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GEOLOGIC OUTLINE OF THE TUSCANY-LATIUM CONTINENTAL SHELF (NORTH TYRRHENIAN SEA): SOME GEODYNAMIC IMPLICATIONS

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Key-words: Seismostratigraphy, North Tyrrhenian continental shelf, Neogene tectonics, Rifting and strike-slip tectonics, Paleogeography.

Riassunto. Vengono presentati i risultati dell'interpretazione di un rilievo sismico ad alta penetrazione coprente la piattaforma continentale tosco-laziale. La colonna stratigrafica completa è composta da cinque unità che, sulla base di dati geologici e di pozzo, sono correlabili con le unità tettoniche e stratigrafiche dell'Appennino settentrionale e centrale. Sopra a tre unità basali deformate, attribuibili alle unità metamorfiche toscane, alla falda toscana, ed ai complessi liguri, poggiano in trasgressione due cicli sedimentari postorogeni.

A partire dalle ultime fasi diastrofiche dell'orogenesi appenninica, l'area studiata subisce un'evoluzione tettonico-sedimentaria diversificata in settori. Nei settori toscani è identificabile una migrazione spazio-temporale degli eventi tettonici da ovest verso est, che comporta il ringiovanimento dei primi sedimenti postorogeni nella stessa direzione. Nel Pliocene inferiore-medio il settore laziale a sud di Civitavecchia viene interessato da un'intrusione magmatica che provoca la locale emersione dei primi depositi postorogeni. Dal Tortoniano superiore (?)-Messiniano fino al Pliocene medio, il settore compreso tra l'Elba e l'Argentario è soggetto ad una dinamica fortemente distensiva accompagnata da importanti componenti trascorrenti, perlopiù di orientazione anti-appenninica. Questa dinamica sviluppa alcuni profondi bacini, caratterizzati da blocchi ruotati e faglie normali listriche, simili ai bacini neogenici tosco-laziali. Tale analogia consente di riconoscere in questo settore di piattaforma la penetrazione del rifting tirrenico entro l'area continentale attualmente occupata dalla catena interna.

Abstract. An old high-penetration seismic survey of the Tuscany-Latium continental shelf furnished useful information on Neogene stratigraphy, structural setting and paleogeography. The seismically penetrated stratigraphic column is composed of five seismic units which may be correlated with the tectonic and stratigraphic units of the inner Apennine belt, described in the literature. Three tectonically superposed units constitute the deformed substratum, transgressively overlain by two postorogenic sedimentary cycles.

From the last diastrophic phases onward, the area underwent a very diversified tectono-sedimentary evolution, which gave origin to different structural landscapes. During the Upper Tortonian (?)-Middle Pliocene time interval the Elba-Argentario sector was subject to remarkable extensional tectonics, accompanied by important strike-slip components of mostly anti-apennine trend.

Analogies with the geodynamic processes that gave rise to the inner belt Neogene basins, lead to interpret this sector of the shelf as the penetration path of the Tyrrhenian rifting within the continental area.

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Introduction.

The narrow strip of the Tuscany-Latium continental shelf is still a poorly-known part of the North Tyrrhenian margin. The low hydrocarbon prospection interest and the intrinsic difficulty in obtaining good deep seismics at acceptable costs, explain why its geological knowledge is rather scarce.

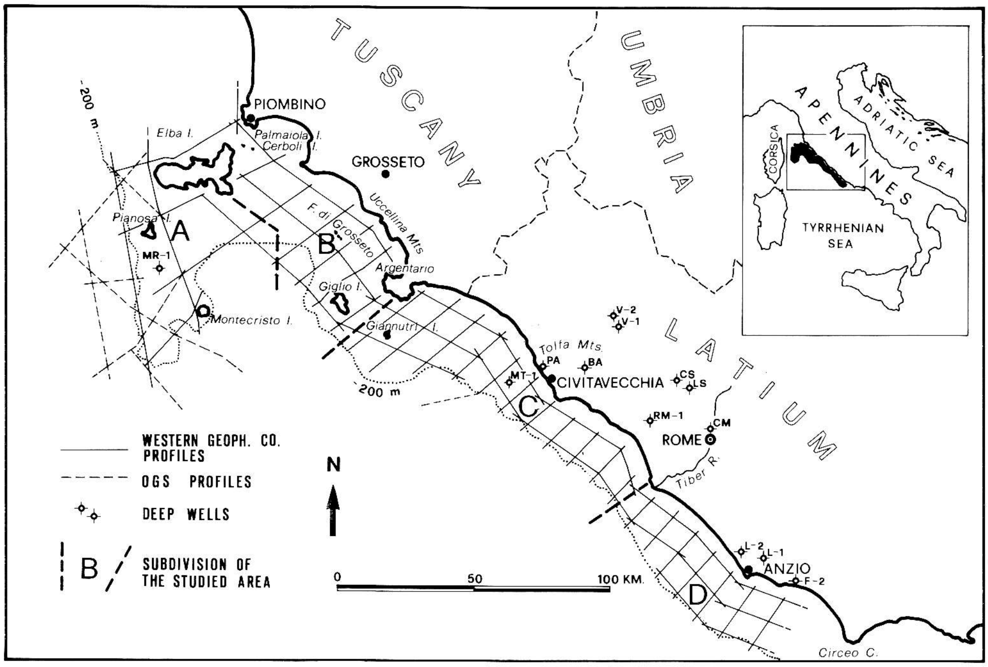

Fig. 1 - Seismic line location map.

This work, conceived as the northward prosecution of a former study on the Latian-Campanian shelf (Bartole, 1984), aims at widening the knowledge of this part of the continental margin by providing a close relationship between the Tuscan-Latian Apennines and its innermost portion, presently constituted by the continental shelf. This strip, in fact, represents a key sector of the Northern Apennines-Tyrrhenian Sea margin, since it is fundamental in understanding the chain vs. back-arc-basin relationships.

The work is based on the main results of structural, stratigraphic and paleogeographic meaning, drawn from a regional study of the continental shelf off the Tuscan and Latian regions in north-central Italy. The examined area lies between Elba Island and Anzio, and roughly corresponds to the strip comprised between the shoreline and the -200 m isobath (see Fig. 1).

The regional seismic study of the so-called "Zone E", explored by Western Geophysical Co. in 1968 for hydrocarbon exploration, constitutes the data base. In addition, some profiles recorded by Osservatorio Geofisico Sperimentale (OGS) integrate the seismic coverage of the area to the west (Fig. 1).

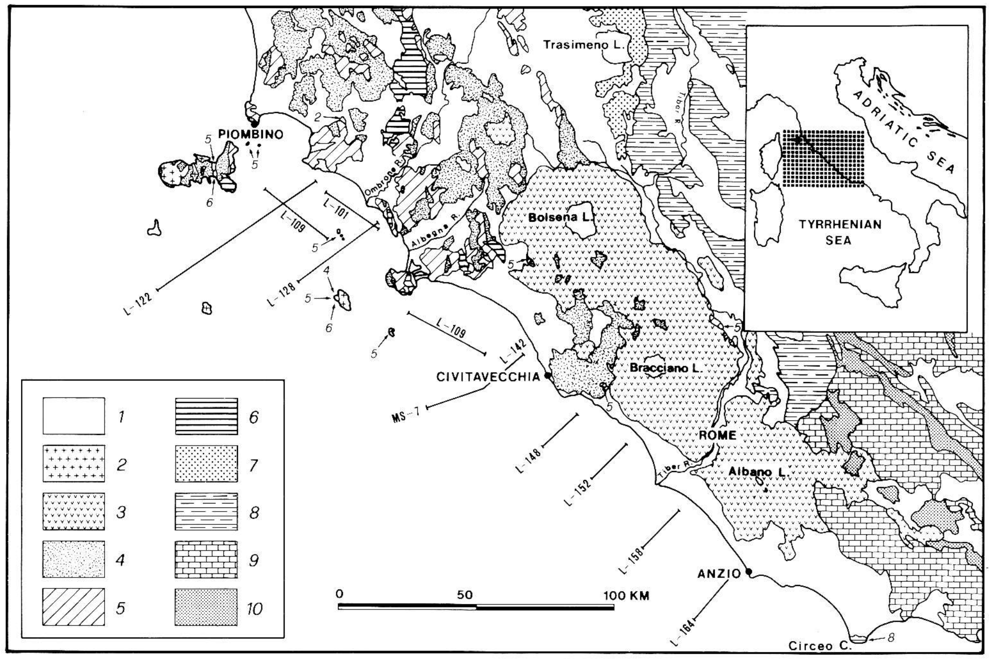

Fig. 2 - Simplified structural map of the inner part of the Northern Apennine belt. Straight lines are the profiles represented in Fig. 4 to 13.
Key to the symbols: 1) postorogenic sediments; 2) postorogenic intrusive magmatism; 3) postorogenic effusive magmatism; 4) Liguride Complexes; 5) Tuscan Nappe; 6) Tuscan metamorphic units; 7) Modino-Cervarola units; 8) Umbria-Sabina units; 9) Latium-Abruzzi carbonate units; 10) Tertiary flysch.

Geological framework.

The studied area represents the innermost portion of the Apennine fold belt, comprised between the islands of Elba, Pianosa, Montecristo and the Apenninic coastal relieves (Fig. 2). The structure of the belt is composed of a complex pile of adriatic-verging nappes of Meso-Cenozoic age, built up during several diastrophic phases that took place in the Oligocene and the Miocene. The terrains of these nappes were deposited in five different paleogeographic domains, namely from west to east: the Ligurian, the Austroalpine (or sub-Ligurian), the Tuscan and the Umbria-Marche Domains. As a consequence, the highest units in the pile are those of the westernmost domains, which overthrust onto the eastern ones. From Upper Miocene to Pleistocene the area underwent an extensional tectonic regime accompanied by an anatectic magmatism of both intrusive and effusive origin. Differential vertical movements created numerous ridges and elongated basins where the postorogenic sedimentation, in some places very thick, accumulated.

Rocks belonging to the nappes and to the autochthonous and parautochthonous basement frequently outcroup along the Tuscan coast, forming the islands, the promontories and the capes located between Piombino and the Argentario Mount (Fig. 2). Further southward, i.e. along the Latian sector of the shelf, the only coastal outcrops are in the proximity of Civitavecchia, as the remaining part of the coast is mainly composed of sedimentary and volcanic deposits of Pleistocene and Holocene age.

For a complete description of the tectonic and stratigraphic units forming the Tyrrhenian side of the chain, the reader should refer to the works of Burgassi et al. (1985), Fazzini et al. (1972) and Parotto & Praturlon (1975). Further details concerning the structure and evolution of the inner chain may be found in many works. We recall those of Accordi (1966), Funiciello & Parotto (1978), Boccaletti & Coli (1985), Boccaletti et al. (1986) and Salvini & Tozzi (1988), just to mention a few.

Seismostratigraphic characters.

The seismic data have been interpreted with the aid of the available geological, geophysical and drilling data. Only three wells have really proved useful for controlling the stratigraphic sequence of the continental shelf: the Martina-1 (MR-I), the Matilde-1 (MT-1) and the Latina-2 (L-2) wells (AGIP, 1977), located respectively in the northwestern, central and southern part of the studied area (Fig. 1). Other useful controls have been furnished by the wells drilled onshore (Fig. 1) and by the geologic maps, as well as the "Carta Strutturale dell'Appennino Settentrinale" (scale 1:250,000 - sheet n. 3) of Boccaletti & Coli (1982), and the "Carta Geologica d'Italia" (scale 1: 500,000 - sheet n. 2) edited by the Servizio Geologico d'Italia (1978). The aeromagnetic map of Italy (AGIP, 1982) and its first interpretative results (Cassano et al., 1986) have also been used for the resolution of both intrasedimentary bodies and deep structures related to the magnetic basement.

Lastly, the voluminous literature on the Apennine chain proved essential in the geologic interpretation, furnishing much information on the tectonics, stratigraphy, paleogeography and evolution of the adjacent emerged areas.

The studied shelf presents very variable structural and seismostratigraphic characters resulting from a diversified tectono-sedimentary evolution. In fact, on the basis of the many peculiarities recognized within the Neogene-Quaternary postorogenic sequence, four sectors have been distinguished, each with rather homogeneous characters. They have been designated by four letters in order to allow quick cross-reference in reading the text (see Fig. 1):

Sector A. It includes the area south of Elba Island as far as the Island of Montecristo, and constitutes the northern portion of the so-called Elba Ridge, a 150 km long, N-S striking positive morphologic feature that separates the Corsica Basin to the west, from the Etruscan Borderland to the east (see Savelli & Wezel, 1979).

Sector B. It is enclosed between Elba Island, Piombino, the Argentario Promontory and the Island of Giglio.

Sector C. It is the shelf portion extending from the Argentario Promontory and the Tiber River mouth.

Sector D. It extends from the Tiber River mouth to Anzio.

Seismic units	Geological and tectonic units of the Northern and Central Apennines	Ages and contacts
1	SECOND POST - OROGENIC CYCLE	Pl_m - Q
2 2'	FIRST POST - OROGENIC CYCLE AND SUBORDINATE SEMIAUTOCHTHONOUS UNITS	M - Pl_m
3	LIGURIDE COMPLEXES	K - Ol
4	TUSCAN NAPPE OR UMBRIA - SABINA UNITS	MZ - PG
5	TUSCAN METAMORPHIC UNITS	PZ - TR

Fig. 3 - Simplified seismostratigraphic column of the Tuscany-Latium continental shelf.

The interpreted seismic profiles show two main groups of reflections, separated by a marked unconformity of regional extent. The upper one, characterized by parallel, subparallel and prograding configurations, belongs to the postorogenic sequence; the lower one, often seismically chaotic or with sparse continuous reflectors, belongs to the strongly deformed units that made up the tectonized substratum.

The control offered by the wells, along with the bibliography data, have permitted a closer seismostratigraphic analysis, making it possible to individualize five seismic units, separated by stratigraphic and/or tectonic boundaries extended throughout all or on part of the survey. Such seismic units may be correlated with the stratigraphic and tectonic units that constitute the inner portion of the north-central Apennines.

The synthesis of the seismostratigraphic interpretation is reported in the scheme of Fig. 3, which presents a complete seismostratigraphic column. The following description, on the other hand, illustrates the characteristics of the five seismic units, examined separately from the lowermost to the uppermost.

Pre-Neogene deformed units.

Unit 5 (Tuscan metamorphic units).

This seismic unit includes terrains which in many maps are comprehensively termed "Tuscan metamorphic units" because of their low-grade metamorphism, such as the Paleozoic basement, the Verrucano Group (Middle Trias) and the Grezzoni Formation (Upper Trias-Upper Cretaceous) (see for instance the "Structural Model of Italy" of Ogniben et al., 1973, or the "Carta Strutturale dell'Appennino Settentrionale" of Boccaletti & Coli, 1982).

None of the wells used in the interpretation reached these terrains. However, the presence of this unit beneath the Tuscan shelf seems documented by two large uplifts of the seismic basement, located on the seaward prosecution of wide onshore structures of the Tuscan metamorphic units. The former uplift occurs southeast of the Elba Island, on the structural prolongation of the Calamita Mount anticline (Fig. 4); the second to the south of the Argentario Promontory (Fig. 8).

Other evidences are given by the outcrops of the eastern Elba Island, the Uccellina Mounts and the western part of Giglio Island (Fig. 1, 2).

Unit 4 (Tuscan Nappe and Umbria-Sabina units).

It includes the sedimentary successions of the Tuscan Nappe and, in the southern part of the studied area, the Umbria-Sabina units, respectively encountered in the wells Matilde-1 and Latina-2 (AGIP, 1977) beneath a blanket of allochthonous materials of the Ligurian complexes.

The well Matilde-1, drilled in sector C, about 13 km offshore Civitavecchia, penetrated a succession of the Tuscan non-metamorphic sequence, i.e. the Tuscan Nappe (Fig. 9). This sequence ranges from the Upper Triassic Burano Anhydrites, encountered at well bottom, up to the Scisti Policromi of Cenomanian age (Table 1).

In sector D, Unit 4 has been distinguished on the basis of the indirect calibration of the Latina-2 well, drilled onshore north of Anzio (Fig. 13). Unit 4 seems represented by the Umbria-Sabina succession, i.e. the pelagic Meso-Cenozoic sequence of the Latium-Abruzzi Apennines.

In sector B, notwithstanding the absence of any offshore and onshore drilling, the presence of the Tuscan Nappe is nevertheless suggested by the numerous outcrops of its sequence located along the Tuscan coast (Piombino, Punta Ala and Uccellina Mounts) and on the islands (eastern Elba, Palmaiola, Cerboli and Formiche di Grosseto) (see Fig. 1, 2).

Geologic evidences that may support the presence of the Tuscan nappe within sector A, instead, are weaker. On the Elba Island, west of the Calamita Mount, there is a small outcrop of the Tuscan non-metamorphic sequence, tectonically superposed upon the Paleozoic basement. A seaward projection of this situation is tentatively represented in Fig. 4, where a flake of Tuscan Nappe is interpreted on the western limb of the structural high.

MATILDE - 1 WELL
(from Agip, 1977)

SEISMIC UNITS	STRUCT'L SIGNIF.	DEPTHS b.s.l. (m)	THICKN. (m)	AGE	FORMATION NAME & DESCRIPTION	LIMITS & UNCONF.
		110	110	-	mare	
1	NEOAUT.	285	175	PLEISTOCENE	argille siltose	
3	LIGURIDE COMPLEX (ALLOCHTHONOUS)	539	254	CRETACEOUS	Flysch calcareo: marne e argille grigio scure e marroni, scagliettate con intercalazioni di mudstones argillosi	t (?)
		2235	1696	CRETACEOUS	Pietraforte: arenarie scure a grana da fine a media con intercalazioni di argille scagliettate grigie e marroni e qualche livello di marna	
		2407	172	UNDEFINED	Argilloscisti varicolori: argille grigie scagliettate varicolori con livelli di mudstones argillosi e di marna (Argilloscisti manganesiferi ?)	t
4	TUSCAN NAPPE	2464	57	CENOMANIAN	Scisti policromi (Scaglia toscana)	
		2503	39	APTIAN-ALBIAN	Scisti policromi (Scaglia toscana)	
		2535	32	BARREMIAN	Maiolica	
		2549	14	MALM ?	Diaspri ?	
		2712	163	M.(U.) LIAS	Calcari selciferi	
		2728	16	SINEMURIAN	Calcari rossi nodulari ammonitiferi	
		3103	375	L. LIAS	Calcare massiccio	
		3667	564	U. TRIAS (RETIC)	Strati di Avicula contorta	
		3676	9	U. TRIAS (NORIC)	Anidriti di Burano	

MONTI DELLA TOLFA
(from Fazzini et al., 1972)

LIMITS & UNCONF.	FORMATION NAME & DESCRIPTION	AGE	INDICATIVE THICKNESS (m)	GROUP	STRUCT'L SIGNIF.
-	argille, sabbie, conglomerati, calcari, arenarie vulcaniti e molasse	U. MIOCENE-PLEISTOCENE	300	-	NEOAUT.
	Arenarie di Manciano	L. MIOCENE	20	-	SEMIAUT.
	Argille e calcari: (Formazione di Sillano)	PALEOCENE ?	20-50	SERIE DELLA PIETRAFORTE (Auct.)	LIGURIDE COMPLEX (ALLOCHTHONOUS)
	Pietraforte: arenarie calcareo-quarzose con livelli argilloso-siltosi	U. CRETACEOUS	400		
t	Argilloscisti varicolori manganesiferi	APTIAN-ALBIAN-U. CRETACEOUS	150-200		
	Flysch arenaceo	OLIGOCENE	100-150	SERIE DEI FLYSCH TOLFETANI (Auct.)	
	Flysch calcareo e marne rosate	M.- U. EOCENE	300		
	Formazione del Mignone: scisti argillosi	PALEOCENE-M. EOCENE	100-150		
	Flysch calcareo con lenti di marne rosse	U. CRETACEOUS-PALEOCENE	700-800		
t	Flysch argilloso calcareo	U. CRETACEOUS	600-700		
	Scaglia toscana	TURON.-OLIGOC.	150	COMPLESSO BASALE (Auct.)	TUSCAN NAPPE
?	Calcari selciferi	M.? LIAS	50-150		
	Calcare massiccio	L.-M.? LIAS	150		

Table 1 - Comparison between the stratigraphic columns of the Matilde-1 well (courtesy of dr. G. Groppi of AGIP Oil Co.) and of the Tolfa Mounts (taken from Fazzini et al., 1972). Vertical hatch represents the Mesozoic stratigraphic hiatuses; t) tectonic contact. Depths and thicknesses not in scale.

Data of the Matilde-1 well have made it possible to compare the stratigraphy of the continental shelf with that of the near Tolfa Mounts taken from Fazzini et al. (1972). The two stratigraphic columns, arranged together in Table 1, provide interesting details and information of this part of continental margin.

Dealing with the succession of the Tuscan Nappe, it is worth noticing that both the top and bottom of the nappe are made up of rocks that were among the main decollement levels of the Apennine overthrusts. The most interesting peculiarity, however, is represented by the two stratigraphic hiatuses identified by the well, and correlated to the wider, Liassic-Cenomanian hiatus of the Tuscan Nappe, recognized on the Tolfa Mounts (Table 1). Both stratigraphic columns witness large discontinuities in the Jurassic and Lower Cretaceous sedimentation, very likely connected to the well-known Mesozoic extensional tectonics which gave rise to complete, reduced and condensed sequences in the external Tuscan domain (Decandia et al., 1981).

Unit 3 (Liguride Complexes).

This seismic unit tectonically lies upon Unit 4 or, when missing, directly over Unit 5. Unit 3 includes terrains of great allochthonous character with respect to the underlying units, such as the Elba Flysch, the Liguride, the sub-Liguride and the Sicilide units. Geologic• controls are given by the wells Martina-1, Matilde-1 and Latina-2 (AGIP, 1977), along with the outcrops scattered on the islands and along the coast (Fig. 1, 2).

These terrains have been grouped into the more comprehensive term "Liguride Complexes" or simply "Ligurides", often used in the figures and in the text as synonym of Unit 3. It may not be excluded, however, that terrains other than the Ligurides, such as some Tertiary flysch, could be interpretatively attributed to this unit because of their particularly chaotic seismic configuration.

Unit 3 has been ascertained in sector A by the Martina-1 well, drilled about 10 km south of Pianosa Island. The borehole penetrated 2876 m of a flysch sequence of Lower Eocene-Upper Oligocene age, without reaching its lower boundary. This sequence, which also includes a massive ophiolitic layer, may be correlated to the Liguride Complexes. In the same sector Unit 3 is involved in many apennine-verging tectonic slices (Fig. 4), which may be related to the Late Oligocene-Early Miocene collision between the Corsica-Sardinia block and the Adriatic microplate (Reutter et al., 1978; Fabbri et al., 1981). At the well, Unit 3 has a considerable thickness, but it rapidly thins out towards the north against the Elba pluton, and towards the northeast where it dies out against the structural high that lies on the prolongation of the Calamita Mount anticline (Fig. 4).

In sector B, where no direct proof exists, the presence of Unit 3 may not be resolved on seismic basis. Some scarce seismic evidence on the lines, supported by the outcrops of sub-Liguride units at Giglio Island, the Argentario Promontory and the Uccellina Mounts (Fig. 1, 2), account for the two dubitative little patches reported in Fig. 14.

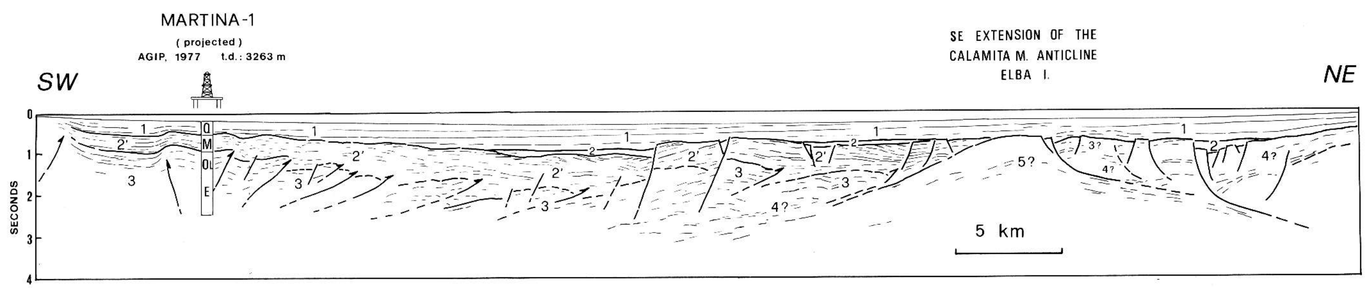

Fig. 4 - Interpretive section of line L-122 south of Elba Island. A compressive structural style dominates the area of the Elba Ridge drilled by the Martina-1 well, while a remarkable extensional tectonics, characterized by listric normal faults, is peculiar of the easternmost portion of the line. See Fig. 2 for location.
Explanation of the symbols: 1) second postorogenic sedimentary cycle; 2) first postorogenic sedimentary cycle within sectors B, C and D; 2') first postorogenic sedimentary cycle within sector A; 3) Liguride Complexes; 4) Tuscan Nappe and Umbria-Sabina units; 5) Tuscan metamorphic units; Q) Quaternary; M) Miocene; OL) Oligocene; E) Eocene.

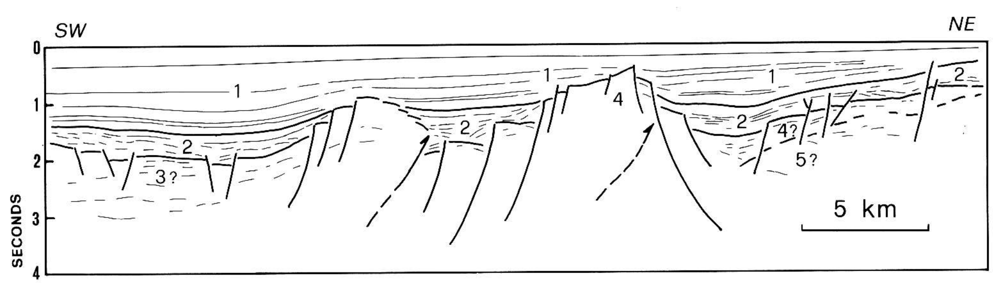

Fig. 5 - Interpretive section of line L-128 off the Tuscan coast, showing deep depressions produced by extensional tectonics. See Fig. 2 for location and Fig. 4 for the explanation of the symbols.

Great spatial distribution and general consistent thickness, both documented by a good seismic response, characterize the Liguride Complexes within sectors C and D, geologically controlled by the wells Matilde-1 and Latina-2 respectively.

As regards sectors C, the comparison of the stratigraphic columns of Table 1 directs our attention to the outstanding differences of the Liguride Complexes as observed in the offshore well and on the near Tolfa Mounts. The first interest concerns their differentiation. At the well these complexes are most probably represented by one tectonic unit, i.e. the Pietraforte Series. On the contrary, in the Tolfa area they are constituted by two tectonically superposed units (Fazzini et al., 1972): the Pietraforte, of Cretaceous-Paleocene(?) age, and the Tolfetani Flysch Series, of Cretaceous-Oligocene age (Table 1).

Another peculiarity is the marked difference of the Pietraforte thickness in the two stratigraphic columns: almost 1700 m at the Matilde-1 well, versus 400 m at the Tolfa Mounts as measured by Fazzini et al. (1972). This fact leads to the simple consideration that such a difference, at a distance of a tenth of kilometres apart, cannot be merely ascribed to stratigraphic causes. Seismic evidences and regional overview, in fact, both suggest that as structural thickening, such as tectonic doublings, overthrust slices, etc. much better account for the anomalous thickness of the Pietraforte Series in the offshore well, and very likely, also of the remaining Liguride Complexes along the Latian shelf area.

Neogene-Quaternary postorogenic units.

In the Tyrrhenian side of the Northern Apennines the last important compressional phase took place near the end of the Miocene: Tortonian in southern Tuscany (Boccaletti et al., 1986), Tortonian (?)-Lower Pliocene in western and northern Latium (Salvini & Tozzi, 1988). From this time on, an extensional tectonic regime affected the area and gave origin to many apennine-trending depressions.

The postorogenic sedimentation, unconformable over the tectonized substratum, began in the Tortonian p.p.-Messinian times with lacustrine deposits that rapidly evolved to open marine facies at the beginning of the Lower Pliocene. This cycle ended with regressive deposits deriving from an extensive Mid-Pliocene uplifting, recognized in southern Tuscany and northern Latium (Ambrosetti et al., 1979; Baldi et al., 1974; Bonazzi et al., 1981; Damiani et al., 1981; Fazzini et al., 1972; Fregni et al., 1985; Malatesta & Zarlegna, 1988). In the Upper Pliocene-Lower Pleistocene, a second minor transgression affected a limited number of basins, being the general uplifting of the Apennine chain already in act.

In the Tuscany-Latium continental shelf, the postorogenic sequence "transgressively" lies over the tectonized substratum, constituted by the Units 3, 4 and 5. The contact is a regional seismic unconformity that marks the passage from the last diastrophic phases to an extensional tectonic regime.

However, seismic, drilling and bibliographic data indicate that the onset of the postorogenic sedimentation occurred earlier in the westernmost zone of the shelf (i.e. sector A), with respect to the eastern ones (i.e. in sectors B, C and D) where the first postorogenic cycle may be dated as Upper Miocene-Middle Pliocene, as well as in the Tuscany-Latium Neogene basins.

These results are in perfect agreement with the literature data on the Neogene evolution of the Northern Apennines. In fact, a regional eastward migration characterized both the orogenic and postorogenic tectono-sedimentary events of the chain (Ambrosetti et al., 1979; Boccaletti et al., 1986). A good example of this migration is given by the data concerning the first neoautochthonous deposits. In sector A, the Lower Miocene clastic sediments that overlie the Eocene-Oligocene flysch at the Martina-1 well, have been classified as a postorogenic sequence because of their stratigraphic position and their mostly undeformed setting (Fabbri et al., 1981). Similar sediments outcrop at Pianosa Island (Middle Miocene, after Colantoni & Borsetti, 1973) and have been dredged south of Martina-1 on the Elba Ridge (Bacini Sedimentari, 1979). On the

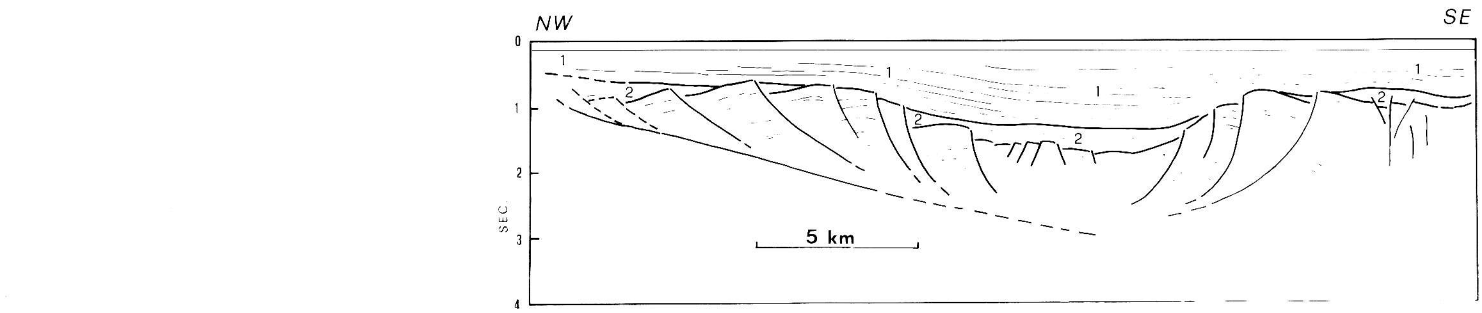

Fig. 6 - Interpretive section of line L-109 off the Tuscan coast (sector B) showing listric normal faults and rotated blocks. See Fig. 2 for location and Fig. 4 for the explanation of the symbols.

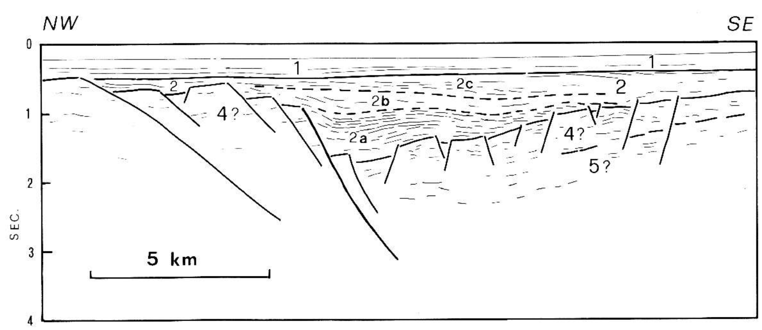

Fig. 7 - Interpretive section of line L-101 off the Tuscan coast, showing basin asymmetry and sedimentary wedging. *a*, *b*, and *c* are subsequences of Unit 2. See Fig. 2 for location and Fig. 4 for the explanation of the symbols.

contrary, in southern Tuscany and northern Latium the postorogenic sedimentation began mostly in the Tortonian p.p.-Messinian with lacustrine facies, as mentioned above.

As a consequence of this tectono-sedimentary migration, the post-orogenic sequence is composed of the following units:

Unit 2' (First postorogenic cycle of sector A).

It represents the first postorogenic cycle within sector A, or in other words within the orogenically innermost sector of the studied area, whose sediments are Lower to Middle Miocene in age. Unit 2' is partially overlapped by the younger Unit 2, as shown in Fig. 4, but in the western part of the sector it is directly overlain by Unit 1.

The upper limit of Unit 2' is a seismic unconformity that from west to east passes from a paraconformity to an unconformity of angular type (Fig. 4). This is due to the eastward progressive involvement in a compressive tectonization, so that Unit 2' changes its character from neoautochthonous to semiautochthonous following the same direction. In fact on the western flank of the large basement uplift southeast of Elba Island, Unit 2' presents a generalized tectonic disturbance and an anticlinal-synclinal setting which have been interpreted as an evidence of a tectonic transport of little magnitude (Fig. 4).

Unit 2 (First postorogenic cycle of sectors B, C and D).

It represents the first postorogenic cycle in the shelf area closer to the continental coast, which may be correlated to the Upper Miocene-Middle Pliocene transgressive-regressive cycle of the inner belt. Consequently, the overlying Unit 1 corresponds to the second postorogenic cycle connected to the second, more limited transgression.

Within sector A, Unit 2 is represented by thin and sparse deposits transgressive over the older Unit 2' (Fig. 4). On the contrary, between Elba Island and the Argentario Promontory (sector B), Unit 2 attains the maximum thickness of the whole studied shelf within three deep depressions separated by two prominent structural highs. In the eastern depression, Unit 2 is up to 1000 ms (two-way times) thick and may be subdivided into three subsequences. The lower one (subsequence *a* in Fig. 7) is characterized by an internal configuration peculiar of a syn-sedimentary rotational tectonics. Low-angle normal faults, in fact, bound this asymmetric depression towards the west (Fig. 5) and the northwest (Fig. 7). The lower subsequence, therefore, represents a clear example of a syn-rift deposit, which may be dated as Upper Tortonian (?)-Messinian in accordance to the birth age of the Neogene basins of southern Tuscany and northern Latium (Bonazzi et al., 1981; Damiani et al., 1981; Fregni et al., 1985).

Within the westernmost and largest depression, Unit 2 maintains an almost constant thickness of about 400 ms (Fig. 5). Even though no apparent sedimentary wedging characterizes this basin, the great extensional component of its forming tectonics is nevertheless documented by the block rotations and the listric normal faults peculiar of its northern part (Fig. 6, 7).

At this point it is very important to remember that similar sedimentary and structural styles are peculiar of the Tuscany and Latium Neogene basins. Very thick deposits (up to 2000 m) ranging in age from Messinian to Middle Pliocene are reported, in fact, for the Volterra, Siena, Radicofani and the mid and upper Tiber Valley Basins (Baldi et al., 1974; Costantini et al., 1980; Costantini et al., 1982; Damiani et al., 1981). Furthermore, an eastward migration of the depocentral axes in the Middle Pliocene time interval has been documented for the Val di Chiana, Siena, Val d'Elsa Basins (Ambrosetti et al., 1979) and for the mid and upper Tiber Valley Basins (Baldi et al., 1974). Even their structural style has much in common with the more or less asymmetric depressions represented in Fig. 5, 6 and 7. Onshore basins are strongly asymmetric too, since they are half-grabens, mostly delimited by master faults on their eastern edge, whose throw may reach some thousand metres (Boccaletti & Coli, 1985; Boccaletti et al., 1985).

Minor, but more constant thicknesses, hardly ever exceeding 300 ms, characterize sector C of the shelf. In a limited zone, northwest of the Tiber River mouth, seismic reflections from Unit 2 show a general incompetence, such as angular unconformities and

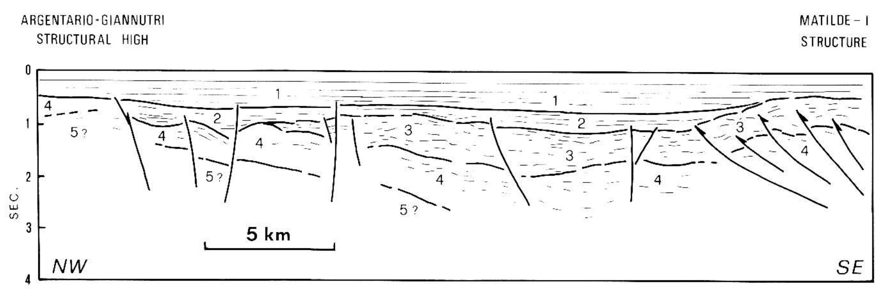

Fig. 8 - Interpretive section of line L-109 off the Latian coast (sector C). Note the thinning out of Unit 3 towards the Argentario-Giannutri structural high. See Fig. 2 for location and Fig. 4 for the explanation of the symbols.

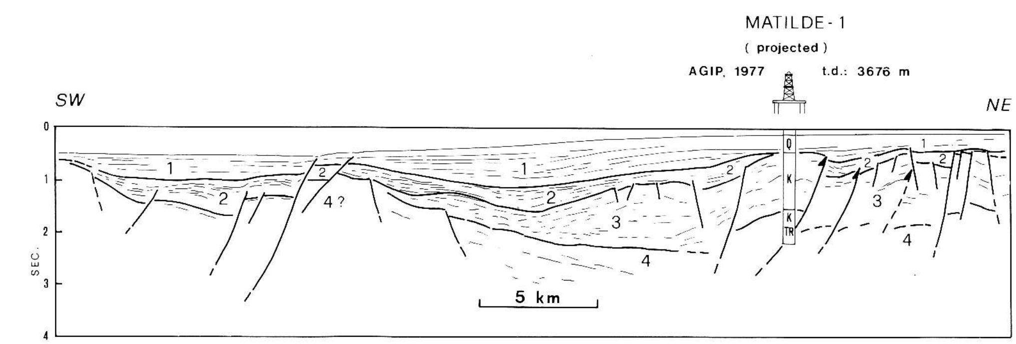

Fig. 9 - Composite interpretive section of lines MS-7 and L-142 of the Latian coast, showing the great thickness of the Liguride Complexes (Unit 3) along the shelf and their thinning out towards the west. See Fig. 2 for location and Fig. 4 for the explanation of the symbols. Q) Quaternary; K) Cretaceous; TR) Triassic.

disharmonic folding, with respect to its lower and upper boundaries (Fig. 11). This portion of Unit 2 has been interpreted as a semiautochthonous deposit, probably linked to the last diastrophic phases, owing to its analogy with the Arenaria di Manciano Formation outcropping on the western side of the Tolfa Mounts (Fazzini et al., 1972).

Finally, as far as sector D is concerned, no distinction in its postorogenic sequence has been made, as weaker reflection continuity and numerous structural highs prevent tracing the seismic unconformity that separates Unit 2 from Unit 1 (Fig. 12, 13). Correlation with the Latina-2 well, however, seems to indicate great thicknesses for the first postorogenic cycle.

Unit 1 (Second postorogenic cycle).

Unit 1 corresponds to the second postorogenic cycle of the shelf, correlatable to the second minor transgression that affected few postorogenic basins of the inner Apennine belt in the Upper Pliocene-Lower Pleistocene times.

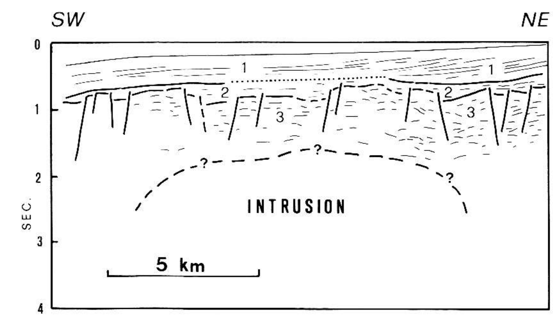

Fig. 10 - Interpretive section of line L-148 off the Latian coast, crossing a Lower-Middle Pliocene intrusive body. Dotted line indicates the peneplanation surface due to the body's ascent. See Fig. 2 for location and Fig. 4 for the explanation of the symbols.

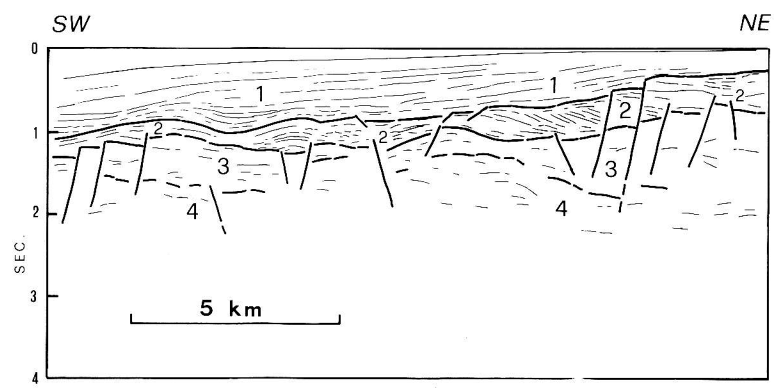

Fig. 11 - Interpretive section of line L-152 off the Latian coast, showing local semiautochthonous characters in the sediments of Unit 2. See Fig. 2 for location and Fig. 4 for the explanation of the symbols.

Its lower boundary with Unit 2 is a paraconformity which tends to an onlap type of contact towards the flanks of the structures (Fig. 8, 9), or to a downlap type as frequently occurs in some more proximal zones of the shelf (Fig.11). At times, it is characterized by two or more closely-spaced unconformities that testify the influence of local tectonic factors in the control of sedimentation.

Both seismic characters and stratigraphic position, hence, make it possible to correlate this unconformity to the well-known "X" horizon of Selli & Fabbri (1971), which has recently been interpreted as the break-up unconformity of the Tyrrhenian Sea, that marks the end of the rifting process and the beginning of a sub-vertical foundering (Trincardi & Zitellini, 1987).

The limit between Unit 2 and Unit 1 may thus be related to the extensive Mid-Pliocene regression documented by many Authors in the post-orogenic basins of the north-central Apennines. In southern Tuscany and northern Latium the regression, which reached a climax in the Middle Pliocene, was accompanied by stratigraphic hiatuses and angular unconformities (Ambrosetti et al., 1979). The uplift was not uniform but developed independently in separate zones (same Authors) in consequence of transcurrent movements along important tectonic lines of anti-apennine trend (ENE-WSW).

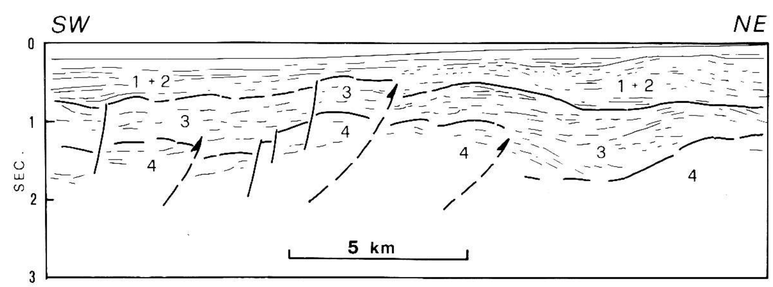

Fig. 12 - Interpretive section of line L-158 off the Latian coast. Wide and gentle folds characterize both the tectonized and the postorogenic units. See Fig. 2 for location and Fig. 4 for the explanation of the symbols.

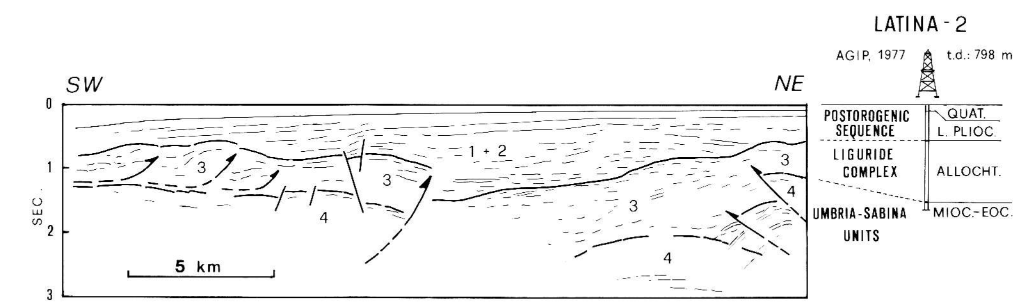

Fig. 13 - Interpretive section of line L-164 off the Latian coast, indirectly calibrated with data of the Latina-2 well (AGIP, 1977). See Fig. 2 for location and Fig. 4 for the explanation of the symbols.

The existence, within some tracts of seismic profiles, of more than one unconformity at the limit between the two postorogenic cycles, may therefore be associated with the activity of these transcurrent lines that, as we shall see further on, seem to progress into the shelf area. Also in the Tolfa-Tarquinia Basin a Middle Pliocene hiatus, related to a transitory uplift, has been documented by Fazzini et al. (1972). Finally, in western Latium, Malatesta & Zarlenga (1988) have pointed out the uplifting of a large area comprised between the Tolfa Mounts, the Albani Hills and Anzio, that again occurred in the Middle Pliocene.

Parallel, sub-parallel and progradational sedimentary styles characterize the internal configuration of Unit 1, the latter style being particularly evident in sector C, where bedding interfaces dip toward both the S and SW (Fig. 10, 11).

Because of their structural-high position, the three well controls (AGIP, 1977) have only partly crossed it: Martina-1: 54 m of Pleistocene clays and sands (Fig. 4); Matilde-1: 175 m of Pleistocene silty clays (Fig. 9); Latina-2: 45 m of Pleistocene tuffs and clays (Fig. 13). Even though the age of the complete stratigraphic section of Unit 1 is unknown, it seems reasonable to refer it to the Mid-Upper Pliocene to Pleistocene time interval, since a substantial continuity between the two postorogenic cycles (Unit 2 and Unit 1) has been noticed in the basinal areas of the shelf.

The most interesting peculiarity of Unit 1 is associated with a large magnetic anomaly located within sector C, about 20 km south of Civitavecchia (Table 2). On the basis of magnetic and seismic evidences, the anomaly has been herein interpreted as due to an igneous intrusion likely of acidic origin, as it results from its low, calculated magnetic susceptibility ($k = 420 \times 10^{-6}$ c.g.s.U.) (Diotallevi, 1981). Its top (2.8 km below s.l., after Cassano et al., 1986) lies within the tectonized units, but the effects of its emplacement are visible in the postorogenic sequence. A large peneplanation surface, recognized near the base of Unit 1 (Fig. 10) testifies a temporary Middle Pliocene period of emersion, linked to the body's ascent. Since this age agrees with the inception of the near Tolfa-Cerite magmatism (see Table 2), dated as Lower-Middle Pliocene on the basis of stratigraphic evidences (Fazzini et al., 1972), the body may be ascribed to the Tuscan petrographic province (Locardi, 1986).

Main tectonic events.

The oldest tectonic movements recognized on the seismic sections are related to the last diastrophic phases. This fact is well documented in sectors A, C and D, while in sector B the considerable postorogenic extension completely masked most evidence of the Apennine orogeny.

South of Elba Island, the overthrusting of the apennine-verging Ligurian flakes occurred before, or not later than, the Lower Miocene, as a thick blanket of neoautochthonous and semiautochthonous sediments of Lower-Middle Miocene age covers the compressive structures (Fig. 4).

Offshore the Tolfa Mounts, the Matilde-1 structure evidentiates two distinct tectonic movements related to the construction of the Apennine orogen (Fig. 8, 9), which could also be extrapolated to other structures of the same sector. A first phase is responsible for the emplacement of the Liguride blanket over the Tuscan Nappe. According to geological evidences on land (Fazzini et al., 1972), this movement of prevailing horizontal component, may have occurred in the Lower Miocene. A second phase, accounting for most of the present-day shape of the structure, involved both the Liguride blanket and the underlying Tuscan Nappe, producing reverse faults and thrust slices (Fig. 8, 9). In agreement with the last orogenic deformations of western Tuscany and Latium (Boccaletti et al., 1986; Salvini & Tozzi, 1988), a Tortonian-Messinian age may be inferred for this phase.

A number of deep-seated features, interpreted as compressive structures of probable Messinian age (Bartole, 1984, fig. 6, 7, 14), distinguishes the shelf sector comprised between the Tiber River mouth and Anzio. Wide and gentle folds within the undifferentiated postorogenic sequence (Fig. 12) evidentiate a tectonic renewal, probably linked to the Pleistocene transgressive motions invoked by Marani & Zitellini (1988) to explain a system of folds and uplifts along the adjacent continental slope.

As far as the postorogenic movements are concerned, a remarkable rifting mechanism, whose inception may be ascribed to Upper Tortonian (?)-Messinian times, affected sector B between Elba Island and Argentario Promontory. Great sedimentary thicknesses (up to 2000 ms in the largest depression), listric normal faults and rotated blocks (Fig. 6, 7), in fact are peculiar of this sector.

In the remaining shelf along the Latian coast (sectors C and D) and south of Elba Island (sector A), there is no apparent evidence of such a mechanism. The postorogenic movements overprinted previous compressive features, some of which are still recognizable, producing mostly planar normal faults of generally small throw, which scarcely ever affected the second postorogenic cycle (Unit 1).

The last tectonic movement recognizable on seismic sections, occurred in the Middle Pliocene-Pleistocene time interval. It consists of a general tilting towards southwest, particularly apparent on the Latian sectors. The tilting of about 1.3°, peculiar of the peneplanation surface south of Civitavecchia (Fig. 10), testifies the "hinge" position of the shelf, with respect to the uplifting Apennine chain to the east and the sinking Tyrrhenian basin to the west.

Table 2 summarizes the main structural elements pointed out from this interpretation. In order to achieve a more comprehensive framework of this part of the continental margin, the results have been integrated with the structural data of Tuscany and Latium regions taken from both geological and geophysical sources (Boccaletti & Coli, 1982; Di Filippo & Toro, 1980; Funiciello & Parotto, 1978; Toro, 1978).

Some of the interpreted features represent the seaward prosecution of onshore structures, such as the Calamita Mt. anticline (southeast of Elba I.), the Argentario-Giannutri structural-high (Fig. 4, 8), and the S. Procula-Pomezia high (southwest of the

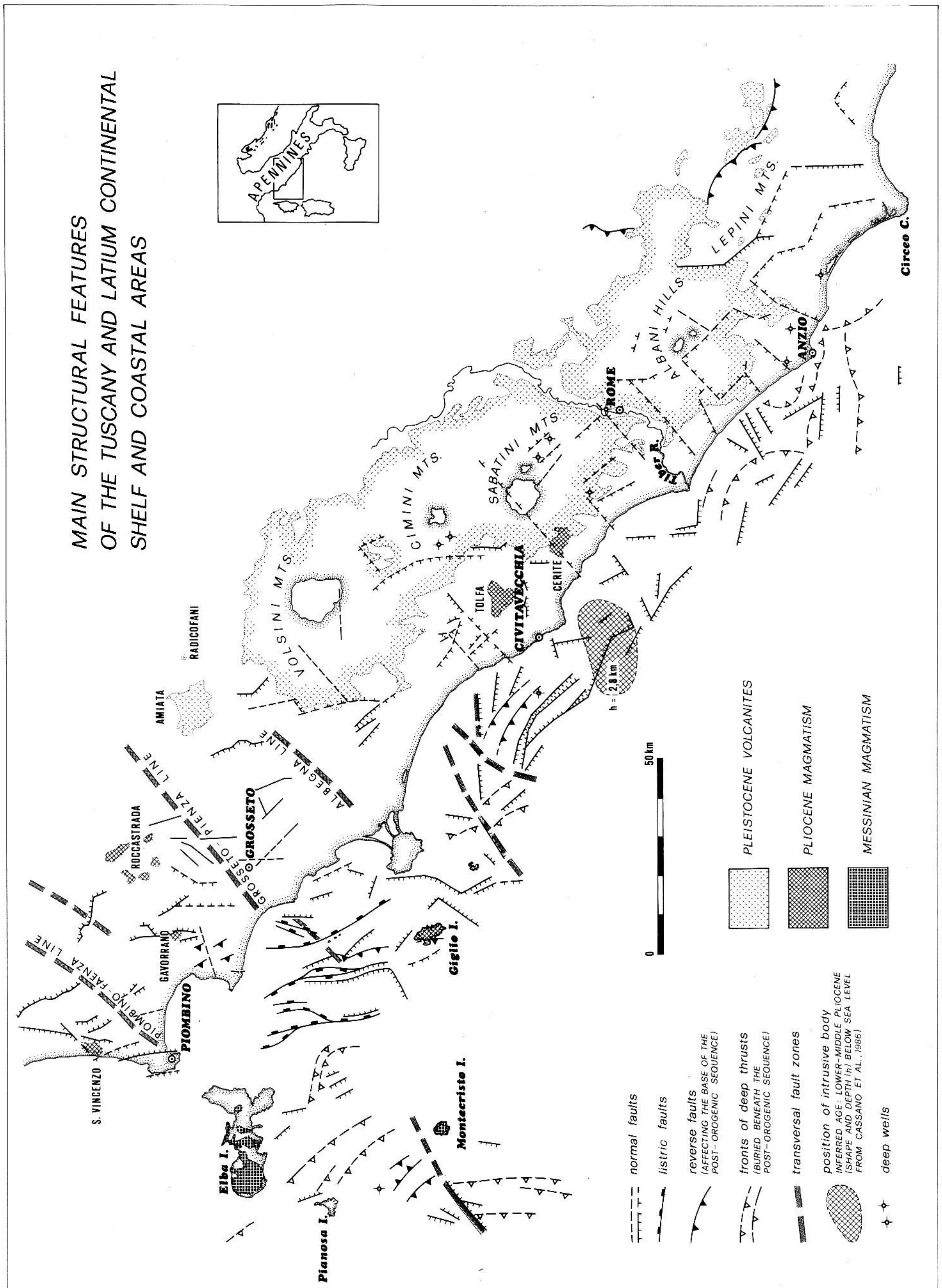

Table 2 - Main structural features of the Tuscany-Latium continental shelf and coastal areas.

Albani Hills). But other features located offshore draw a greater interest from a structural point of view. Among these, the most peculiar ones are some tectonic lines that most likely constitute the seaward prosecution, or the minor branches, of important trascurrent lines, well-known in the North Apennines, such as the "Piombino-Faenza", the "Grosseto-Pienza" and the "Capalbio-Perugia-Iesi" lines. See for instance fig. 3 of Bartolini et al. (1983), fig. 1 of Boccaletti & Coli (1985) and fig. 1 of Fazzini & Gelmini (1984).

Evidence of the transcurrent component of these lines (heavily dashed in Table 2), mainly rise from regional considerations. A valuable help in this sense is given by the paleogeographic scheme of Fig. 15. The figure, in fact, clearly shows that the Lower Pliocene paleogeography of the Tuscan margin was strongly influenced by the anti-apennine transcurrent tectonics, which produced sharp bendings and shiftings of the axes of the extensional basins.

Additional evidences of strike-slip tectonics come from the structural map of Table 2. They are: a transversal (NE-SW) line near Montecristo Island which divides apennine (NW-SE) trends to the north from meridian (N-S) trends to the south; the rhomboid basin, i.e. the main depression located between Elba and Giglio islands, which may be thought of as a strike-slip basin of pull-apart type; and a few NE- and E-oriented lineaments, which occur between Giglio I. and Civitavecchia. As for their relative horizontal displacement, left-lateral movements seem to prevail, at least in the above mentioned rhomboid basin. If it is interpreted as a pull-apart, its shape is indeed congruent with a sinistral offset of anti-apennine direction, which, in turn, agrees with the left-lateral shiftings of the North Tyrrhenian magnetic basement (see Cassano et al., 1986, their table 2) and with the movements of the transversal deformation bands in Southern Tuscany, north of the "Capalbio-Perugia-Iesi" line (Boccaletti & Coli, 1985).

Paleogeography.

The potential paleogeographic content of the seismic data used in this interpretation has been reported in two maps, free of any palinspastic restoration, the first connected with the Liguride Complexes (Unit 3), the other with the first postorogenic sedimentary cycle (Unit 2).

The first map (Fig. 14) is a crop-and-subcrop map illustrating the present-day regional distribution of the Liguride Complexes, both in the studied shelf and in the Northern Apennines. Data have assembled from many bibliographic sources in order to complete their extension within the continental area. Because of the relatively small horizontal displacement due to the postorogenic extensional tectonics, the situation represented in Fig. 14 could be referred to the Upper Miocene, or in other words to the end of the last orogenic phases that affected the Tyrrhenian side of the north-central Apennines (Boccaletti et al., 1986; Salvini & Tozzi, 1988). During these phases, widespread gravity phenomena affected both the Ligurides and their basement, particularly

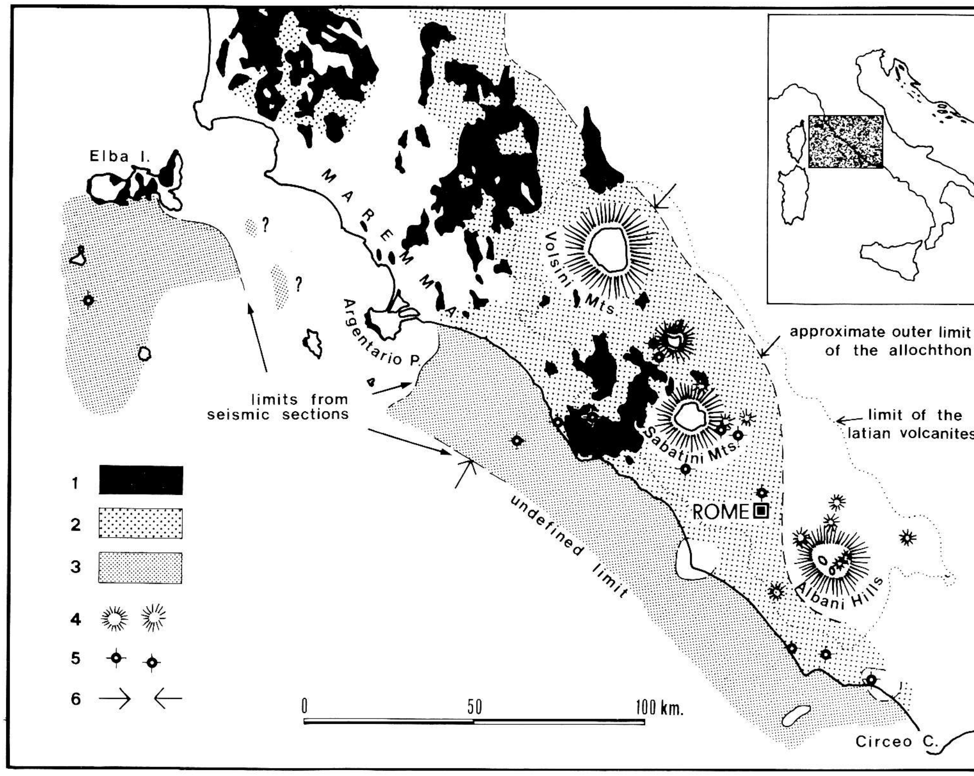

Fig. 14 - Present day extension of the Liguride Complexes in the Tuscany-Latium Apennines and their continental shelf.
1) Outcrops of the Liguride Complexes; 2) their onshore extension beneath the sedimentary and volcanic covers; 3) their offshore extension beneath the continental shelf; 4) phreatomagmatic centres; 5) deep wells; 6) position of the NE-striking transect cited in the text.
Land data taken from: Funiciello et al. (1977); Funiciello & Parotto (1978); Di Filippo & Toro (1980, 1982); La Torre et al. (1981).

in southwestern Tuscany, causing large tectonic transport and denudation (Giannini & Lazzarotto, 1975; Boccaletti et al., 1981).

Along the Latian tract of the margin the Ligurides occupy a large band lying over both sides of the coastline. As a matter of fact, seismic sections, geological, geophysical and drilling results support their presence both beneath the Latian shelf and beneath the vaste sedimentary and volcanic covers of the southern Maremma, of the Volsini and Sabatini Mounts.

The Tuscan portion of the margin shows a quite different distribution pattern of the Liguride Complexes. Their continuity, characteristic of the Latian margin, is here interrupted by a large bare area, which comprises the northern Maremma and its surrounding zones, along with the shelf sector B (from Elba I. to Argentario P.). In this latter, in particular, few geologic controls (see Fig. 2) and scarce seismic evidence do not substantiate a significative presence of the Liguride Complexes. If the hypothesis of their absence were confirmed, it would be reasonable to assume a pre-postorogenic structural configuration for sector B somewhat similar to that of northern Maremma. Therefore, it may be postulated that the area of southern Tuscany that underwent the Tortonian gravity tectonics, enlarges as far as this sector of the Tuscan shelf.

On the contrary, the shelf area south of Elba Island, tested by the Martina-1 well (Fig. 4), is characterized by a continuous areal distribution of the Ligurides, whose further southward extension has been demonstrated in Bacini Sedimentari (1979).

To conclude the discussion on these complexes, so widespread in the inner Apennine belt and beneath the shelf, it is worthwhile saying few words about their western limit. Reprocessing of old deep-water seismic data (Bartole et al., 1988) provided a valuable help in distinguishing a limit on the continental slope offshore Civitavecchia (Fig. 9). At the present time, there is no way to ascertain whether this limit has local or regional significance. Nevertheless, since no geophysical or geological evidence of

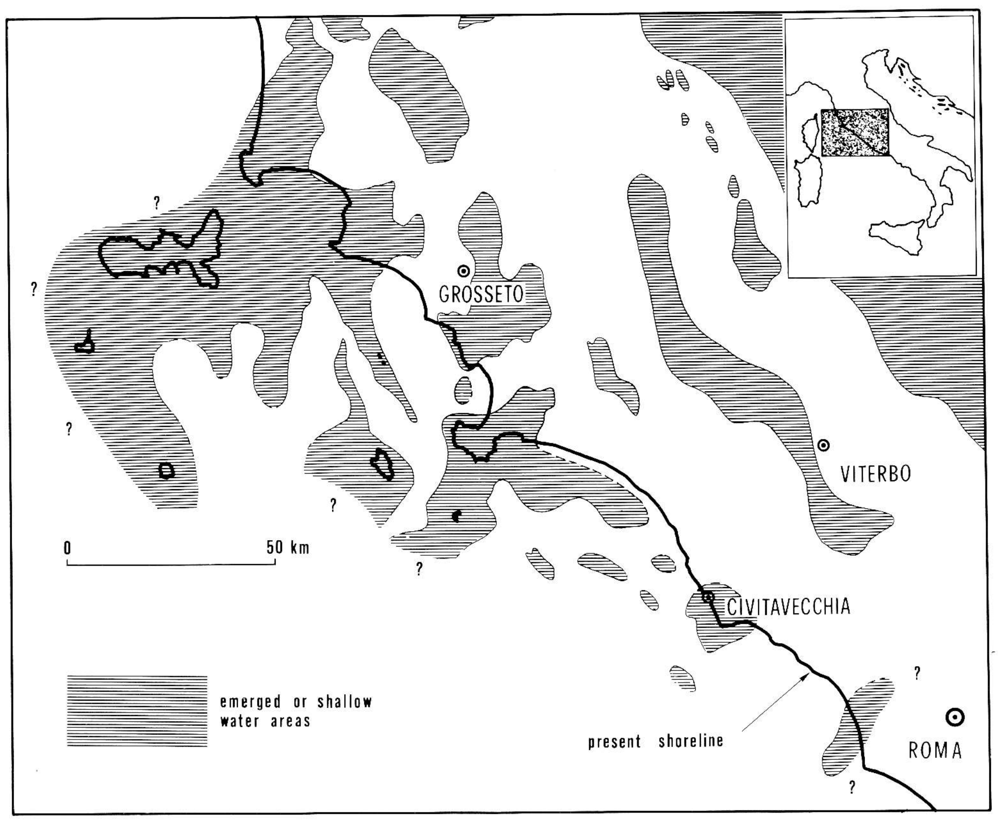

Fig. 15 - Tentative paleogeographic scheme of the Tuscany-Latium continental margin towards the end of the Lower Pliocene.

Ligurides exists further southwest (see the "Carta litologica e stratigrafica dei mari italiani" by Colantoni et al., 1981), a total width of about 90 km may be assumed as a merely indicative value, at least for the NE-striking transect across the Latian margin shown in Fig. 14.

A somewhat different and more complex situation characterizes the area south of Elba Island. Here, seismic sections of this sector along with previous works (Barbieri et al., 1981, fig. 2; Fabbri et al., 1981, fig. 4) indicate that the Liguride Complexes enter the Corsica Basin. Since they also outcrop, with Europe-vergence, in the Alpine Corsica (see Ogniben et al., 1973), it seems reasonable to expect, also on the basis of Martina-1 data, that their westernmost apennine-verging limit could run along the eastern flank of the Corsica Basin, close to the Island of Pianosa.

As far as the first postorogenic cycle (Unit 2) is concerned, its areal extension provided the basis for the construction of a tentative paleogeographic scheme of the Tuscany-Latium continental margin at an age referred to the end of Lower Pliocene (Fig. 15), i.e. at the time the inner belt underwent the maximum transgression of the Pliocene sea (Ambrosetti et al., 1979; Pasquarè et al., 1985). Keeping in mind the limits of resolution peculiar of the seismic method, it is possible to make the following comments on Fig. 15. The map illustrates an archipelago configuration with two different patterns of the land-to-sea ratio. To the north, large islands and elongated peninsulas alternate with basinal areas oriented both in apennine (NNW-SSE) and anti-apennine (NE-SW) directions. The last trend, as already mentioned, reflects the great strike-slip component, peculiar of the Upper Miocene-Middle Pliocene extensional tectonics of southern Tuscany. Evidences of this component are recognizable in the NE-striking inlets around Grosseto and the Argentario Promontory. On the contrary, only small and sparse islands dominate the Latian paleomargin, except for the long apennine-trending ridge (the "Castell'Azzara-Monte Razzano Ridge" of Baldi et al., 1974), located west of Viterbo.

Concluding remarks.

Correlation with geologic controls and comparison with literature data, have ascertained the stratigraphic and-structural connection of the Tuscan-Latian shelf with the inner part of the north-central Apennine belt. The different tectonic styles recognized in the four sectors in which the studied area has been divided, represent the rheologic response of the upper crust to tectonic mechanisms of different origin, which succeeded and superposed to each others.

In the Tuscan sector of the shelf, the eastward rejuvenation and progressive deformation of the first postorogenic deposits are congruent with the time-space migration of the Neogene tectono-sedimentary events peculiar of the Apennine chain.

Compressional, extensional and transcurrent structural styles coexist in different proportions. While the first two are evident on seismic sections, the last may better be resolved from regional considerations. Both the structural (Table 2) and the paleogeographic (Fig. 15) maps, in fact, evidentiate tectonic trends and basinal axes transversal to the general NW-SE grain.

Even though the relative strik-slip displacement cannot be resolved, it stands out however, that the transcurrent tectonics played a very important role in the Neogene evolution of the margin. The Lower Pliocene paleogeography (Fig. 15) witnesses that strike-slip motion was a fundamental component of the rifting mechanisms, particularly in the Tuscan portion of the shelf. It permitted its fragmentation into tectonically independent bands, whose differentiation took place in Upper Miocene-Middle Pliocene times.

Similar processes, but of minor magnitude, very likely characterized the Latian shelf. They are responsible for the Lower-Middle Pliocene intrusion offshore Civitavecchia, which would represent a new-found magmatic body of the Tuscan petrographic province.

Finally, it is worth making some consideration about the remarkable extensional tectonics recognized in the Elba-Argentario sector, as it has a geotectonic implication for the evolution of the Apennine Chain-North Tyrrhenian postorogenic system. Recent studies in the Northern Tyrrhenia Sea (Zitellini et al., 1986) evidentiated an Upper Miocene-Middle Pliocene postcollisional rifting, related to the oceanization processes peculiar of the central bathyal plain (Trincardi & Zitellini, 1987). After the former Authors, the Tuscan margin "never underwent horizontal extensional tectonics", being the rifting mechanisms confined into the deep-water areas to the southwest of the Tuscan shelf.

The present work, instead, contrasts this assumption. Interpretive schemes of the depressions represented in Fig. 4, 5, 6, 7, along with the structural and paleogeographic map of Table 2 and Fig. 15 respectively, show that not only rifting but also strike-slip mechanisms affected the Tuscan shelf.

On the basis of these evidences, there are three concluding points that merit emphasis:

1) The likeness of the mechanisms that gave origin to the depressions of the Tuscan shelf and to the Tuscany-Latium Neogene basins, is interpretable in terms of common geotectonic evolution, i.e. a rifting process for both the submerged and the emerged zones of the inner belt. On this subject it is worth remembering that a "continental" rifting in southern Tuscany had already been hypothesized by Bettelli et al. (1981).

2) As widespread rifting mechanisms have been ascertained in the deep-water areas of the North Tyrrhenian Sea (Zitellini et al., 1986), it may be concluded that the rifting also propagated within the continental area, the Tuscan shelf representing its penetration way.

3) Lastly, if important transcurrent components will be also ascertained further to the south, i.e. into the deep-water areas, then a trans-tensional model could be applied for the North Tyrrhenian Basin-Apennine Chain postcollisional system.

Acknowledgements.

This research is CNR-Role of the strike-slip and vertical tectonics in the Mediterranean Neogene Contribution 1.

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