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ALLOSTRATIGRAPHY AND SEISMIC STRATIGRAPHY OF THE MIOCENE SEDIMENTS OF THE SPICCHIAIOLA - POMARANCE AREA, SOUTHERN SIDE OF THE VOLTERRA BASIN (TUSCANY, ITALY).

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Key-words: depositional units, seismic stratigraphy, extensional tectonics, Miocene, Tuscany.

Riassunto. Sono stati considerati i dati di superficie e quelli ricavati da profili sismici relativi al settore meridionale del Bacino di Volterra (Toscana, Italia) con lo scopo di determinare le unità deposizionali e la geometria di questo settore dell'Appennino durante il Miocene. Tra i sedimenti del substrato pre-miocenico e quelli del Pliocene sono state individuate quattro unità deposizionali: la prima (Unità 1) comprende i sedimenti marini del Serravalliano superiore-Tortoniano inferiore; la seconda (Unità 2) include i termini lacustri e lagunari del Tortoniano superiore-Messiniano inferiore; la terza (Unità 3) materializza il ciclo marino del Messiniano inferiore; la quarta (Unità 4) rappresenta la facies continentale di "Lago-mare" del Messiniano superiore. La deposizione di queste unità mioceniche è legata alla tettonica estensionale, attiva almeno dal Tortoniano e responsabile della formazione di semi-graben e delle discontinuità fra le unità.

Abstract. The objective of this work is to analyze the Miocene depositional units of the southern side of the Volterra Basin (Tuscany, Italy) utilizing outcrop and seismic data and to establish the major events that led to their formation.

Four depositional units have been recognized: Unit 1 is characterized by marine sediments of late Serravallian-early Tortonian age; Unit 2 is characterized by fluvio-lacustrine and brackish deposits of late Tortonian-early Messinian age; Unit 3 is characterized by marine deposits of early Messinian age; Unit 4 is characterized by the lacustrine deposits ("Lago-mare" facies) of late Messinian age. The deposition of these four units is associated with an extensional tectonic regime that has been active in Tuscany at least since the late Tortonian. This regime generated half graben type structures in which deposition occurred. The recognized unconformities between the units are mainly related to uplift as a consequence of the extensional tectonic regime.

Introduction.

The Volterra Basin is one of the large neoautochthonous, NW-SE elongated basins (Fig. 1) which formed in western Tuscany since the Miocene. These basins are separated laterally by bedrock ridges composed mainly of carbonates and sandstones (Ligurian and Tuscan nappes). Lengthwise, these basins are subdivided into sub-basins by transversal morphological and structural highs (Bartolini et al., 1983). Liotta (1991) has interpreted these transversal structures as transfer zones. There are two hypotheses about the origin of the basins. The first considers them to have formed as the result of an extensional regime that acted continuously in Tuscany from the Miocene up to the Recent (Scandone, 1979; Patacca & Scandone, 1989; Serri et al., 1992; Lavecchia & Stoppa, 1992; Bertini et al., 1992; Bossio et al., 1993; Carmignani et al., 1994, 1995; Elter & Sandrelli, 1995; Lazzarotto et al., 1995). According to this hypothesis the extension in Tuscany occurred in two distinct stages. The first stage took place between late Burdigalian and early Tortonian times, and involved low angle normal faults, leading to a stretching of the crust by 120%. The second extensional stage started in late Tortonian, continues to the Present and is responsible for the formation of the narrow, long grabens (or half-grabens) that characterize the morphology of the region.

The second hypothesis considers that the basins of western Tuscany have formed as piggy-back or thrust top basins, and were affected by extensional stresses that started only in the Present (Bonini et al., 1994; Boccaletti et al., 1995; Bonini & Moratti, 1995; Boccaletti et al., 1997).

The objective of this paper is to integrate outcrop data with subsurface seismic information to define the Miocene depositional units and the geometry of the southern side (Spicchiaiola-Pomarance area) of the Volterra Basin, thus, to establish the relative validity of the "all extensional" and the "compressional-extensional" hypotheses of formation for the basin. In this context the unit is "a mappable stratiform body of sedimentary rock that is defined and identified on the basis of its bounding discontinuities and their correlative conformities" (NACSN, 1983, p. 865, modified by Walker, 1992).

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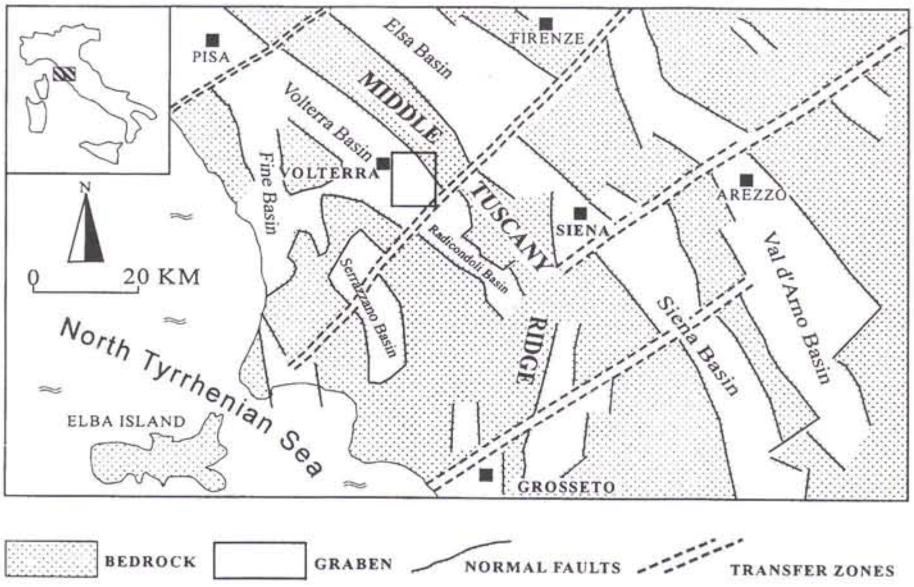


Fig. 1 - Extensional neoautochthonous basins of Southern Tuscany. The square indicates the studied area.

Surface data.

The sedimentary fill of the southern part of the Volterra Basin is Middle Miocene (late Serravallian) to Middle Pliocene in age. It spans the interval between *Neogloboquadrina continuosa/Globorotalia siakensis* Zone (*Neogloboquadrina continuosa* Subzone) and the *Globorotalia aemiliana* Zone, according to the planktonic foraminiferal zonal scheme of Iaccarino and Salvatorini (1982), partially revised by Foresi et al. (in press) for the Middle Miocene and the interval *Discoaster kugleri* Zone - *D. surculus* Zone according to nannofossil zonation indicated by Mazzei & Oggiano, 1990; Bossio et al., 1991; Francolini et al., 1990 and Foresi et al., submitted).

Four units can be recognized in the Miocene (Fig. 2). The correlation of these units with the bio-chronostratigraphic scheme and the geochronological scale is illustrated in Fig. 3.

Unit 1. This unit is known in the literature by the name of "Arenaria di Ponsano" (Giannini & Tongiorgi, 1959; Mazzanti et al., 1981; Mazzei et al., 1981; Foresi et al., 1996a, b). It crops out only near Volterra (Ponsano locality; Fig. 2), in the eastern side of the studied area, and near Siena (Rencine locality). It lies unconformably on bedrock, represented in this area by the Ligurian Nappe. According to Elter & Sandrelli (1995), Unit 1 is autochthonous and not semiallochthonous as reported in the preceding literature (Baldacci et al., 1967; Decandia et al., 1993). The maximum thickness of the unit, measured in the Ponsano outcrop, is 550 m.

Unit 1 is characterized by sandstones alternating with marlstones (Fig. 4). The sandstones are fine to medium grained, well sorted, yellow or grey-yellow and well cemented (calcareous cement), normally in strata 5-6 m thick; conglomerates occur only in the uppermost part of the sandstones. The marlstones are massive, grey, with a variable amount of sand. Both the sandstones and the marlstones are highly bioturbated and the primary structures have been obliterated, except in the upper part of the unit. In the sandstones it is possible to recognize trace fossils of the *Skolithos* ichnofacies (Foresi et al., 1996b). The sediments of Unit 1 commonly are very fossiliferous and the most common fossils are bivalves, gastropods, echinoids and balanids. Bone fragments and teeth of fishes are rare (Menesini, 1967).

Unit 1 was deposited in a marine environment. The marlstones are indicative of the deep inner shelf, the sandstones of the shoreface (Fig. 4; Foresi et al., 1996a, b). The age of Unit 1 is late Serravallian-early Tortonian (Mazzanti et al., 1981; Mazzei et al., 1981; Foresi et al., 1996a).

Unit 2. Unit 2 is well represented in outcrop at the NE side of the studied area. Recently it has been studied by Bossio et al. (1996a) and it includes in the lower part the "Conglomerato di Pod. Luppiano" and "Argille del T. Fosci", and in the upper part the "Spicchiaiola" Formation and "Argille a *Pycnodonte*" Formation p.p. (Fig. 5). The lower part of this unit is known in the literature with the name of "Serie Lignitifera" (Trevisan, 1951; Mazzanti, 1961, 1966; Lazzarotto & Mazzanti, 1978; Bossio et al., 1993). Unit 2 is characterized by conglomerates, sandstones, clays and gypsum. It lies unconformably both on Unit 1 and bedrock. The thickness of the unit, measured in the Spicchiaiola area, is 500 m.

The conglomerates are poorly organized (toward the base) to organized, clast supported and generally, in thick amalgamated beds (50 to 150 cm thick). They are composed of clasts derived from bedrock (Ligurian Nappe), moderately well rounded and subspherical. Internal-

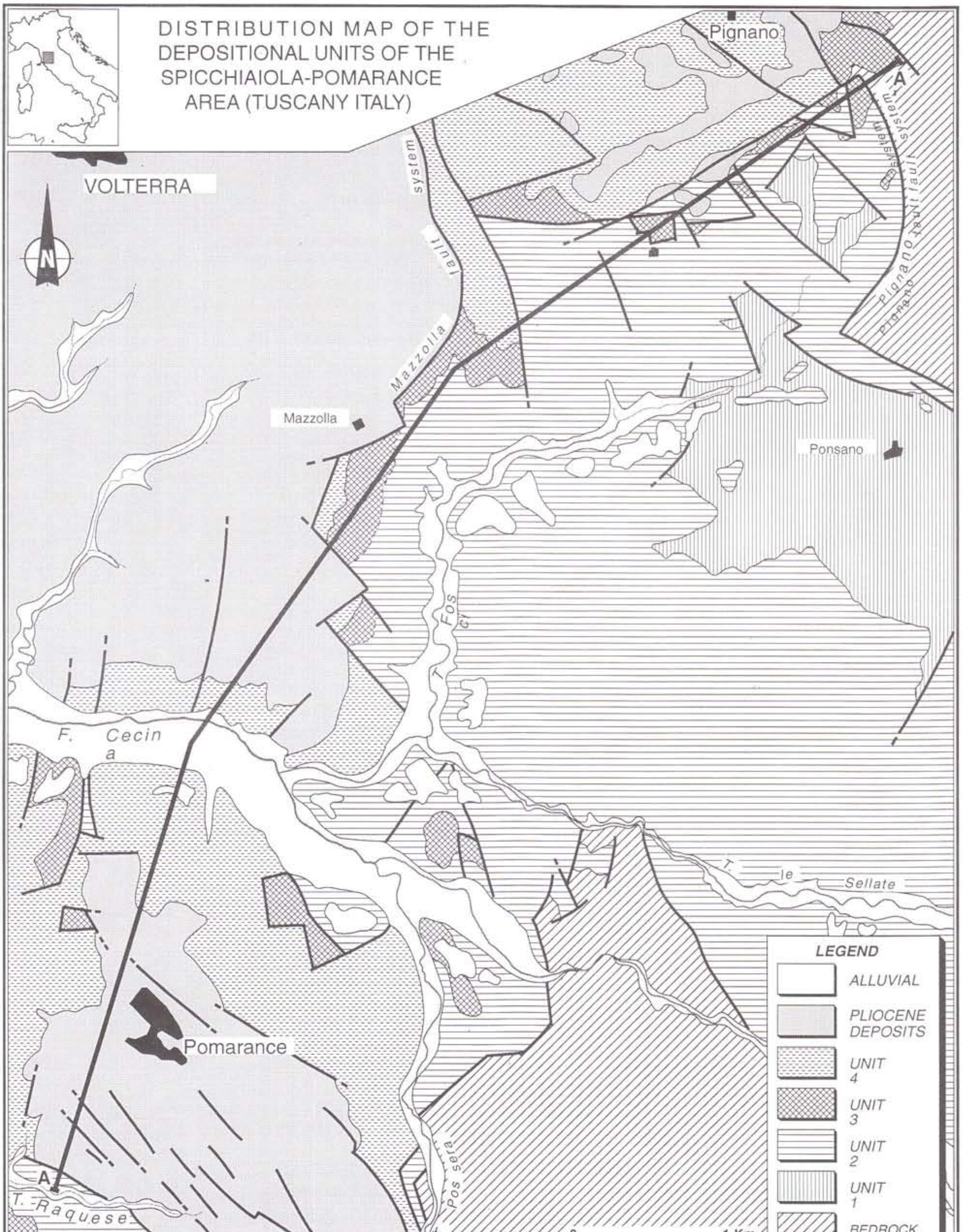


Fig. 2 - Map distribution of the depositional units of the Spicchiaiola-Pomarance area, southern side of the Volterra Basin. A-A', section reported in Figure 9.

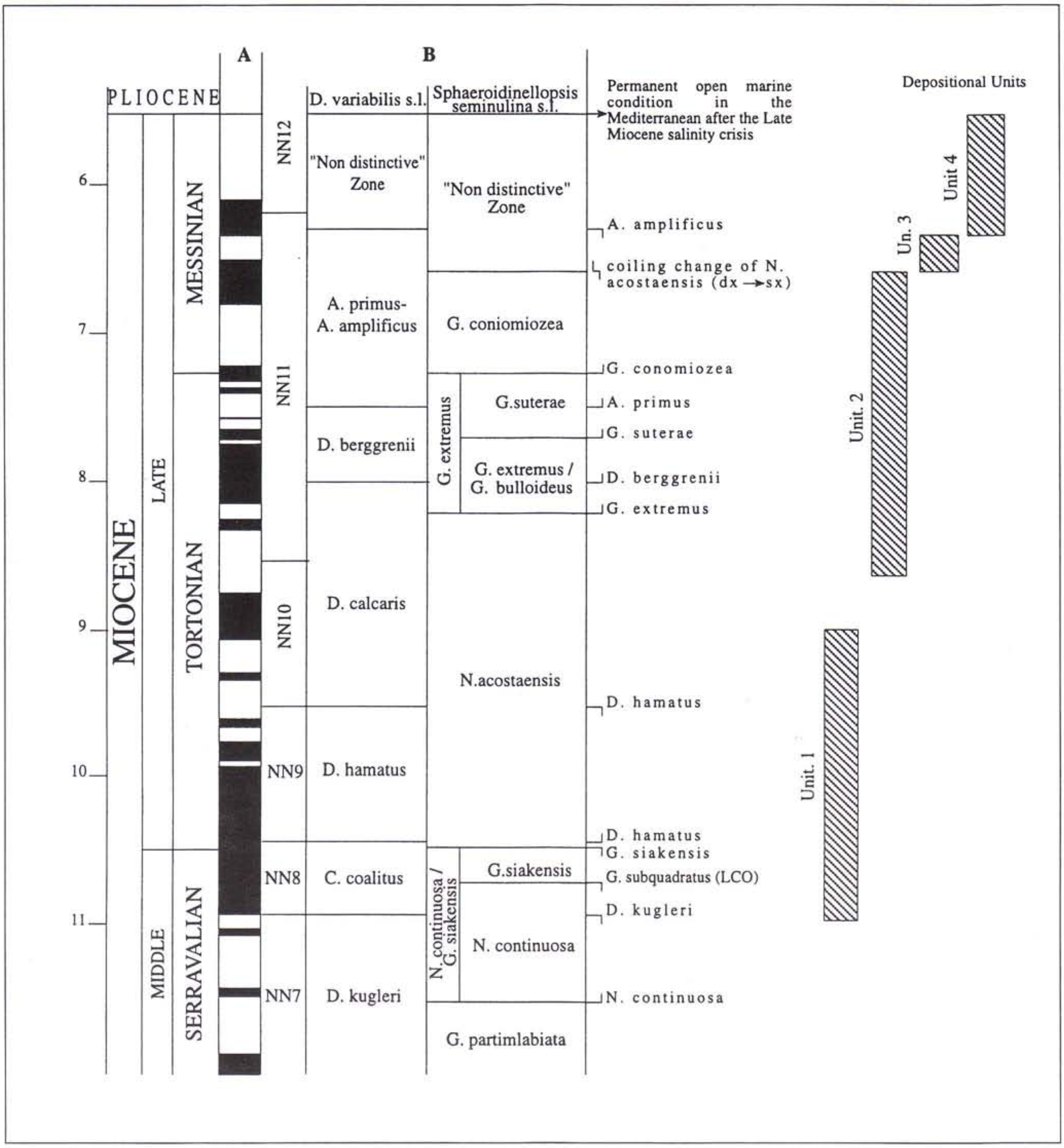


Fig. 3 - Correlation between the units and the bio-magneto-chronostratigraphic and geochronologic scheme. A - Magnetostratigraphic scale after Cande and Kent (1995); B - bio-chronostratigraphic scheme after Bossio et al. (1991) and Foresi et al. (submitted).

ly they show foresets, cut and fill and wide channel structures. They have been interpreted as the subaerial part of an alluvial fan complex (Martini et al., 1995; Pascucci, 1995). The sandstones are coarse to medium-fine grained. Coarse sandstones are poorly sorted, yellowish brown, well cemented, locally containing granules and sparse pebbles. They occur in medium to thick beds, generally planar bedded to massive, seldom showing trough cross-bedding: ripple cross-lamination and cross beds occur preferentially toward the top of the unit. The medium and fine sandstones are grey to yellowish brown in colour, plane laminated, thin to thick bedded. They contain granules and sparse small pebbles. The sandstones have been interpreted as distal fluvial deposits and turbid flow or turbidite layers deposited in a relatively deep lake. The clays are grey, massive with occasional plant material. Local interlayers of sandstone and rare conglomerates are present (Fig. 5). In the lower

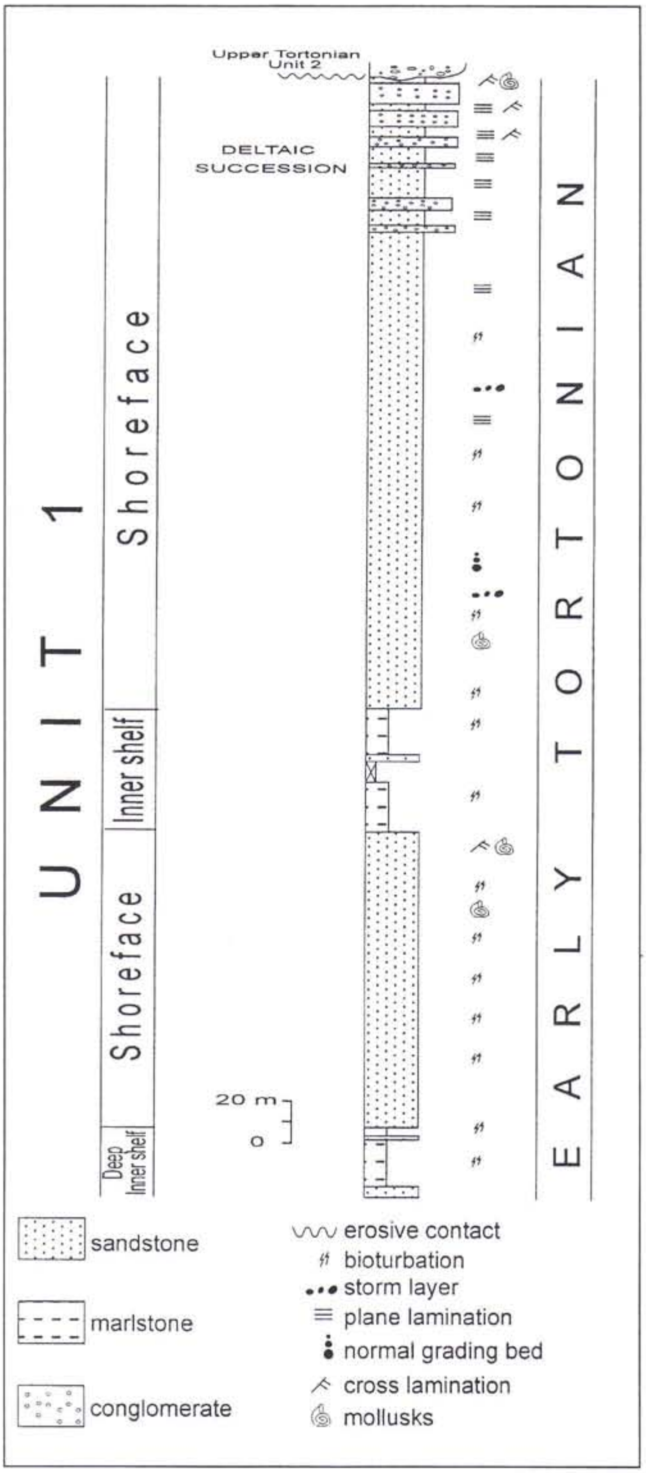


Fig. 4 - Stratigraphic sections of Unit 1 measured at Ponsano (after Foresi et al., 1996a). The base of this unit does not crop out at this locality.

part of the unit, a few thin beds (some metres thick) of lignite are often interbedded with the clays. The name of "Serie Lignitifera" (lignitiferous series) derives from the presence of these organic layers. The clays are indicative of deep lacustrine settings. The evaporative deposits are composed of gypsarenites, clays with interbedded gypsarenites and local alabastrine gypsum. They occur at the bottom of the "Spicchiaiola" Formation or in the upper portion of the unit, at the base of the "Argille a *Pycnodonte*" Formation. In the first case their thickness is about 15 m, while in the second they reach a thickness of about 20 m.

Two different fossil assemblages characterize the lower and the upper part of Unit 2. The lower part is characterized by cap of gastropods (opercula of *Bithynia*), vegetable materials (chiefly oogonia of *Characeae* and plant material) and lacustrine ostracods. The upper part is characterized by gastropods (especially *Melanopsis* and *Teodoxus*), bivalves *(Lymnocardium* and *Dreissena*), serpulids (in the sandy-marl facies) and vegetable remains. Furthermore a consistent change in the microfauna has been recorded. In fact, in this upper part foraminifers and ostracods of brackish environment are present (Bossio et al., 1996a).

Fossiliferous and lithological characteristics indicate that Unit 2 was deposited initially in a fluvio-lacustrine environment which later became a brackish lagoon which experienced periods of high salinity (Fig. 5). The age of the lower part of Unit 2 is late Tortonian and that of the upper part reaches the earliest Messinian. This age is confirmed by preliminary radiometric dating (8.1 ± 0.1 Ma) of a volcanoclastic layer interbedded with the sediments of the "Serie Lignitifera" near the studied area (D'Orazio et al., 1995).

Unit 3. The unit is present in the central part of the studied area and lies unconformably (with angular unconformity) on bedrock and on Unit 2, or, in places, conformably (correlative conformity) on Unit 2. Unit 3 is characterized (Fig. 5) by conglomerates ("Conglomerati di Villa Mirabella"), limestones ("Calcari di Castelnuovo") and clays ("Argille a *Pycnodonte*" Formation p.p; Cerri & Sandrelli, 1994; Bossio et al., 1996a). The three lithologies show interfingering relationships. Conglomerates and limestones have a marginal position in the sedimentary basin, whereas the clays occur mainly toward the center of the basin. The unit ranges from 30 m to 50 m in thickness.

The conglomerates are clast supported with calcareous sandy matrix. Pebbles are mostly composed of limestones, well rounded, variable in size (5-10 cm average) and show perforation from lithophagous organisms. The clasts derive from the Ligurian nappe and the Tuscan Nappe. Macrofossils are rare or absent in the conglomerates. Conglomerates mark the early Messinian marine transgression in the area (Bossio et al., 1994, 1996a). The limestones are bioclastic and rich in terrigenous material. Bioclasts are of molluscs (*Chlamys*, *Pecten*, *Ostrea*), echinoids, bryozoans and anellids (*Ditrupa*). Associated with these, mounds of rhodolites and/or *Porites* occur. They have been interpreted as patch reef de-

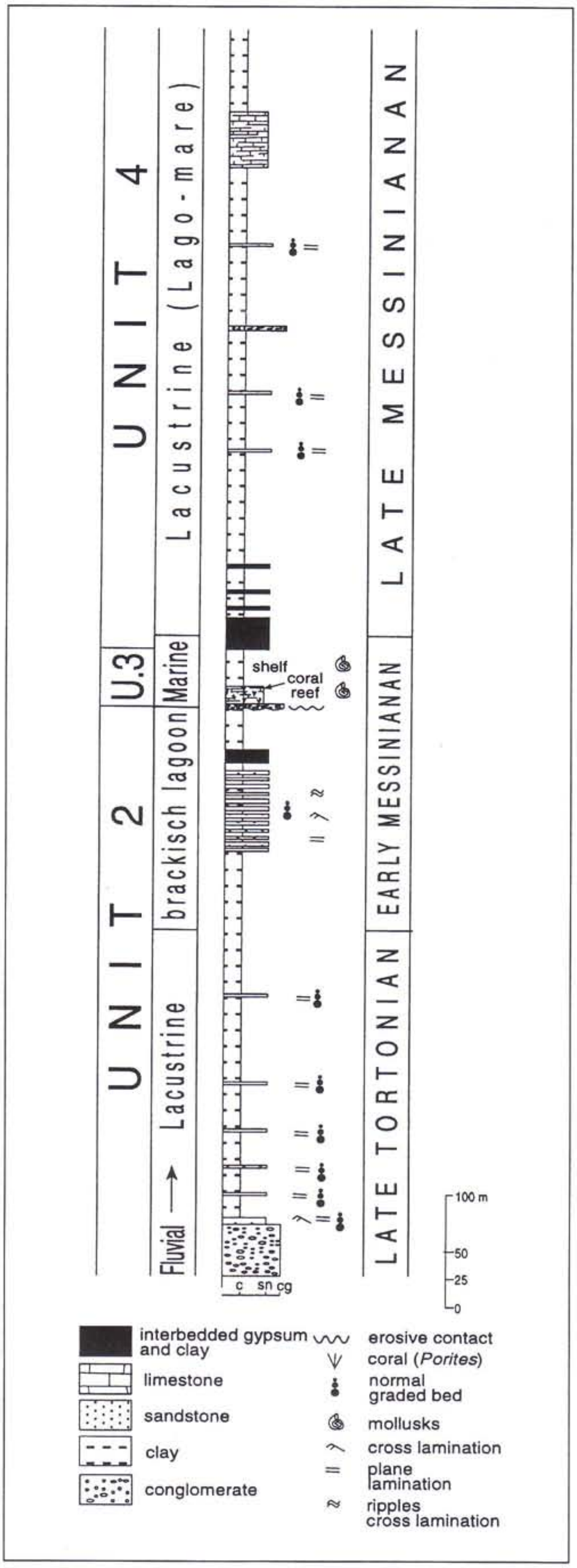


Fig. 5 - Stratigraphic section of the Upper Miocene Units (2, 3, 4) of the Spicchiaiola-Pignano area (after Bossio et al., 1994). c - clay; sn - sandstone; cg - conglomerate.

posits (Bossio et al., 1994, 1996a). Clays are grey, massive with locally some thin sandstone interlayers. These sandstones are fine grained, graded, yellowish and plane laminated. In places, ripple cross-lamination also occurs. Specimens of *Pycnodonte navicularis* are present in the clays and are often very abundant. More rarely, other small bivalves have been observed (*Corbula gibba*).

The concentration of microfauna and the nannoflora vary considerable in the unit. In the limestone facies, benthonic foraminifers and ostracods are very common, whereas the calcareous plankton is generally characterized by few, generally small, specimens. In the "Argille a *Pycnodonte*" micro and nannoplankton assemblages are abundant and frequently oligotypical. In the benthonic assemblages, *Bolivina dentellata*, *B. dilatata* and *Bulimina echinata* are the taxa that abound. Ostracod assemblages are represented by few species.

Unit 3 was deposited in a marine environment, inner neritic zone (Bossio et al., 1996a). Clay can reach the outer part of the shelf (Bossio et al., 1996a). Micropaleontological assemblages allow us to recognize episodes of anoxic conditions at the bottom and hypersaline water masses in the basin.

The age of this unit is early Messinian. According to Bossio et al. (1994, 1996a) the fossil assemblages are indicative of the lowermost part of the Non Distinctive Zone (foraminiferal biostratigraphy) and of the uppermost part of the *Amaurolithus primus-A. amplificus* Zone (calcareous nannoplankton biostratigraphy).

Unit 4. The unit is present in the Spicchiaiola and Cecina River areas. Its lower contact is indicated to be an unconformable one by seismic data (see later), but such an unconformity is not recognizable in the outcrop. The upper boundary of the unit grades conformably (correlative conformity) in to the Pliocene clays. Unit 4 ("Argille e gessi del F. Era Morta" p.p. and "Conglomerati di Borro Sassicaia"; Cerri & Sandrelli, 1994) is characterized by clays with interbedded sands (turbidites), gypsum, reworked gypsum and conglomerates. The thickness of the unit measured in the Spicchiaiola area is 500 m (Fig. 5).

At the base of Unit 4, a thick continuous level of gypsum is present. This level represents the Messinian evaporative period of the Mediterranean. It is characterized by the following primary facies: finely crystalline, laminated, selenitic and arenitic. Diagenetic alabastrine gypsum is present as well.

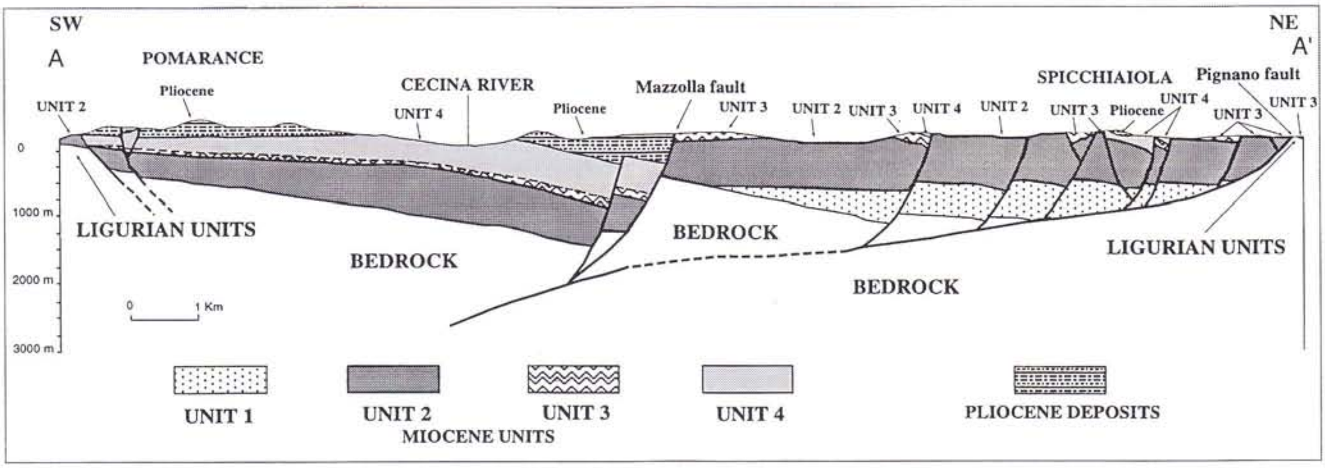
The clays are brown-grey, with a variable amount of massive or laminated marls (calcareous shale). Small pebbles occur isolated or in clusters. The sands are grey, medium grained, normally in beds 5 cm to 1 m thick. Plane lamination is locally well developed. Both clay and sand are lacustrine deposits. The pebble conglomerates are clast supported, poorly organized in beds 1 m thick with sandy matrix. Clasts are moderately well rounded with average size of 5-6 cm, mostly composed of limestones or sandstones derived from Ligurian Nappe and subordinately from Tuscan Nappe. In places pebbles of aplite (Eurite Auct.) and gypsum are present. Conglomerates have been interpreted as mass flow deposits.

A poor macrofauna characterizes sediments of this unit; some layers are rich of *Dreissena*, sometimes associated with *Lymnocardium*, limnic gastropods and serpulids. Among the microfossils, *Tecamoebas*, oogonia of *Characeae* and other remains of vegetation have been found. The foraminifers are poorly represented and ostracod assemblages are generally very rich in specimens of a few species. Some of these are typical of the Parathetis biofacies (Bossio et al., 1996a) and they are present only in the uppermost part of the unit.

Unit 4 was deposited in a shallow lacustrine environment characterized by fresh to brackish water; this environment is well known in the literature with the name of "Lago-mare". The age of the unit is late Messinian (Bossio et al., 1994, 1996a).

Seismic analysis.

In the Volterra area seismic profiles have been obtained by AGIP to explore for gas (Mariani & Prato, 1988). Seismic data, still under proprietary confidence, were obtained using 24 channels and a vibroseis source with shot spacing of 40 m, providing a subsurface coverage of 6000%. Their processing has been carried using the elaboration sequence explained by Mariani & Prato (1988). Data from a seismic profile running almost parallel to the geological section (Fig. 2, 6A) will be presented here. The line-drawing relative to the seismic profile (Fig. 6B) shows two different reflection patterns. Along the SW side (Pomarance - Cecina River) reflectors are well defined and organized, while along the NE



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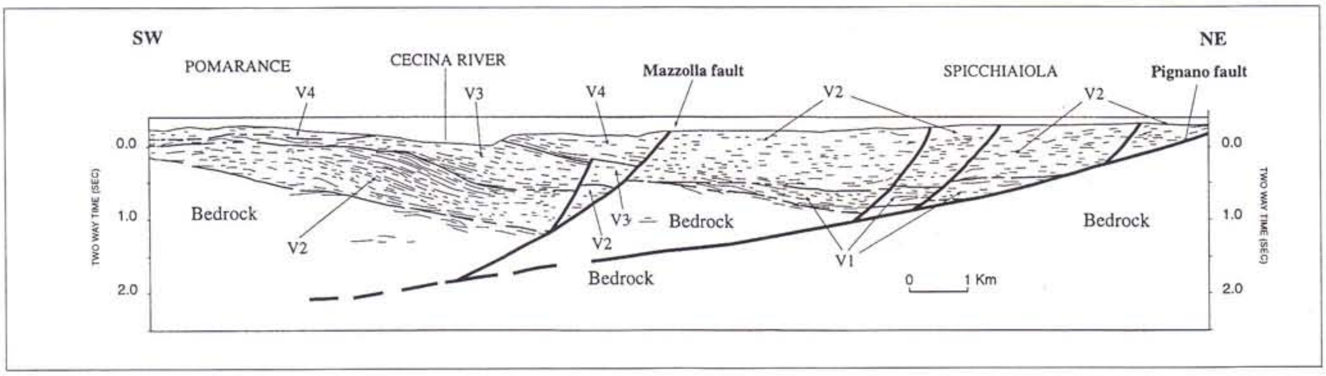

B

Fig. 6 - A) Geological section of the Spicchiaiola-Pomarance area, showing the relationships between the four depositional units. B) Line drawing (in two way time) relative to a seismic profile that crosses the Spicchiaiola-Pignano area. The geometry of the Upper Miocene basin is well displayed. Note the half graben geometry, the listric geometry of the Pignano fault and the prograding clinoforms from SW to NE. The faults flatten toward a common, deep, *décollement* surface. On the hanging-wall side of the basin, the presence of clinoforms could be related to a delta complex prograding toward the central part of the basin. The Mazzolla fault in the central part of the profile delimits the Pliocene basin. The seismic profile, at this moment is not available for publication.

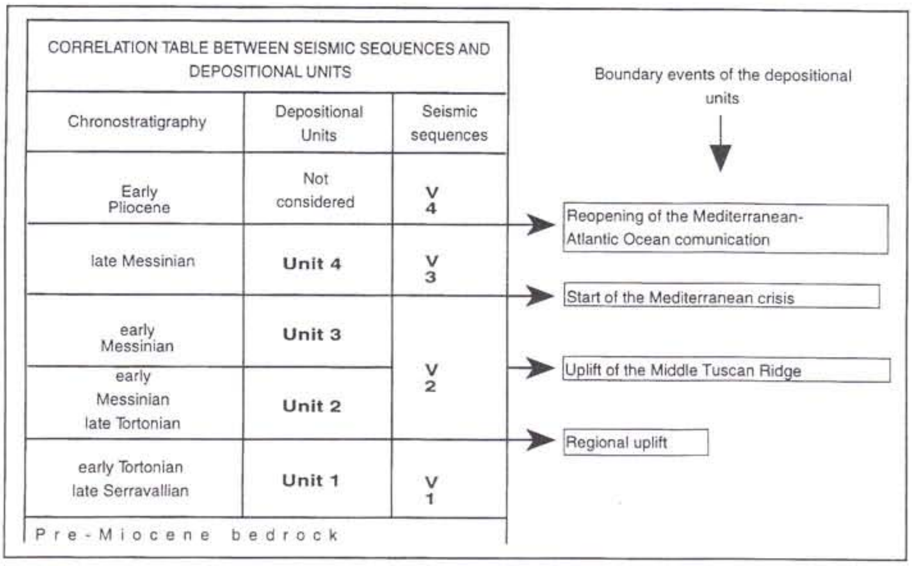

Fig. 7 - Relationship between seismic and depositional units. In the figure are also indicated the relative periods of uplifting and subsidence related to the extensional tectonic regime.

side (Spicchiaiola) reflectors are less well defined. This fact may be related to the numerous normal faults present in this part of the area which modify the seismic signal quality.

Four seismic sequences can be recognized (Fig. 7). The first seismic sequence (V1) is characterized by reflectors that are generally not continuous, with poorly defined trends. However, onlaps on bedrock (Ligurian Nappe) are locally well defined. This seismic sequence is present only in the northern part of the profile and it corresponds to the depositional Unit 1. The second seismic sequence (V2) is generally characterized by discontinuous, poorly organized reflectors, although in places they define an angular unconformity with the underlying seismic sequence 1 and the bedrock. In the Cecina River area, better defined and continuous reflectors show prograding clinoforms from southwest toward the central part of the basin. This V2 sequence corresponds to both outcropping depositional Units 2 and 3. Due to the reduced thickness (30-50 m), Unit 3 cannot be identified in this area with seismic data. The various reflector patterns of V2 in the Cecina River area (Fig. 6B) can be interpreted as follow. The discontinuous poorly organized reflectors may be associated with conglomeratic topset lenses of a prograding delta. The well defined clinoforms may represent sands, fine conglomerates and clays derived from such a delta.

The third seismic sequence (V3) is characterized by well defined reflectors in the lower part of the sequence showing clear onlap on sequence V2. The high amplitude reflectors at the base of the sequence V3 can be associated with the gypsum layers alternating with clays which formed during the Mediterranean evaporative period. In the upper part of the sequence the reflectors become less well defined. V3 corresponds to depositional Unit 4. The fourth seismic sequence (V4) shows well defined continuous reflectors in the lower part and less well defined ones in the upper part. Seismic sequence V4 corresponds to the Pliocene deposits (Fig. 6B).

Structure.

Several normal faults mapped in outcrops (Fig. 2) and reported in the geological cross section of Fig. 6A, are also recognizable in the seismic profiles (Fig. 6B). In the subsurface, they show a listric geometry flattening toward a common, deep *décollement* surface (Fig. 6B). They define a half-graben type basin. The easternmost large fault (Pignano fault system; Figs. 2, 6A, 6B) cuts through the Ponsano Sandstone (Unit 1), and acted as the active master fault during the late Tortonian and Messinian; that is, during the sedimentation of the depositional Units 2, 3 and 4 (or seismic sequences V2 and V3). In fact the maximum thickness of the Upper Miocene sediments occurs at the footwall of this fault. In the Pliocene, the Mazzolla fault (Mazzola fault system; Figs. 2, 6A, 6B) became the active master fault during the deposition of the marine Pliocene sediments. These sediments have the maximum thickness at the footwall of the Mazzolla fault (Bossio et al., 1995, 1996a). This demonstrates a significant shift of the depocenter of the Volterra Basin through time.

Discussion.

In the southeastern area of the Volterra Basin there is no indication, on the surface or in the seismic section, of major compression. All the faults we have observed are normal ones. Therefore, for this area at least, extensional forces were responsible for the initiation and subsequent development of the basin.

In this area, we can further observe that normal faults cut through all the sequences and they join a basal fault which dips shallowly into the bedrock. The thickness of the seismic sequences, combined with outcrop evidence, indicate that the seismic sequence V1 is and can be present only in the area northeast of the Mazzolla fault (Fig. 6). This is the Ponsano Sandstone Unit which has been reported by Elter & Sandrelli (1995) to be widespread, although discontinuously, over western Tuscany and parts of the Tyrrhenian Sea (Lazzarotto et al., 1995; Pascucci, 1996). This unit has been interpreted by Elter & Sandrelli (1995) to represent deposition of the first extensional stage of this region.

The evolution of the basin during the Late Miocene is well documented in this area, although slightly complicated by subsequent dissection during the Pliocene. Four major events can be recognized.

The first event starts with the unconformity between Units 1 and 2. This unconformity records a tectonic uplift during the Tortonian which has been recognized along the Tyrrhenian side of the Northern Apennines (Patacca & Scandone, 1989; Carmignani et al., 1994; Baldi et al., 1994; Bossio et al., 1993). This event is marked by an abrupt change in the environmental conditions from marine (Middle-Upper Miocene p.p.) to continental (Upper Miocene p.p.). During this time, a period of non deposition occurred. The deposition of Unit 2 is connected with new extensional activity and the formation of narrow half-graben.

The second event is marked by the unconformity between Units 2 and 3. This can be recognized in outcrop near the locality of Spicchiaiola. It may be related to the uplift of the ridge (Middle Tuscany Ridge) present at the eastern boundary of the Volterra Basin (Bossio et al., 1995). The same unconformity has been documented also by Bossio et al. (1996b) in western areas (Fine Basin, Fig. 1), therefore it records both a general uplift of this side of Tuscany during the early Messinian and contemporaneous relative fall of sea level elsewhere.

The third event is documented by the unconformity between Units 3 and 4 and is well represented in the seismic profile. It records a drastic drop of sea level, a change from a marine (Unit 3) to a lacustrine (Unit 4) environment and intense erosion at the margin of the basin and consequent emplacement of gypsum and other marginal materials into the deeper part of the basin as gravity flows. The origin of this event can be considered eustatic rather than linked to a tectonic regional uplift.

The fourth event is marked by a new period of tectonic activity during which the Upper Miocene sedimentary basins was dissected, and a new depositional basin formed during the Pliocene. This event is contemporaneous with the reopening of the Mediterranean-Atlantic Ocean communication. In the seismic profile this new tectonic activity is documented by the westward shifting of the half-graben master fault (from Pignano to Mazzolla fault system, Fig. 6).

The seismic data indicate that the geometry of the late Tortonian-Messinian basin is similar to that of the Type A model of half-graben (Fig. 8) proposed by Leeder & Gawthorpe (1987) and modified by Martini & Sagri (1993). In fact, on the hanging-wall side (Fig. 6B) of the basin, a large alluvial-delta complex prograded into a water body in the central part of the basin, while coarse-grained fan delta complexes characterized the footwall side of the basin (Martini et al., 1995; Pascucci, 1995).

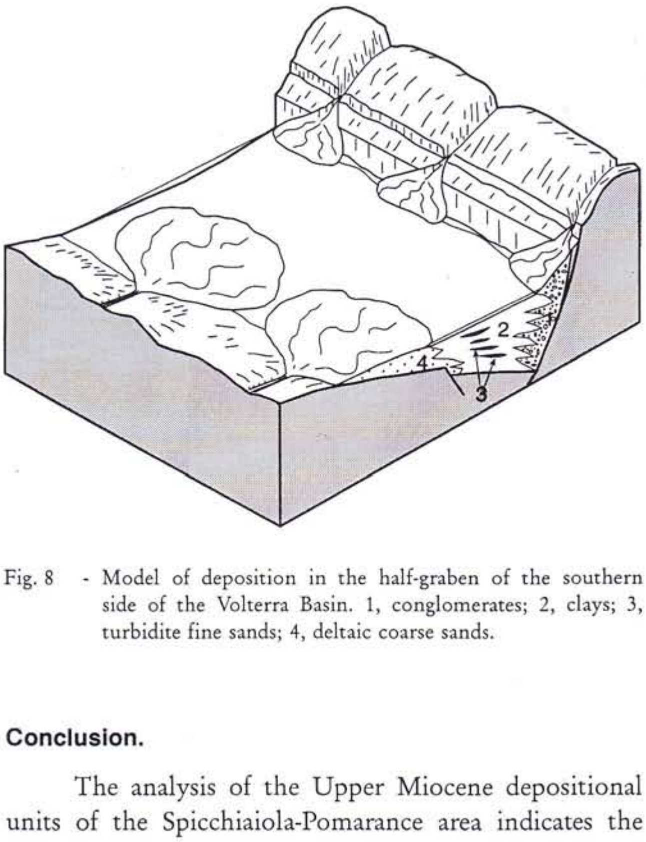

Fig. 8 - Model of deposition in the half-graben of the southern side of the Volterra Basin. 1, conglomerates; 2, clays; 3, turbidite fine sands; 4, deltaic coarse sands.

Conclusion.

The analysis of the Upper Miocene depositional units of the Spicchiaiola-Pomarance area indicates the following.

1 - In the southeastern part of the Volterra Basin there is no evidence of major compressional events, thus the basin developed under an extensional regime.

2 - Sedimentation during the upper Tortonian-Messinian occurred in half-graben type basins.

3 - The depocenter of the Upper Miocene basin is not the same as that of the Pliocene basin. In fact, the former is close to the Pignano fault (Pignano fault system), whereas that of the Pliocene is close to the Mazzolla fault (Mazzolla fault system); that is, it moved westward through time.

4 - The unconformities between Unit 1 and Unit 2, Unit 2 and Unit 3 can be related to uplift as a consequence of the regional extensional tectonic regime that affected Tuscany from the upper Tortonian. The uncon-

formity between seismic unit V 3 and Pliocene sediments is related to a new tectonic phase of activity that redefined the geometry of the Volterra Basin.

5 - The unconformity between Units 3 and 4 can be related to the drastic drop in sea-level that led to the Messinian "salinity crisis" of the Mediterranean Sea. In this case eustasy played a major role.

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