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THE LIGURIAN SEA: NEW SEISMOTECTONIC EVIDENCE

Summary. The current and historical seismicity of the Ligurian Sea and surrounding regions has been analyzed in order to obtain closer seismotectonic correlations. The seismicity and focal mechanisms indicate particular differences between the different sectors of the Ligurian Basin. The aseismicity of the eastern side of the Basin, corresponds to an active band in the western side, where there is transpression along both the margin foot and the basin axis. The margin, as evidenced by a seismic reflection survey, appears to be segmented by a fault system consisting of a net of transversal faults intersecting step faults parallel to the coast. At the foot of the margin, sedimentary basins displaced en echelon are cut throughout their thickness by active normal faults, and the seismic activity concentrates at the intersections of main faults. To explain apparently contrasting results, a simple couple of forces acting in opposite directions in the Ligurian Sea and in the Po Valley has been hypothesized.

INTRODUCTION

The Ligurian Sea, which represents the maximum extent of the Ligurian-Balearic furrow and is delimited by a system of normal faults, shows structural features supporting its tensional origin. The crustal thinning and the high heat flow (Cermak, 1990; Cermak et al., 1992) also strongly support this idea.

This distensional structure, sideways cutting the Ligurian-Provencal structure, from the most external units of the Provencal basin reaches the inner Piedmontese Units of the Voltri Group. As summarized by Guieu and Roussel (1990), the Ligurian-Provencal basin has suffered, from Oligocene times, an extension of the ''oceanized area'' in the center of the basin with openings, which propagated from SW to NE, by faults transverse to the basin axis (i.e. Capo Mele-Cap Corse and Cassidaingne-Asinara lines) and delimiting sectors of different dimensions and ages of stretching. Similar considerations of an extensional origin should be extended to the Upper Tyrrhenian Sea and to the Northern Apennines.

The tensional nature of the upper Tyrrhenian basin, which can be considered as a submerged sector of the western side of the Northern Apennines cut by normal faults in a semi-graben system (Giglia, 1973), contrasts with the compressive character of the Apenninic fronts (Elter et al., 1975).

In this picture, where stretching and tectonic distension dominate, the seismicity is of strongly

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contrasting behaviour. The reverse faulting mechanisms shown by the strongest earthquakes in the western side of the Riviera (Bethoux et al., 1988) and in the deepest crust of the Northern Apennines (Augliera et al., 1990) seems more coherent with a compressive regime than with a continuation of distension.

At least two schools of thought seek to explain the genesis of current seismicity and the active tectonics presented in the area: one considers the actual dynamics as due to a compressive reactivation of the Ligurian Sea (Rehault et al., 1984; Bethoux et al., 1992). The second frames both activities into a geodynamic context which involves a more localized renewal of distension (Fanucci and Nicolich, 1986).

The surface tectonics at this moment do not provide suitable evidence to support one hypothesis or the other. So that, in the light of the actual knowledge (presence of an intense stretching and crustal thinning, asymmetry of the distribution of seismicity, evidence of compressive focal solutions, and high heat flow), any general kinematic model, which has to correlate a distensive tectonic regime with a compressive seismogenetic field, requires very complex assumptions.

To contribute new evidence for solving this apparent paradox, in this paper a revised seismotectonic picture is compared with new data obtained on the shallow structures from seismic reflection profiles.

SEISMICITY

Data source

The historical and instrumental seismic activity of the Ligurian belt is sufficiently well documented.

From the historical point of view, even if suitable information on felt earthquakes can be found since the 16th century (earthquake of the 20 July 1564, Imax=IX MCS), a clear distinction between on land and offshore earthquakes can only be made for the period since 1800 (Postpischl, 1985; Eva et al., 1985). This is due to the incompletness of the macroseismic data sets used to define macroseismic epicenters. So that, the oldest off-shore earthquakes are wrongly attributed to areas of maximum felt intensity along the coast. On the other hand, instrumental seismicity gives suitable information on epicentral coordinates only after the 1960's. Indeed, only after these years does the increasing number of seismic stations on both sides of the French-Italian border allow increasingly precise focal parameters.

At present, at least five digital seismic networks continously operate in the south-western Alps and Liguria (IGG, EOPGS, LDG/CEA, SISMALP, SISLIG), and nearly 40 stations are located at a distance of less than 250 km from the Ligurian Sea epicentral areas. Fig. 1 shows the distribution of major earthquakes ($M \geq 4$, Imax ≥ VI MCS) in the Liguria Sea and adjacent areas for the period 1800-1981.

Recently, a revision of instrumental seismic activity for the period 1971-1989 in northwestern Italy has been performed (Eva et al., 1992). For the revision, all P and S phase data recorded by permanent and temporary seismic stations, operating approximately within a radius of 300 km from the epicenters, were collected.

The data file, derived from direct readings and seismic bulletins, has been used to relocalize the earthquakes with a standars procedure (HYPO-ELLIPSE program; Lahr, 1979), adopting seven different propagation models. The models, obtained from inversion of local seismic data and derived from the results of refraction seismic profiles in the region, have been associated with different groups of stations according to their geo-structural characteristics. Clearly these models consider a bi-dimensional horizontal layering for the travel-path epicenter-station.

The file has been integrated for the period 1990-1992, by the same procedure, using data from the previously mentioned digital networks. The complete data file obtained represents the database for the following seismotectonic correlations.

Figs. 1 and 2 show the seismicity in the periods 1971-1981 and 1982-1992 separately.

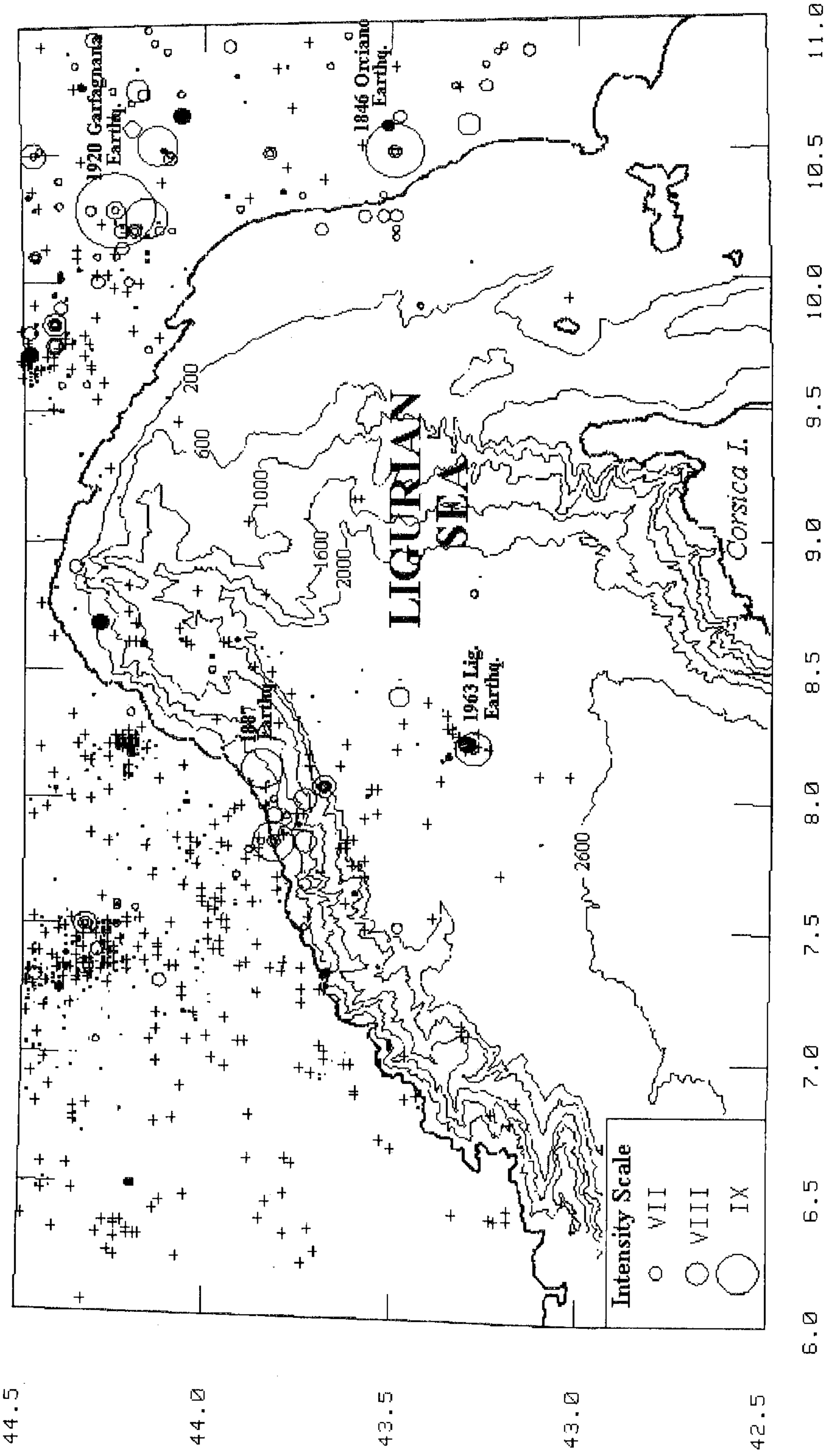

Fig. 1 — Seismicity 1800-1981. Open circles indicate the historical events (1800-1970); black dots and crosses are related to instrumental period 1971-1981 (crosses=no magnitude data).

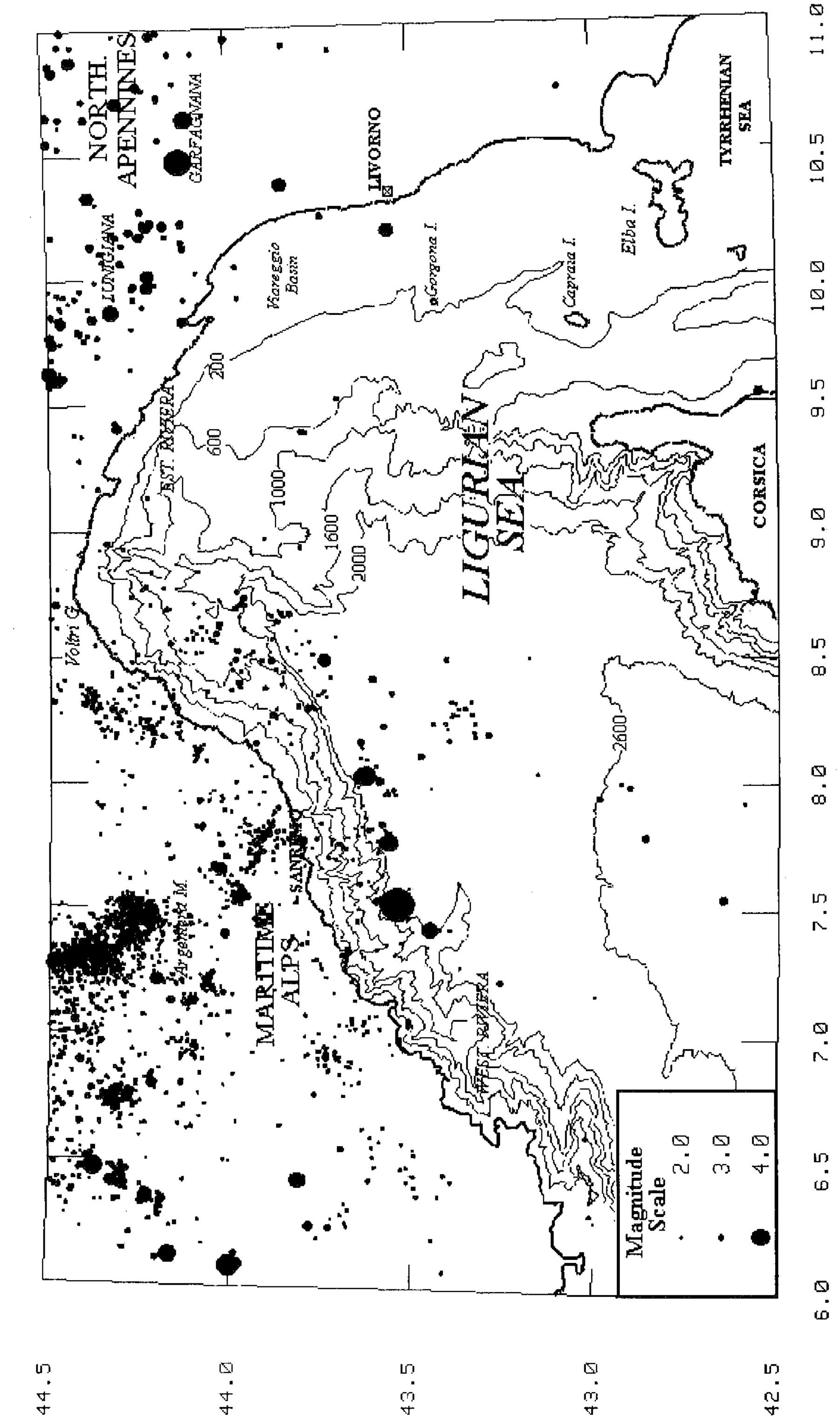

Fig. 2 — Instrumental seismicity recorded in the period 1982-1992 for M ≥ 2.0 and horizontal and vertical errors less than 10 km.

This differentiation is needed because in the first period the accuracy of location and definition of earthquake magnitude is less than for the following years. This is mainly due to the increased number of seismic stations and the introduction of digital techniques in acquisition and processing of seismic data. In particular, the latter figure shows the geographic distribution of earthquakes, selected according to the precision of focal coordinates (horizontal and vertical errors less than 10 km). In both figures the circle dimensions are related to the focal volume of earthquakes according to the relationship proposed by Bath and Duda (1964).

A comparison between the two figures indicates that, in most areas, the seismicity distribution appears stable in space and time (e.g., Central Ligurian Basin, the Brianconais Arc and the Apennines). At this point, the well localized seismic activity of the second period (1982-1992) can be considered sufficient to describe the connection between earthquakes and active structures.

Seismicity distribution

The data collected emphasize the peculiar seismic pattern of this region, which can be subdivided in two parts: the westernmost side, characterized by continous seismicity of low energy that sometimes reaches high magnitudes (Diano Marina event of 23 February 1887 with an extimated M=6.0-6.2, Capponi et al., 1985; Ligurian Sea earthquake of 19 July 1963, M=6.0, Bossolasco and Eva, 1965), and the central-eastern, nearly aseismic side (Bossolasco et al., 1972; Fanucci et al., 1989; Bethoux et al., 1992).

Indeed, the Tyrrhenic area, even though strongly tectonized, as shown in Fig. 3, where recent seismicity (horizontal and vertical errors less than 5 km) has been superimposed on a structural map (CNR-P.F. Geodinamica, 1990), is characterized by a nearly complete absence of seismic activity, except for the narrow zone off-shore Livorno; this area was reactivated in April 1984, with a sequence following an earthquake of M=4.6, after a "silent" period of about 140 years.

The previous noteworthy seismic event was the Orciano earthquake of 14 August 1846 (Imax=IX MCS). This shock produced serious damage on land (Albini et al., 1991) and many foreshocks and aftershocks occurred in the Tyrrhenian Sea, also producing some solitary waves along the coast. The reactivated area corresponds to the Livorno-Gorgona line, a vertical transcurrent fault well displayed by seismic reflection data (Fanucci and Nicolich, 1986).

The most important activity concentrates in the western Ligurian basin and along the Alpine margin where the seismicity affects an area with a roughly triàngular shape, between the maritime Alps and the northern margin of the Ligurian "sphenocasm".

This area can be subdivided into three different parts: the zone near the triangle top (between Genoa and Imperia), extending up to the Genoa canyons, which is characterized by a diffuse seismicity of low energy; the inner zone, close to the coastal line between Imperia and Nice, where the activity follows the trend of the tectonic scarps which delimit the basin and lower the substratum; and the external edge, trending NE-SW, where an alignment of foci seems to mark the basin center and coincides with salt diapiric structures limiting the western side of the Ligurian sphenocasm.

The last two zones were the sites of the largest shocks in last two centuries: respectively the 23 February 1887 quake which was located offshore at a distance of about 10-15 km from Imperia (Capponi et al., 1985; Ferrari, 1991), and the sequence of the July 1963.

On land the seismic activity is very different. East of Genoa, it is associated with the distensive structures of the inner Apennines (Garfagnana and Lunigiana grabens). However recent results (Augliera et al., 1990; Tomaselli, 1993) carried out with a local network indicate that the seismic activity affects the whole lithosphere. In this area, there is evidence of focal depths reaching 60-70 km.

The Western Riviera comprises the structures of the Ligurian Alps, which are a poly-deformed chain where all the elements forming the Western Alps outcrop. The whole zone is strongly faulted, and from surface data it is not possible to distinguish active faults. The seismicity shows some clusters and alignements of foci. The most significant is represented by the Saorge-Taggia line, which appears as an active neotectonic fault system of dextral transcurrent character (Be-

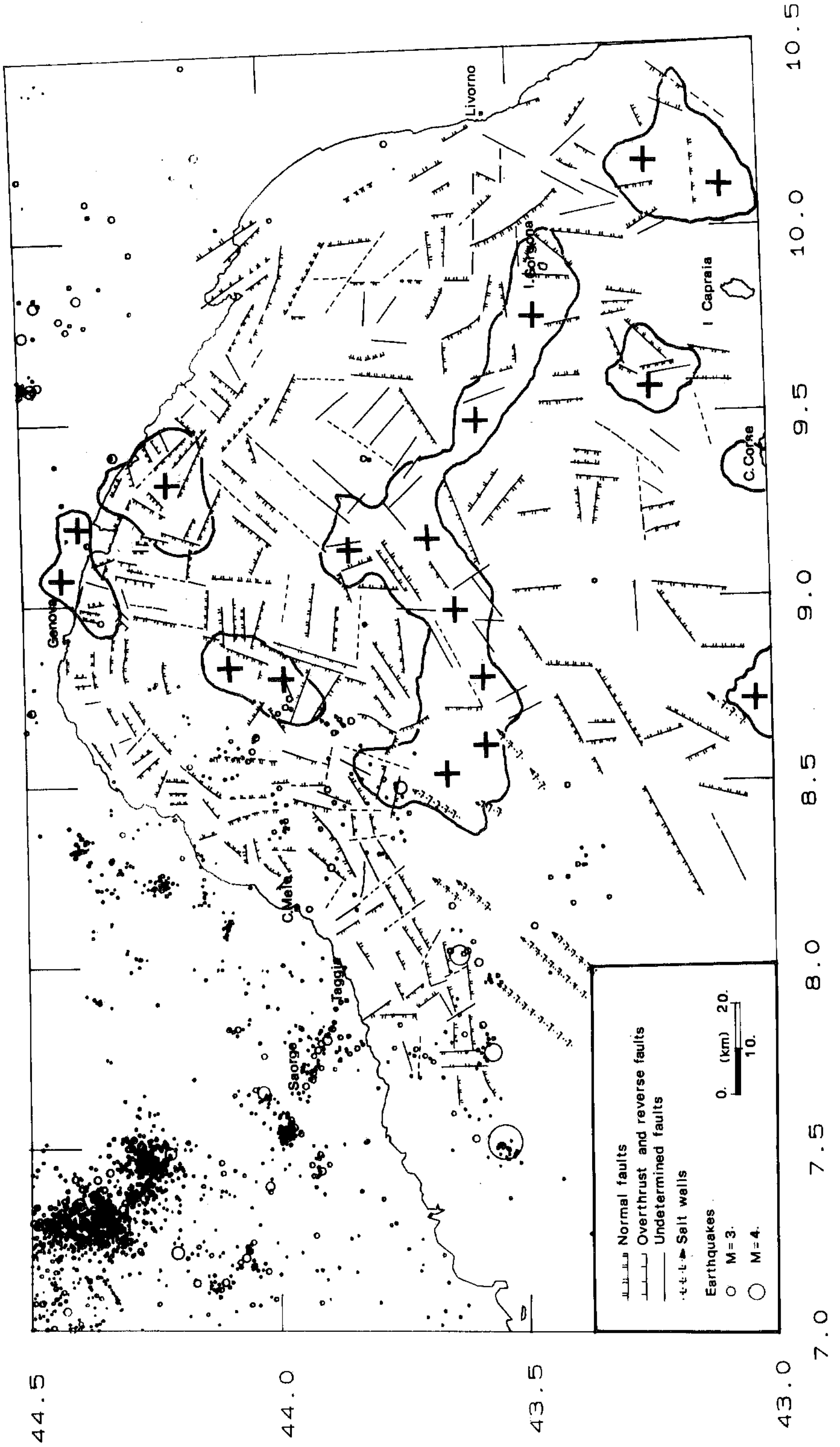

Fig. 3 — Seismotectonic sketch map of the Ligurian Basin (modified from CNR-PFG, 1990). The seismicity for the period 1982-1992 (horizontal and vertical errors less than 5 km). The plus signs show the regions of gravimetric and magnetic highs probably related to the ophiolitic suture zone.

Table — Focal solutions computed for the Ligurian Sea and Western Ligurian margin.

N	DATE	Or. Time (h:mn:s)	Lat. (°N)	Long. (°E)	H (km)	Ml	Pl. Az	1 Dip	Pl. Az	2 Dip	P-axis Az	P-axis Dip
1	19.07.63	5:45:29	43° 19.8'	8° 9.0'	14	5.6	176	53E	40	46W	107	4
2	19.07.63	5:46:04	43° 20.4'	8° 9.6'	31	6.0	176	53E	40	46W	107	4
3	04.01.81	4: 9:20	44° 15.6'	7° 18.6'	5	3.5	50	84E	145	50W	104	22
4	22.04.81	4:26:21	43° 18.6'	8° 13.8'	2	4.5	60	68N	150	90W	103	15
5	04.12.83	17:34:51	43° 51.6'	7° 45.6'	1	3.5	10	54W	120	65E	160	46
6	04.10.85	13:17:22	43° 37.8'	8° 5.4'	12	4.1	35	71E	134	66W	85	4
7	04.10.85	15:22:11	43° 38.4'	8° 5.4'	13	3.9	30	45W	5	48E	107	1
8	05.10.85	15:58:40	43° 37.2'	8° 2.0'	16	3.1	40	77E	135	69W	88	5
9	01.05.86	0:28:02	43° 27.6'	7° 25.3'	10	3.9	28	64W	112	78W	162	9
10	20.10.86	20:29:11	43° 55.8'	7° 42.6'	2	3.0	23	79W	115	80E	159	15
11	29.10.86	8:13:34	43° 53.4'	8° 16.2'	5	3.0	24	84W	115	81E	159	11
12	26.12.89	19:59:59	43° 32.4'	7° 32.4'	7	4.5	15	60E	231	36W	119	13
13	15.04.90	7:50:36	43° 34.8'	7° 48.6'	5	4.3	25	70E	278	51N	148	12
14	02.07.90	18:42:30	43° 56.0'	7° 41.0'	2	2.7	190	63N	123	53E	152	49

thoux et al., 1988).

The focal depth distribution of the better localized shocks (horizontal and vertical errors less than 5 km) is shown in Fig. 4, where two profiles, crossing the Maritime Alps and the western Ligurian Sea seem to indicate a gradual deepening of active zones from the continental to the oceanic sectors. In particular the profile A-A' outlines two separate zones: one lying under the Alpine margin (in correspondence to the penninic structures), and the second linked with the continental crust of the Ligurian Sea. In both cases the active zone is mainly restricted to the first 10 km of the crust.

The westernmost profile, confirming the minimum of activity along the coastal region, shows increasing focal depths proceeding towards the open sea. Foci affect the shallowest layers on land ($h \leq 10$ km) and the intermediate or deep crust off-shore ($10 \leq h \leq 20$ km). Focal values greater than 20 km in the profile B-B' are strongly questionable. Indeed the big azimuthal gap in recording stations and the strong lateral variations in che crust, showing a transition from continental to oceanic structure, prevent suitable depth evaluations of the most distant shocks from the coast.

Focal mechanisms

Several focal mechanisms (see the Table) have been computed in the area (Bossolasco et al., 1972; Fréchet, 1978; Réhault and Bethoux, 1984; Hoang-Trong et al., 1987; Bethoux et al., 1988; Bethoux et al., 1992), and all spotlight the notable stability of the nodal plane directions: N 20°-40° or N 110°-130°. These two directions exactly coincide with the structural framework of the Ligurian Sea: lineations parallel to the rifting axis trending N 30°-40° and lineations perpendicular to the basin axis, assimilated to transform faults (Réhault, 1981). They also correspond to two conjugate directions - the "Cevenole's" and "Argentera's" fault systems, respectively trending NNE-SSW and NW-SE (Lemoine et al., 1989; Vialon et al., 1989) - which are reactivated again and again, as pre-existing planes of weakeness.

All focal solutions computed for events with magnitudes ranging from 4 to 6 (solutions 1, 2, 4, 12, 13 of Table 1) clearly indicate compressive tectonics. It is worth noting that these events are located in the deep basin or at the foot of the Riviera margin.

On the margin or on the coast, strike-slip mechanisms along normal planes prevail. On the coast, the main activity seems concentrated along the N 120° Saorge-Taggia lineament. Three focal solutions (5, 10, 14) are homogeneous and coeherent with the orientation of this lineament, reactivated as a strike-slip fault.

Thus, focal mechanisms reveal very different tectonics between the basin, the margin foot and the coast. In the basin, compression with P axes oriented nearly W-E predominates; on the margin, coherent P-axes trend WNW or NW. Along the coast, where compressive axes are oriented nearly NS, the mechanisms are in agreement with the transcurrent character of structures (strike-slip faults) in the region.

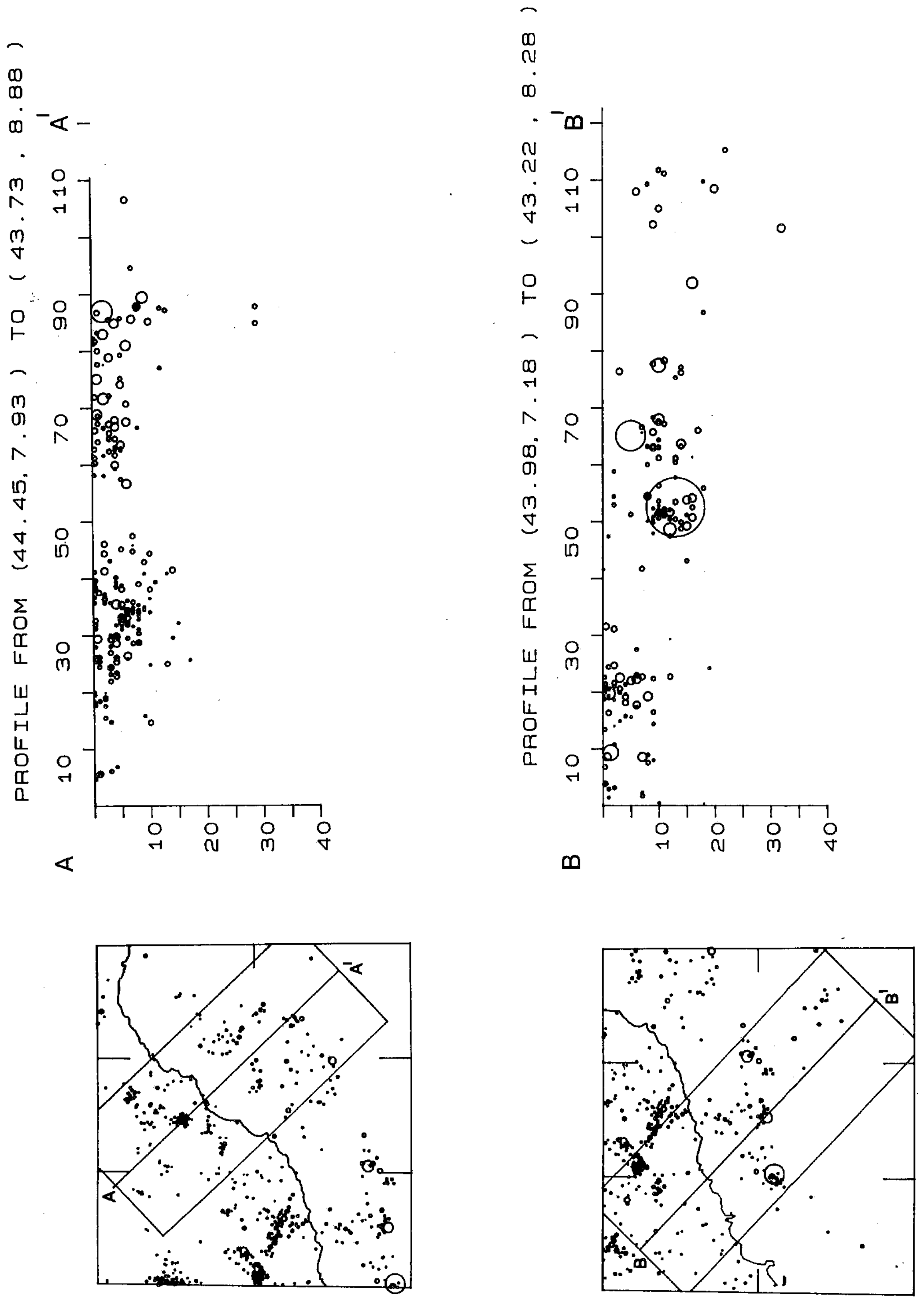

Fig. 4 — Seismicity cross-sections through the Western Ligurian margin (Period 1982-1992, events with horizontal and vertical errors less than 5 km).

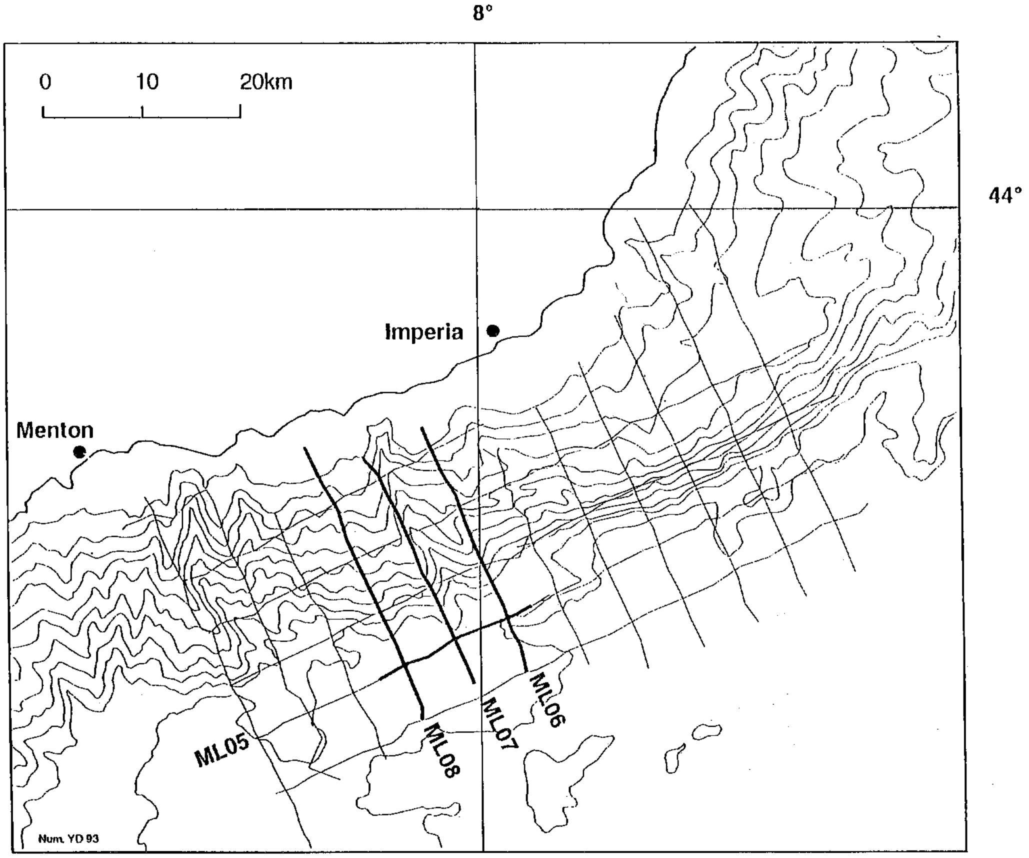

Fig. 5 — Positions of seismic profiles of the Maligu cruise; the thickest lines correspond to the profiles considered in the present work.

GRAVIMETRIC DATA

The Ligurian Sea is characterized by the presence of a very high positive Bouguer anomaly, whose maximum (+160 mGal) is centered on the west side of Corsica (Morelli et al., 1977; Klingelé et al., 1992). This anomaly, which rapidly decreases toward the continental margin, is determined by the strong crustal thinning due to the relatively recent process of oceanization.

The irregulat shape of the iso-anomalies derives from the overlapping of local (low wave-length) and regional (long wave-length) anomalies. The analysis of the gravimetric field by Cattaneo et al. (1986) using bidimensional filters, isolated the contribution of shallow (high-frequency) structures from the deepest ones (low-frequency). According to these Authors the map obtained with a high-pass filter ($\lambda \leq 50$ km) represents the contribution of the shallowest bodies ($h \leq 4$ km). With reference to Fig. 3 the distribution of the positive residual maxima, represented in the map by the areas with large plus signs, indicates the strong deformation undergone by the crustal structures.

Comparing these results with the aeromagnetic map of the Ligurian Sea (AGIP, 1983; Bolis et al., 1981; Wornik et al., 1992), shows the close correlation, both in position and orientation, between gravimetric and magnetic highs. Thus they could have been generated by ophiolitic and/or volcanic bodies buried under the Tertiary sediments of the shallowest layers.

These bodies which lie along the limit of the crustal doubling between the Adria and European plates very probably belong to the ophiolitic suture of the Liguro-Piedmontese Triassic Ocean, split by the tectonic events following continental collision. As regards the volcanoes, their origin is probably linked to rifting processes that occurred between Oligocene and Miocene times (Réhault, 1981). As shown by the tectonic map of the area, in the central part of the Ligurian Gulf, a main system of normal faults, distributed in a fan shape trending NNE and NE, appears to have fractured, translated and rotated the ophiolitic bodies.

The main secondary maximum located in the center of the Ligurian Sea appears to delimit the seismic belt of western Liguria.

The gravimetric minima of Tuscany and the north Tyrrhenian Sea are clearly connected with the post-Tortonian tectonic basins filled with light sediments. The Viareggio basin penetrates into the Genoa Gulf and its northern extension is bounded by a system of normal faults following the same trend as the gravimetric minimum.

In the Ligurian-Provencal basin, the most regular trend, without significant high-frequency anomalies, indicates a dependence on deep crustal or mantle structures that are better correlated with the main regional gravimetric field.

Recently, analyzing the geoid undulation, Lelgemann and Kuckuck (1992) have evaluated the gravity disturbing vector, which is related to the free air anomaly at the earth's surface. According to the map drawn by these Authors, the horizontal component of the gravity disturbance vector shows two main zones of "structural instability" (maximum of the vector) surrounding the northern margin of the Ligurian Sea. One of the maxima is centered on the continental margin of western Liguria, and the second is connected with the Apennines chain. In both cases the seismicity is situated along the zone of maximum vector gradient.

SEISMIC REFLECTION PROFILES

In order to improve the link between the geophysical data summarized above and the structures of the margin at sea, a seismic survey (MALIGU cruise) was performed in the western Riviera from 7° 30' to 8° 30' longitude in April-May 1992 (Chaumillon, 1992). The locations of the new seismic profiles are shown in Figure 5.

West of this zone, a synthesis of existing profiles (ECODIV and SEADOME cruises) was done by Savoye and Piper (1991), and later by Chaumillon (1992).

During the MALIGU cruise, the acoustic source used was a SODERA S80 watergun (1.3 litres) towed at 7 m depth. Shot interval was 10 s, and speed of the ship 5.5 knots. The streamer was towed at about 10 m below the sea surface. The seismic data were recorded on a Bell and Howell recorder with a length of 2.5 s two-way traveltime (TWT). This means that lithologic facies and structures can be recognized to depths down to 3 or even 4 km below sea bottom.

Correlation between reflectors on the continental slope is difficult because of the complex margin morphology and the lateral facies variations (Gennesseaux and Glacon, 1972; Mauffret et al., 1973; Le Cann, 1987; Savoye and Piper, 1991). In spite of this, good identification of the key seismic reflectors and the main acoustic facies was possible in the studied zone, due to the high density of seismic profiles (3 miles apart) and the data homogeneity.

We present here four single-channel seismic reflection profiles obtained during the MALIGU cruise in the vicinity of the Furia di Taggia canyon, just south of San Remo. This zone was recently crossed by the deep reflection seismic profile (line M-10) during the CROP-mare experiment, and furthermore is of interest because of its seismic activity and the presence of a typical deep canyon.

Figs. 6, 7, 8, show three seismic profiles (ML08, ML07, ML06) striking NNW-SSE (i.e., perpendicular to the coastline), thus providing cross-sections of the margin on both sides of the Furia di Taggia canyon, from west to east, respectively.

Fig. 9 is part of the seismic line (ML05) parallel to the margin foot, which intersects the previous three orthogonally.

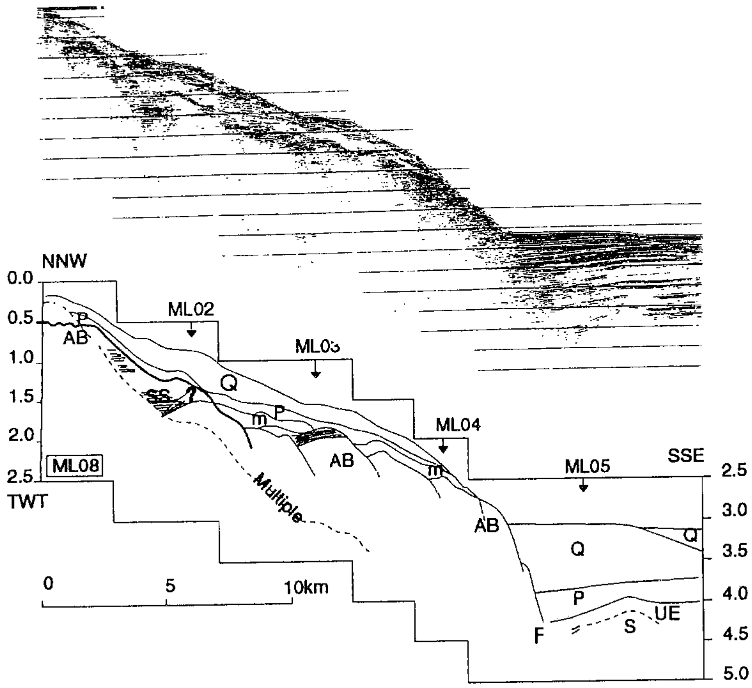

Fig. 6 — ML-08 profile (Q: quaternary sediments; P: Pliocene or lower Pliocene; m: Miocene deposits; UE: Upper evaporites; S: Messinian salt Units; SS: Synrift sediments; AB: acoustic basement; F: normal fault system).

As noticed previously by Savoye and Piper (1991), the seismic stratigraphy is relatively simple. The major reflector, called "E" by these authors, is at about 4 s TWT throughout the whole basin, and is the top of a set of strong and continuous reflectors, which are typical of the last sequence of the Messinian period, and are thus identified as the Upper Messinian Evaporite layer (UE). Below it, a curved, strong and discontinuous reflector appears from place to place: this is the top of the Messinian salt unit (S), and the deepest seismic facies which can be recognized on these seismic lines. This layer is generally strongly deformed into a dome shape by diapirism, especially in the eastern part of the margin (Chaumillon, 1992). Consequently, the upper sedimentary cover is also deformed, and sometimes appears uplifted at the foot of the margin (ML06, Fig. 8).

Above reflector "E", a very thick sedimentary sequence, the Pliocene-Quaternary unit, shows two main acoustic facies: the upper one, with numerous sub-parallel and continuous reflectors, attributed to the Quaternary (Q on profiles); and the lower one, more transparent, probably of Pliocene age (P on profiles). These sediments range from hemipelagites and sandy turbidites to sand and coarse gravels (Savoye and Piper, 1991). Transition between the lower and the upper unit acoustic facies within the Plio-Quaternary layer is attributed to the Quaternary climatic changes. This soft and thick Plio-Quaternary layer shows internal evidence of active faults, which generally seem to be linked with the dome-shaped salt and upper evaporite diapirism (Figs. 6, 7, 8). Whether this deformation is also related to any present-day tectonic activity remains unclear. Whatever the case, it its whorth noting that this zone of deformation is strictly limited to the foot of the margin, and clearly increases in intensity in the vicinity of the steep normal fault system (F on profiles 6, 7, 8) which shifts the acoustic basement (AB) and the upper evaporites (UE).

Fig. 9 also shows that long wavelength undulations of the UE top occur at the same position along the foot of the margin, thus revealing the existence of a local subsident zone alternating with a strongly uplifted block (see ML06, Fig. 8). This phenomenon is considerably amplified

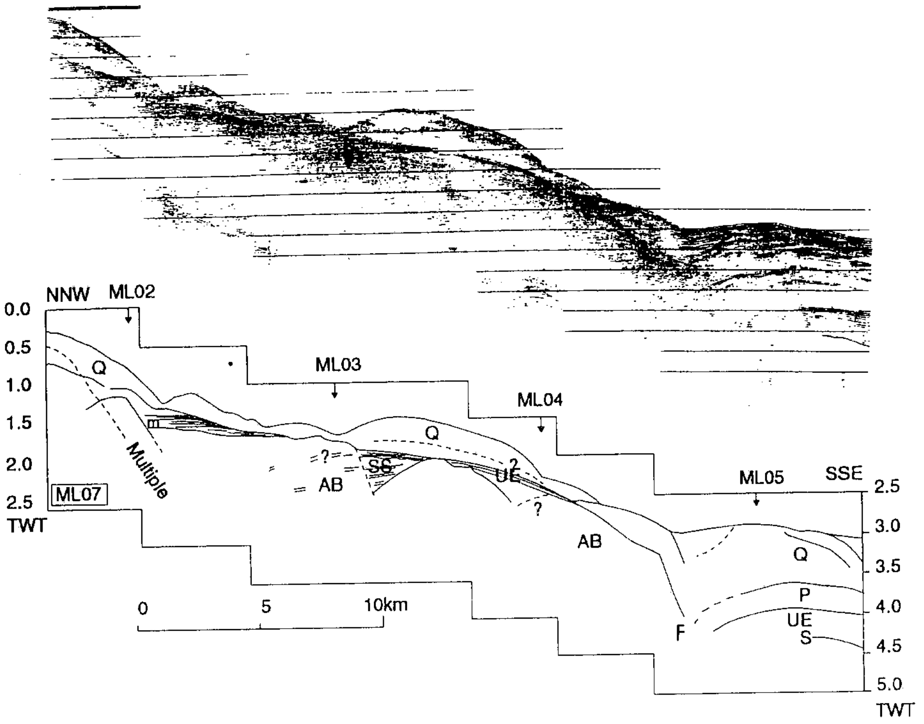

Fig. 7 — ML-07 profile (same symbols of Fig. 6).

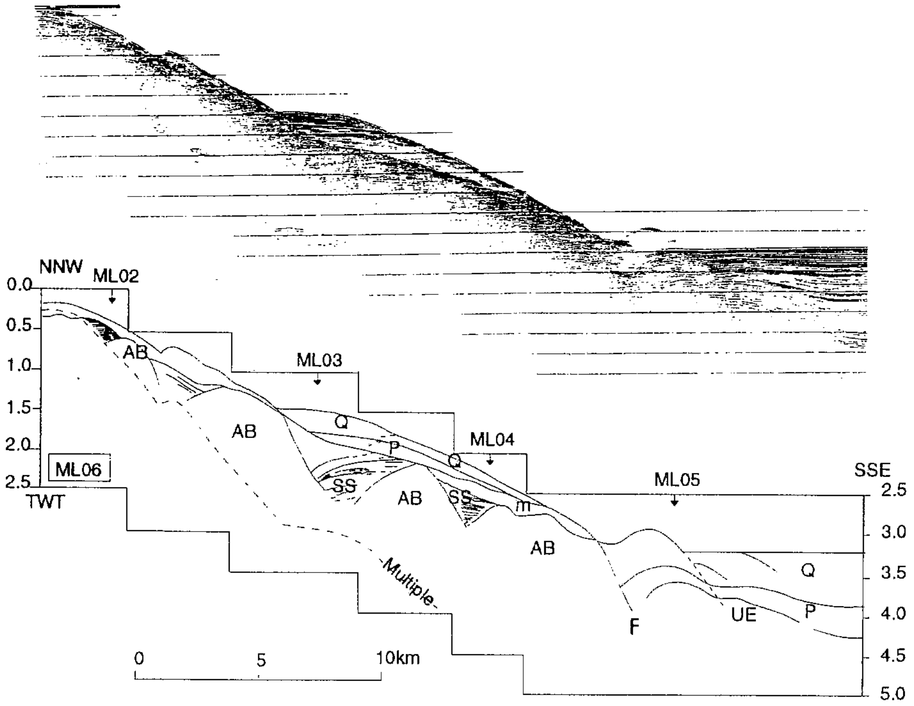

Fig. 8 — ML-06 profile (same symbols of Fig. 6).

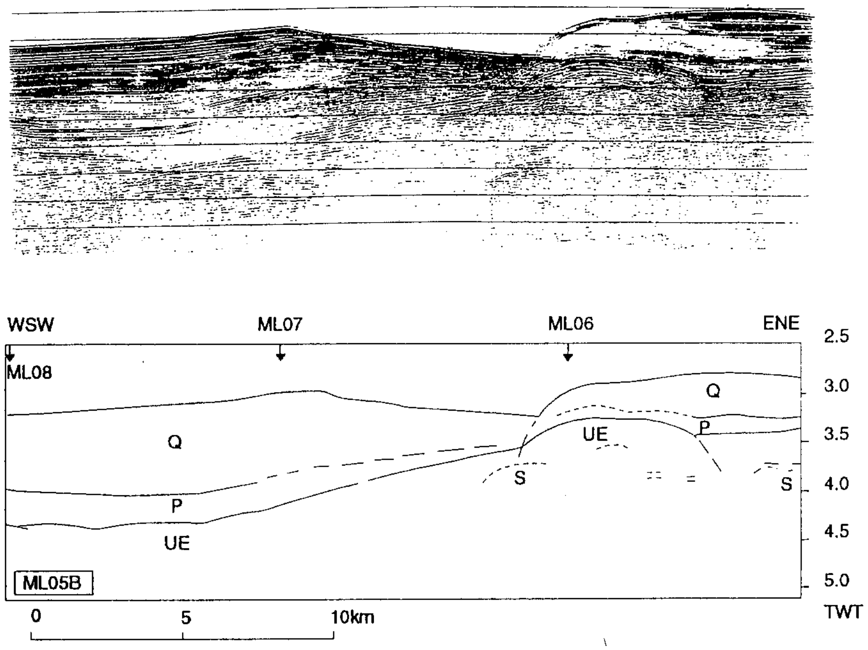

Fig. 9 — ML-05 profile (same symbols of Fig. 6).

just in the eastern zone, where the slope is the steepest (Chaumillon, 1992).

Another point is that the limit between the uplifted block and the subsident zone coincides with the prolongation of the Furia di Taggia canyon, which is believed to be of tectonic origin, like other canyons of the margin.

All these observations converge to indicate a link with deep-seated tectonic activity, as previously suggested by Rehault (1981) and Le Cann (1987).

Lateral correlation between reflectors on the continental margin, although less easy, has also been done using the longitudinal profiles.

A prominent feature of the margin stratigraphy is the presence of a major discontinuity, easily identified because everywhere stronger than other reflectors: this is the late Messinian erosional surface, called "M" by Savoye and Piper (1991), marking the last episode of the Messinian crisis (Ryan and Cita, 1978; Rehault, 1981). From bottom to top, the different acoustic facies and their abreviation on cross-sections are the following:

- The acoustic basement (AB) corresponds to the Eocene or Mesozoic pre-rift formations; this unit is highly diffracting and reflective. It is sometimes possible to recognize a rough stratification inside it, but we can usually identify only the tops of tilted blocks, more or less affected by erosion. This geometry and position of blocks constitute a very clear and prominent inheritance from the Oligocene rifting stage of the continental margin.

- The syn-rift sediments (SS) are probaly Oligo-Miocene in age. Their wedging is sometimes clearly visible on some half grabens (see for example ML07, Fig. 7).

- The upper evaporites (UE) are transgressive on the lower part of the margin: in spite of the very strong late Messinian erosion, they are sometimes conserved here (see ML07, Fig. 7), or even in a much higher position just south of Imperia, at about 1,5 TWT (Chaumillon, 1992). This observation is of importance because it allows us to deduce a minimum vertical offset between the reflector UE in the basin and the reflector UE on the margin. Two-way traveltimes of 1.3 s, 1.5 s, and 0.8 s (minimum values) are measured on profiles ML08, ML07, ML06, respectively, even when less organized acoustic facies of older Miocene deposits (m on profiles) are probably the only remnant post-rift sediments before the Pliocene-Quaternary

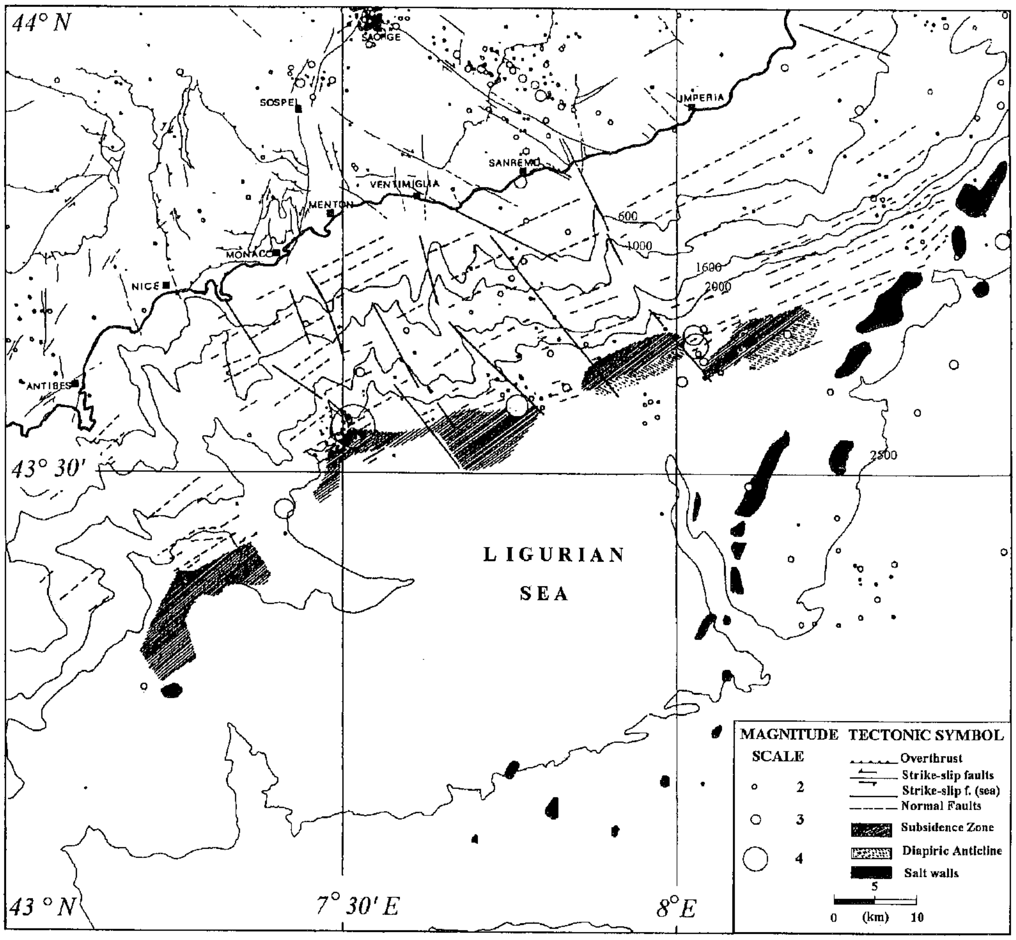

Fig. 10 — Seismotectonic map of Western Ligurian basin. The tectonic map is modified from Chaumillon (1992); seismicity for period 1982-1992 (horizontal and vertical errors less than 5 km).

(see ML08 and ML06, Figs. 6 and 8). This implies that a major tectonic displacement has taken place from late Miocene times at least between the foot of the margin and the lower slope, where a very steep normal fault system (F) is clear.

Above the "M" erosional surface, the Plio-Quaternary unit is clearly subdivided into two sedimentary episods, as in the basin. The lower unit is also identified as hemipelagic marls, whose age is probably Pliocene or basal Pliocene to middle Pliocene. In the active canyons of the margin, most of the sediments are eroded, and the acoustic facies becomes very diffracting. Elsewhere, the Plio-Quaternary layer shows classical features of turbidite-type deposits above a steep slope (Savoye and Piper, 1991).

DISCUSSION AND CONCLUSION

All new information on seismicity and neotectonics obtained from seismic profiles is summarized in Fig. 10. This figure displays the westernmost sector of the basin and evidences the differences between structures, the margin and the oceanic basin.

From the tectonic point of view, the difference of direction assumed by the structural fractures on land and off-shore is notable. On land the lineaments, trending N 120°, are known to be old reactivated faults. On the margin, the fault system, trending mainly N 160°, is younger and corresponds to transverse faults perpendicular to the margin created during the rifting stage. Along these faults, submarine canyons are found intersecting a secondary step fault system parallel to the coast.

All the margin appears as disjointed blocks displaced en echelon, as depicted by the distribution of sedimentary basins located at the margin foot. The sedimentary basins are sheared throughout their thickness by normal faults and show, on the basis of the subsidence of Plio-Quaternary sediments, that the tectonic activity is younger proceeding ENE from the French coast. The basement, as displayed in Fig. 9, shows significant undulations well correlated with different blocks. These undulations could be deformation folds in the sedimentary overburden above basement normal faults. This kind of deformation may be caused by differential vertical motion due to rotation of basement blocks by a single couple mechanism (McKenzie and Jakson, 1983; Saltzer and Pollard, 1992). Thus, an en echelon surface block system tilted by a rotation of basement blocks could be caused by an uplifting coupled with a displacement of the crustal layers towards ENE.

It is noteable that the seismicity appears mainly concentrated at the foot of the margin at the intersections of fault systems. Here the focal mechanisms indicate nodal planes coherent with the fault pattern and transcurrent movements along the fault directions, with a compressive stress component oriented nearly NS. The co-existence of transcurrence and overthrust fault solutions indicates the transpressive character of the margin.

In the basin, the most characteristic feature is the presence of a wall of salt diapirism along the basin axis limited to the south by a zone of high heat flow. Along this zone, some major shocks have occurred in recent times. The focal mechanisms studied for these earthquakes show overthrust or transpressive solutions, with P axes tranding nearly east.

In general the seismicity is associated with the coldest crustal regions and, refering to the heat flow density map (Cermak et al., 1992), it is seen that seismicity borders the areas of high heat flow, located in the oceanized basin and extending from the Corsica margin to Tuscany.

We now summarize the seismotectonic features of the different sectors of the Ligurian Sea basin:

- The main Ligurian Basin (sensu strictu) is a very deep depression created by the stretching of the Ligurian-Balearic lithosphere, characterized by a high heat flow, a thinned crust and an evident aseismicity.

- A transpressive activity affects the western margin, with a seismicity mainly concentrated along the margin foot, and the axial zone of the basin.

- Complex shallow neotectonics, with continental characteristics, are present in the crust of the central and eastern Ligurian Sea, with deformation bands distributed in a fan shape from the basin depression (s.s.) up to the Viareggio and Genoa sedimentary basins. These distensive bands split up the ophiolitic suture.

As evidenced by the EGT (Egger, 1992), the whole crust also presents an intense tectonisation without any significant evidence of seismicity.

The presence of a Ligurian lithospheric indenter below the Northern Apennines, with a continous seismicity distributed from the surface down to the lowest lithospheric layers, has been evidence by the EGT (Buness and Giese, 1990); and tomographic studies (Spakman, 1990; Cattaneo et al., 1993) have shown the presence of down-dipping lithospheric ''roots'' (ca. 200 km depth).

The presente tectonic setting of the Ligurian Sea basin outlined above is the result of the complex evolution of the whole Alps-Apennines system. However, the seismicity, mainly occurring in zones of weakness or along reactivated structures, has to be considered in the framework of the present stress field caused by the different mobilities of the two opposite-vergent chains.

The Alps and Apennines were generated at different times by thrust processes associated respectively with an ENE-dipping subduction, following the mantle flow, and a W-dipping subduction (against the direction of the mantle flow) (Doglioni, 1992). In this process the Ligurian Basin represented the Northen-Apennine back-arc.

At present, the Northern Apennines is rotating toward NE, and overthrusting the crust of the Adria plate (Po Valley), which is at the same time underthrusting the Eastern Alps (Castellarin and Vai, 1986). This rotation also induces the squeezing of the Padanian crust, which is forced towards the Western Alps.

The consequent collision increases the bending of the chain and induces compressive residual stresses perpendicular to the chain axis. At present, the Alps-Apennine system is undergoing the residual effects of the original stress field. So that a force couple, oriented W in the Po Valley and ENE in the Ligurian Sea is still acting.

The "null zone" might be located along the western Ligurian coast in correspondence to the band of minimum activity.

In this context, it can be postulated that in the Provencal Basin, the mantle flow drives a thinned floating lithosphere ENE, which then penetrates into the center of the Ligurian Gulf. This motion creates a compressive system of forces with sinistral transpression along the margin and dextral transpression along the central axis of the Ligurian Basin. At the margin foot the ligurian lithosphere underthrusts the continental crust of the Maritime Alps, uplifting and tilting the crustal blocks along the margin and reactivating inherited fault systems on the coast.

The crust of the eastern basin, under the driving forces, is compressed and strained against the Apennines. The residual light compressive forces deform the crustal plate, producing a gradual raising and thickening. On the surface, this produces plastic deformations of sedimentary layers that radiate from the center of the basin.

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