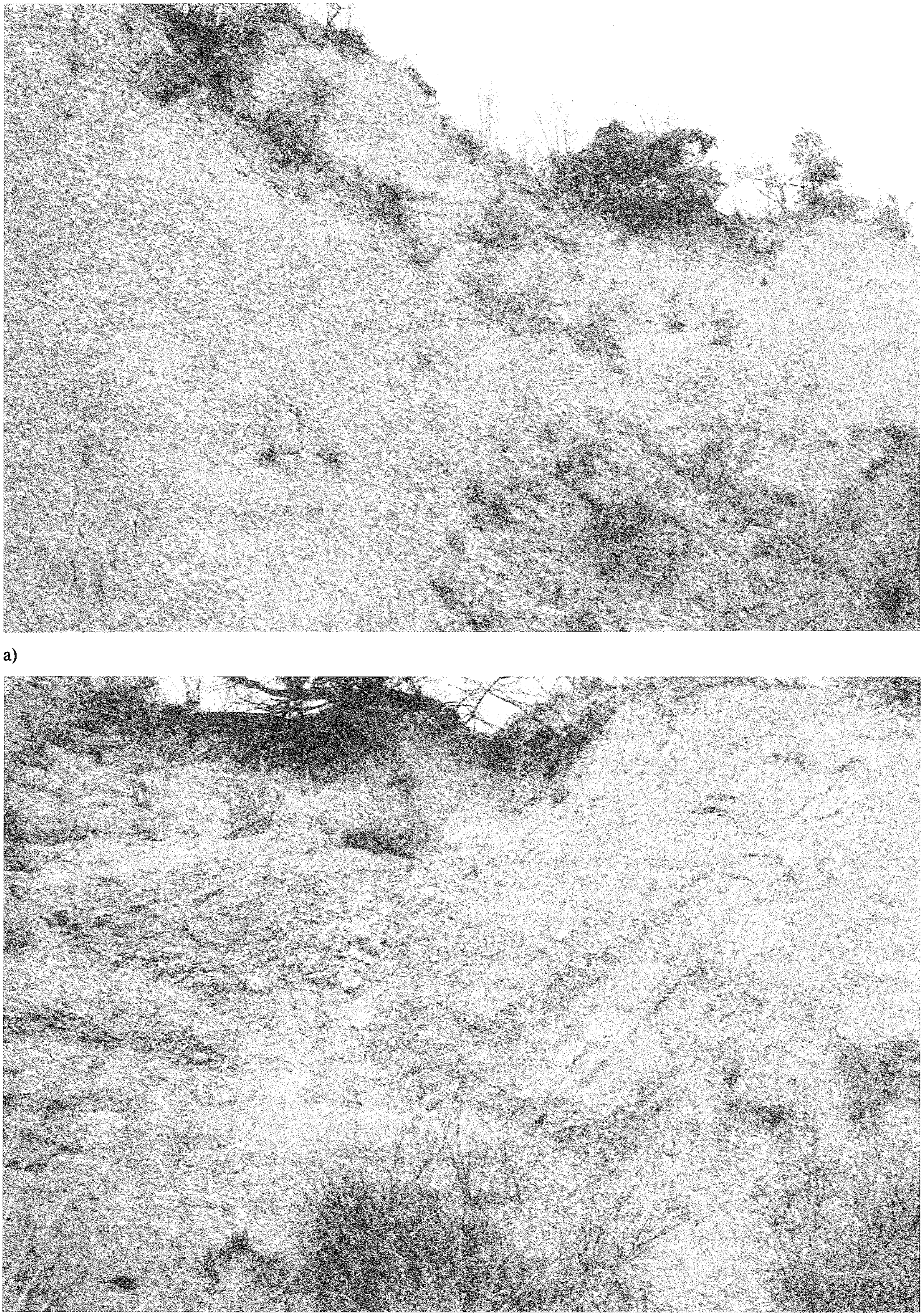
[1] The strike directions of the faults are here indicated following the "right hand convention"; that means that the azymuth direction is the one from which the observer sees the bed dipping toward his right.



a)

b)

Fig. 8 - "*Argille sabbiose e conglomerati della Sterza*". a) Mesoscopic listric growth fault; b) detail; "*Grotte di Strido*" southern Sterza valley.

tranfer zone. This explains the interference between NW-SE and NNE-SSW fault systems in the southern sector. The extensional behaviour of transfer zones is well documented by FACCENNA *et alii* (1995). If we take into account the timing given by D'ORAZIO *et alii* (this volume) for the upper Miocene pre-evaporitic succession of the Sassa area, and we assume that the Sterza and the Sassa sub-basins formed at the same time, we can assign to the lower UBSU a duration of roughly 2.5 Ma. It's easy to imagine that the synsedimentary slip along the listric master fault hasn't been continuous, but has proceeded through moments of activity and periods of quiescence, leading to sudden changes of the sedimentation versus subsidence ratio. This could have caused the alternation of pelagic and deltaic deposition. Of course we can't rule out climatic changes as an efficient mechanism to produce such stratigraphic pattern, but we have no data to support this hypothesis.

In late Messinian times the half graben, filled with the lower UBSU (we'll call it the Sterza half graben), underwent uplift and erosion; afterwards a new N10° listric fault formed (or was simply reactivated) 1 km west from the Sterza half graben master fault, tilting it about 20°, and causing the accumulation of a clastic wedge (*"Conglomerati di Poggio rosso"* unit of SARTI & TESTA, 1994) in a new half graben. An alluvial fan sloping north formed also on the overstep zone between the two faults. The new sediments covered unconformably the lower UBSU. The new formed fault remained active for a short period during latest Messinian. The earliest Pliocene units were deposited conformably on the latest Messinian deposits all around the Fine and Volterra basins (BOSSIO *et alii*, 1978; 1981; BARTOLETTI *et alii*, 1985; BOSSIO *et alii*, 1994; SARTI & TESTA, 1994). Therefore there is no evidence for a tectonic event at the beginning of Pliocene. As already said, the lowermost Pliocene marine transgression was an eustatic event shared by the whole Mediterranean. Of course we have to admit that the Volterra basin kept on subsiding, along the structures formed in uppermost Messinian. Interpreting a NE-SW seismic section across the Era valley, MARIANI & PRATO (1988) put a sequence boundary at the Miocene-Pliocene limit. They don't show any well data to support this attribution. My guess is that their Pliocene sequence can include also latest Messinian sediments, which are perhaps hardly recognizable in their seismic section due to their small thickness. The early Pliocene sediments display marginal facies in the western sector of the mapped area, and a shelf facies in the eastern, as well as south of the mapped area, in the lower Cecina valley (Fig. 1). That means that the Montecatini structural high (located on the hanging wall of the Sterza half graben) was completely, or at least partially, submerged under the early Pliocene sea, and after (maybe at the end of early Pliocene) it started uplifting. This vertical movement was probably responsible for the regression observed in the lower Pliocene succession in the lower Cecina valley (BOSSIO *et alii*, 1994). The last tectonic event in the examined area produced the NW-SE systems that we see cutting the entire succession in the Sterza valley. These systems, in the rest of the Volterra basin cut middle Pliocene sediments. It's likely that in the Sterza valley the tectonic event that created these structures, reactivated the NW-SE transfer systems formed during the deposition of the lower UBSU.

This is the picture that comes out from the simple interpretation of cross cutting relationships among the different systems of surface structures. We have no subsurface data in this area, but we can try to model the structures at depth by making some assumptions. That will give new clues to the interpretation of the tectonic history of this area.

MODELLING THE GROWTH FAULT

To analyse the original shape of the Sterza half graben we have to eliminate the effect of all the post-early Messinian deformation. Let's begin by examining three geological sections across the Sterza half graben (Tav.1). Sections 1, 2 and 3 are all taken perpendicular to the master fault of the Sterza half graben and cut it at progressively higher structural levels, since the basin is structurally lowered northward by a normal fault staircase, probably formed during the middle Pliocene event. The three sections form a narrow angle with the middle Pliocene structures; hence practically neither tilting nor extension, related to them is recorded in the sections.

Therefore, restoring the sections to their early Pliocene position just needs the elimination of the uplift. Fig. 9b shows section 2 restored at early Pliocene time. To eliminate the deformation occurred in late Messinian, we've got to operate a clockwise rotation of the whole hanging wall of the western fault. The difference in the amount of tilting between section 2 and sections 1 and 3 is probaly due to a higher slip rate in the central part of the fault than at the edges. Anyhow we will use section 2 for our modelling: therefore we will rotate back our structure of 20°. Fig. 9c shows section 2 at the end of early Messinian, that is at the end of the deposition of the lower UBSU and before the erosional event occurred before the deposition of the upper UBSU. The missing (eroded) part of the lower UBSU has been reconstructed projecting the entire hanging-wall succession on section 2.

Section 2 is the more appropriate for modelling the shape of the Sterza half graben, because the lower UBSU features there the greatest variation of bed attitudes. From east to west infact, we see a 57° dip domain, then a 50°, a 40°, a 38° and finally a 35° domain (Tav. 1). Both the western and the eastern N10° faults outcrop in section 2, being sutured, the first by recent landslides and debris, and the second by the upper UBSU. Nontheless we can assume their location by projecting them along strike from section 1. We are going to give some constraints to the shape of the Sterza half graben listric fault, through the analysis of the dip domains. XIAO & SUPPE (1992) model the relationships between fault shape and rollover shape, beginning from the case of a normal fault with a single sharp bend, and passing then to a multiple-sharp-bend fault which approximates quite well a continuously curved normal fault. The clay models of a normal fault with a single sharp bend show that the bending of the beds in a rollover is not accomodated by shear, as is the case for fault-bend folding, but through a tight complex of synthetic and antithetic minor faults which form a kink band (Fig. 10). This is bounded by two parallel surfaces which are antithetic to the fault when this is concave upward, and syntethic when it is convex. The attitude of these two surfaces is the collapse direction ψ, which, in uniaxial stress conditions, can be assumed

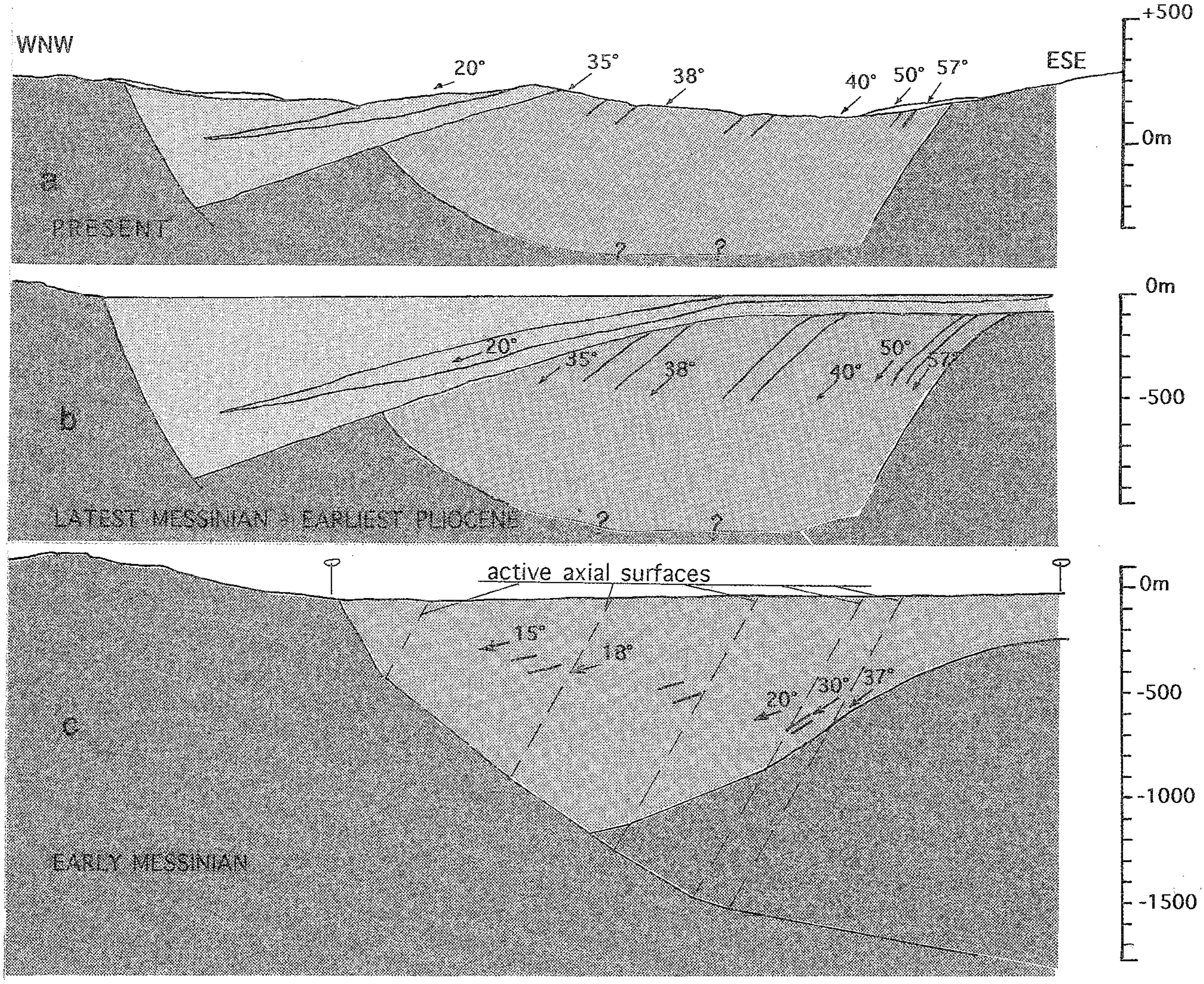


Fig. 9 - Palinspastic restoration of section 2, for the legend see Tav. 1, the horizontal scale is the same as the vertical scale. 9a - section 2 at present, the two faults on the left have been projected from section 1 (Tav. 1); 9b - section 2 at latest Messinian-earliest Pliocene, the hanging wall flat of the upper UBSU has been projected from section 3; 9c - section 2 at the end of early Messinian; to eliminate the tilting connected with the deposition of the upper UBSU, the lower UBSU has been rotated 20° clockwise around a pole located where the beds turn to horizontal; The eroded part has been replaced assuming no erosion on the hanging wall flat of the lower UBSU in section 3, and projecting it on section 2; the dashed lines represent the active axial surfaces, separating the dip domains. The fault shape has been modelled as a multiple bend fault, the bends have been placed where the active axial surfaces (AAS) cross the higher segment of the fault, the angles of the fault have been calculated through Xiao and Suppe's formula.

to be 60°. These surfaces divide the rollover in three portions:

a) the collapsed portion, bounded by the master fault on one side and the first of the two surfaces, which is fixed to the sharp bend in the master fault, and is called active axial surface (AAS).

b) The deformed portion, where the collapse of portion (a) is accomodated through bending. It is bounded by the AAS and the inactive axial surface (IAS), which is fixed to the beds.

c) The undeformed portion (Fig. 10).

As the rollover grows, larger and larger parts of the collapsed portion cross the AAS, being deformed, while the AAS and the IAS depart from each other, thus enlarging the deformed portion (Fig. 11). In a growth rollover, the deformed portion is bounded at the top by the growth axial surface (GAS), which connects the AAS and the IAS and represents the locus where each bed has crossed the AAS immediately after deposition (Fig. 11).

Xiao and Suppe's model gives the equations to correlate the change in the dip of bedding in the rollover (δ), the cutoff angle of bedding in the upper fault segment θ, the change in dip of the fault ϕ, and the collapse direction measured relatively to undeformed bedding ψ. The geometrical relationships among these parameters are evidentiated in Fig. 12. In a multiple bend model, each sharp bend in the fault generates a deformed portion in the rollover, bounded by a AAS and a IAS. Of course, as the rollover grows, each deformed portion incorporates all the deformed portions located on the hanging wall side, increasing their deformation, hence the attitude of the beds. What we end up with is a large deformed area where, going from the hanging wall toward the fault, the attitude decreases, each time an AAS is crossed (Fig. 13).

Basing on this model we can reconstruct the shape of the Sterza master fault (Fig. 9c). The AAS are traced on each limit between two dip domains; the first segment of the fault is prolonged till it reaches the first

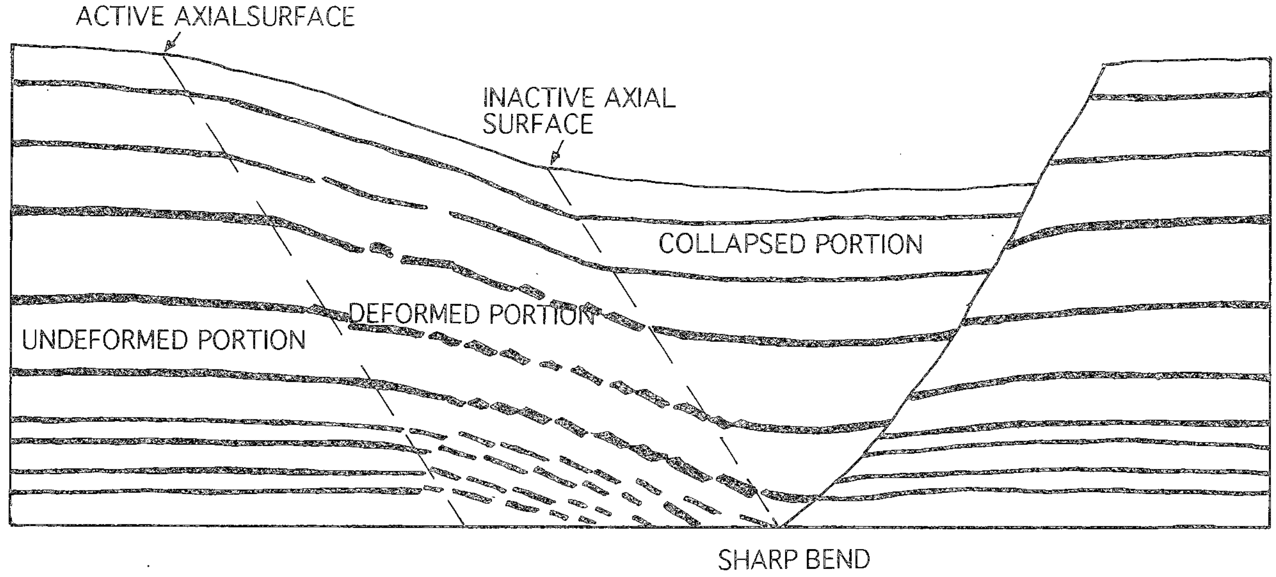


Fig. 10 - Sketch of a clay model of nongrowth rollover, with one sharp bend. The active and inactive axial surfaces are shown. From right to left we can recognize: a collapsed portion, between the fault and the AAS, a deformed portion, between the AAS and the IAS, and an undeformed portion left of the IAS (modified after Xiao & Suppe, 1992).

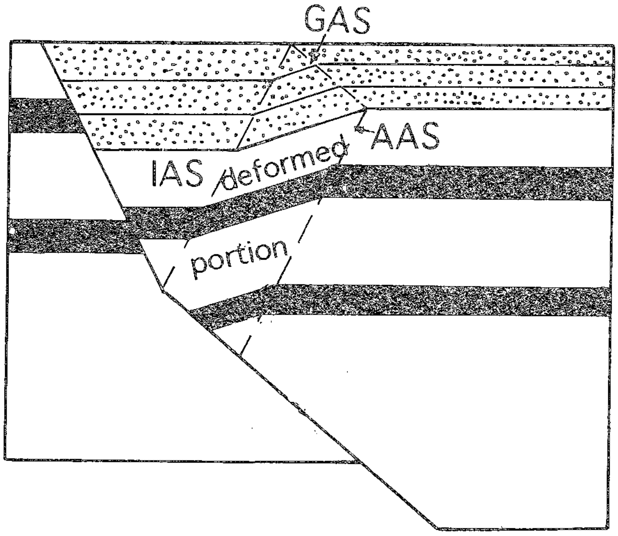


Fig. 11 - Model of a growth rollover with a single sharp bend. Pregrowth beds are black and white, growth beds are dotted. The deformed portion of the rollover (see Fig. 10), is bounded at the top by the growth axial surface (GAS), that connect the AAS and the IAS, passing through all the points where the syn-rift beds bend. From Xiao & Suppe (1992).

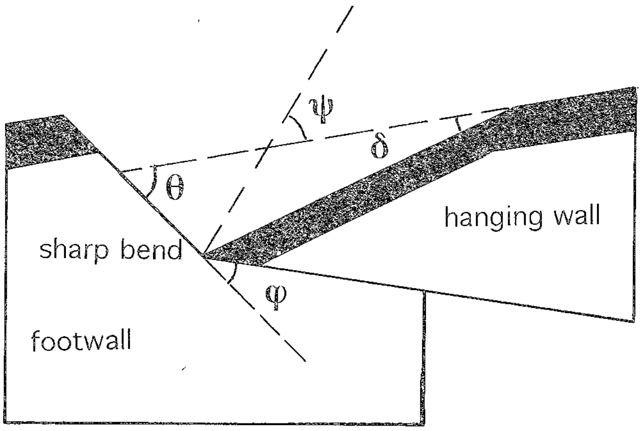


Fig. 12 - Geometrical relationship between fault shape and rollover shape for a single sharp bend fault: δ = change in the dip of bedding in the rollover; θ = the cutoff angle of bedding in the upper fault segment; ϕ = the change in dip of the fault; ψ = the collapse direction measured relatively to undeformed bedding. From Xiao & Suppe (1992).

AAS, then the angle of the fault ϕ, is calculated through Xiao and Suppe's formula. These operations are repeated for each dip domain.

The assumptions we need to make are:

1) since the fault separates the bedrock (already compacted) from the syn-rift sediments, its shape has not been deformed by compaction;

2) θ (fault dip at surface) = ψ (collapse direction) = 60°.

What we really have, to be precise, is a compacted model. Nontheless we must consider also that most of the sediments across the section are shaly, and their compaction could have sensibly modified the stratal geometry in the rollover. We don't have subsurface data, but, being the sediment supply west-east we can predict a lithological transition from shales into sands and conglomerates downdip along the depositional surfaces; in this way the problem of ignoring compaction is less dramatic. At this point we are able to calculate the extension created by the opening of the Sterza half graben, putting the pin-points at the footwall edge and on the hangingwall flat. we obtain an extension of 1025 m on a section of 3475 m. The thickness of the entire reconstructed succession is about 1200 m.

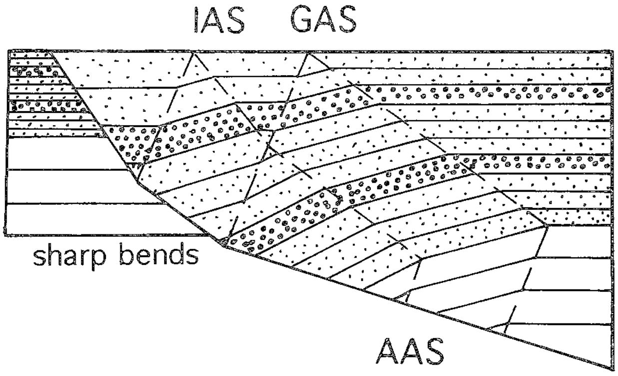


Fig. 13 - Model of a multiple bend growth fault. Pregrowth beds are white, growth beds are dotted. Each sharp bend generates a deformed portion, bounded by AAS, IAS, and GAS. As the rollover grows, the deformed portions relative to the different sharp bends in the fault overlap; the beds in the overlap areas are stepper.

DISCUSSION

The general tectonic evolution of the area has already been discussed in a previous paragraph. That has been done to keep the results directly derived from the data separated from the results of a modelling that has required a number of more or less reliable assumptions. It is clear infact, that all the reconstructed geometry of the rollover, may be sensibly modified by changing the assumed θ and ψ values. Therefore what we can do now is discussing, if and how this model fit the general tectonic setting of the area, and how the tectonic evolution reconstructed for this area provides further clues to understand the dynamics ruling the formation of Neogene basins in Tuscany.

As already discussed, the lower UBSU of the Sterza half graben is the lateral equivalent of the fluviolacustrine plus the brackish water deposits that, in the rest of the Volterra basin, underlie the Messinian marine sediments (Sarti & Testa, 1994). All this stratigraphic interval, in the Volterra basin, has an average thickness, at surface, of 500 m, reaching almost 1000 m only in the Radicondoli area (Fig. 1). Our model displays a succession even thicker. Nevertheless, the examined data from the Sterza area demonstrate how such different thicknesses can be explained with different tectonic settings (e.g. rollover versus hangingwall flat).

We've already said that compaction is much complex to be calculated in our case, but we can make a rough conservative estimate. At surface, along section 2, shales are much more abundant than sands, but to take into account the possible transition from shales into sands and conglomerates at depth, let's consider that our succession is made up of 50% shales and 50% sands. Assuming a porosity reduction of 35% for shales and 10% for sands, we obtain a thickness of at least 1600 m. Basing on the absolute ages given by D'Orazio *et alii* (this volume) to the upper Miocene pre-evaporitic succession, we may assign to our sequence a duration not longer than 2.5 Ma. The sedimentation rate obtained with these data is approximately 0.6 mm y^{-1}. This value is quite compatible with a subsiding

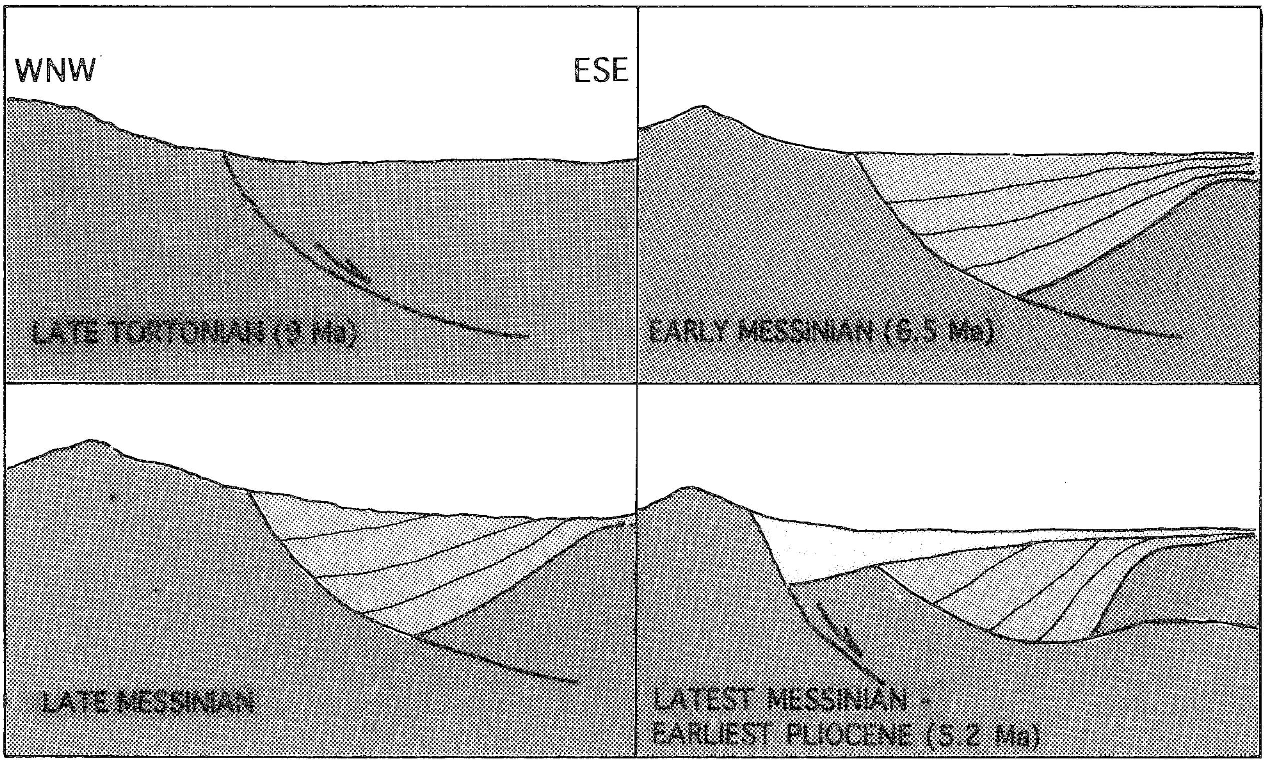


Fig. 14 - Tectonic evolution from late Tortonian to late Messinian of the Sterza valley, along section 2. 14a - Late Tortonian (approximately 9 Ma): a listric normal fault starts to dissect the area; 14b - early Messinian (app. 6.5 Ma) a half-graben has been opened along the listric fault, and has been filled with a clastic wedge (the lower UBSU); 14c - late Messinian (app. 6 Ma): the area is uplifted, and the lower UBSU is partly eroded; 14d - late Messinian-earliest Pliocene: another listric normal fault forms west of the previous, and another syn-rift clastic wedge (the upper UBSU) is deposited unconformably on the previous; the tilting related to this new half graben, increases by 20° the dips of the lower UBSU. Sketch not in scale.

lacustrine delta environment. For all these arguments the model seems to be realistic.

At this point we are able to draw a cartoon of the upper Miocene tectonic evolution of the examined area (Fig. 14). At late Tortonian (Fig. 14a), about 9 Ma (D'Orazio *et alii*, this volume), extensional tectonics started to dissect the area with a major ESE dipping listric fault. A transfer zone bounded at south this structure, and connected it with another rift sub-basin (Val di Cecina - Sassa area). A syn-rift clastic wedge was accumulated in the space opened (Fig. 14b). The opening developed at different velocities through time. Probably in a moment of higher subsidence rate, the threshold, separating this sub-basin from the sea, sank down, and a brackish water environment was established. The sub-basin kept on subsiding, probably until the beginning of the salinity crisis. At late Messinian (Fig. 14c) the area underwent uplift and erosion, and immediately after the Sterza valley got to subside again along a new fault opened west of the previous. A new sedimentary sequence was unconformably deposited on the previous (Fig. 14d).

This kind of evolution has been suggested for other portions of the Volterra basin: Sassa area (Bossio *et alii*, 1994), Marsiliana area (Costantini *et alii*, 1994). The occurrence of local uplift movements characterises, at late Messinian, these areas, where, at lower Pliocene, the presence of igneous bodies at depth is ascertained (Franceschini, 1994). Nobody has ever demonstrated or even hypothesised the presence of an igneous body under the Montecatini area, but, as a matter of fact, that area is affected by a quite strong thermal anomaly (Baldi *et alii*, 1994a).

It's not the purpose of this paper to propose a tectonic model that explains all the structural complexity of central Tuscany. All I want to suggest is that the upper Tortonian - lower Messinian rifting phase, may have caused enough extension to trigger partial melting at crustal depth. That led to the formation of magmatic igneous bodies that caused local uplifts. This might have occurred also slightly before the ascertained age of the plutons (early Pliocene) being responsible for the upper Messinian unconformity.

CONCLUSIONS

Many papers have dealt with the stratigraphy of the Neogene basins of Tuscany, providing a lot of fundamental data for the comprehension of the tectonic evolution of Tuscany from upper Miocene to Pleistocene (see Bossio *et alii*, 1993, for a review). Little effort instead has been put to understand what were the active structures during the sedimentation. This paper is a first attempt to address the problem of upper Miocene tectonic evolution of central Tuscany, from a tectonic-sedimentary standpoint.

The results must be split in two cathegories, basing on reliability. With a good degree of reliability we can make the following statements:

— extensional tectonics started to open the Sterza area at upper Tortonian;
— rifting developed along a NNE-SSW direction, forming a half graben with an east dipping listric master fault on the west side;
— a clastic lacustrine succession at least 1200 m thick was deposited in the half graben by eastward flowing streams;
— a much thinner succession, featuring lacustrine evaporitic episodes, was deposited on the hanging-wall flat;
— the Sterza half graben was part of a wider basinal area going from the Castellina ridge to the mid Tuscany ridge (*Dorsale medio-toscana*);
— rifting and sedimentation ceased sometime, in a time interval spanning from the deposition of gypsum to upper Messinian;
— the Sterza half graben was uplifted and partially eroded during late Messinian;
— at uppermost Messinian the area underwent renewed subsidence along the same directions, leading to the deposition of an upper Messinian - lower Pliocene sequence.

Next statements, instead, can be considered just working hypotheses:

— the sedimentation in the syn-rift sequence developed through minor tectonically driven sequences;
— a transfer fault connected the Sterza sub-basin to the Val di Cecina - Sassa sub-basin with a sinistral offset;
— the amount of extension during the deposition of the lower UBSU was not less than 1000m on a section of 3400.

The last point is in good agreement with what Baldi *et alii* (1994b) found in the Larderello geothermal area, through a structural analysis supported by subsurface data.

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