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Active and recent deformation at the Southern Alps – Ligurian basin junction

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Abstract

The Southern Alps – Ligurian basin junction is one of the most active seismic areas in Western Europe countries. The topographic and the structural setting of this region is complex because of *(i)* its position between the high topography of the Southern Alps and the deep, narrow Ligurian oceanic basin, and *(ii)* the large number of structures inherited from the Alpine orogeny. Historical seismicity reveals about twenty moderate-size earthquakes (up to M=6.0), mostly distributed along the Ligurian coast and the Vésubie valley. A recent geodetic experiment shows a significant strain rate during the last 50 years in the area between the Argentera massif and the Mediterranean coastline. Results of this experiment suggest a N-S shortening of about 2-4 mm/yr over the network, this shortening direction is consistent with the seismological (P-axes of earthquakes) and the microtectonic data. The Pennic front (E-NE of the Argentera massif) and the northern Ligurian margin are the most seismically active areas. In the Nice arc and in the Argentera massif, some seismic lineaments correspond to faults identified in the field (such as the Taggia-Saorge fault or the Monaco-Sospel fault). In the western part of the Alpes Maritimes, no seismic activity is recorded in the Castellane arc. In the field, geological evidence, such as offsets of recent alluvial sediments, recent fault breccia, speleothem deformations, radon anomalies and others indicates recent deformation along these faults. Nevertheless, to this date active fault scarps have not been identified: this probably results from a relatively high erosion rate versus deformation rate and from the lack of Quaternary markers. We also suspect the presence of two hidden active faults, one in the lower Var valley (Nice city area) and the other one at the base of the Argentera crustal thrust-sheet. Offshore, along the northern Ligurian margin, the seismic reflection data shows traces of Quaternary extensional deformation, but the accuracy of the data does not yet allow the construction of a structural map nor does it allow the determination of the continuity between the offshore and onshore structures. From these data set we propose a preliminary map of 11 active faults and we discuss the questions which remain unsolved in the perspective of seismic hazard evaluations.

Keywords: Active fault, hidden fault, historical seismicity, Ligurian basin, Quaternary deformation, seismic hazard, Southern Alps

Introduction

Western European countries are presently considered as areas of low- to moderate seismicity. Nevertheless, because of the high vulnerability associated to most of these regions, some recent seismic events have involved dramatic social and material damages (*e.g.*, 600 peoples died during the 1887, M=6.4 Ligurian earthquake, *e.g.* Ferrari, 1991 and Laurenti, 1998). Furthermore, paleoseismic investigations reveal strong earthquakes in European areas of present-day moderate activity, such as the Lower Rhine Embayment (Camelbeeck et al., 2000), as well as in areas of unknown historical activity, such as the Catalan coast range (Masana et al., 2000). The present-day seismicity at the junction between the Southern French Alps and the Ligurian Basin (the so-called «Alpes Maritimes» region) is one of the most active (high number of events and magnitude up to 6.0) among the western European countries. In addition, the vulnerability is also a major concern because of the 2.500.000 inhabitants who are presently living between Cannes and Genoa and because of the numerous industries that set here.

The location, the maximum magnitude and the frequency of earthquakes are the basis of seismic hazard assessment. The parameters necessary for seismic hazard evaluations are quite difficult to estimate in areas of low deformation such as southeastern France. In spite of a well expressed seismicity, numerous problems remain that make this assessment a challenge, *e.g.: (i)* the deformation is distributed between onshore and offshore areas; and *(ii)* the lack of Quaternary deposits in onshore areas prevents the use of excavation methods, and consequently makes the determination of the reccurence intervals of earthquakes difficult.

We are currently performing an interdisciplinary study, involving instrumental seismology, geodesy, field tectonic and geomorphology (Larroque et al., 2000). The aim of this paper is first to summarize evidence of active deformation and to propose a schematic map of the active structures in this area. Afterwards, the objectives are to describe the geometry of the faults and their segmentation, and the relationships between onshore and offshore structures. From these observations and the paleoseismicity at regional scale, we attempt to better estimate the seismic hazard in the Alpes Maritmes.

Tectonic and geomorphologic setting

The studied area is located at the termination of the Southern French Alps between the high elevation crystalline massif of the Argentera and the low topographic Ligurian oceanic basin (A, Figure 1).

In the western mediterranean-alpine region, the deformations result mainly from *(i)* the convergence between the Africa and Eurasia plates since 100 My and *(ii)* the opening of the narrow Liguro-Provençal oceanic basin. The convergence between the two plates currently occurs at a rate of 6.2+/-0.5 mm/yr in a 163N+/-9° direction at the longitude of the Western Alps according to the Nuvel-1A plate motion model (DeMets et al., 1994). Although this far-field kinematic framework seems well-constrained, the kinematic of the present-day deformation within the Africa-Eurasia plate boundary in the Western Mediterranean remains poorly known because of the complex tectonic structures inherited from the 100 My alpine history and the low strain rate.

The Southern Alps– Ligurian basin junction is a highly complex geological region where three major geological units are joining: (1) the crystalline unit of the Argentera massif, (2) the sedimentary units of the southern subalpine massifs (the so-called «Castellane» and «Nice» arcs) overthrusting their foreland southward and (3) the small oceanic Ligurian basin with a steep and narrow northern margin. The Castellane and Nice arcs are a series of south-verging fold and thrusts involving the Mesozoic to Paleogene sediments, translated above a basal decollement zone in the upper triassic evaporites (Perez, 1975; Laurent, 1998; B, Figure 1). These subalpine nappes were previously the sedimentary cover of the Argentera massif. In the Southern Alps – Ligurian basin junction, the building of reliefs occured during two main steps since Oligocene time:

(1) Extensive phases, involved by a counterclockwise rotation of the Corsica-Sardinia block, leading to the opening of the Ligurian oceanic basin from 28 to 18 My (Westphal et al., 1976).

(2) Compressive phases led to the emplacement of the Argentera massif, of the Castellane and Nice arcs from 15 My (Bulard et al., 1975; Gidon & Pairis, 1992), and to the development of the molassic Valensole and Var basins.

The uplift of the Argentera massif has been recently investigated using apatite and zircon fission-track analysis of numerous samples collected throughout the massif. Several uplift events are recorded since 23 My and Bigot-Cormier et al. (2000) point out a recent uplift acceleration since 3.5 My which is certainly related to tectonic process.

The present-day large-scale geomorphology is dominated by sharp relief: only 80 kilometres separate the coastline from the summits of the Argentera massif (3000 m). Onshore, gorges with current depth up to several hundred metres incise the topography. Offshore, there is no continental shelf, the continental slope is steep (average gradient of 11%, with gradients up to 27%) and the 2200 m isobath (foot of the margin) is at only 24 kilometres from the coastline. This continental slope is cut by large and deep submarine canyons, such as the Var canyon, a system which is still very active, for sediments transit, nowadays (Klaucke et al., 2000).

The present-day seismicity: an alignement-type epicenters distribution

The Côte d'Azur and the Argentera regions were periodically shaken by earthquakes of moderate magnitude (Table 1). The Ligurian earthquake (Febuary 23, 1887), for instance, has an equivalent magnitude of 6.4 (Ferrari, 1991) and the July 19, 1963 reached

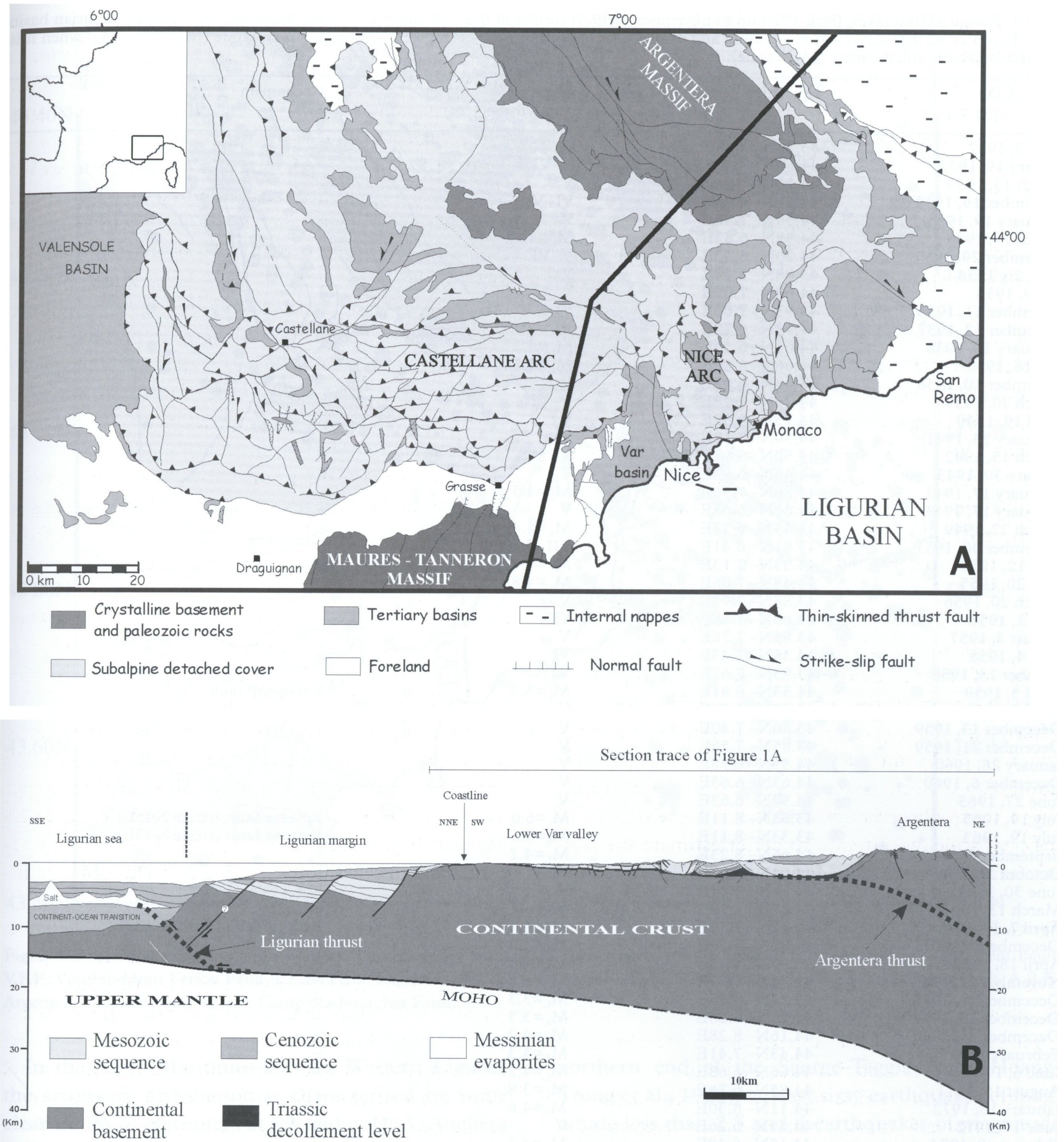

Fig. 1. (A) Structural map and (B) crustal-scale cross-section of the Southern Alps– Ligurian basin junction (modified from Laurent, 1998).

the magnitude 6.0 (Bossolasco & Eva, 1965). The last noticable earthquake (M_L=4.7) occured on April 21, 1995 (Courboulex et al., 1998). Finally, between 1920 and 2000, at least 76 events in the magnitude range 4.0-6.0 or intensity V and more (MCS scale) have occurred in this area.

The Southwestern Alps are densely covered by permanent seismological networks [ReNaSS (Réseau National de Surveillance Sismique), TGRS (Très Grande Résolution Sismique), RAP (Réseau Accélérométrique Permanent) and LDG (Laboratoire de Détection Géophysique)]. The maximum X-Y error on the location of epicenters is around 2.5 kilometres (Nicolas et al., 1998). The seismological data collected for the last 30 years attest that earthquakes are not uniformly distributed in our area of interest (Béthoux et al., 1998). Most of the seismicity is concentrated along the northeastern side of the Argentera massif following the Pennic front and along the northern margin of the Ligurian basin (Figure 2), where the largest instrumental earthquakes have occurred (1963, M_b=6.0; 1989, M_L=4.5; 1995, M_L=4.7).

Table 1. Recent earthquakes, from 1920 up to november 1999, recorded at the junction between the Southern Alps and the Ligurian basin (from Levret et al., 1996; Nicolas et al., 1998 and TGRS data base). For each event, we point out the magnitude (M_L, M_b or M_w) when it is available otherwise the intensity (MCS scale).

Date (A.D.)	Epicenter	Magnitude or intensity	Mechanism
April 5, 1922	43.78N - 6.50E	V	–
January 19, 1932	44.66N - 6.78E	V–VI	–
March 13, 1933	44.20N - 5.95E	V	–
September 19, 1933	44.41N- 6.46E	VI–VII	–
February 19, 1935	44.30N- 7.40E	V	–
March 19, 1935	44.58N- 6.63E	M_L=4.9	–
September 29, 1935	44.20N- 6.40E	V–VI	–
April 26, 1936	43.88N- 7.45E	V	–
July 9, 1936	44.53N- 7.05E	V	–
December 11, 1936	43.93N- 7.66E	VI	–
December 12, 1937	44.93N- 6.72E	VI	–
February 15, 1938	44.61N- 6.55E	M_L=4.2	–
July 18, 1938	44.66N- 6.60E	M_L=5.1	–
December 10, 1938	44.43N- 6.43E	V	–
March 20, 1939	44.75N- 7.28E	V–VI	–
April 19, 1940	44.75N- 6.58E	V	–
February 23, 1941	44.50N- 7.10E	V	–
March 15, 1942	44.52N -6.66^E	V	–
January 30, 1943	44.46N- 6.83E	V	–
February 17, 1947	44.86N- 7.30E	M_L=4.5	–
February 17, 1949	44.31N- 6.68E	V	–
March 22, 1949	44.45N- 6.37E	M_L=4.4	–
November 30, 1951	43.81N- 6.41E	VII–VIII	–
May 12, 1955	44.53N- 7.13E	M_L=4.7	–
June 20, 1955	44.48N- 7.06E	M_L=4.8	–
March 20, 1956	43.88N- 7.95E	V	–
June 1, 1956	44.68N- 7.18E	VI	–
August 3, 1957	43.83N- 7.76E	V	–
May 4, 1958	44.38N- 7.43E	VI	–
October 13, 1958	43.93N- 7.67E	V	–
April 5, 1959	44.53N- 6.81E	M_L=5.3	Strike-slip fault
July 17, 1959	44.53N- 6.71E	V	–
December 13, 1959	43.80N- 7.40E	V	–
December 21, 1959	43.85N- 7.55E	V	–
January 28, 1960	44.55N- 6.73E	V	–
December 6, 1960	44.63N- 6.63E	V	–
June 27, 1963	44.90N- 6.63E	V	–
July 19, 1963	43.33N- 8.11E	M_b=6.0	Reverse fault (strike N45E)
July 19, 1963	43.33N- 8.11E	M_b=5.6	Reverse fault (strike N45E)
September 5, 1963	44.65N- 8.23E	M_L=4.2	–
October 22, 1963	44.05N- 6.07E	V	–
June 30, 1964	44.71N- 7.31E	V	–
March 13, 1965	44.07N- 7.18E	M_L=3.7	–
April 7, 1966	44.12N- 7.39E	M_L=4.4	Reverse fault (strike N120E)
December 6, 1967	44.00N- 7.23E	M_L=3.2	–
April 18, 1968	43.95N- 8.13E	M_L=4.5	–
November 22, 1969	44.38N- 6.63E	M_L=3.6	–
December 29, 1970	44.23N- 8.25E	M_L=3.3	–
December 30, 1970	44.20N- 8.28E	M_L=3.5	–
December 31, 1970	44.16N- 8.28E	M_L=4.2	–
February 1, 1971	44.43N- 7.41E	M_L=4.3	–
June 6, 1971	44.66N- 6.68E	M_L=4.2	–
August 15, 1971	44.85N- 6.76E	M_L=3.8	–
January 18, 1972	44.11N- 8.30E	M_L=4.6	–
June 19, 1972	44.41N- 6.26E	V	–
February 8, 1974	44.15N- 6.48E	M_L=4.3	–
August 7, 1974	44.43N- 6.38E	M_L=3.1	–
February 6, 1977	44.49N- 7.34E	M_L=4.0	Reverse fault (strike N110E)
March 3, 1977	44.69N- 6.69E	M_L=4.0	Normal fault (strike N160E)
January 5, 1980	44.98N- 7.47E	M_L=5.3	–
October 10, 1980	44.45N- 7.15E	M_L=4.3	–
April 22, 1981	43.31N- 8.23E	M_L=4,5	Strike-slip fault
March 20, 1983	44.34N- 6.48E	M_L=4.1	–
June 19, 1984	44.05N- 6.15E	M_L=4.3	–
June 30, 1984	44.05N- 6.13E	M_L=4.1	–
October 4, 1985	43.63N- 8.09E	M_L=4,1	Reverse fault (strike N35E)
May 1, 1986	43.43N- 7.45E	M_L=3.9	Left-lateral fault (strike N150E)
December 26, 1989	43.54N- 7.54E	M_L=4,5	Reverse fault (strike N50E)
April 15, 1990	43.58N- 7.81E	M_L=4,3	Strike slip fault
April 21, 1995	43.46N- 7.34E	M_L=4,7	Dextral reverse fault (strike N100E)
February 24, 1997	43.70N- 8.50E	M_L=4.1	–
June 26,1997	43.90N- 7.20E	M_L=3,8	–
October 10, 1997	42.20N- 6.60E	M_L=4.5	–
November 11, 1997	44.10N- 7.90E	M_L=4.0	–
July 7, 1999	44.64N- 6.81E	M_L=3.9	–
November 1, 1999	43.80N- 7.30E	M_w=3,4	Left-lateral fault (strike N45E)

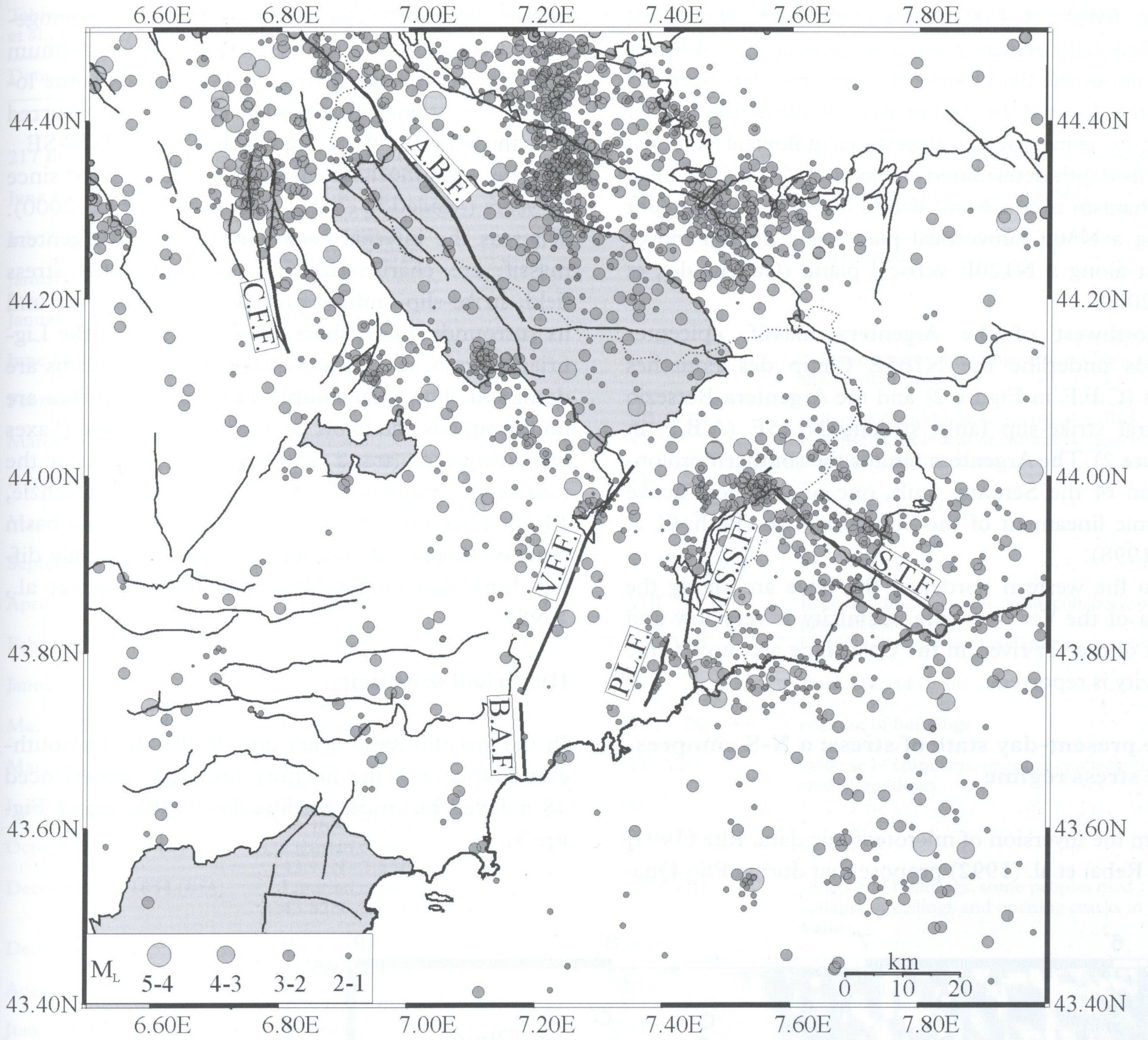

Fig. 2. Instrumental seismicity from 1980 to 1999 (modified from BCSF) and major onshore faults, B.A.F.: Saint Blaise-Aspremont Fault, V.F.F.: Vésubie-Mont Férion Fault, P.L.F.: Peille-Laghet Fault, M.S.S.F.: Monaco-Sospel-Saorge Fault, S.T.F.: Saorge-Taggia Fault, A.B.F.: Argentera-Bersezio Fault, C.F.F.: Camp des Fourches Fault.

In the Alpes Maritimes and the Western Liguria, the seismicity distribution is characterized by some clear trends of epicenters at sea and onland (Augliera et al, 1994). In some places, there is a correlation between the seismic lineaments and some of the faults that have been recognized in the field. Particularly, we observe:

An alignement of epicenters which corresponds to the dextral strike-slip fault which runs between Saorge and Taggia (S.T.F. in Figure 2) and the parallel faults, trending N120E (Hoang-Trong et al., 1987; Augliera et al, 1994; Eva et al., 2000). This fault system was recently the location of some small earthquakes (Béthoux et al., 1992), *e.g.* December 4, 1983 (M_L=3.5) and October 20, 1986 (M_L=3.0). During the last quarter of 1983, a seismic swarm occured along the valley of the middle Roya river, at the northern end of the Saorge-Taggia fault (Hoang-Trong et al., 1983): at least sixty earthquakes of magnitude less than 2.5 and 4 earthquakes of magnitude around 3 have been recorded. The multiple event mechanism and the N110E linear trend of the swarm indicate a major role of the Saorge-Taggia fault during this seismic swarm.

The conjugate direction N30E is recognized in the field as the Monaco-Sospel-Saorge (M.S.S.F. in Figure 2). In the northeastern prolongation of this fault, we observe an alignement of epicenters along the N30E direction which allow to propose the continuation of the Monaco-Sospel-Saorge fault at depth in the N-E direction until several tens of kilometres.

Thirty kilometres east of Nice, a segment of the N20E left-lateral Peille-Laghet fault (P.L.F. in Figure 2) probably produced the November, 1st 1999 earthquake (M_W=3.4, Courboulex et al., 2000). This fault displays field evidence of recent activity (see the section about the field data). The epicenter has been accurately located 1+/–2 km west of the Peille-Laghet fault by using the 20 closest seismological stations, and its depth determined around 2+/–3 km. The focal mechanism is consistent with a left-lateral movement along a N30E subvertical plane or a dextral movement along a N120E vertical plane (Courboulex et al., 2000).

Northwest of the Argentera massif, epicenter trends underline the N165E Camp des Fourches fault (C.F.F. in Figure 2) and the Argentera-Bersezio dextral strike-slip fault, striking N145E (A.B.F. in Figure 2). The Argentera fault is the southern prolongation of the Sérenne fault, one of the most active seismic lineament of the Southern Alps (Béthoux et al., 1998).

To the western border of the Nice arc, along the delta of the Var river, the seismicity is very low and west of the Var river, in the Castellane arc, no seismic activity is reported.

The present-day state of stress: a N-S compressive stress regime

From the inversion of microtectonic data, Ritz (1992) and Rebaï et al. (1992) propose that during Plio-Quaternary time, the regional stress field was homogenous, with a roughly N-S direction of the maximum principal compressive stress (σ_1). However, some local perturbations of this main stress field occurred near the major faults, along which σ_1 trends NW-SE.

Many focal mechanisms have been computed since 30 years (Madeddu et al., 1996; Baroux et al., 2000). Whereas the internal zones, north of the Argentera massif, are characterized by an extensional stress field, strike-slip faulting prevails at the Nice arc and its surroundings. Offshore, along the foot of the Ligurian margin, reverse and strike-slip mechanisms are dominant. The focal solutions of the earthquakes are homogeneous and allow us to propose that the *P*-axes of earthquakes (trend NW-SE to N-S) are near the maximum compressive stress direction (McKenzie, 1969). Therefore, the Southern Alps– Ligurian basin junction displays a state of stress which strongly differs from that of the Alpine chain (Béthoux et al., 1998).

Historical seismicity

In the last thousand years until 1920, the far southeast France and the northwestern Italy experienced 58 indexed historical earthquakes (Table 2 and Figure 3).

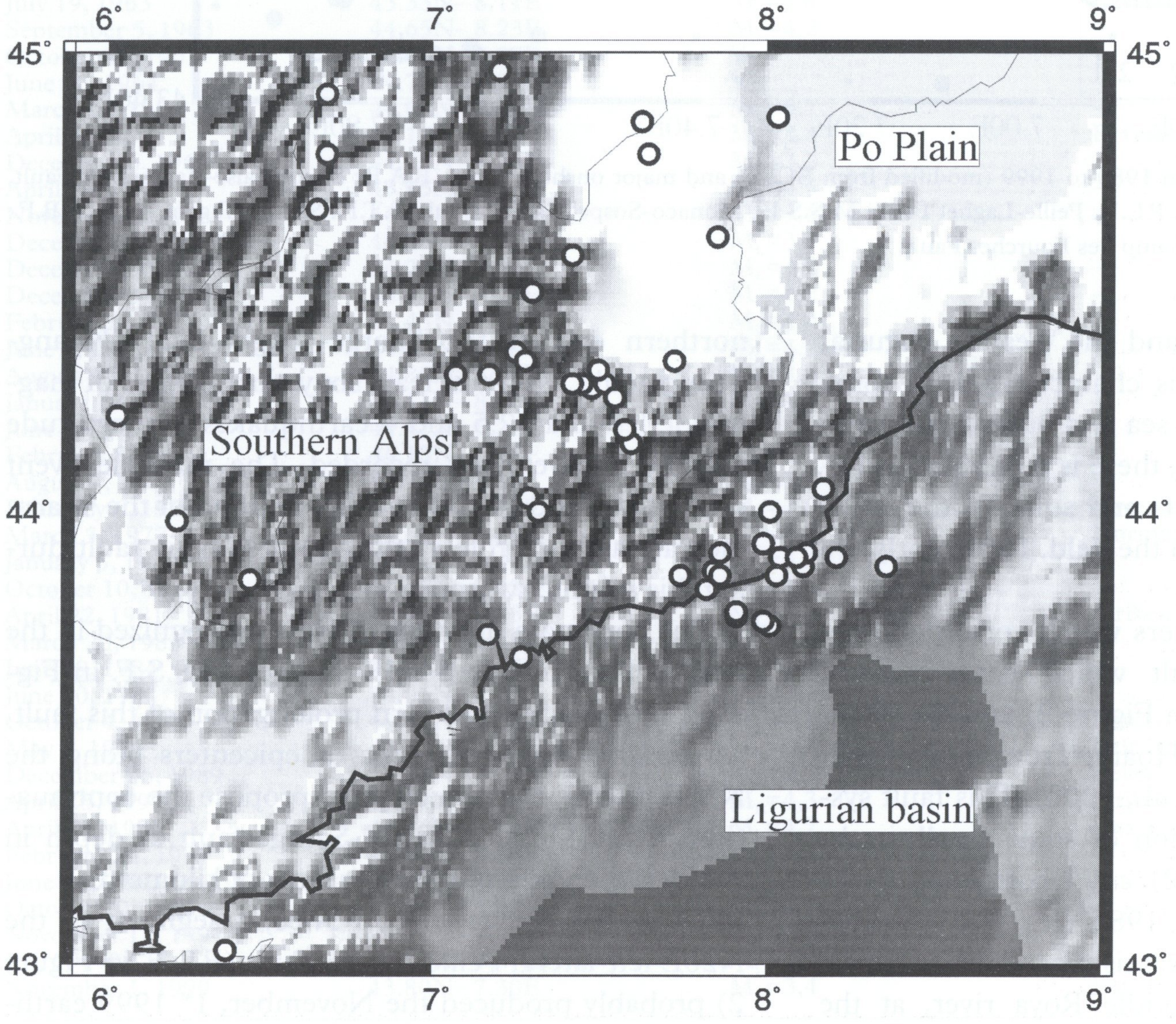

Fig. 3. Historical seismicity: white dots are macroseismic locations of epicenters for the events with an intensity higher than V (see Table 2 for data).

Table 2. Some characteristics of historical earthquakes until 1920. Data are from Boschi et al., 1995 (*); Lambert & Levret, 1996 (#); Boschi et al., 1997 (€) and Laurenti, 1998 (§).

Date	Location	Intensity	Effects
322 BC (*€)	Western Liguria 44.00N- 8.00E	–	–
217 BC (*€)	Western Liguria 44.00N- 8.00E	–	destruction of numerous cities, collapse of mountain, offsets of river
June 13, 1494 (*#€§)	Vésubie valley 43.68N- 7.25E	VI	collapse of buildings, panic in Nice
July 20, 1564 (*#€§)	Roquebilière 44.03N- 7.27E	IX - X	destruction of Roquebilière, more than 300 peoples died
January 31, 1612 (#)	Liguria	VI - VII	–
June 30, 1612 (§)	Near Nice	–	–
January 18, 1618 (#)	Vésubie valley 43.88N- 7.28E	VIII	–
June 14-16, 1618 (§)	Near Nice	–	collapse of some buildings around Nice and in the Vésubie valley
February 15, 1644 (*#€§)	Vésubie valley 44.00N- 7.30E	VII - VIII	collapse of buildings, some peoples died
March 9, 1753 (#€)	Piedmont 44.93N- 7.18E	VII	collapse of roofs and of chimneys, destruction of military fortifications
December 31, 1773 (#)	Queyras 44.66N- 6.63E	VI	–
March 31, 1806 (#)	Liguria 44.85N- 7.61E	V - VI	–
September 5, 1807 (#)	Liguria 44.78N- 7.63E	V - VI	–
April 2, 1808 (*#€)	Pellice valley 44.83N- 7.27E	VIII	large building damages, some collapse, some peoples died
February 23, 1818 (#€§)	Ligurian coast 43.82N- 7.65E	VII - VIII	building damages and collapse
January 8, 1819 (#€)	Ligurian coast 44.05N- 8.20E	VI	small cracks in wall
May 26, 1831 (*#€§)	Ligurian coast 43.85N- 7.85E	VIII - IX	collapse of buildings
March 23, 1835 (€)	Liguria 44.33N - 7.55E	VI - VII	collapse of chimneys, opening cracks in the wall of buildings
June 17, 1849 (#)	Piedmont 44.18N- 7.56E	V	–
October 13, 1851 (#)	Ligurian coast 43.91N- 7.85E	V	–
December 29, 1854 (#€§)	Ligurian coast 43.82N- 7.55E	VII - VIII	collapse of buildings, some peoples died collapse of ceilings and opening cracks in the walls
December 12, 1855 (#)	Verdon 43.85N- 6.43E	VIII	–
August 30, 1858 (#€)	Piemont 44.32N- 7.33E	VI	collapse of roofs
June 9, 1863 (#)	Barrème 43.98N- 6.21E	VII	–
May 19, 1866 (#)	La Motte du Caire 44.21N- 6.03E	VII - VIII	large building damages
January 22, 1878 (#)	Piedmont 44.60N- 7.48E	V - VI	–
June 7, 1878 (#)	Piedmont 44.48N- 7.28E	VII	–
November 27, 1884 (#€)	Queyras 44.78N- 6.66E	VII	opening cracks, collapse of chimneys, collapse of small buildings
July 1, 1885 (#)	Piedmont 44.25N- 7.53E	V - VI	–
February 23, 1887 (*#€§)	Ligurian coast 43.88N- 8.00E	X	collapse of mountain, destruction of numerous cities along the Riviera, tsunami waves, more than 600 peoples died
August 18, 1888 (#)	Ligurian coast 43.90N- 8.08E	V	–
September 16, 1890 (#)	Ligurian coast 43.86N- 8.02E	V	–
May 8, 1892 (#)	Taggia 43.78N- 7.90E	V	–
November 26, 1892 (#)	Limone Piemonte 44.27N- 7.46E	V	–
November 27, 1892 (#)	Limone Piemonte 44.28N- 7.50E	V	–
January 2, 1893(#)	Piedmont 44.30N- 7.15E	V - VI	–
April 6, 1894 (#)	Piedmont 44.28N- 7.43E	V	–
July 19, 1894 (#)	Taggia 43.83N- 7.81E	V	–
February 3, 1895 (#)	Liguria 43.90N- 8.20E	V	–

Table 2. Contineous.

Date	Location	Intensity	Effects
March 18, 1895 (#)	Piedmont 44.28N - 7.40E	V	–
December 25, 1895 (#)	Liguria 43.88N - 8.35E	V	–
October 16, 1896 (#)	Liguria 43.76N - 7.98E	VII	–
October 12, 1897	Imperia 43.93N - 7.98E	V	–
December 26, 1899 (#)	Cuneo 44.34N - 7.24E	V	–
April 5, 1900 (#)	Cuneo 44.56N - 7.40E	V	–
May 1900, 10 (#)	Cuneo 44.30N - 7.05E	V - VI	–
April 20, 1901 (#)	Cuneo 44.31N - 7.48E	VI	–
April 4, 1903 (#)	Liguria 43.88N- 8.10E	V - VI	–
July 12, 1904 (#€)	Briançon 44.93N- 6.85E	VII	opening craks in the wall of military buildings, collapse of chimneys
November 15, 1904 (#)	Taggia 43.86N- 7.73E	V	–
May 30, 1905 (#)	Piemont 44.33N- 7.71E	VI	–
August 11, 1906 (#)	Taggia 43.86N - 7.85E	VI	small building damages, felt by numerous people
May 27, 1909 (#)	Liguria 43.91N - 8.11E	VI	felt by numerous people
October 5, 1909 (#)	Piemont 44.73N - 7.15E	V	–
September 27, 1911 (#)	Barrême 44.03N - 6.36E	V V	– –
July 24, 1913 (#)	Piedmont 44.35N- 7.23E		
May 1, 1917 (#)	Liguria 44.05N- 8.16E	V	–
November 28, 1919 (#)	Piedmont 44.15N- 7.58E	V - VI	–

At least two of these earthquakes caused serious regional casualities: the Roquebilière earthquake (1564) and the Ligurian earthquake (1887), that reached an intensity of X MCS (Boschi et al., 1995; Lambert & Levret, 1996; Boschi et al., 1997; Laurenti, 1998; Working Group CPTI, 1999). The Ligurian earthquake produced tsunami waves observed along 250 km of the Ligurian coast from Genoa to Cannes, with run-up heights around 1-2 m (Eva & Rabinovitch, 1997).

The location of these historical epicenters is not accurate enough for them to be attributed to known active faults. Nevertheless, the Argentera-Bersezio fault is proposed to be the locus of the July 18, 1938 and for the April 5, 1959 earthquakes (Ghafiri, 1995). The historical data show that three regions encompass more than half of the events registered: the Vésubie valley, the Ligurian coast and the Piedmont. The Vésubie-Mt Férion fault (V.F.F. in Figure 2) may have been the location of the 5 earthquakes that strongly shook this valley. But most events felt along the Ligurian coast have offshore epicenters and are therefore related to unidentified faults. The historical data set also indicates that no earthquakes have been reported west of the Var river, in the Castellane arc.

Geodetic measurements: a N-S shortening about 2-4 mm/yr

Because of low expected strain rates, close to the accuracy of the geodetic techniques, direct measurements of crustal strain in the southern French Alps are challenging and must use strategies specifically designed for detecting very low tectonic signals. One possibility is to use old triangulation (or trilateration) measurements. A GPS field experiment has been performed in 1998: we combined first- and second-order triangulation data, collected in 1948 by the French «Institut Géographique National», with GPS data collected at 14 of these IGN sites. The network covers the southern part of the Argentera massif, the Castellane arc, down to the mediterranean coastline (Figure 4).

From the combination of the GPS and triangulation data, Calais et al. (2000) obtained the direction of the maximum compressive principal strain rate (geodetic unit of deformation), that correspond to «*P*-axis» in the seismological nomenclature.

The results show that a deformation significantly different from zero affected most of the network during a period of 50 years. The maximum compressive

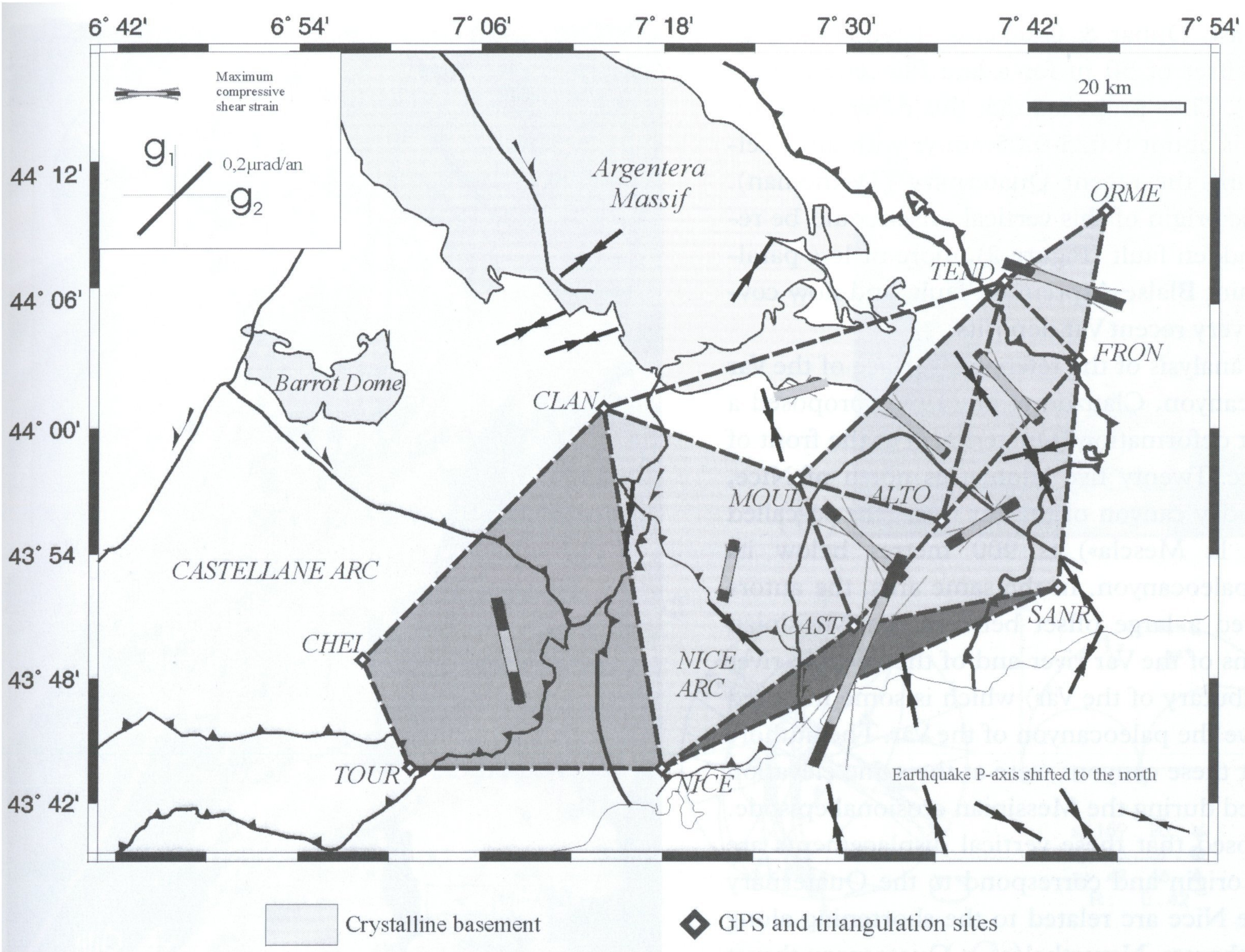

Fig. 4. Geodetic deformation map over 50 years showing the final shear strain rate solution obtained from the combination of triangulation and GPS data. The spatial distribution of the shear strain rate displays 3 domains with homogeneous behaviour. (1) N-S compression in the western half of the network (grey area), (2) NE-SW compression in the southern part (strong grey area) and (3) NW-SE compression in the remaining part of the network (ligth grey area). The black arrows show P-axis of earthquakes (modified from Calais et al., 2000).

shear strain rate is in the order of 0.1-0.2 µrad/yr over distance in the order of 30 km. The spatial distribution of the shear strain rate displays 3 domains with homogeneous behaviour: N-S compression in the western half of the network, NE-SW compression in the southern part and NW-SE compression in the remaining of the network (Figure 4). The NE-SW direction obtained in the coastal area is considered as an artefact related to the very elongated shape of this triangle (Calais et al., 2000). The N-S to NW-SE compression is in agreement with the seismological (*P*-axes strikes of earthquakes) and the microtectonic data that both are consistent with a N-S to NW-SE compressive strain and stress in the Southern Alps during the Quaternary. Assuming a rate of 0.1-0.2 µrad/yr, the N-S shortening over the whole network is in the order of 2-4 mm/yr (Calais et al., 2000).

Field evidence of active and recent deformation

Evidence of active and recent deformation has been reported in the Alpes Maritimes:
Marine Pliocene sediments that disconformably overlie the western edge of the Nice arc along the left bank of the Var river have been locally folded and faulted (including the Nice city area itself). Thirty kilometres north of Nice, remnants of these sediments have been uplifted as high as 1100 m (Irr, 1984; Clauzon et al., 1996; Fauquette et al., 1999). Pliocene and Quaternary sediments have been clearly more uplifted and deformed on the eastern side of the Var river than on the western side (Dubar & Perez, 1989; Schroetter, 1998). These differential movements, from both sides of the lower Var valley, are probably related to the recent thin-skin southward thrusting of the Nice arc and more accurately to the recent activity of the so-called 'Vésubie-Mont Férion' (V.F.F. in Figure 2) and 'Saint Blaise-Aspremont' (B.A.F. in Figure 2) fault system. Furthermore, this inherited N-S fault zone show radon anomalies interpreted by Borchielini et al. (1991) as an evidence for tectonic activity.

On both side of the Var river mouth, the identification and the datation of late Pliocene and Quaternary terraces allow to quantify the relative differential uplift between the eastern and western sides of the river near the coast. Dubar & Gugliemi (1996) found an altitudinal offset of 50 m for a late Pliocene terrace (2-1.67 My). They proposed that this differential uplift velocity is about 0.025-0.05mm/yr with an acceleration during the recent Quaternary (Tyrrhenian). The tectonic origin of this vertical offset could be related to a hidden fault (Figure 2), more or less parallel to the Saint Blaise-Aspremont fault, and now covered by the very recent Var deposits.

From an analysis of the reference surface of the Var Messinian canyon, Clauzon et al. (1996) proposed a more recent deformation (Quaternary) at the front of the Nice arc. Twenty five kilometres north of Nice, the present-day canyon of the Var river (the so-called «gorges de la Mescla») is 900 metres below its Messinian paleocanyon. In the same area, the autors also observed a large offset between the Messinian paleocanyons of the Var river and of the Vésubie river (a major tributary of the Var) which is some hundred metres above the paleocanyon of the Var. The authors assume that these canyons were at the same elevation when formed during the Messinian erosional episode. They proposed that these vertical displacements are of tectonic origin and correspond to the Quaternary uplift of the Nice arc related to the shortening along the frontal thrusts. Nevertheless, a Quaternary thrust at the southwestern boundary of the Nice arc has not yet been identified.

The endokarst, where vegetation is absent and erosion is reduced, is a very well protective place to observe and measure tiny movements (Gilli, 1981). In the grotte of 'Les Deux Gourdes', near the Vésubie-Mont Férion fault (V.F.F. in Figure 2), Gilli (1986) observed a Holocene concretioning on the fault plane: stalactites, stalagmites and flowstones. Lengthwise fractured pillar, displaced stalactite/stalagmite and folding of the stalagmitic flowstones are interpreted as the result of at least 2 episodes of movement along the fault plane with a total amplitude of 10 cm (Figure 5). In the Castellane arc, Gilli & Delange (1999) found evidence for very recent (some tens of thousand years ?) southward thrusting from offsets in speleothems built in karstic galleries along the north-dipping frontal thrust. Similar evidence is observed along the Calern thrust (north of Grasse, Figure 1) where a study is in progress using a micrometric sensor in order to quantify the assumed present-day displacement.

Plio-Pleistocene sediments have been deformed along the left-lateral N20E Peille-Laghet fault (P.L.F. in Figure 2): a network of striated fault planes cross-cut Plio-Quaternary breccia with N-S to NE-SW directions (Figure 6).

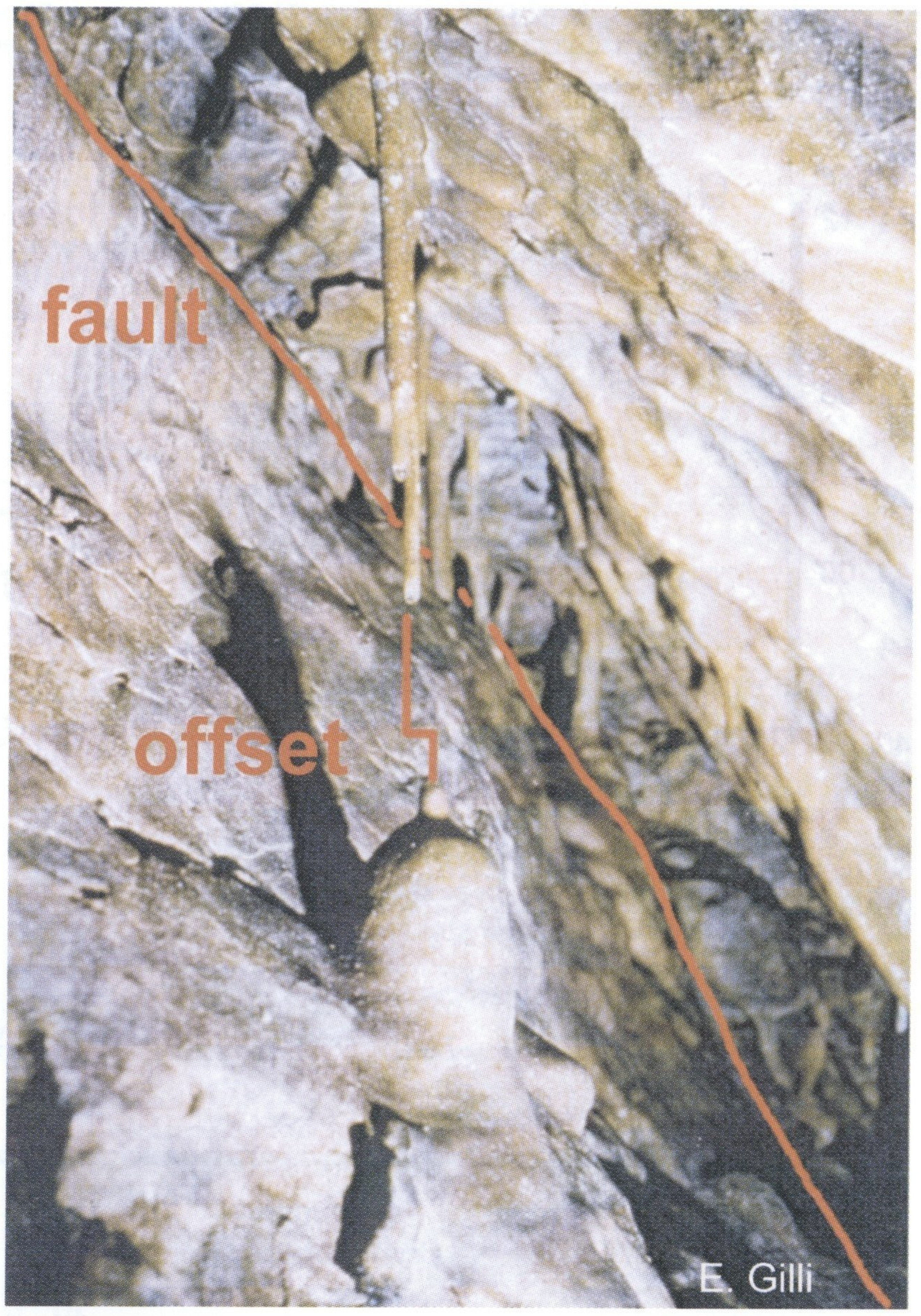

Fig. 5. Stalactite/stalagmite offset on a fault plane neighbouring the Vésubie-Mont Férion fault. This fault plane recently suffered a dextral strike-slip movement of some centimetres that could be of seismic origin (photo E. Gilli).

The inversion of the microtectonic data leads to a principal compressive stress axis trending N160E for the Plio-Quaternary times (Rebaï, 1988 and Ritz, 1991). The focal mechanism of the November 1st, 1999 earthquake is consistent with the microtectonic data and could suggest a steady-state tectonic regime since several million years with a stress field that probably did not change significantly during this period.

The rectilinear and narrow seismogenic lineament striking N120E between Saorge, on the Roya river, and Taggia, on the Ligurian coast, is probably one of the most spectacular feature in this region (S.T.F in Figure 2). The trace of the fault is obvious at the regional scale (on topographic maps and spot satellite images) through the Ligurian flysch unit. However, in the field, it is quite difficult to identify a recent fault scarp at the outcrop scale (Cosani, 1997). This is probably due to the low-resistance flysch rocks which produce a very smooth topography. In the Taggia area, Plio-Pleistocene sediments show recent faulting and tilting (Hoang-Trong et al., 1987; Cosani, 1997; Eva et al., 2000).

In the Argentera massif, the NW-SE Argentera

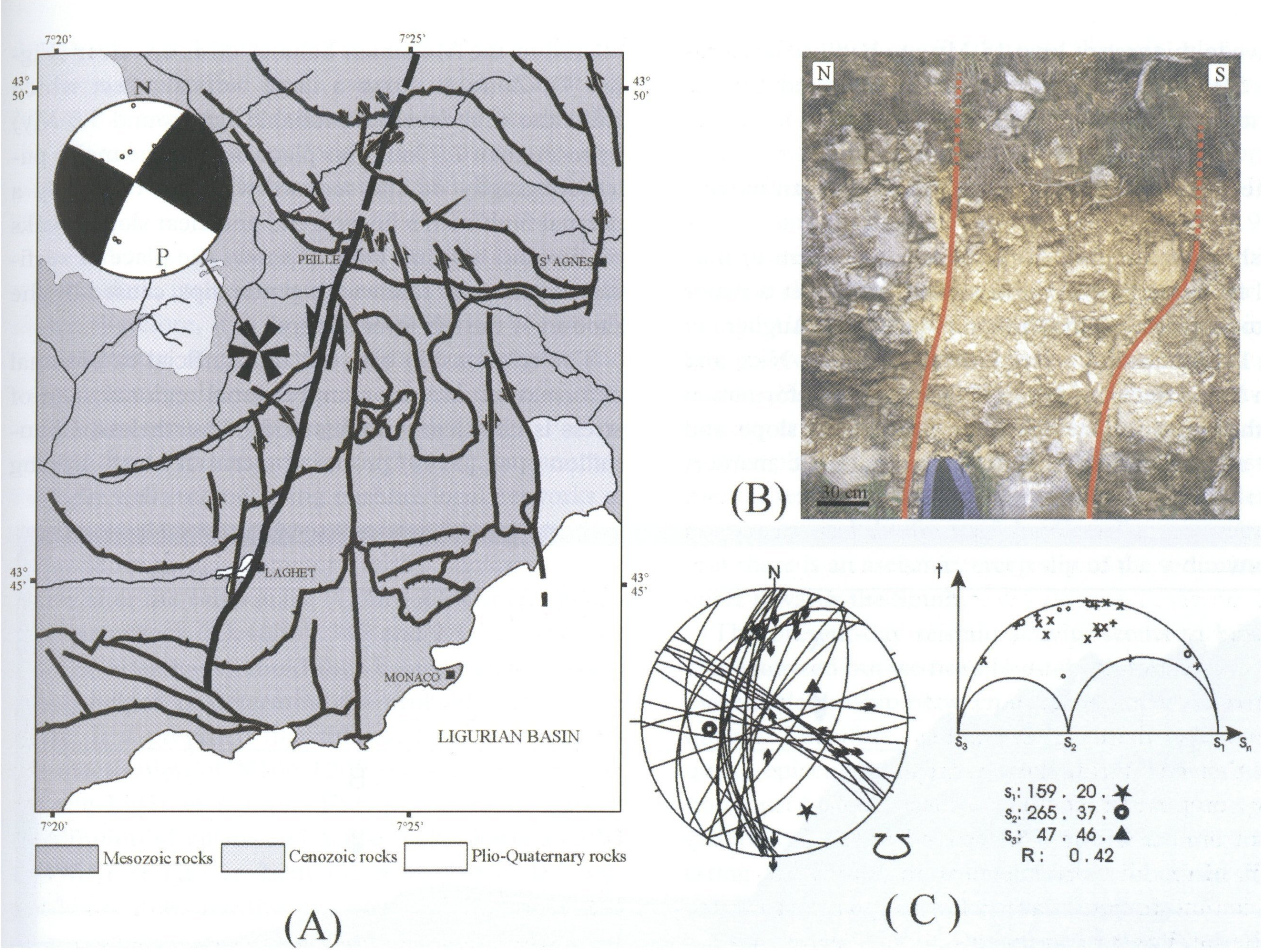

Fig. 6. (A) Structural map of the Peille-Laghet fault area (from Gèze & Lanteaume, 1963 and Rebaï, 1988). The focal mechanism of the November 1st, 1999 earthquake is consistent with a left-lateral movement along a more or less N30E fault. (B) Near Laghet, striated fault planes (red lines) crosscut Plio-Quaternary breccia. (C) The inversion of microtectonic data leads to a principal compressive stress axis trending N160E (Ritz, 1991).

fault (A.B.F. in Figure 2) displays field evidence for recent reverse dextral movement (Vogt, 1981; Combes, 1984; Ritz, 1991; Grellet et al., 1993). Gidon (1977) described offsets of morainic crest lines and Sauret & Terrier (1987) pointed out tectonic scarps, along the direction of the Argentera fault, that affect moraines dating from the last glacial maximum (18 000 yr B.P.). As a whole, evidence for active deformation is preserved for more than 10 km along the fault. Furthermore, Baubron (1987) performed geochemical analyses and detected helium and radon anomalies straight above the trace of the fault that suggest a current tectonic activity.

At the northwestern edge of the Argentera massif, large normal faults, such as the Camp des Fourches fault (up to 1500 m of vertical offset), have been developed during Pliocene time (C.F.F. in Figure 2). These faults affect the Meso-Cenozoic sedimentary cover, and are interpreted by Labaume et al. (1989) as the result of gravitational collapse in response to the upper Miocene crustal thickening. No evidence for Quaternary deformation has been reported in the field along the Camp des Fourches and the neighbouring faults, although north of the Argentera massif, Sue et al. (1999) have demonstrated active widespread extension in the internal zones of the Alpes, based on focal mechanisms determination and field data.

Below the Argentera massif, several authors (*e.g.* Siddans et al., 1984; Ritz, 1991; Laurent, 1998) have proposed the existence of a crustal blind thrust fault, connected to the South with the decollement layer in the Triassic evaporites underlying the Castellane and Nice arcs (B, Figure 1). This crustal ramp (B, Figure 1) could be associated with the recent basement uplift of the Barrot Dome and the Argentera massif (Bigot-Cormier et al., 2000). But no surficial E-W structure related to this deep-seated shortening has been reported in the field, for instance.

In the Castellane arc, field study does not allow us to identify recent deformation features, this is consistent with the historical and instrumental seismicity data but not with the data obtained in caves by Gilli & Delange (1999). It is known that the deformation was active in this area at least 15 My ago because the middle Miocene molasse deposits are covered by the frontal thrust of the Castellane arc (Figure 1).

Where are the active faults in the Ligurian basin?

Offshore, at the foot of the margin, a system of normal faults parallel to the basin axis expresses a major tectonic feature (Chaumillon et al., 1994; Augliera et al., 1994). Seismic reflection data between Nice and San Remo show evidence of Quaternary deformation at the transition between the continental slope and the abyssal plain. Several lithostratigraphic markers related to the Messinian Salinity crisis are clear (Figure 7): Zone A shows a large vertical offset which shifts the «EU» level (of probable age around 5.3 My) by more than 1.7 km. This place depicts the major paleotopography on the section, which is obviously a normal fault with a linear trend and clear slope breaks on top and bottom. Point B shows the place of surficial flexures and faults with gentle dips, caused by the motion of the salt layer at depth.

The relationship between this surficial extensional deformation and the compressional regional state of stress is not clearly understood. Nevertheless, Chaumillon et al. (1994) proposed a crustal north-dipping

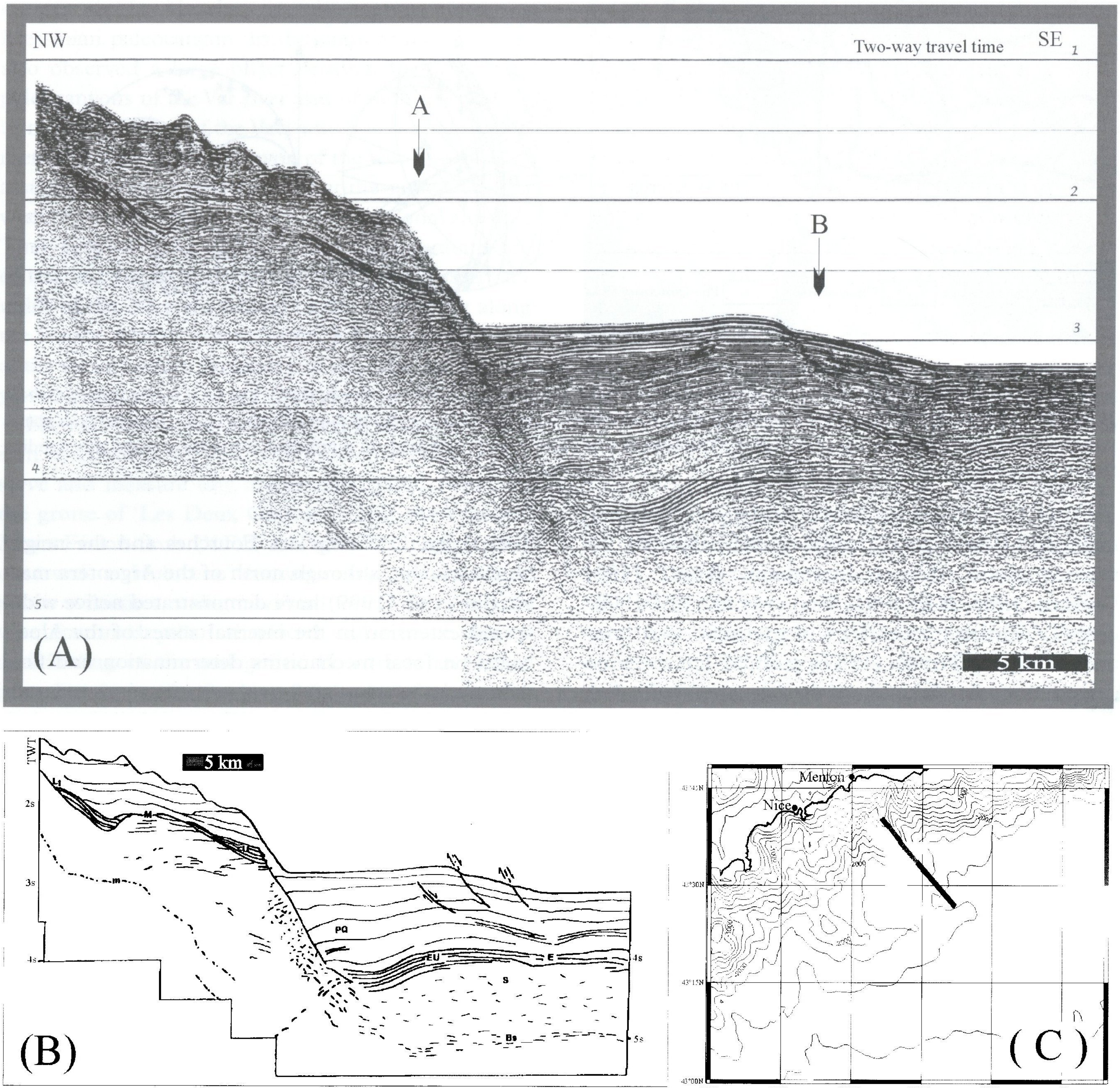

Fig. 7. (A) Monochannel seismic section obtained off Menton. This section has been done using a 80 ci– water gun on board Research Vessel Tethys II (INSU-CNRS), (B) line drawing of the seismic section (A) and (C) bathymetric map of the Ligurian northern margin and location of the seismic section (A).

thrust fault (B, Figure 1) at the base of the continental slope responsible for its current uplift at a rate of 0.3 to 0.5 mm/yr. This thrust could also account for the reverse earthquake focal mechanisms reported along the margin (Béthoux et al., 1988; Bétoux et al., 1992).

As indicated by the epicenter distribution and the seismic data, intense seismic activity also occurs offshore: therefore, it is important to define accurately the geometry of the active offshore structures and their continuity between the ocean and the continent in order to estimate the length of active faults. For example, the 1995 Ventimiglia earthquake was seismologically well studied, using onshore local networks of short-period and broad-band seismic stations and an ocean bottom seismometer (OBS) deployed a few hours after the earthquake (Courboulex et al., 1998). The mainshock (43.46N-7.34E and 9 +/- 2 km deep) and the aftershocks could thus be accurately located, which helped to determine the probable active fault plane. It is proposed that this earthquake represents the reactivation of N100-120E transverse faults that cut the Ligurian margin. This area shows a general distribution of paleo- and active faults dominated by a NW-SE trend (*e.g.* Lemoine et al., 1989). It is important to note that this moderate-size event occured on a short fault segment that has a limited surface expression, and which was not previously recognized as being active. Nevertheless, the seismicity on this segment is comparable to that observed along the parallel active system of the Saorge-Taggia fault (S.T.F. in Figure 2). This illustrates the role of inherited, deep-rooted, transcurrent features in the tectonic reactivation of the northern Ligurian margin (Courboulex et al., 1998).

Other offshore faults could also have an important seismogenic potential, but the relationships between offshore and onshore faults are unknown. Therefore a complete and accurate structural map of the Ligurian margin, contiguous with map for the southern Alps, is an important prerequiste for understanding regional tectonic processes and thus for the evaluation of the the seismic hazard.

Discussion

The linear trend pattern of epicenters together with the recent geodetic measurements attest that the Southern Alps – Ligurian basin junction is a region affected by active tectonics. All the field data collected by various geologists in the last decades are not always conclusive but display some evidence of surficial consequences related to these recent and active deformations (*e.g.* scarps along the Argentera-Bersezio fault, Plio-Quaternary tectonic breccia along the Peille-Laghet fault and offset of Quaternary terraces at the Var river mouth…). Since 20 My, the major deformations shifted from West to East: ages are upper Miocene in the Castellane arc (Laurent, 1998), Plio-Quaternary in the Nice arc (Perez, 1975; Ritz, 1991) and presently, the regional seismic activity is maximum in the Ligurian area whereas west of the Var river, the Castellane arc is considered to be now inactive. Nevertheless, from investigation of karstic galleries, Gilli & Delange (1999) propose a present-day activity at the front of the Castellane arc: this observation implies *(i)* either that the historical and instrumental seismicity are not representative of the deformation around the front of the Castellane arc, *(ii)* or that there is an aseismic, creep slip of the sedimentary cover towards the South.

The present-day seismic activity seems to be well characterized but we need to establish a clear and unbiased relationship between mapped faults and earthquakes. Therefore, a better determination of earthquake epicenters is necessary and depth determination must be improved. We are currently working on a calibration of the permanent network around interesting faults with accurate locations obtained from dense temporary networks of seismographs.

Despite the lack of Quaternary markers, we propose a preliminary map with 11 major active tectonic features including the 2 assumed onshore hidden faults (*i.e.* the frontal thrust of the Argentera massif and the lower Var valley fault) and the offshore Ligurian thrust (Figure 8).

This map is mainly based on the linear trends of epicenters and on the limited field evidence for recent and active deformation (Table 3). If the regional deformation is mainly related to localised movements along the principal faults identified in this work, then we can identify the deformation and the kinematics of the blocks (figure 8). Although the displacement along these faults is likely to be very small, a further GPS experiment of semi-permanent measurements should help us to understand the regional way of deformation.

But, in contrast with other regions of moderate seismicity (*e.g.* Camelbeek et al., 2000; Masana et al., 2000), clear surficial evidence of coseismic fault activation has not been identified in the field for instance. However, some moderate-size earthquakes sometimes produce a surface rupture, *e.g.*: *(i)* Cabrera & Sébrier (1998) pointed out a surface rupture associated with a 5.3 magnitude earthquake in Peru, *(ii)* Basili at al. (1998) and Meghraoui et al. (1999) described discontinuous coseismic surface ruptures of near 60-500 m along a total length of 5 km associated

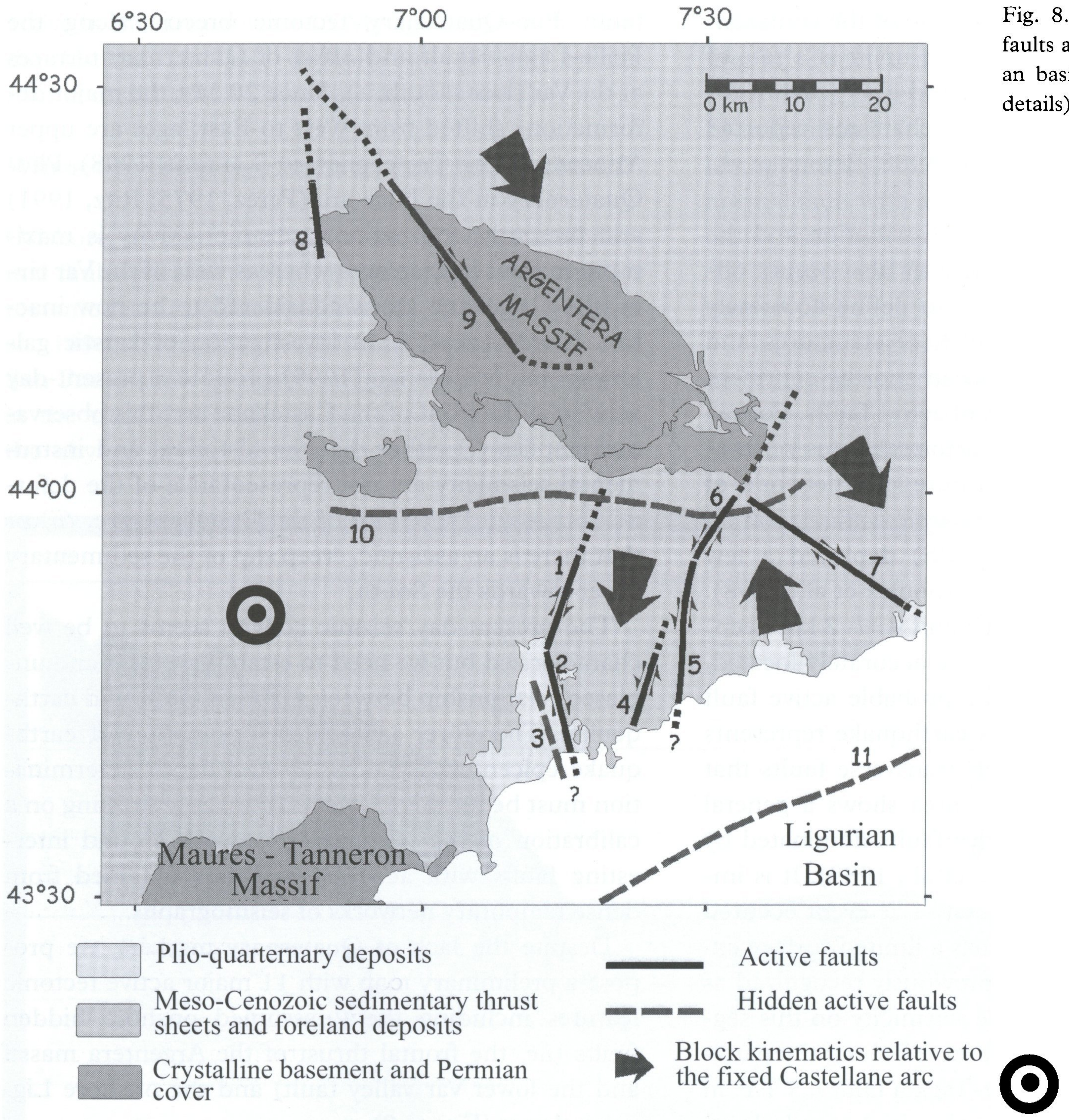

Fig. 8. Preliminary map of active faults at the Southern Alps– Ligurian basin junction (see Table 3 for details).

Table 3. Geometric and kinematic parameters, seismicity rate and field evidence for the 11 proposed active faults at the Southern Alps – Ligurian basin junction. The quality of the historical data is related to the region around the fault, but the quality of the data is not accurate enough to relate a historical event to a fault.

Name of the fault	Orientation	Kinematic	Length (km)	Seismicity		Field evidence
				Historical	Instrumental	
1 - Vésubie – Mt Férion	N20E	Dextral	20	yes	Low	uplift of the Plio-Quaternary
2 - St Blaise – Aspremont	N175E	and reverse	15	no	No	conglomerates of the Var river
3 - Lower Var valley	N175E	Reverse	–	-	–	vertical offset of Quaternary terraces
4 - Laghet-Peille	N20E	Sinistral	10-18	no	Low	crosscut Plio-Quaternary breccia
5 - Monaco-Sospel	N10E	Sinistral	20	no	Moderate	–
6 - Sospel-Saorge	N40E	Sinistral	40	no	Moderate	–
7 - Saorge-Taggia	N120E	Dextral	40	yes	Moderate	scarps
8 - Camp des Fourches	N165E	Normal	20	yes	Moderate	–
9 - Argentera-Bersezio	N140E	Dextral	70	yes	Low	scarps
10 - Argentera thrust	N90E	Reverse	–	–	Low	hidden fault
11 - Ligurian thrust fault system	N70E	Reverse	–	yes	Moderate	Offshore

with the third event (M_s=5.5) of the 1997 Umbria-Marche earthquake sequence and *(iii)* Azzaro (1999) observed some coseismic surface ruptures related to small earthquakes at the Mt Etna, in an area conditionned by volcano-tectonic activity. Therefore, in terms of seismic hazard, one important question remains: Are there any active faults scarps which could be identified onshore in the Alpes Maritimes, and if not, why ?

Erosion tends to erase the fine morphological traces of tectonic deformation. Generally, in the Mediterranean region, the removal of material is difficult to quantify accurately because of a complex topographic and climatic setting and because erosion was not uniform during Quaternary time due to strong climatic changes. Based on geologic reconstructions and estimated river loads, Saunders & Young (1983) proposed a mean denudation rate of around 0.1 mm/yr for high relief terrains in the Mediterranean area since the last glacial maximum (18 ky B.P.). Thus, a vertical scarp of 1 m could be strongly degraded within only 10 kyr. Such scarps are assumed to be produced by a magnitude 6.5 earthquake (Well & Coppersmith, 1994). Historically, our region has suffered such earthquakes, but the erosion rate is probably larger than the fault slip rate and therefore, the surficial expressions related to recent fault activity may not be easily visible.

The geodetic measurements in the Alpes Maritimes reveal a N-S shortening about 2-4 mm/yr between the coast and the Argentera massif during the last 50 years. This strain rate is about twice larger than the values obtained in the Western Provence area (west of the Castellane arc) by Ferhat et al. (1998), which is consistent with the very low level of seismicity and few geological evidence for active deformation in Provence compared to the Alpes Maritimes. The question remains whether the present-day strain rate measured in the Alpes Maritimes is entirely associated or not with significant earthquakes. The answer is probably not, since the largest earthquakes known in the area during this period occurred offshore (M_b=6.0, 19/7/1963) and can account for a maximum coseismic displacement rate of 1 mm/yr onshore which cannot explain the geodetic signal (Calais et al., 2000). This displacement rate has been obtained using a simple elastic dislocation model (Okada, 1993) and a coseismic slip of 10 cm on a SW-NE thrust fault located 100 km offshore. We therefore conclude that the shear strain rates measured in the geodetic network mostly reflect interseismic deformation.

Our attempt to gain a better understanding of the seismic hazard in the Southern Alps – Ligurian basin junction shows the problems related to investigation of active tectonics in areas of low to moderate seismicity. Although we have seismological, geodetic and tectonic informations, we cannot yet provide a detailed definition of the active tectonic framework. Apparently, the current methodologies for investigation of active tectonics in this kind of area can only give partial information.

Conclusions

The presence of active deformation in the Southern Alps and at their junction with the Ligurian basin is shown by numerous phenomena: offsets of Plio-Quaternary sedimentary formations, historical seismicity, present-day seismic linear trends and significant geodetic strain rates between the coast and the Argentera massif. Onshore, this deformation is mostly accommodated by a few faults inherited from the Miocene alpine orogeny. These active faults can be identified in the field, except for the possible hidden Argentera thrust and the lower Var valley fault. Offshore, the faults inherited from the openning of the Ligurian basin have been reactivated but the data sets (seismicity catalogue, seismic-reflection sections and bathymetry) are not yet dense enough to provide a fully controlled structural sketch (for example, the Ligurian thrust is probably a complex fault system).

Though a preliminary map of 11 active faults can be proposed, the few accurate knowledges on the length of the potentially active fault segments in relation with the regional present-day state of stress prevents to estimate a possible maximum magnitude for this region. Therefore, some major questions remain open and must be addressed in the future in order to obtain more complete data for seismic hazard evaluations: *(i)* Are the proposed active faults divided in different segments of different size and activity ? *(ii)* What are the relationships between offshore and onshore active structures ? *(iii)* The largest earthquakes recently recorded are located offshore (with a magnitude of up to 6.0); are some onshore faults able to produce an earthquake with such a magnitude ? *(iv)* The recurrence intervals for major earthquakes are unknown; are they of the order of tens of thousand years or of thousands of years ? What are the ages of the last events on active faults ? We believe that these questions can be solved in the future, by combining *(i)* geodetic measurements, *(ii)* accurate location of earthquakes, and *(iii)* detection of sites suitable for paleoseismological investigations. Finally, it is currently difficult to determine reliable sites for paleoseismology mainly because the morphological evidence of present-day activity is lacking, nevertheless the current field study and geophysical prospecting through the Plio-Quaternary deposits of the lower Var valley could reveal some area suitable for trenching.

Furthermore, the wide range of geological basements in this region (crystalline rocks, sedimentary rocks, colluvium, alluvium) and the sharp topography are responsible for the amplification of ground shaking in areas subject to site effects. For example, the November 1st, 1999 Peille earthquake was clearly felt by the population, although its magnitude was small (M_w=3.4, Courboulex et al., 2000). Finally, we may note that the valley of Peille is often shaken during earthquakes, which could be explained by ground amplification (Duval, 1996; Gaffet et al., 1998; Larroque et al., 1999). Therefore, the study of such a densely populated and geologically varied area also requires taking into account site effects as a major component of seismic hazard assessment.

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