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Seismotectonics of a low-deformation area: the central Western Alps (Italy)

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ABSTRACT This work is based on the integration of detailed field mapping, structural analysis and updated seismological data for the central Western Alps. In this area, three regional, steeply-dipping fault systems seem to be connected to the current seismic activity: the Longitudinal Faults, in the western part, the Transverse Faults, in the central part, and the Col del Lis-Trana Deformation Zone, in the eastern part. Structural and seismological data suggest that since the Late Oligocene, a dextral transtensive regime has been active in this area. The Canavese Line seems to represent the structure that decouples this stress regime, acting inside this sector of the chain, from the transpressive regime that characterizes the adjacent westernmost Po Plain. At a regional scale, this transtensive regime is induced by the coexistence of two driving forces: the counterclockwise rotation of the Adria plate and the body forces acting inside the chain. These two different forces, induced respectively, the dextral and normal components of movement along the major faults bounding the Western Alps. The data fit in a model of dextral transcurrence at the scale of the Western Alps. The data presented in this work contribute to an updated seismic macrozonation of the western Alpine chain, a very populated area where, up to now, only marginal seismotectonic studies have been carried out.

Key words: seismotectonics, recent seismicity, Western Alps.

1. Introduction

The western Alpine Arc (Fig. 1) is a rather complex structure which was initiated during convergence and collision more than 35 Myr ago, when the Adriatic micro-plate, moving northwards with respect to the European foreland, caused sinistral transpression in the Western Alps while the central and eastern Alps underwent head-on convergence and collision (Ricou and Siddans, 1986). The complexity of this sector and the relationship with the adjacent structures are confirmed by the geophysical data, which highlight a sharp change of the stress regime between the chain, undergoing an extensional-to-transtensive regime, and the westernmost Po Plain, where a transpressive regime is present (Eva *et al.*, 1997; Eva and Solarino, 1998; Delacou *et al.*, 2004; Béthoux *et al.*, 2007).

The central sector of the western Alpine Arc (Fig. 2) is an area where seismic activity is of low-to-moderate magnitude; however, a few strong historical earthquakes (up to intensity VIII)

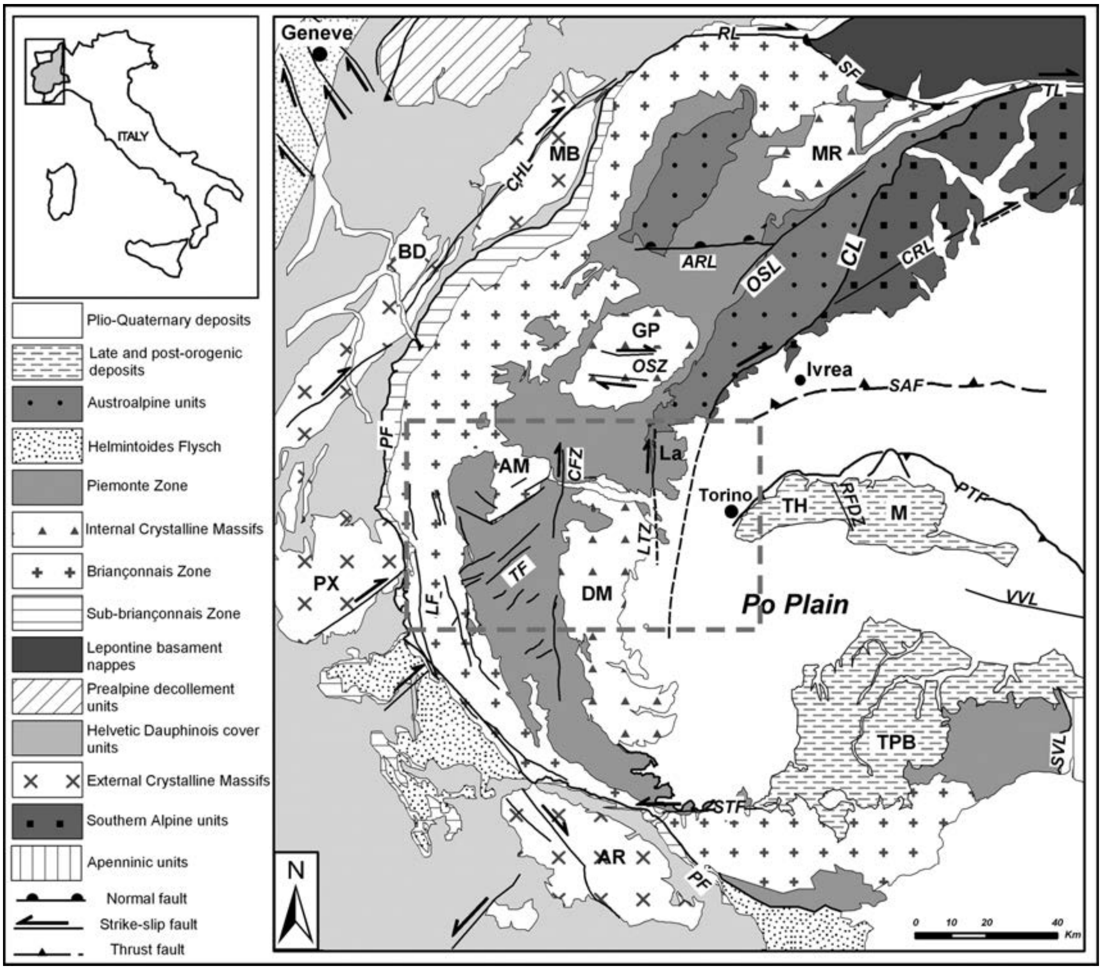

Fig. 1 - Tectonic sketch map of the western Alps. The dashed grey rectangle indicates the area shown in Figs. 2 and 3. AM: Ambin Unit, AR: Argentera Massif, BD: Belledonne Massif, DM: Dora-Maira Unit, GP: Gran Paradiso Unit, La: Lanzo ultramafic complex, M: Monferrato, MB: Mont Blanc Massif, MR: Monte Rosa Unit, PX: Pelvoux Massif, TH: Torino Hill, TPB: Tertiary Piemonte Basin, ARL: Aosta-Ranzola Line, CFZ: Colle delle Finestre Deformation Zone, CHL: Chamonix Line, CL: Canavese Line, CRL: Cremosina Line, LF: Longitudinal Fault System, LTZ: Col del Lis–Trana Deformation Zone, OSL: Ospizio-Sottile Line, OSZ: Orco Shear Zone, PF: Penninic Front, PTF: Padanian Thrust Front, RFDZ: Rio Freddo Deformation Zone, RL: Rodano Line, SAF: Southern Alpine Thrust, SF: Simplon Fault, STF: Stura Fault, SVL: Sestri-Voltaggio Line, TF: Transverse Fault System, TL: Tonale Line, VVL: Villalvernia-Varzi Line. (after Bigi *et al.*, 1990).

have occurred there, causing significant damage (e.g., the 1808 events). This aspect has led, through the years, from the beginning of the 1980's, to a fairly accurate knowledge of the seismicity; however it is only in the last decade that research (Sue and Tricart, 1999, 2002, 2003; Carraro *et al.*, 2002; Polino *et al.*, 2002; Tallone *et al.*, 2002; Perello *et al.*, 2004; Balestro *et al.*, 2009a, 2009b; Perrone *et al.*, 2009a, 2009b, 2010a, 2010b) has focussed on the analysis of the brittle-ductile to brittle structures that dissect this part of the Alpine chain. Thus, up to now, a close investigation of the relation between fault network and seismicity of the area in the broader

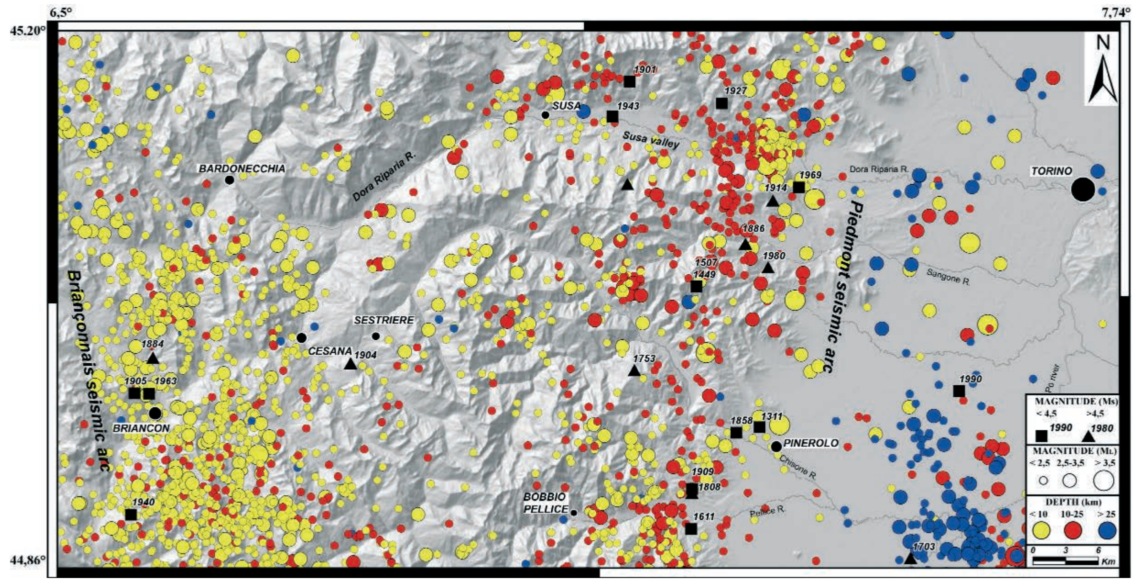

Fig. 2 - Instrumental and historical seismicity in the central Western Alps. Instrumental seismicity from the database of the Regional Seismic Network of northwestern Italy (RSNI). Historical seismic events from the CPTI catalogue (Gruppo di Lavoro CPTI, 2004).

scale has not been possible. More recent studies (Sue and Tricart, 2002, 2003; Sue *et al.*, 2007) focussed mainly on the Briançonnais area (France) and interpreted the seismicity of the innermost part of the area under study in this paper as completely separate from surface structures. However, the many shallow seismic events recorded during the last few years suggest that a closer analysis is worthwhile.

With the aim of pursuing a more detailed outline of the relationships between superficial tectonic lines and seismic occurrences, we summarize, in this paper, the main geological surveys conducted in the central Western Alps and combine their results with an updated seismological database of the Regional Seismic Network of north Western Italy (RSNI hereinafter). As known, the detection of potentially seismogenic faults is particularly important in areas where many infrastructures and densely populated villages are concentrated, and, in turn, may have relevance in terms of seismic hazard, even in areas where seismicity is of moderate energy. Here, the goal is primarily to distinguish between seismogenic and non-seismogenic structures, and possibly to get some inferences about their size and extension; moreover, the results will have to be estimated in a seismic hazard context.

2. Tectonic evolution

In the central Western Alps, tectonic units that represent different paleogeographic domains crop out (Fig. 3). These units shared a long and complex tectonic and metamorphic evolution starting from the closure of the ancient Ligurian-Piedmont ocean (upper Jurassic-Lower Cretaceous). Their tectonic juxtaposition occurred, in general, mostly under high pressure/low

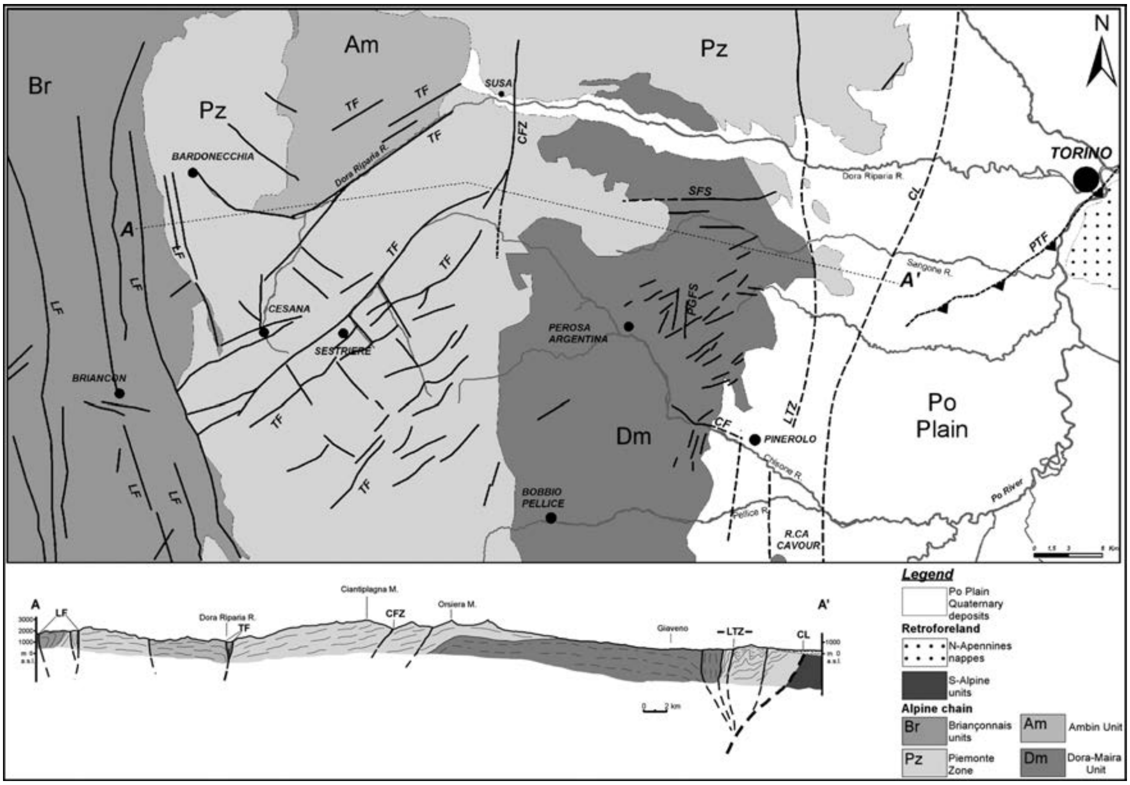

Fig. 3 - Tectonic map of the central Western Alps (a). CF: Chisone Fault, CFZ: Colle delle Finestre Deformation Zone, CL: Canavese Line, LF: Longitudinal Fault System, LTZ: Col del Lis–Trana Deformation Zone, PGFS: Pinasca-Gran Dubbione Fault System, PTF: Padanian Thrust Front, SFS: Sangone Fault System, TF: Transverse Fault System. Geological section across the analyzed area (b). The trace of the section is shown in Fig. 3a.

temperature (HP/LT) to blueschist metamorphic conditions [Polino *et al.* (1990) with reference therein]. The geometrically deepest element is represented by the Dora-Maira Unit (DM), a slice of continental crust belonging to the Internal Cristalline Massifs. Above the DM, the oceanic-derived units of the Piemonte Zone are found, whereas the uppermost tectonic elements correspond to the Briançonnais Units, representing slices of the paleo-European continental margin.

The central Western Alps are bordered by two crustal tectonic discontinuities (Figs. 1 and 3): the Canavese Line (CL) and the Penninic Front (PF). These two discontinuities separate the central Western Alps, characterized by HP/LT metamorphic assemblages, respectively from the South Alpine and Helvetic Domain. These two last domains were only weakly affected by Alpine metamorphic re-equilibration.

The CL corresponds to a steep dextral-reverse fault that was active mainly during the Oligocene–Miocene (Schmid *et al.*, 1987, 1989). This fault has been traced also to the central and south Western Alps, where, according to several geological, seismic, gravimetric and magnetic investigations (Lanza, 1975; Ménard and Thouvenot, 1984; Nicolas *et al.*, 1990; Béthoux *et al.*, 2007; Mosca *et al.*, 2009), it is masked by the Quaternary deposits of the Po Plain.

The PF separates the units belonging to the Paleogene Alpine orogenic wedge from the underlying Helvetic units. Seismic sections (Roure *et al.*, 1990) show that this structure moderately dips to the east. Structural data indicate that the PF is characterized by polyphasic activity: it was active as a major thrust fault in the Early Oligocene (Tricart, 1984) whereas the PF has undergone an extensional reactivation (Tricart *et al.*, 2001) since the Miocene.

Between the CL and the PF, other minor semi-brittle -to-brittle discontinuities are present, mostly mapped in the last few years (Barfety *et al.*, 1996; Carraro *et al.*, 2002; Polino *et al.*, 2002; Perrone, 2006; Balestro *et al.*, 2009a, 2009b). These structures correspond to:

- Col del Lis-Trana Deformation Zone [LTZ in Figs. 1 and 3; Balestro *et al.* (2009a, 2009b)], a N-S striking structure that runs for about 35 km from the lower Lanzo Valley to the lower Sangone Valley. Seismic sections carried out south of the LTZ reveal that the metamorphic basement is displaced by roughly N-S steep faults (Bertotti and Mosca, 2009). This suggests that the LTZ may extend beneath the Quaternary deposits of the western Po Plain up to the Pellice Valley (Fig. 3), reaching a total length of about 50 km. Inside the LTZ, which corresponds to a 1.0-1.5 km-wide, sub-vertical zone, all the pre-existing syn-metamorphic structures are rotated parallel to its boundaries. Both map-scale geological features and mesoscale fault-slip data indicate a main, right-lateral sense of movement for the LTZ. These structures show mostly brittle-ductile deformation mechanisms. N-S trending folds and minor reverse faults indicate also a minor shortening component of displacement for the LTZ. Subsequently, this structure underwent an extensional reactivation attested by overprinting striae generations and by cross-cutting relations between transcurrent and normal faults. On the basis of its geometry and kinematics, the LTZ is interpreted as a sub-parallel minor fault strand of the Canavese Line (Balestro *et al.*, 2009b; Perrone *et al.*, 2010a, 2010b). West of the LTZ, some E-W striking, left-lateral faults are present (Sangone Fault System and Chisone Fault, SFS and CF in Fig. 3), interpreted as LTZ, second-order, antithetical structures. Between these second-order E-W faults, also some minor N-S right-lateral (Pinasca Gran Dubbione Fault System, PGFS in Fig. 3) and NE-SW normal-left faults have developed [see also Perrone (2006) and Perrone *et al.* (2009b, 2010a) for a more detailed discussion].

- Colle delle Finestre Deformation Zone [CFZ in Figs. 1 and 3; Carraro *et al.* (2002) and Cadoppi *et al.* (2007)]. CFZ is a steeply dipping structure that extends for about 15 km from the lower Susa Valley to the middle Chisone Valley. In its southern termination, the CFZ juxtaposes different units of an oceanic setting (Carraro *et al.*, 2002). Mesoscale fault-slip data indicate that the CFZ is a polyphasic structure characterized by early, right-lateral activity, associated to brittle-ductile structures, and subsequent normal reactivation (Tallone *et al.*, 2002; Cadoppi *et al.*, 2007), occurring under brittle deformation conditions.

- Longitudinal Fault System [LF in Figs. 1 and 3; Barfety *et al.* (1996) and Sue and Tricart (2002, 2003)]; the LF is characterized by several, sub-parallel N-S to NW-SE striking fault segments. These structures are usually steeply dipping and can be followed for more than 100 km, displacing the Briançonnais Units, in the north, and the Argentera Unit, in the south. The faults are usually sub-vertical and, according to Sue and Tricart (2002, 2003), were characterized by an earlier normal activity and by a subsequent right-lateral reactivation in the Pliocene.

- Transverse Fault system [TF in Figs. 1 and 3; Barfety *et al.* (1996) and Sue and Tricart (2002, 2003)]; TF corresponds to several sub-parallel NE-SW and E-W faults, up to 20-25 km long, that

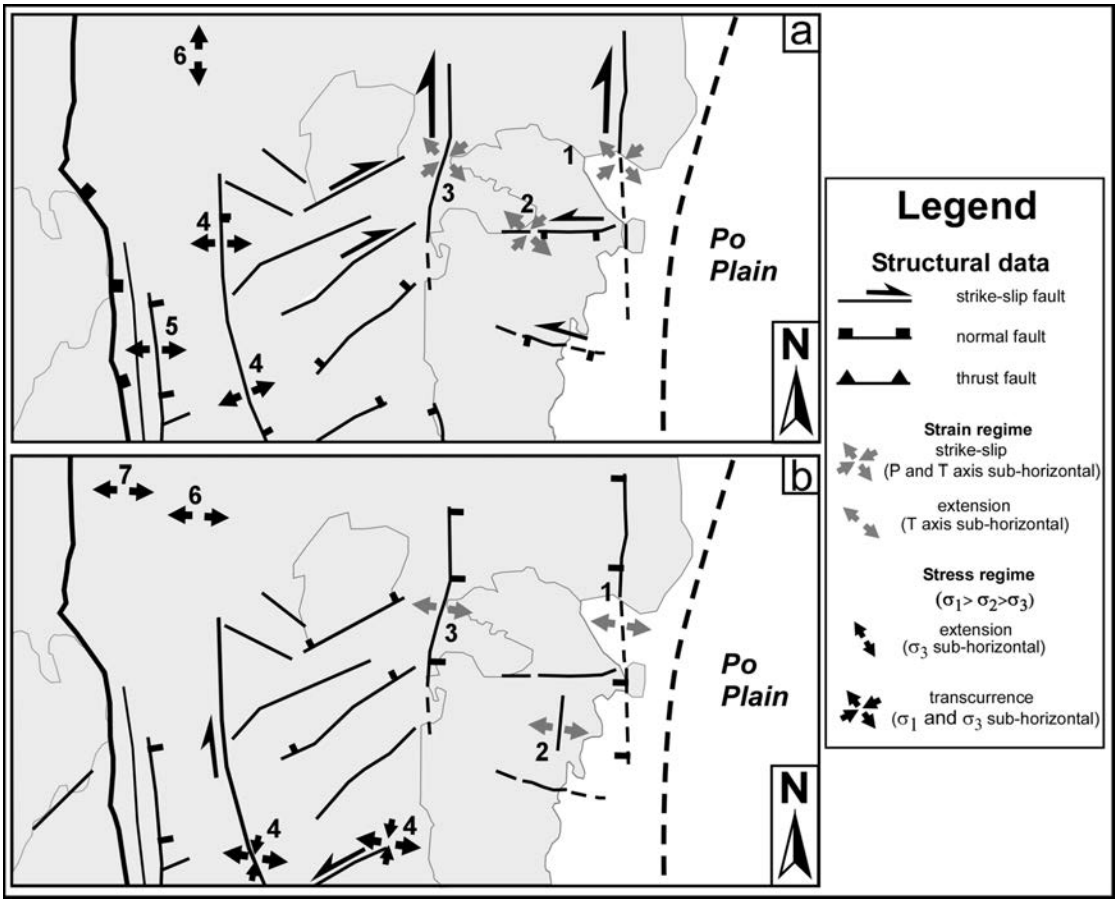

Fig. 4 - Two hypothetical steps of the post-Oligocene tectonic evolution of the central Western Alps (see details in the text). Abbreviations as in Fig. 3. Reference index on the map are: 1 = Balestro *et al.* (2009b), 2 = Perrone *et al.* (2010a), 3 = Tallone *et al.* (2002), 4 = Sue and Tricart (2003), 5 = Sue and Tricart (1999), 6 = Champagnac *et al.* (2006), 7 = Ceriani and Schmid (2004), 8 = Malusà (2004) (modified from Perrone *et al.*, 2010a).

displace the Piemonte Zone units. The TF is usually steeply dipping and confined within the LF. East of the village of Briançon, the TF is described as a system of normal faults, some of which show evidence of left-lateral reactivation (Sue and Tricart, 2003). In the middle Susa and Chisone valleys (Figs. 1 and 3), they are described as right-lateral faults, reactivated by normal movements (Malusà, 2004; Perello *et al.*, 2004). On the basis of these cross-cutting relations and kinematics, Sue and Tricart (2002, 2003) interpreted the LF and the TF as systems of first and second order faults, respectively.

Between the LF and the TF, in the high Susa Valley (Figs. 1 and 3), a minor, steeply dipping, WNW-ESE fault system is also present (Polino *et al.*, 2002). The kinematics of these faults is still poorly known, even if Malusà (2004) indicated them as normal faults.

In describing the post-metamorphic tectonic evolution of the area, two main faulting stages can be distinguished (Perrone *et al.*, 2010a) (Fig. 4). The first (late Oligocene-Early Miocene) is related to the dextral movements along the LTZ, the CFZ and the CL. Between these structures,

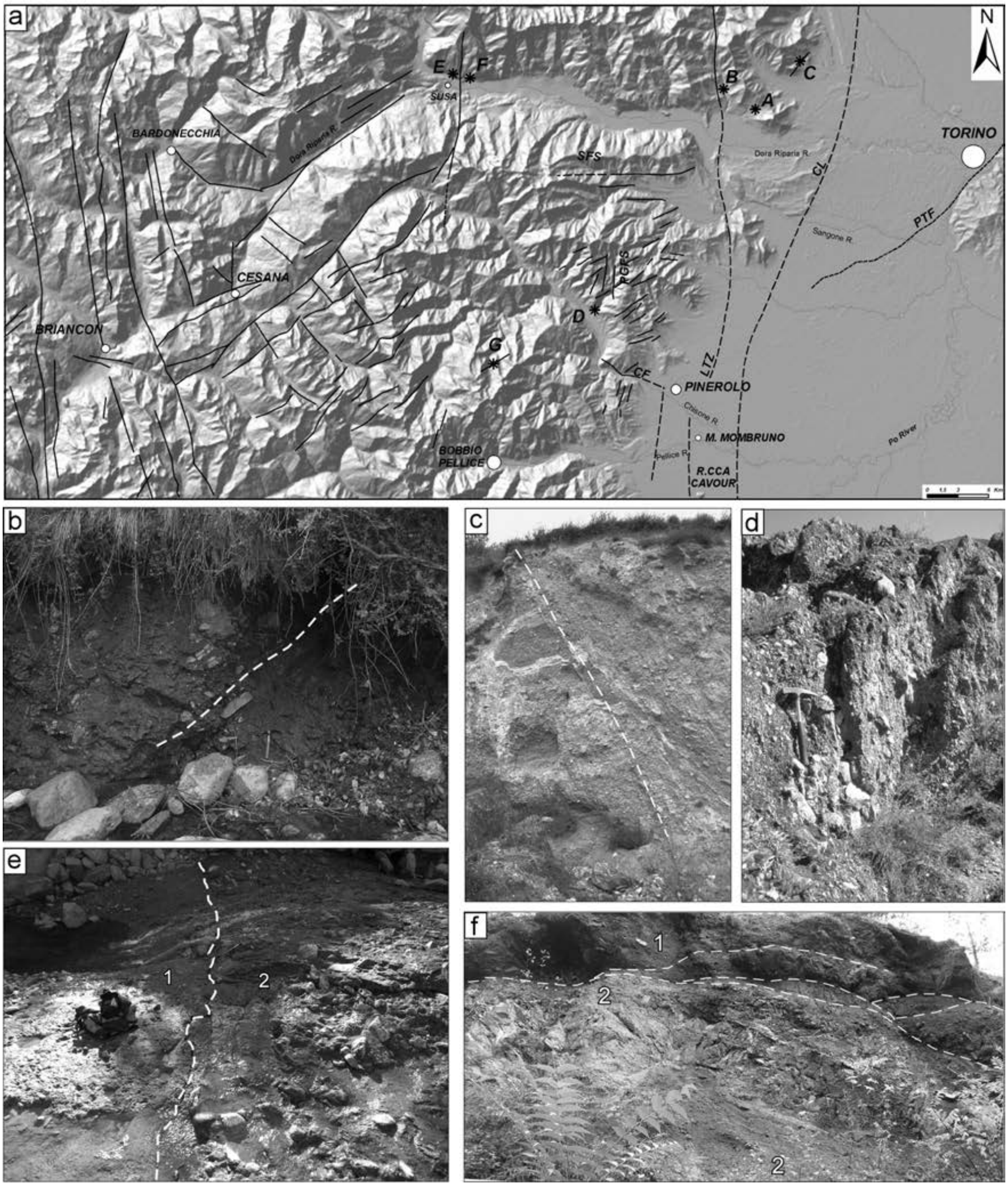

Fig. 5 - (a) Structural map with locations of the sites where faulted Quaternary deposits are observed, (b) N-S normal fault displacing Early Pleistocene stream deposits (site B in a; Messa stream), (c) alluvial deposits displaced by N-S normal faults (site F in a), (d) alluvial deposits steepened by N-S faults (site E in a), (e) N-S striking normal fault juxtaposing fine grained deposits (1), in the hanging-wall, against coarse-grained deposits (2), in the footwall (site C in a), (f) ENE-WSW striking faults (site A in a) juxtaposing Early Pleistocene deposits (1) against the bedrock (2; peridotites and serpentinites). [modified from Cadoppi *et al.* (2007) and Perrone *et al.* (2010b)].

the PGFS and the SFS were active as right-lateral and left-lateral faults, respectively. In the western part of the area, instead, the LF and the TF were active as systems of normal faults (Fig. 4a). The dextral movements observed along the TF in the middle Susa Valley may be related to the partitioning of the dextral component of movement between N-S major and NE-SW minor faults (Perello *et al.*, 2004) or to local block rotation.

In the second faulting stage (post- Early Miocene, Fig. 4b), the LTZ, the CFZ and the PGFS, in the eastern part of the area, are reactivated as transtensive/normal faults while the LF and the TF, in the western part, change to systems of right-lateral and left-lateral faults, respectively.

This complex kinematic evolution fits in a model of dextral transtension at the scale of the Western Alps, induced by the coexistence of two different driving forces active since the late Oligocene: the counterclockwise rotation of the Adria plate and the body forces acting inside the chain (Sue and Tricart, 2003; Perrone *et al.*, 2010a, 2010b). This coexistence may have induced strain partitioning and, subsequently, complex spatial and chronological relations between transcurrent and extensional movements on a regional scale (see also Champagnac *et al.*, 2006). Strike-slip movements along the analysed faults are consistent with a NNE-SSW to NE-SW shortening direction with a NW-SE to E-W extension; normal movements are instead, consistent with a steeply-dipping shortening with an E-W to NW-SE extension (Fig. 4). The transition from the first to the second faulting stage in the analysed area is therefore interpreted as a tectonic continuum, related to the prevalence of the buoyancy forces on the strike-slip movements. It may have, therefore, caused the permutation between maximum and intermediate shortening axes (Hu and Angelier, 2004) with a roughly constant extension direction (Sue and Tricart, 2003; Perrone *et al.*, 2009a, 2010b).

3. Evidence of Quaternary tectonic activity

In the Pleistocene, several glacial pulses deeply remodelled most of the valleys that drain the central Western Alps. The erosive activity of the Pleistocene glaciers, at first, and the Pleistocene interglacial and Holocene post-glacial stream erosion, then, together with the low-deformation rates caused a poor preservation of the Quaternary superficial tectonic deformations. The occurrence of many deep seated gravitational slope deformations, whose geomorphological features (such as km-scale scarps along mountain slopes) are similar to those of recent faults, make the detection of evidence of current tectonic activity more difficult. However, some features, probably related to Quaternary tectonic activity, have been recently highlighted, and are briefly summarized in the following (Fig. 5).

The lower part of the Pellice and Chisone Valleys are filled by lacustrine Pleistocene deposits that reach 250 and 100 m of thickness respectively (Collo, 1996). These deposits unconformably rest on the Alpine Basement and are separated from fluvial deposits of the western Po Plain by a rocky threshold localized at the Chisone and Pellice Valley mouths. As these two valley segments did not host a Pleistocene glacier, Collo (1996) proposed a tectonic origin for these intermountain basins, due to the differential uplift of the westernmost Po Plain with respect to the innermost sector of the central Western Alps. Even if the geometry of the threshold is still not known in detail, it can be reasonably assumed that it may correspond to faults roughly perpendicular to the Chisone and Pellice Valley axes. A reflection seismic profile carried out at the Pellice Valley

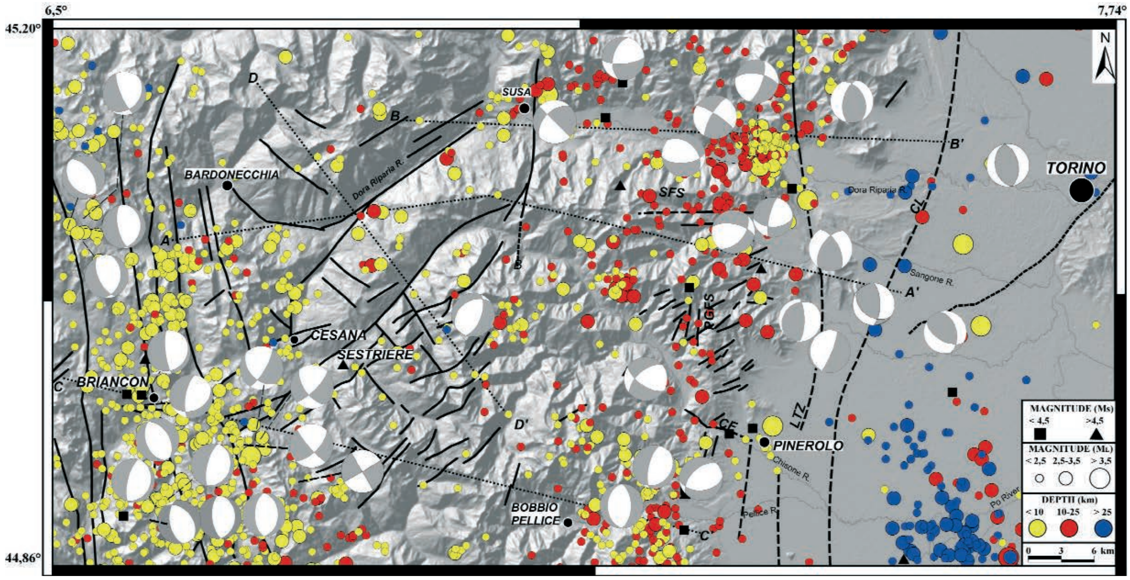

Fig. 6 - Seismotectonic map of the central Western Alps. Instrumental seismicity with 3 km of horizontal and vertical location error. Historical seismicity as in Fig. 2. Instrumental seismicity from the database of the RSNI. Focal mechanisms from Nicolas *et al.* (1990), Eva *et al.* (1997), Sue *et al.* (1999), Delacou *et al.* (2004), Béthoux *et al.* (2007), Perrone *et al.* (2010b). Abbreviations as in Fig. 1.

mouth shows that the metamorphic basement is dissected by steeply dipping faults, interpreted as roughly N-S faults (Mosca, 2006; Bertotti and Mosca, 2009). The Pleistocene activity of these faults may have driven the uplift of both the bedrock at the Chisone and Pellice Valley mouths and of the Rocca di Cavour and Madonna di Montebruno inselbergs (two outcrops of metamorphic basement belonging to the Dora-Maira Unit, aligned along a N-S direction; Fig. 5). These N-S striking faults may correspond to the southern prolongation of the LTZ and should give evidence of its activity at least up to Pleistocene times. Possible evidence of LTZ Quaternary activity also derives from the observations of mesoscale brittle deformations affecting Lower Pleistocene deposits covering the Lanzo Ultramafic Complex (Perrone *et al.*, 2010b). N-S normal faults and E-W faults, showing both strike- and dip-slip striae on fault surfaces, dissect these deposits (sites A, B, C in Fig. 5). A probable tectonic origin for these deformations is supported by the absence of glacial deposits and landforms near these sites.

In the Chisone Valley, at the Gran Dubbione tributary valley mouth, the lacustrine deposits are displaced by N-S reverse faults [site D in Fig. 5; Collo and Giardino (1997)]. These deformations may give evidence of the Quaternary activity of the PGFS. In the Pellice Valley soft-sediment deformations were observed inside lacustrine successions by Collo (1990) as well.

Cadoppi *et al.* (2007) also showed the occurrence of Quaternary deposits displaced by N-S normal faults (sites E and F in Fig. 5) along the trace of the Colle delle Finestre Deformation Zone (CFZ). A probable glaciotectonic origin for these deposits is not excluded as they are located in an area strongly remodelled by the Pleistocene glaciers.

Collo (1994) also describes a NE-SW fault displacing the late Upper Pleistocene glacial

Table 1 - Locations and parameters of historical earthquakes (from Gruppo di Lavoro CPTI, 2004). Y: year; M: month; D: day; H: hour; M: minutes; S: seconds; Lat.: latitude; Lon.: longitude; Ms: estimated magnitude; Io: intensity.

Y	M	D	H	M	S	Locality	Lat. N (°)	Lon. E (°)	Ms	Io
1311						Pinerolo	44.885	7.327	4.3	60
1449						Pinasca	45.000	7.250	4.3	60
1507						Pinasca	45.000	7.250	4.3	60
1611	1	15				Luserna	44.800	7.250	4.0	55
1703	12	28				Villafranca	44.780	7.505	5.1	75
1753	3	9	13	15		Valle del Chisone	44.930	7.180	4.9	65
1785	9	12				M. Orsiera	45.083	7.167	4.8	70
1808	4	2	16	43		Valle del Pellice	44,830	7.250	5.6	80
1858	10	25	1	42	30	Valle del Chisone	44.880	7.300	4.3	60
1884	11	27	22	15		Alpi Cozie	44.930	6.620	5.1	65
1886	9	5				Val di Susa	45.036	7.306	5.0	65
1901	3	29	7	5		M. Lera	45.167	7.167	4.0	55
1904	7	12	5	32		Alpi Cozie	44.930	6.850	4.7	60
1905	1	21				Francia	44.900	6.600	4.3	60
1909	10	5	1	10	2	Torre Pellice	44.833	7.250	4.0	55
1914	10	26	3	45		Tavernette	45.072	7.337	5.1	70
1927	12	11	15	49		Val di Susa	45.151	7.275	4.4	55
1940	4	29	2	21	48	Francia	44.800	6.600	3.8	60
1943	5	22	19	3		Val di Susa	45.138	7.148	4.4	50
1963	6	27		11		Hautes-Alpes	44.900	6.617	4.0	55
1969	10	9	3	31	36	Giaveno	45.083	7.367	4.2	60
1980	1	5	14	32	26	Giaveno	45.017	7.333	4.7	/
1990	2	11	7		38	Canavese	44..918	7.558	4.4	60

deposits in the Faetto Valley (Germanasca Valley, site G in Fig. 5). Displacement of the glacial moraines and striae on minor fault surfaces suggests a normal component for this fault. Its geometry and kinematics, which conform to the NE-SW faults of the middle Chisone and Susa valleys, suggest that some Transverse Faults may have been active up to Quaternary times.

Finally, Sue *et al.* (2007) described some neotectonic structures in the south Western Alps (Ubaye Valley, France), such as counter-slopes in glacial moraines and small river offsets that could be probably related to the recent activity of the TF.

4. Seismotectonic analysis

The central Western Alps are characterized by a low-to-moderate magnitude seismicity (M_L< 5.0). Instrumental seismicity is mostly concentrated along two sub-parallel, longitudinal bands (Fig. 2)

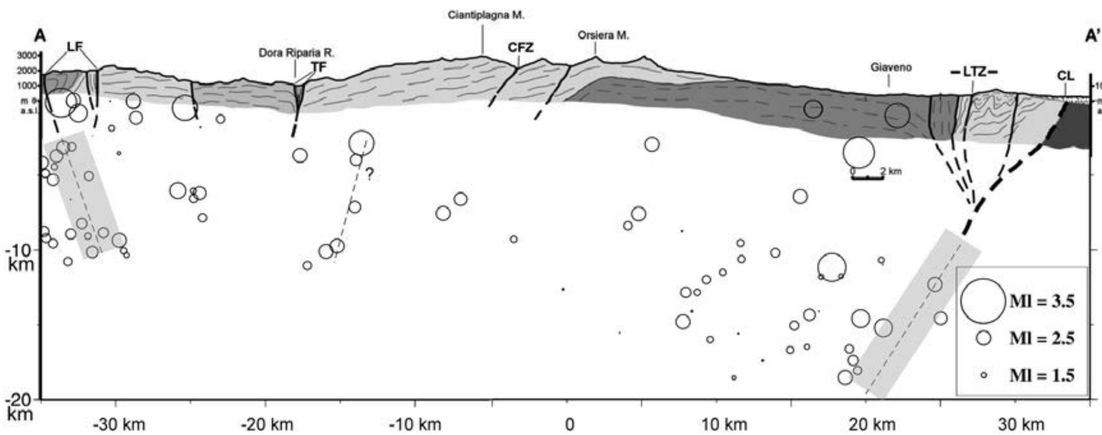

Fig. 7 - Seismotectonic section across the central Western Alps. The areas where a geometric correlation between faults and seismicity is observed are in grey. The trace of the section is shown in Figs. 2 and 6. Abbreviations as in Fig. 1.

respectively named Briançonnais and Piedmont seismic arc (Rothè, 1941; Sue *et al.*, 1999; Delacou *et al.*, 2004). The seismicity is more diffused between these two arcs, even if some epicentre alignments may be observed. The depth of hypocentres increases from the Briançonnais, where it is mostly confined in the first 5 km of crust, to the Piedmont arc where it reaches a 20 km depth [Figs. 7 and 8; see also Sue *et al.* (2002) for a more detailed discussion].

Historical seismicity is mostly concentrated in the innermost part of the chain, at the boundary between the chain and the Po Plain [Gruppo di Lavoro CPTI (2004), Figs. 2 and 6, and Table 1]. It must be remarked that the location of historical events is based on the description of their effects and it depends on the number and quality of the available information; these are in turn biased by local soil and topographic effects and by the vulnerability of the buildings. In practice, the location of a macroseismic event is the barycentre of the damaged area and its accuracy is way too low for an instrumental location. In a seismotectonic context, the location of historical events can be used to estimate the seismic potential of an area, in terms of the magnitude of the greatest earthquake ever recorded. No direct association to faults can be made, since the accuracy of the instrumental location is not comparable with the size and extension of the seismogenic structure.

The fact that the magnitude of historical events is obtained by some kind of indirect computation, so that a comparison between instrumental and historical magnitudes is not feasible must be also taken into account; the values associated to older events are then roughly indicative of the phenomenon and may be used to distinguish strong events.

The estimated magnitude (M_S) of the historical events in the area does not exceed 5.6, correspondent to an intensity minor-equal to VIII MCS. In particular, the 1808 earthquakes (Figs. 2 and 6), which struck the lower Pellice Valley, caused much damage to the villages and the infrastructures in this area (Boschi *et al.*, 2000; Gruppo di Lavoro CPTI, 2004). According to Vassalli Eandi (1808), the 1808 seismic episodes triggered some landslides (between Torre Pellice and Villar Pellice) and caused some trenches (Luserna) and variations in the capacity and

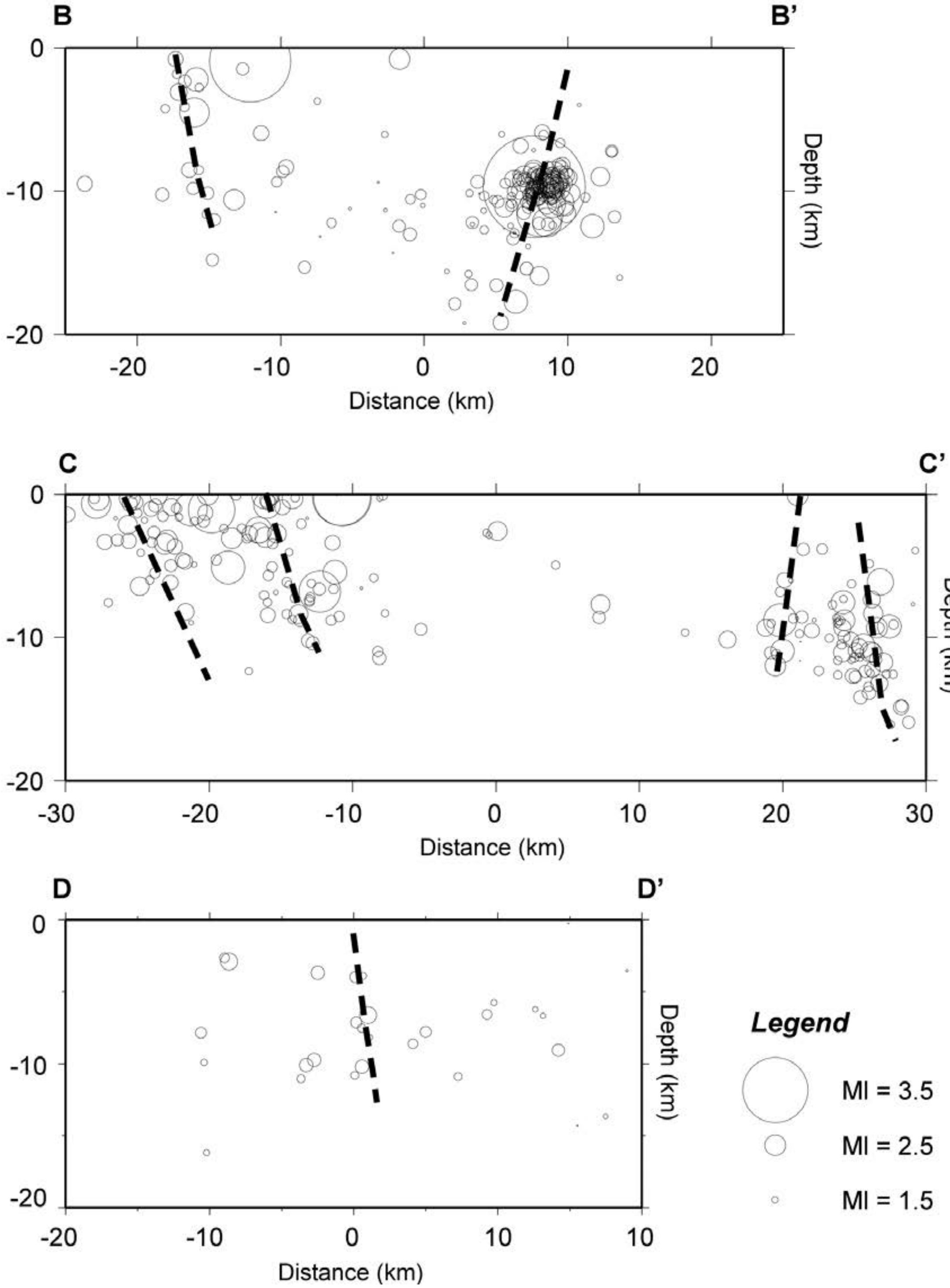

Fig. 8 - Seismic sections across the regional fault systems. The traces of the sections are shown in Fig. 6.

Table 2 - Locations and parameters of focal mechanisms. Y: year; M: month; D: day; H: hour; M: minutes; Lat.: latitude; Lon.: longitude; Depth: depth; M_L: Magnitude; Az1: strike of nodal plane; Dip1: dip of nodal plane; AzP: trend of P axis; DipP: dip of P axis dip; AzT: trend of T axis; DipT: dip of T axis; Ref.: references. B: Béthoux *et al.* (2007); E: Eva *et al.* (1997); N: Nicolas *et al.* (1990); P: Perrone *et al.* (2010b); S: Sue *et al.* (1999); U: Unpublished data.

Y	M	D	H	M	Lat. N (°)	Lon. E (°)	Depth	M_L	Az1	Dip1	Rake1	AzP	DipP	AzT	DipT	Ref.
1969	10	9	3	31	44.950	7.400	33.0	4.2	174	11	-118	29	54	198	35	U
1971	8	15	0	36	44.830	6.800	0.0	3.4	150	89	-179	15	1	105	0	E
1980	1	5	14	31	45.034	7.419	4.0	4.8	215	55	140	92	2	185	51	E
1981	2	8	4	30	45.152	7.439	5.0	4.4	335	40	60	266	9	153	69	E
1983	1	22	12	41	45.190	7.150	5.0	4.1	192	51	-155	41	43	142	12	N
1983	9	6	22	43	44.970	7.390	5.0	3.8	0	72	75	101	26	249	60	N
1989	12	13	8	8,2	44.788	6.715	9.8	2.3	5	30	-80	69	74	268	15	S
1990	1	20	19	25	45.135	7.131	1.1	2.1	315	90	-140	188	27	82	27	S
1990	2	11	7	0	44.965	7.547	16.0	4.2	120	55	60	231	6	333	65	E
1990	2	11	7	7	44.987	7.476	24.0	2.7	0	65	120	69	15	313	59	E
1991	2	11	15	44	44.865	6.738	6.0	3.8	45	65	-10	5	24	270	11	S
1991	2	13	12	55	44.868	6.750	5.6	2.8	135	45	-160	341	42	90	19	S
1991	2	13	15	50	44.868	6.750	3.9	3.0	45	75	-30	1	32	97	9	S
1991	7	29	8	46	44.851	7.215	8.8	1.1	45	25	-60	81	64	293	22	S
1991	8	12	22	56	44.803	6.766	2.7	2.2	0	35	-90	90	80	270	10	S
1992	9	13	5	0	45.105	7.610	4.3	3.4	350	50	90	80	5	260	85	U
1993	7	10	20	4	44.894	6.621	2.8	2.2	65	35	-40	61	57	300	19	S
1993	10	30	5	45	44.797	6.630	5.6	1.2	170	55	-70	131	72	246	8	S
1993	12	14	3	7,1	45.038	6.542	7.1	1.9	10	25	-70	61	67	265	21	S
1994	2	9	8	33	45.058	7.345	15.2	1.8	90	50	-20	60	40	316	16	S
1994	6	18	4	60	44.866	6.636	9.2	1.2	160	45	-80	156	83	63	0	S
1994	9	17	11	47	45.034	6.527	8.7	1.5	135	35	-100	262	78	52	10	S
1995	11	22	11	13	45.043	6.544	8.4	2.1	40	30	-30	36	52	267	26	S
1996	10	22	3	40	44.755	7.030	9.0	0.8	20	60	-110	249	68	124	13	S
1996	12	11	17	50	44.848	7.262	16.5	1.5	85	45	-60	74	69	334	4	B
1996	12	16	5	22	45.047	7.302	16.2	1.4	40	50	-140	245	53	343	6	B
1997	2	21	19	52	44.809	6.641	8.1	1.8	25	20	-80	98	65	287	25	S
1997	2	21	20	1,8	44.814	6.649	9.9	1.9	125	50	-80	88	81	208	5	S
1997	7	19	1	26	45.028	6.543	9.8	2.0	10	35	-60	25	69	259	13	S
1997	8	3	10	26	44.903	6.622	7.5	1.8	45	20	-40	64	55	276	31	S
1999	4	18	15	4	44.923	7.220	0.5	2.1	230	60	-150	85	41	178	3	P
2000	4	1	1	21	45.101	7.312	10.4	3.0	314	41	-49	306	62	196	10	P
2000	5	31	7	46	44.816	7.178	10.7	3.6	0	55	-90	285	25	105	65	U
2004	8	14	0	30	45.101	7.328	6.2	3.1	210	75	170	76	4	167	18	P
2004	5	17	6	9	45.108	7.334	10.1	3.0	20	70	-150	242	35	148	5	P

brightness of the springs. Some historical events (in 1884, 1905, 1940 and 1963) are also widespread near Briançon (Figs. 2 and 6). Only one of the latter earthquakes (1884) reached an intensity of VI-VII MCS (see Fig. 2 and Table 1). Only the 1904 seismic event is located between the two seismic arcs described above.

In this study, the relations between seismicity and fault network were investigated by comparing the available information in both the map-view (Fig. 6) and the cross-sections (Figs. 7 and 8). The total width of the cross-sections is 6 km. The locations of the seismic events have been taken from the database collected by the RSNI, established in 1963 as a single observatory which evolved into a local network, monitoring the seismicity of Liguria and Piemonte, from the 1980's onwards; the network expanded then to a regional one when more seismic stations were installed in Toscana and Valle d'Aosta. The data collected by the network have been regularly published in the ISC bulletins and contributed to the various national projects for the compilation of comprehensive Italian catalogues [CSI, Castello *et al.* (2006)]. Only the best located earthquakes (horizontal and vertical error less than 3 km) were selected by us from the instrumental seismicity recorded in the period 1985-2009. The compilation and location of seismic events was carried out by merging data of the network itself and those provided by neighbouring institutions that run a seismic network (ETH Zürich, LDG Paris, Sismalp Grenoble, Renass Strasbourg). Earthquakes were located with the Hypoellipse program (Lee and Lahr, 1980) using a one-dimensional (1D), layered, crustal velocity model adapted from the one proposed by Kissling *et al.* (1995). The location represents the best compromise between the accuracy that can be reached using seismograms affected by timing errors, phase picking uncertainties, uneven distribution of seismic stations and that required by seismotectonic studies on seismogenic structures of limited size. Fig. 6 shows the map of well-located epicentres. The magnitude of the seismic events spans from M_L 2.0 to 4.8.

In the western part of the studied area, corresponding to the Briançonnais seismic arc, epicentres tend to align along a NNW-SSE direction joining the LF, as already pointed out by recent works (Sue *et al.*, 1999, 2002, 2007; Sue and Tricart, 2003). The depth of the hypocentres is mostly confined to the shallower 10 km (see seismic sections of Figs. 7 and 8). In the innermost part of the chain, in correspondence with the Piedmont seismic arc, epicentres are aligned along a roughly N-S direction and resemble, within their location error, the trace of the LTZ. Here, seismicity extends down to 20 km of depth (see Figs. 7 and 8). Between the two seismic arcs, epicentres seem to form sub-parallel clusters in a NE-SW direction, in some cases joining the Transverse Fault System especially in the middle Susa and Chisone valleys (Figs. 5 and 6). Hypocentres are mostly confined to relatively shallow crustal levels (10-15 km, see section C-C' in Fig. 8). In the westernmost Po Plain, by contrast, the hypocentres become abruptly deeper and reach more than 40 km of depth (Cattaneo *et al.*, 1999).

In the seismic cross-section A-A' (Fig. 7), which overlaps the geological section of Fig. 3 and crosses the central part of the area, hypocentres design steeply dipping alignments that correlate, within the location error of the earthquakes, with those of the LTZ and LF at depth.

The section B-B' (Fig. 8) crosses the northern part of the area. This section shows that seismicity is mostly concentrated in correspondence with the northern segments of the LTZ and of the CFZ, where two, steeply dipping surfaces are highlighted by the hypocentres. This could suggest a present-day activity for the CFZ, even if no clear geological evidence seems to confirm such a hypothesis yet. No seismic events seem to be, instead, related to the CL.

The section C-C' (Fig. 8), which crosses the southern part of the area, shows also how hypocentres are correlated with the LF in the western part of the area, mostly confined in the shallower 10 km of crustal thickness. In the eastern part of the section, hypocentres highlight some sub-vertical surfaces that could be related to the current activity of roughly N-S faults, that may have also caused the development of Pleistocene intermountain basins in the Chisone and Pellice valleys (see above).

Finally, in the section D-D' (Fig. 8), perpendicular to the Transversal Fault System of the middle Susa and Chisone valleys, hypocentres seem to define a steeply dipping surface extending down to 10 km of depth, in correspondence to these faults.

In order to get more inferences about the characteristics of the mapped faults, the focal mechanisms available for the area were compared with the fault kinematics in order to estimate the compatibility between geological structures and seismological data.

A comprehensive collection of the majority of the data used in this work has been published on the Earthquake Mechanisms of the Mediterranean Area (EMMA) database (Delacou *et al.*, 2004; Vannucci and Gasperini, 2004; Perrone, 2006, 2010b; Béthoux *et al.*, 2007). The compilation of the focal mechanisms for the main recent earthquakes shows different solutions between the chain and the adjacent sectors of the Po Plain (Fig. 6 and Table 2). In the chain, transtensive and extensional solutions are predominantly found, indicating an extensional regime roughly perpendicular to the trend of the chain. These solutions are in fact consistent with sub-horizontal ENE-WSW trending T-axes with steeply dipping P-axes. In the Po Plain, by contrast, transpressive solutions are prevalent, mostly indicating an E-W shortening (Eva *et al.*, 1997; Eva and Solarino, 1998).

Close to the LTZ most of the focal mechanisms show roughly N-S striking, steeply dipping nodal planes (Fig. 6), in agreement with the geometry of this structure. West of the LTZ these nodal planes are associated both to strike-slip and transtensional/extensional solutions. East of the LTZ, instead, mostly transpressive solutions are observed. Also along the LF a correspondence between the geometry of the faults and that of nodal planes of focal mechanisms is observed. Focal solutions of this area are, in fact, characterised by N-S to NNW-SSE striking nodal planes (Fig. 6), associated to extensional, transtensive and strike slip solutions (Sue and Tricart, 2003; Sue *et al.*, 2007). Along the TF, the few focal mechanisms calculated for this area mostly show strike-slip and transtensive solutions. Nodal planes are usually NE-SW and NW-SE striking and steeply dipping. Conversely, epicentres along the CFZ and the southern continuation of the Canavese Line are almost absent, suggesting a scarce activity at present.

Geodetic data are, in general, in agreement with the seismological ones. The available GPS data indicate that the area under study is characterized by low-deformation rates [minor than 2 mm/year, Calais *et al.* (2002)] and show that the more elevated axial part of the chain is currently undergoing a WNW-ESE lengthening while the boundaries of the chain are shortening. In particular, the lengthening is of the order of about 1.4±0.4 mm yr^{-1} while in the westernmost Po Plain 1.0±0.5 mm yr^{-1} of shortening is observed.

5. Discussion

The integration of surface geology and seismological data, in map view (Fig. 6) and cross-sections (Figs. 7 and 8), allowed us to investigate the relations of both the geometry and the kinematics between the faults and seismicity in the central Western Alps. As a general comment, a correspondence between the regional faults and the distribution of the epicentres is observed (Fig. 6).

In the eastern part of the analysed area, the trend of epicentres resembles, within the location errors, the trace of the Lis-Trana Deformation Zone and, westwards, of the PGFS. Both mesoscale faults affecting Pleistocene deposits and the occurrence of Pleistocene intermountain basins, probably induced by the LTZ activity (see above), suggest that both the LTZ and the PGFS may have been active in the Quaternary. Most of the epicentres of the strong historical earthquakes are also aligned along the LTZ (1886, 1914, 1927, 1969, 1980; Figs. 2 and 6) and close to the PGFS (1449, 1507). In the cross-sections (Figs. 7 and 8), the geometry of the activated fault planes resemble that of the mapped faults (LTZ). Near the LTZ, most of the focal mechanisms show roughly N-S striking, steeply dipping nodal planes. West of the LTZ, the nodal planes are characterized by strike-slip movements while east of this structure transpressive solutions prevail (Fig. 6). In the western part of the analysed area, the epicentres show a correspondence with the LF. Historical earthquakes that struck this sector are mostly concentrated near the village of Briançon (1884, 1905, 1940, 1963; Figs. 2 and 6). Here, the very shallow seismicity strongly supports the connection between surface structures and seismicity, as already stressed by Sue *et al.* (2007). Moreover, the hypothesis that the current seismicity is associated with the activity of the LF is confirmed by the NNW-SSE orientation of the nodal planes of focal mechanisms in this area. In the central part of the area, the seismicity seems to be associated to the current activity of the NE-SW faults (Transverse Fault System), which show rare evidence of Quaternary tectonic activity. No strong historical earthquakes struck this area. Also focal mechanisms show mostly NE-SW nodal planes in this area, indicating a probable connection between activated and mapped faults.

Structural and fault-slip data indicate that, since the Late Oligocene, in the inner Western Alps the regional post-metamorphic faults show complex polyphasic activity, characterized by both transcurrent and normal movements. Recent works [see Perrone *et al.* (2010a) with reference therein for a more detailed discussion] have proposed that in the axial sector of the Western Alps these regional fault systems accommodated a bulk dextral transtensive regime (see Fig. 4), induced by the coexistence of different driving forces acting at regional scale. The strong dextral component of movements along the major faults that bounds the Alpine Chain both in the external [Penninic Front, Perello *et al.* (1999); Chamonix-Rhone Line, Gourlay and Ricou (1983); Longitudinal Faults, Sue and Tricart (2003); NW-SE Fault System, Tricart (2004)] and in the inner sectors [Canavese Line, Schmid *et al.* (1987, 1989); LTZ, Balestro *et al.* (2009b)] may be related to the counterclockwise rotation of the Adria plate since the Oligocene (Collombet *et al.*, 2002). The normal movements may instead be caused by the body forces acting inside the more elevated part of the chain, as already proposed by the some authors (Eva *et al.*, 1997; Sue and Tricart, 2003; Delacou *et al.*, 2004, 2008). Inside the chain, these gravitational body forces tend to equilibrate the belt by balancing the gravitational potential energy between its core and its margins. Uplift is therefore expected at the core of the belt, as an isostatic response to this equilibration. Champagnac *et al.* (2007), however, suggested that climatic change and erosion should also be considered important factors driving the uplift of the Western Alps.

In the analyzed area, strike-slip movements were consistent with a NNE-SSW to E-W shortening and with a N-S to NW-SE extension; normal movements along these faults were instead consistent with an E-W to NW-SE extension and with a sub-vertical shortening direction (Fig. 4). Focal mechanisms show strike-slip, transtensive and extensional solutions inside the chain while transpressive solutions are prevalent at the extreme limit with the Po Plain. Strike-slip solutions are consistent with a N-S to NE-SW shortening with an E-W to NW-SE extension. Normal solutions are, instead, consistent with a steeply dipping shortening direction with an E-W to NW-SE extension (Eva *et al.*, 1997; Sue *et al.*, 1999; Perrone *et al.*, 2010b). The agreement between structural and seismological data both in terms of geometry and kinematics indicate that the dextral transtensive regime in the central Western Alps is still ongoing, as already shown in recent works (Sue and Tricart, 2003; Delacou *et al.*, 2004, 2008; Sue *et al.*, 2007). By contrast, in the westernmost Po Plain only transpressive solutions are present. These data are also confirmed by available GPS data which show that the central Western Alps are extending while the westernmost Po Plain is undergoing contraction (Delacou *et al.*, 2004, 2008). This suggests that convergence between Adria and Europe is still ongoing even if the magnitude of recent earthquakes and GPS data indicate very low deformation rates (Calais *et al.*, 2002; Delacou *et al.*, 2004, 2008). Available crustal velocity field data also confirm the counterclockwise rotation of the Adria plate (Nocquet and Calais, 2003).

Deep geophysical data (Paul *et al.*, 2001) suggest that the LTZ may overlap the western side of the high velocity anomaly of the Ivrea body, considered a slice of the Adriatic mantle (Schmid and Kissling, 2000) or a lower crust material (Scafidi *et al.*, 2009), suggesting, moreover, that surface structures may be rooted at depth into the boundary between geological bodies characterized by a strongly different density.

6. Summary and conclusions

This work merges, with unprecedented details, new geological, structural and seismological data for the central Western Alps, a wide portion of the Western Alps, where an updated seismotectonic model accomplishing all the available data was lacking. This integrated approach allowed us to investigate the connection between faults and seismic activity. The data presented indicate that since the Late Oligocene a dextral transtensive regime is active in this area. At the regional scale, this transtensive regime induced a complex spatial and temporal strain partitioning between strike-slip and normal movements along the faults dissecting this sector of the Western Alps. Three regional fault systems may be connected with the current seismic activity: the LF, in the western part, the TF, in the central part, and the Lis-Trana Deformation Zone (LTZ), on the eastern side. As, in general, trace length of the potentially seismogenic faults dissecting the central Western Alps are not longer than 30-40 km, an earthquake not exceeding a maximum magnitude 6.5 might occur in the area (Wells and Coppersmith, 1994), as the estimated magnitude of the strongest seismic events (see Table 1) confirms.

Our data indicate that the Canavese Line could be interpreted as the structure that decouples the current stress regime in the innermost Western Alps, as proposed also by Béthoux *et al.* (2007) in the south Western Alps.

At a crustal scale these data fit with the geodynamic models that predict a counterclockwise rotation of the Adria plate (see Calais *et al.*, 2002; Collombet *et al.*, 2002). It is worth noting that some papers (D'Agostino *et al.*, 2008; Mantovani *et al.*, 2009) suggested that the Adria plate is currently fragmented into different blocks by regional faults. According to these works the extensional collapse of the Western Alps should be connected with the fragmentation of the Adria plate.

The proposed geodynamic model does not fit with a current tectonic activity of the Stura fault (STF in Fig.1; Giglia *et al.*, 1996). It must, however, be remarked that no geological evidence of Quaternary activity for this fault has been found [see Perrone *et al.* (2010b) for a more detailed discussion about the geodynamic model].

This study also shows that the integration between different techniques like surface geology and seismology represents a fruitful approach even for the seismotectonic analysis of areas characterized by low-deformation rates and by very scarce geological evidence of current tectonic activity (tectonic deformations affecting Pleistocene deposits are in fact mostly observed). This study, moreover, furnishes for the first time, new, detailed information about the relations between faults and seismicity of a wide and highly populated part of the Italian Western Alps, representing the basis for an appropriate and more adherent seismic macrozonation of this area.

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