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A Closing Ligurian Sea?

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Abstract—Two earthquakes occurred in the Ligurian Sea in December 1989 and April 1990. Both were widely felt along the French and Italian Rivieras, thus reminding us of the seismic risk in this region. The significant increase in the number of seismic stations in the area facilitated the study of these two shocks and their related aftershocks. Using different techniques (absolute and relative hypocentral locations, doublet analysis and waveform modeling), we computed accurate hypocentral locations and estimated the location-error range for earthquakes in this area. We also computed the focal mechanisms for both mainshocks, and we present here a synthesis that integrates previous data. The reactivation in compression of the Ligurian Sea sphenochasm is confirmed, which would eventually result in the closing of an aborted oceanic domain. As the seismic activity is clearly restricted to the northern margin, we suggest it locally results from the lateral expulsion of the south-western Alps along the Apulian indenter.

Key words: Earthquakes, aftershocks, spatial distribution, Ligurian Sea, seismicity.

Introduction

The seismic activity of the Ligurian Sea is usually low but some destructive earthquakes are known to have occurred there in historical times: the last one was the Imperia event of 23 February 1887. It caused 670 deaths, 540 injuries, and severe damage (Capponi *et al.*, 1980). The earthquake of 19 July 1963 ($m_b = 6.0$ to 6.2, according to Bureau Central International de Séismologie) occurred relatively offshore, thus being felt over a large area with minor damage only (Bossolasco and Eva, 1965). We present here the study of two recent earthquakes. The first one was located 25 km offshore, and occurred on 26 December 1989 at 19:59 UTC ($M_L = 4.5$). It was widely felt on the French and Italian Rivieras, where it reached

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a maximal MSK intensity of V. A second earthquake ($M_L = 4.3$) occurred on 15 April 1990 at 07:50 UTC, some 30 km farther east. Both shocks were followed by several aftershocks.

Five digital seismological networks are presently operating in the south-western Alps and Liguria region (IGG, EOPGS, LDG/CEA, SISMALP and SISLIG)[6], which provides a total of 82 stations, with 48 of them being located at distances less than 300 km from the Ligurian-Sea epicentral area (Fig. 1). Seismograms were quickly gathered through EARN and TRANSPAC communication networks, and converted to a common format. This large amount of high-quality digital data allows us to obtain accurate results, even for low-magnitude aftershocks.

The difficulty in studying the Ligurian-Sea seismic area is twofold. First, the seismic network, taken as a whole, has a clear azimuthal gap towards the south (Fig. 1). However, the recent installation of 2 stations in Corsica in 1989 complements the sole station previously operated there, and allows us to significantly reduce this gap. Second, the structural pattern of the network area is very complex: the south-western Alps—including at depth the southern end of a mantellic intrusion known as the Ivrea body—the crystallophyllian massifs of Maures, Esterel and Corsica, with the oceanic domain of the Ligurian Sea in between, contribute, through their heterogeneities, to strong anomalies in the propagation of seismic waves (CATTANEO *et al.*, 1985).

Sophisticated techniques such as doublet analysis and waveform modeling should allow us to estimate the location-error range for classical hypocentral locations, an important parameter for the seismic risk in this area. The new available data should also allow us to compute constrained focal mechanisms, thus spotlighting the regional tectonics. The purpose of this paper is therefore to provide a seismological analysis of these two seismic crises, to discuss the improvement in accuracy furthered by the recent increase in the number and quality of regional seismological stations, and to revisit the Ligurian-Sea tectonics in the light of these new data.

Study of the Main Shocks

Location

The hypocentral locations of the two events were computed using the station set shown in Figure 1, and regional crustal models such as the ones described by

[6] IGG: Istituto Geofisico e Geodetico (Genova, Italy). EOPGS: Ecole et Observatoire de Physique du Globe (Strasbourg, France). LDG/CEA: Laboratoire de Détection et de Géophysique (Bruyères-le-Chatel, France). SISMALP: Laboratoire de Géophysique Interne et Tectonophysique (Grenoble, France). SISLIG: Centre Scientifique de Monaco (Monaco).

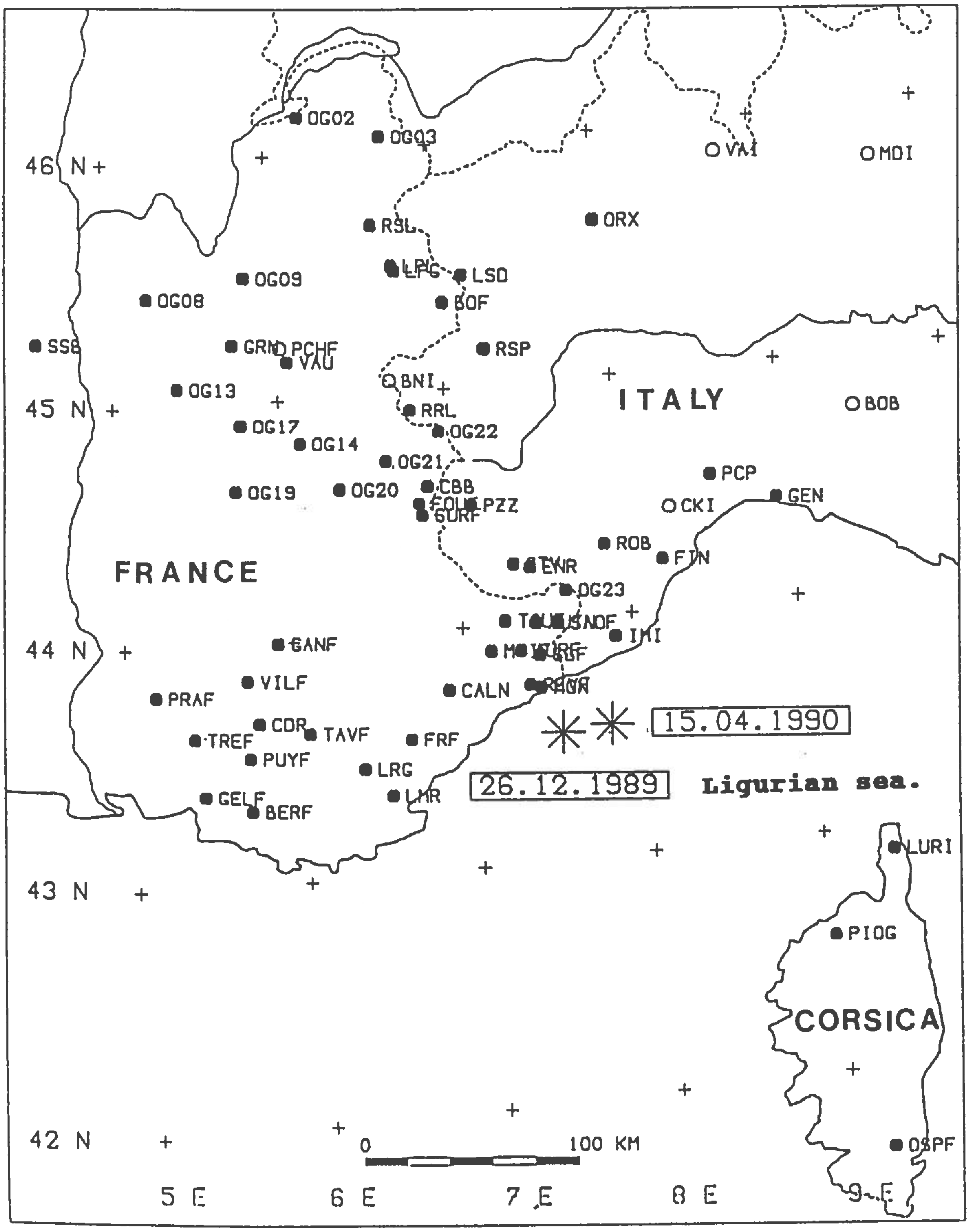

Figure 1
Seismological stations used in this study. Full symbols: digital records; open symbols: analogue records; position of the two mainshocks (this study) shown by stars.

MANTOVANI (1983), BETHOUX *et al.* (1986), or GUYOTON (1991). Results are consistent and the dispersion for the first epicenter (26 December 1989) is 2 km in latitude and 3 km in longitude. Our ultimate values for the epicentral coordinates are

$$43.54°\text{N} \pm 1 \text{ km}, \quad 7.54°\text{E} \pm 1.5 \text{ km}.$$

The focal depth is less constrained; according to the various locations, it varies between 7 and 14 km. For the second epicenter (15 April 1990), the dispersion is 6 km in latitude and 3 km in longitude. The epicentral coordinates are

$$43.58°\text{N} \pm 3 \text{ km}, \quad 7.81°\text{E} \pm 1.5 \text{ km}.$$

Again the computations only provide an estimate of focal depth (5 to 12 km).

For both events, the dispersion of the focal depth is probably to be ascribed to the large variations in the Moho depth in the coast/hinterland area (14–35 km), which was variously tackled by the various relocations. We are going to attempt a better determination of this focal parameter through the computation of synthetic seismograms. Nonetheless this waveform modeling requires the knowledge of focal mechanisms.

Focal Solutions

We computed the focal mechanisms for both mainshocks using the sense of first motion as recorded by the regional stations (up to 70 readings for the 1989 event). We used the velocity model listed in Table 1, provided by a seismic-refraction profile carried out on the very spot of the 1989 event (RECQ *et al.*, 1976). The tests we performed—using various focal depths, as well as different velocity models—show that, even if take-off angles are modified, the resulting focal solutions are rather stable. The solutions shown in Figure 2 were obtained using the FPFIT program (REASENBERG and OPPENHEIMER, 1985), which has the advantage of objectively

Table 1

Velocity model after RECQ *et al. (1974); quality factors after* BERTIL *et al. (1989)*

Thickness (km)	*P* velocity (km/s)	*S* velocity (km/s)	Specific weight (kg/m³)	*P* quality factor	*S* quality factor
1	2.60	1.53	1,800	50	50
1	3.50	2.04	2,000	200	100
1	4.50	2.60	2,600	400	200
5	6.05	3.54	2,800	700	350
12	6.50	3.80	2,900	800	400
	8.05	4.70	3,300		

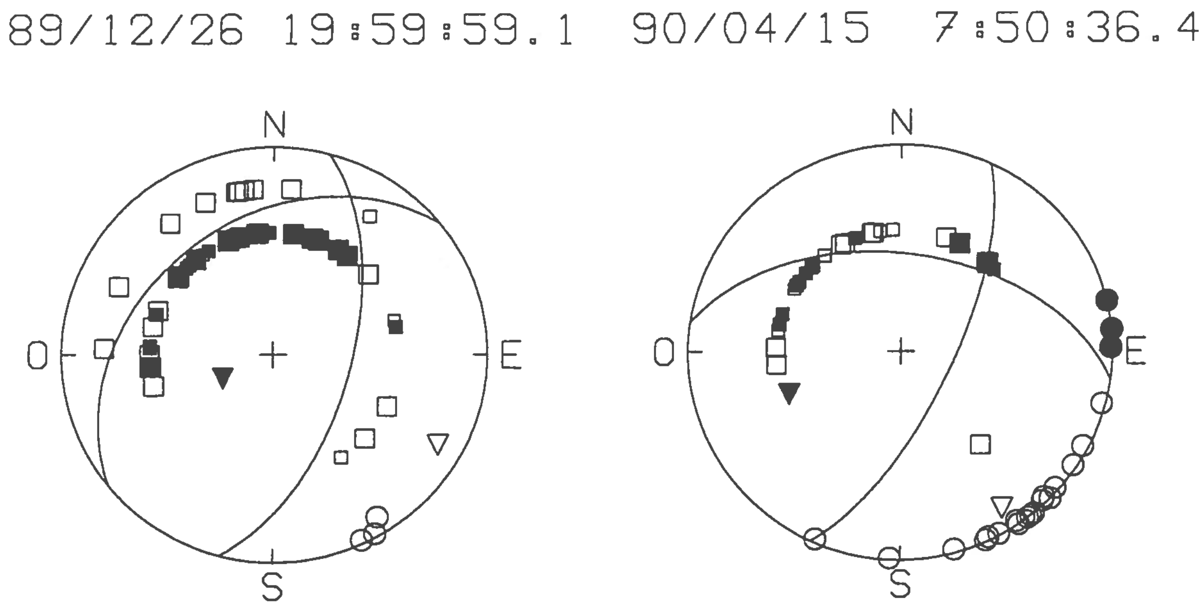

Figure 2
Focal solutions obtained for the two mainshocks. Open triangles show *P* axes; full triangles show *T* axes. Strikes and dips of the nodal planes and *P* axes: 26-December-1989 event: $P1 =$ N15/60, $P2 =$ N231/35, $P =$ N119/77; 15-April-1990 event: $P1 =$ N25/70, $P2 =$ N278/52, $P =$ N148/79.

computing the best statistical fit. For the 1989 event, we get a very well-constrained mechanism, showing almost pure compression with a *P* axis oriented N119°E. This solution is close to that found by RITZ *et al.* (1990) in a preliminary study. Because the 1990 shock was two tenths lower in magnitude and maybe also slightly shallower, first-motion readings are not so consistent for long-range stations—mainly in the NW quadrant. However, short-range stations, plotted in the SE quadrant, show that the strikes of the nodal planes (N25°E and N98°E) are well-constrained, even if their dips still have a high degree of freedom. The 1990 event clearly shows a southwards-rotated *P* axis (N148°E). Changing the dips of the nodal planes will not change this orientation significantly.

Determination of Source Depth by Waveform Modeling

By analyzing the waveforms of the seismograms and the relative amplitude of the crustal phases, it is possible to refine the determination of source and propagation parameters. The discrete-wave-number representation method (BOUCHON and AKI, 1977) computes the exact response of a stack of visco-elastic layers to any type of dislocation source. Using this method, CAMPILLO *et al.* (1984) and BERTIL *et al.* (1989) showed that the waveforms are very dependent on the focal depth.

To apply this method to the present data we used the same crustal model as discussed previously. The quality-factor model is based on results by BERTIL *et al.* (1989) in the south-western Alps. As both mainshocks have an M_L magnitude close to 4, the source time function was chosen as a smooth ramp with a rise time of 0.2 s. The focal mechanisms are depicted above. Synthetics were computed for 5 different depths (5, 7, 10, 13, and 16 km), and were compared with the data. Figure 3 shows the 1989 event as recorded at LRG station. (This station recorded an unclipped signal at an epicentral distance of 95 km because of the availability of a low-gain channel.) The best fit, as given by the cross-correlation between observed and synthetic envelopes, is obtained for a 7-km focal depth: increasing or decreasing this parameter mainly results in increasing the P-to-S amplitude ratio which is very low in the observed seismogram.

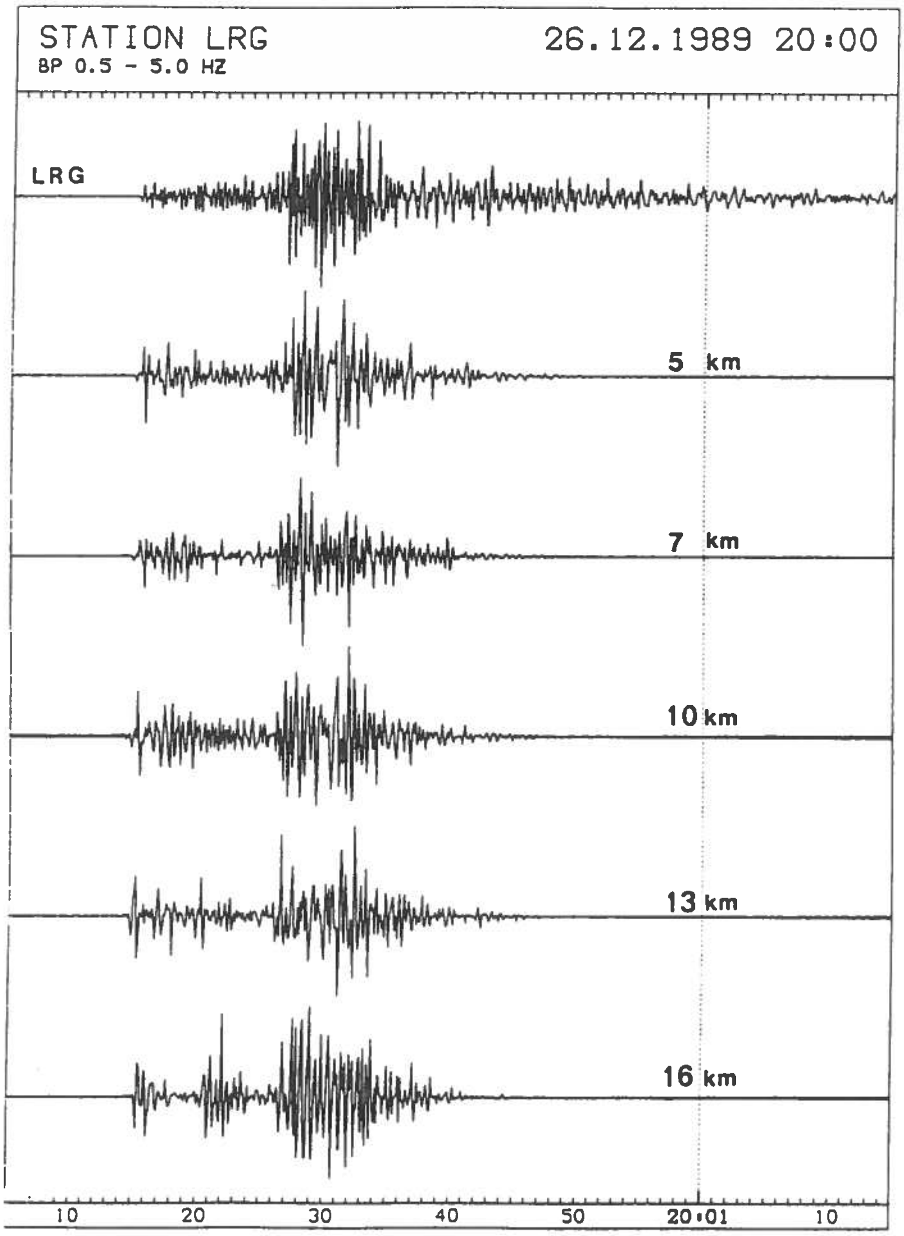

Figure 3
(Top) seismogram observed at station LRG and (below) synthetic seismograms obtained for different focal depths. The observed record is low-pass filtered with a cutoff frequency of 5 Hz to be compared with the synthetics.

Aftershock Study

Both mainshocks were followed by aftershock sequences. The 26-December-1989 event was followed by 30 aftershocks which occurred during the next 3 days. Due to very low M_L magnitudes between 2.3 and 2.9, these aftershocks were recorded by short-range stations only. Arrival times are available in at least 12 stations for ten of them. The 15-April-1990 event was followed by 9 aftershocks of very low magnitude (only one of them registered an M_L magnitude higher than 2). The following study will therefore be focused on the first crisis. Three relocation techniques, increasing in sophistication, will be shown to cluster the aftershocks in a pinpoint focal zone.

Aftershocks were first independently located using the local crustal model listed in Table 1. As already pointed out, only short-range stations along the Rivieras recorded them correctly, while no data are available from the Corsican stations. Relocating the 1989 mainshock employing the same station subset points out the key role of these Corsican stations: with no constraint in the southern azimuth and poor constraint in the west, the epicenter is shifted by 3 kilometers towards the north-northwest. We find the aftershock zone to be stretched along the same direction with a 7-km dispersion. A higher accuracy in relocations is theoretically reached if the relative positions of the aftershocks are computed versus the mainshock location. Results are displayed in Figure 4b and in Table 2. The aftershocks are considerably more clustered around the mainshock than in the previous locations. Nevertheless, the extent of the swarm remains large (4 km).

Table 2

Relative relocation of the aftershocks of the 26-December-1989 event, using the master-event location (number 0) and the crustal model listed in Table 1

Number	Date	Origin time (h:min:s)	Latitude (°N)	Longitude (°E)	Depth (km)	R.M.S. (s)
0	26.12.1989	19:59:59.19	43.540	7.540	7	
1	26.12.1989	20:36:20.00	43.534	7.532	6	.40
2	27.12.1989	03:43:37.72	43.527	7.543	7	.18
3	27.12.1989	07:33:41.94	43.518	7.542	6	.15
4	27.12.1989	09:18:19.19	43.524	7.523	8	.15
5	27.12.1989	11:28:45.14	43.547	7.535	7	.14
6	27.12.1989	14:31:44.48	43.551	7.543	9	.12
7	27.12.1989	15:02:51.99	43.541	7.537	8	.13
8	28.12.1989	02:02:07.40	43.530	7.534	6	.30
9	28.12.1989	05:02:49.29	43.550	7.522	8	.12
10	29.12.1989	10:18:02.56	43.547	7.547	7	.13

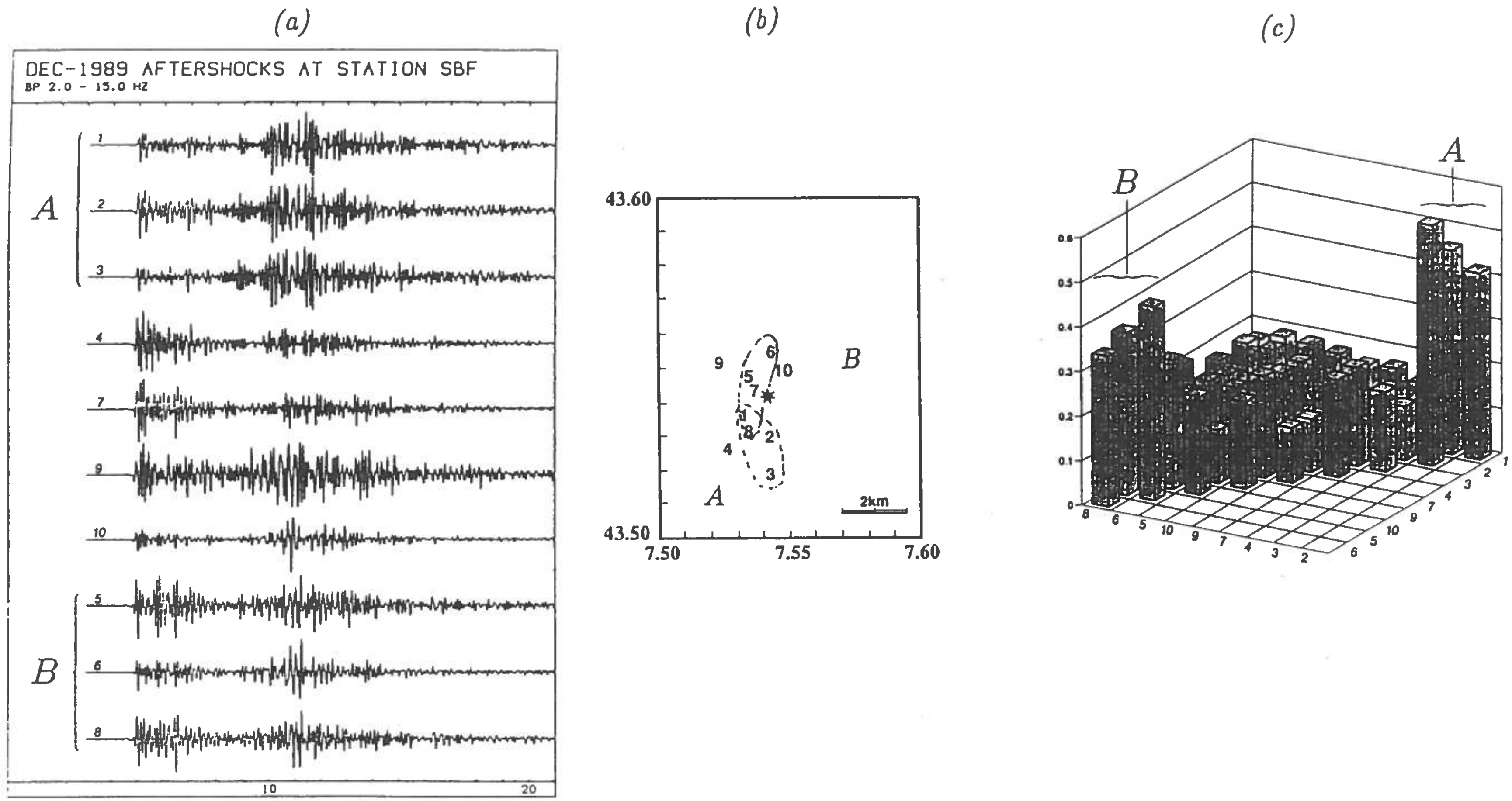

Figure 4
December-1989 aftershock study. (a) Band-pass-filtered normalized signals recorded at station SBF show that some aftershocks are very similar (class A and class B) whereas others are uncorrelated; class-A events show an energetic 2-burst *S* arrival preceded by a characteristic high-frequency phase; class-B events show a progressive *S* arrival and a 3-burst *P* arrival (better seen for event 5); to some extent event 10 could belong to class B. (b) Map of relative locations using the master-event technique (main shock shown by star): aftershock epicenters are scattered over a 3 km × 5 km area with class-A and class-B events being intermixed. (c) 3-D block diagram showing the maximum of the cross-correlation coefficients between signals shown in (a).

The visual comparison of the seismic waveforms, as recorded in the same station, allows us to distinguish several aftershock classes (Fig. 4a). The waveform variations between the aftershocks may be due to different focal mechanisms. As already stressed, these aftershocks were recorded in a dozen stations only and it is not possible to compute focal mechanisms for each of them. However, first motions may be compared in these stations for each event: a clear polarity reversal is observed for some events. If these aftershocks are clustered in different zones the cross-correlation between seismograms for events in the same swarm should allow us to obtain significant information on the relative positions of the hypocenters. We present in Figure 4c the result of the cross-correlation computed for the various records in station LMR: 2 groups of events are clearly evidenced: events 1, 2, 3, and events 5, 6, 8 (Fig. 4a).

The coherency between these signals allows us to estimate the time delays along the seismograms, following the doublet method developed by POUPINET *et al.* (1984). This kind of analysis usually provides a variation in the delay curve when S waves are encountered, with this variation being directly linked to the change in hypocentral distance. For example, in Figure 5 we observe delay variations of about 10 ms for the first doublet (events 1 and 3 recorded in station SBF) and 5 ms for the second one (events 2 and 3 recorded in station ENR). Hypocentral distance variations are therefore of the order 80 m between events 1 and 3 and 40 m between events 2 and 3. The same technique, when applied to different pairs of events and different stations, shows that changes in hypocentral distance keep to the same order of magnitude (less than 100 m). We may therefore safely conclude that aftershocks of the same class are clustered in a focal zone less than 100 m in diameter. This result provides interesting conclusions on the accuracy which can be achieved when using standard relative relocation techniques. The 3-km dispersion that was found for the class-A (events 1, 2, and 3) and class-B (events 5, 6, 8) clusters gives a good estimate of the actual accuracy, since the doublet method implies a pinpoint focal zone. An important consequence of this computation is that the aftershock zone cannot be used to distinguish which of the two nodal planes is the actual fault plane.

Ligurian Tectonics Revisited

What comes out in the seismicity map of the Ligurian Sea (Fig. 6) is the asymmetry of the seismic activity that is concentrated on the northern margin of the sphenochasm, in a roughly triangular shape. The 1989 event, off Nice, is located at the western limit of this active area. It is also in coincidence with the structural limit between the calcareous Provencal domain and the allochthonous Cretacean nappes of the south-western Alps (RECQ *et al.*, 1976; RÉHAULT, 1981). The 1990 event is located further east, off San Remo, in the area of the 1887 intensity-X earthquake

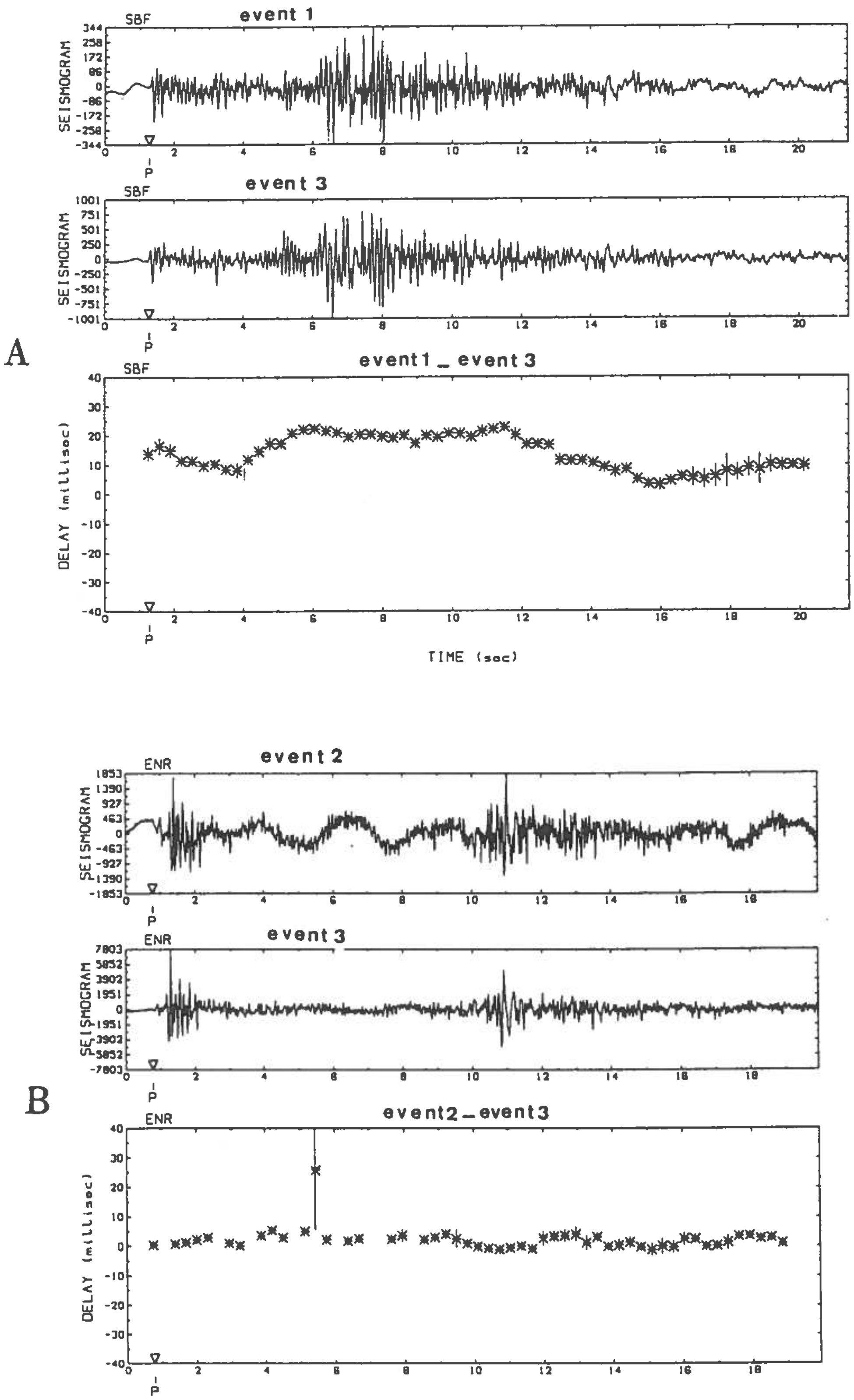

Figure 5
An example of doublet analysis for class-A aftershocks: (a) Events 1 and 3 recorded at station SBF. (b) Events 2 and 3 recorded at station ENR. Time delays are computed along the seismograms using cross-correlation techniques. Delay-variation when *S* waves are encountered provides information on changes in hypocentral distances.

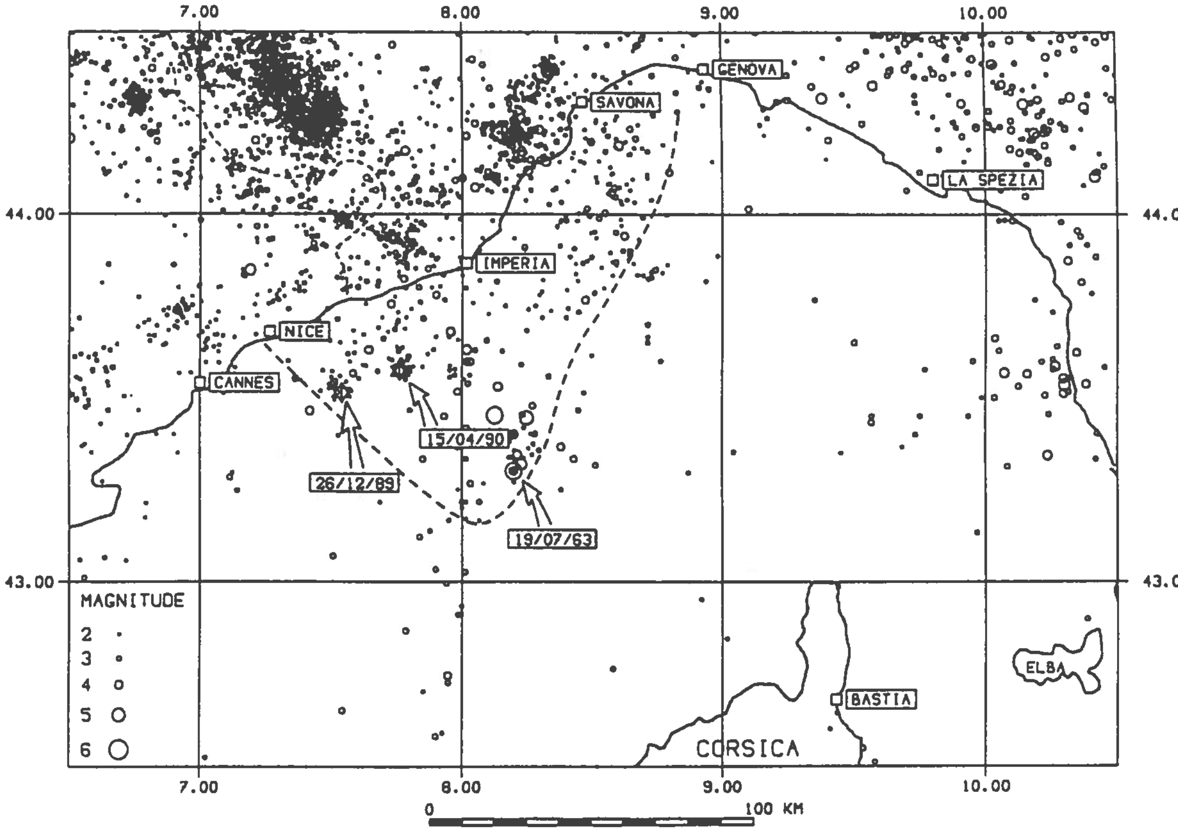

Figure 6
Instrumental seismicity (1963–1990) of the south-western Alps/Ligurian Sea area. Position of the two mainshocks (this study) shown by stars. The seismically active area is surrounded by a dashed line.

(CAPPONI *et al.*, 1980). If we also consider the location of the 1963 $m_b = 6.0$ earthquake, Figure 6 makes clear that the present activity is focused on the western part of the active area, as defined by instrumental seismicity.

Several focal mechanisms (Fig. 7a) have been computed in the area (BOSSOLASCO *et al.*, 1972; FRÉCHET, 1978; RÉHAULT and BETHOUX, 1984; HOANG *et al.*, 1987; BETHOUX *et al.*, 1988). They all spotlight the remarkable stability of the nodal plane directions: N20– –40°E or N110– –N130°E. These two directions coincide with the structural framework of the Ligurian Sea: lineations parallel to the rifting axis trending N30– –N40°E and lineations perpendicular to the basin axis, assimilated to transform faults (RÉHAULT, 1981). For the 1990 event, the nodal plane N25°E computed here is consistent with these results. For the 1989 event, N15°E and N51°E nodal planes have been evidenced: which of both is the fault plane? We already pointed out that the aftershock study does not allow us to decide which of the nodal planes is the actual rupture plane, as we could evidence no hypocenter alignment. Particularly, for the 1989 crisis, the waveform analysis supports the hypothesis of different swarms with different focal mechanisms and located on different faults. In this case, the distinction between the fault plane and the auxiliary plane must be generally based on a judicious comparison with the local geology. According to numerous authors (RECQ *et al.*, 1976; RÉHAULT, 1989; PAUTOT *et al.*, 1984; LE CANN, 1987), structural as well as salt domes directions clearly reorient themselves from a NE-SW to a N–S direction, west of the Ligurian basin, on the provencal margin. We consequently argue for a N15°E fault plane corresponding to the 1989 shock.

All focal solutions previously computed for events with magnitudes ranging from 4 to 5.9 clearly indicate compression tectonics in this region (Fig. 7a). The

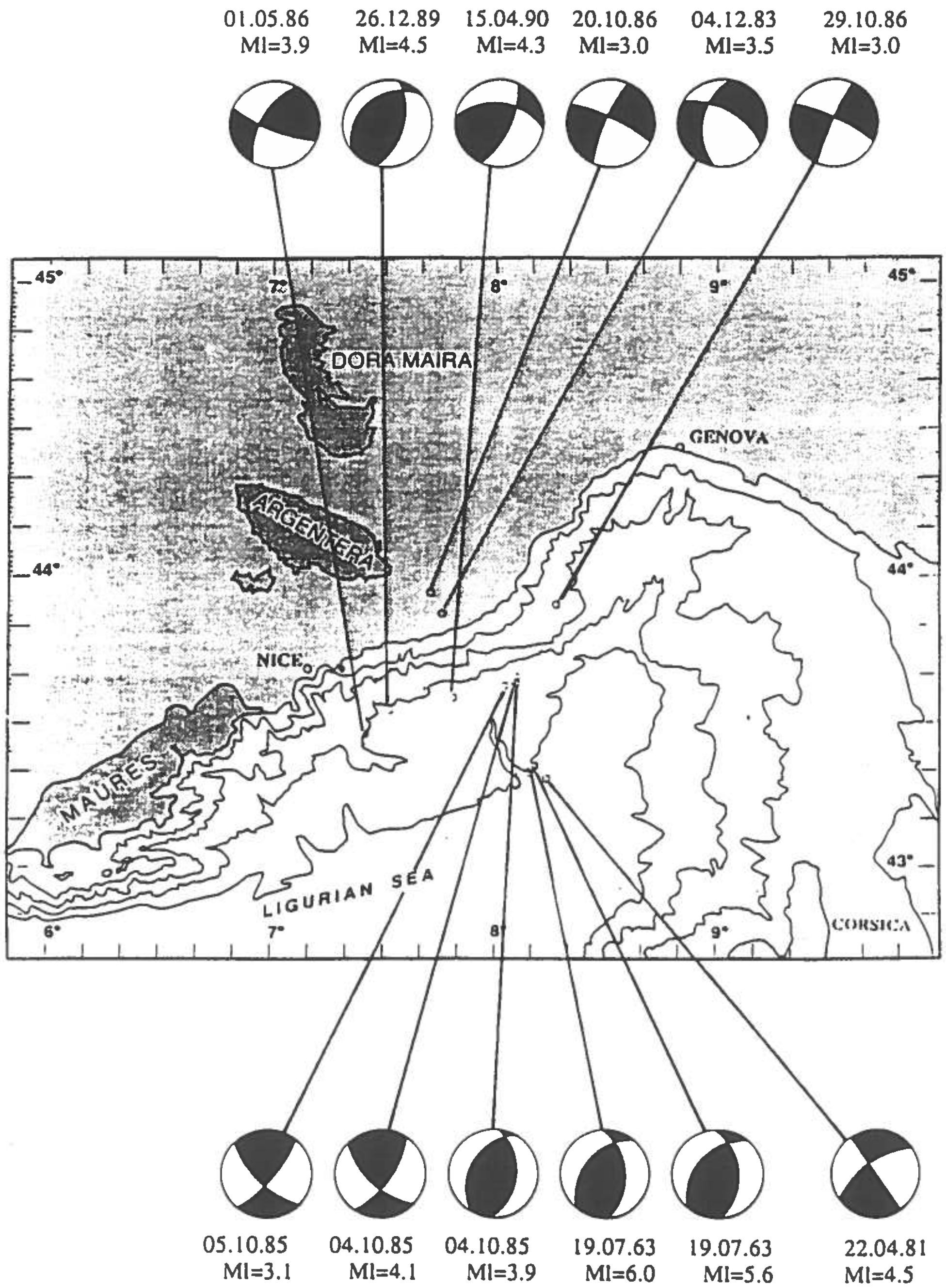

Figure 7(a)

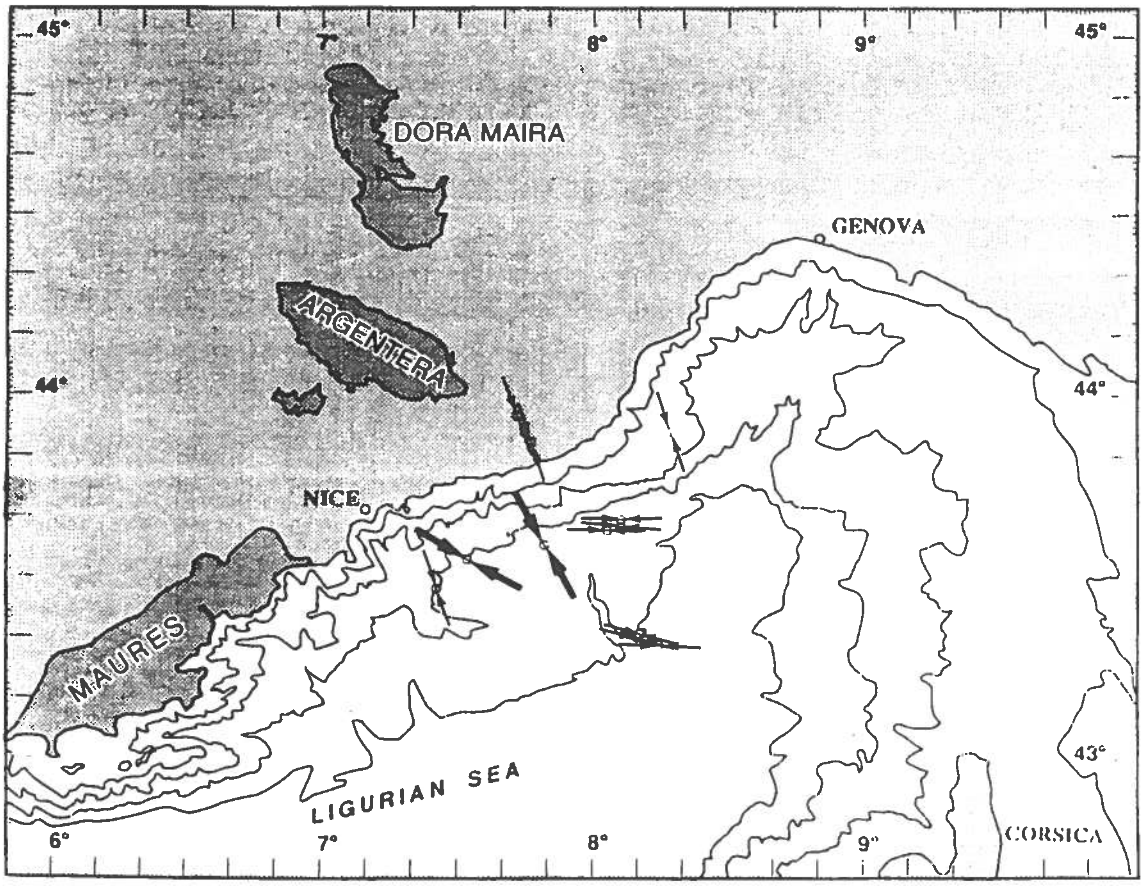

Figure 7(b)

Figure 7

(a) Focal solutions available in Ligurian Sea: data from BOSSOLASCO *et al.* (1972), RÉHAULT *et al.* (1984), HOANG *et al.* (1987), BETHOUX *et al.* (1988), and this study. (b) Corresponding *P* axes (in bold: *P* axes found in this study). Superimposed bathymetric map with contours in meters.

1989 event has a pure reverse-faulting mechanism (Fig. 2a), with a N119°E *P* axis close to the solution computed by several authors (BOSSOLASCO and EVA, 1965; MCKENZIE, 1970; FRÉCHET, 1978) for the July 1963 $m_b = 6.0$ earthquake. The 1990 event also has a compressive mechanism, but with a *P* axis rotated to N148°E (Fig. 2b). These *P*-axis directions are not consistent with neighbouring mechanisms (Fig. 7b) or the previous picture of the stress field, while the two new focal solutions clearly demonstrate this compressive trend, it does not now seem sound to assume a stress reorientation between the oceanic basin and the continental margin. The 1989 event is clearly located on the margin and corresponds to a N119°E *P* axis, whereas the May 1986 shock, which occurred close to it, corresponds to a well constrained focal solution with a N175°E *P* axis. The April 1990 solution has a N148°E *P* axis whereas the crisis of 1985, located very close to it, was characterized by a N110°E *P* axis. The smooth stress pattern proposed by RITZ *et al.* (1990), which took into account only a limited number of focal solutions in the Ligurian

Sea may thus appear oversimplified. The *P*-axis direction seems far more influenced by the reactivation of synrift fault planes trending N30°E and N110°E. They correspond to the two conjugate directions—NNE–SSW Cevenole direction and NW–SE Argentera direction (LEMOINE *et al.*, 1989; VIALON *et al.*, 1989)—which are reactivated repeatedly, as pre-existing planes of weakness. In this hypothesis a clear discrepancy may occur between the main stress direction and the *P*-axis direction as demonstrated by MCKENZIE (1969), ANGELIER (1979), ARMIJO and CISTERNAS (1978) and pointed out more precisely by CÉLÉRIER (1988).

From previous focal solutions BETHOUX *et al.* (1988) postulated that the northern margin of the Ligurian Sea is submitted to a general compressive trend which results from the tectonic setting of this area: blocked between south-western Alpine thrust zones and the Appenninic suture in the eastern gulf of Genova, the Ligurian basin is thought to be closing. In the light of Figures 6 and 7 this study allows us to make clearer this hypothesis. The E–W *P* axes could actually represent local deviations of the general N–S stress pattern (PHILIP, 1987), while the seismic activity is restricted to the northern margin of the Ligurian basin. The clearly compressive character of this activity is confirmed. It results from the lateral expulsion of the south-western Alps along the south-western sidewall of the Apulian indenter (TAPPONNIER, 1977; VIALON *et al.*, 1989). The closing of the Ligurian Sea would only be a dynamic consequence of this lateral expulsion. Therefore, it should rather be considered a half-closing, limited to part of the northern margin.

Conclusions

The improvement and gathering of the regional seismological networks has allowed a thorough study of these two seismic crises in the Ligurian Sea. The use of several networks and several location techniques has allowed us to analyze the error range for results obtained in this area and to deduce accurate hypocenter locations. The focal depth, an important parameter for any seismic-risk assessment along the French-Italian Rivieras, was discussed using synthetic seismograms. The aftershock study also revealed that the 1989 crisis had a pinpoint focal zone, and it underlined the complexity of rupture mechanisms, even for a low-magnitude crisis.

The focal mechanisms of the main events have been computed with precision and confirm the previous, less constrained, results obtained for the Ligurian Sea. A key result of this study is the re-examination of the hypothesis of the stress rotation in the area, which appears to be considerably more complicated than was previously thought. The reactivation in compression of the northern part of the Ligurian Sea is confirmed and we suggest it locally results from the lateral expulsion of the south-western Alps along the Apulian indenter.

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