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Seismotectonic investigations in the inner Cottian Alps (Italian Western Alps): an integrated approach

Gianluigi Perrone(1), Elena Eva(2), Stefano Solarino(2), Paola Cadoppi(1,3,4), Gianni Balestro(1,3), Gianfranco Fioraso(3), Sergio Tallone(3)

(1) Dipartimento di Scienze della Terra, Università di Torino, Via Valperga Caluso 35, Torino, Italy

(2) Istituto Nazionale di Geofisica e Vulcanologia,-CNT, c/o Dipteris Dipartimento Studio del Territorio e delle sue risorse-Università degli Studi di Genova, Viale Benedetto XV,5 16132 Genova, Italy

(3) CNR-IGG Unità di Torino, Via Valperga Caluso 35, Torino, Italy

(4) NATRISK - Centro Interdipartimentale sui Rischi Naturali in Ambiente Montano e Collinare - Università di Torino - Via Leonardo da Vinci 44, Grugliasco (IT)

Corresponding author: Gianluigi Perrone, E-mail address: gianluigi.perrone@unito.it, tel: +390116705187, fax: +390116707155

Abstract

This work integrates the results of recent geological-structural studies with new seismological data for the inner Cottian Alps to investigate the connection between faults and seismicity. The major post-metamorphic tectonic feature of this sector is represented by a N-S structure, named Lis-Trana Deformation Zone (LTZ). Since the Late Oligocene this structure accommodated right-lateral (Late Oligocene-Early Miocene) and subsequently normal (post-Early Miocene) displacements. In the Pleistocene, the activity of the LTZ seems to have caused the development of lacustrine basins inside the valleys that drain this sector of Western Alps. The present-day seismicity joins the northern part of the LTZ and, southwards, other minor sub-parallel structures. In transversal cross-section hypocentres highlight steep surfaces. Focal mechanisms calculated along this structure show both extensional and strike-slip solutions, mostly with one roughly N-S striking nodal plane.

Both sub-horizontal (with NE-SW to ENE-WSW trend) and steeply dipping P axes with N-S to NW-SE sub-horizontal T axes are observed.

Even if clear evidence of Quaternary tectonic activity in the area is missing, on the basis of the available seismological and geological data we propose that in the inner Northern Cottian Alps the present-day seismic activity may be connected to the LTZ, interpreted as minor sub-parallel fault strand of the Canavese Line. The kinematics of this structure is consistent with the focal mechanisms calculated in this area. Structural and seismological data indicate that LTZ is active under a bulk dextral-transtensive regime since the late Oligocene in the inner Cottian Alps, in agreement with the data published for the adjacent domain of the chain.

Keywords: Western Alps, active faults, seismology, structural geology, brittle tectonics.

Introduction

The inner Cottian Alps (Fig. 1), one of the mostly populated sectors of the Alpine chain, are located in an area of a low- to moderate- magnitude seismicity (Ml<5; Capponi et al., 1981; Eva et al., 1990) even though characterized in the past by some earthquakes (Fig. 1) causing both material and social damages (VIII degree Mercalli scale (MCS); Camassi and Stucchi, 1997).

Although the frame of seismicity is quite well known, the relation between faults and earthquake sources is still under debate due to the fair knowledge of the fault network affecting this area. Moreover, the low deformation rates and the occurrence of several glacial-interglacial cycles during the Pleistocene partly masked the morpho-structural evidences of the recent tectonic activity.

Because of this gap, up to now, seismic activity has been interpreted as completely separated from all the surface structures. Instead, at depth the seismicity clearly seems to be localized along the western edge of the highly velocity anomaly of the Ivrea body (Bethoux et al., 2007; Sue et al., 2007).

Recent studies (Balestro et al., 2009a, Perrone et al., 2009), based on detailed field mapping and structural analysis, allowed to locate the trace and characterize the size and extension of the regional faults that dissect the inner Cottian Alps. In this paper we combine the results of these novel studies and updated seismological data with the aim to investigate the relations between mapped faults and seismic activity.

Previous studies (Eva et al., 1997; Eva and Solarino, 1998; Delacou et al., 2004) underlined a sharp change in the stress regime between the inner sector of the chain and the westernmost Po Plain. At present the boundary between those two sectors is still poorly known. Different geodynamic models have been proposed to explain this dual stress regime such as: 1) westward thrusting at depth with secondary tensional effects at very shallow crustal levels (Eva et al., 1997), 2) E-W regional dextral transpression combined with gravity forces (Delacou et al., 2004; 2008), 3) south-westward extrusion (Sue et al., 2007; Bethoux et al., 2007), 4) slab break-off (Sue et al., 1999), 5) westward extrusion (Giglia et al., 1996).

Despite the relatively small size of the analyzed area, the study here presented may contribute to furnish more details on the current dynamics of this sector and, as a consequence, of the whole Western Alps.

Seismotectonic setting

Instrumental and historical seismicity

In the Cottian Alps the present-day seismicity is mostly concentrated at the boundary with the Po Plain, along a roughly N-S trending zone (Fig. 1). This alignment of the seismicity, in the literature known as Piémontais seismic arc (Rothé, 1941; Eva et al., 1990), borders the eastern side of the Dora Maira Unit, that extensively outcrops in this sector. Instrumental seismicity is usually characterized by low to moderate magnitude (Ml=1-5). Inside the chain, the depth of the hypocentres is limited to the upper 15-20 km, whereas earthquakes in the westernmost Po Plain are distributed throughout the entire crustal thickness of 40-50 km (Eva et al., 1997; Eva and Solarino, 1998). In the South-Western Alps this seismic activity is mostly located along the western boundary of the high-velocity Ivrea body (Bethoux et al., 2007), considered as a slice of Adriatic mantle (Schmid and Kissling, 2000; Finetti, 2005) or as lower crust material (Scafidi et al., 2009).

The focal mechanisms (Eva et al., 1997; Eva and Solarino, 1998; Delacou et al., 2004; Béthoux et al., 2007), indicate a contrasting stress regime in the inner Cottian Alps (Fig. 2; Table 1). Transpressive solutions, with sub-horizontal roughly E-W trending P axes, are in fact prevalent beneath the westernmost Po Plain. Conversely, transtensive and extensional solutions, with steep P axes and sub-horizontal ENE-WSW trending T axes, are widespread inside the chain (Eva et al., 1997; Eva and Solarino, 1998; Sue et al., 1999; Delacou et al., 2004). Bethoux et al. (2007) proposed that the tectonic boundary between those two sectors may correspond to the southern prolongation of the Canavese Line in the South-Western Alps.

Historical records of seismic events display as similar distribution as the instrumental seismicity. Most of the historical earthquakes that struck the Cottian Alps are, in fact, concentrated in its innermost sector, aligned along a roughly N-S direction (Fig. 1). Those earthquakes were felt in the villages located at the mouths of the main valleys of this sector of the chain. Magnitudes of the larger historical events range from M_S= 4.0 to 5.5 (Camassi and Stucchi, 1997) with an Intensity (Io) of VI-VIII degree MCS (Camassi and Stucchi, 1997). In particular the 1914 October 26 event (M_S= 4.7) reached an intensity Io=VII in the villages around Coazze (Lower Sangone valley, Fig.1). The 1808 earthquake, the largest damaging event that struck the area, reaching an intensity Io=VIII with a M_S=5.5, was felt in the villages of the Lower Chisone and Pellice valleys. This earthquake triggered some landslides (between Torre Pellice and Villar Pellice) and caused some trenches, fissures, variations in the regime of the springs and water overflowing in small channels (Vassalli Eandi, 1809; Boschi et al., 1995).

GPS data

In general GPS data indicate that the deformation inside the chain is limited (less than 2 mm/yr; Calais et al., 2002; Delacou et al., 2004; 2008). Recently published GPS measurements indicate contrasted types and rates of deformation inside the Western Alps .

Inside the chain, GPS measurements roughly indicate NW-SE extension, perpendicular to the trend of the chain. Along a NW-SE section across the W-Alps, between Lyon and Modane, a lengthening at a rate of 1.4±0.4 mm/yr is observed. By contrast, the westernmost Po Plain is currently undergoing shortening with 1.0±0.5 mm/yr of E–W to NW–SE convergence between Modane and Turin (Calais et al., 2002).

In general, despite the limited accuracy of GPS and time span of observation of less than 10 yr, geodetic data are in good agreement with seismotectonic data, indicating that the core of the chain is currently undergoing an orogen-perpendicular extension, whereas the border of the chain are still in compression (Delacou et al., 2004; 2008).

Tectonic setting

In the inner Cottian Alps both continental (Dora-Maira and Ambin Unit) and oceanic-derived (Piedmont Zone) metamorphic units, belonging to the Penninic Domain of the Western Alps, are present (Fig. 3). Well preserved peridotites outcropping in the core of the Lanzo ultramafic complex (La in Fig. 3), mostly escaped Alpine metamorphism, represent a slice of lithospheric mantle (Elter et al., 2005 and reference therein).

The above mentioned tectonic units were superposed in HP-LT metamorphic conditions. The nappe stack were subsequently deformed by km-scale south verging folds developed in greenschists facies metamorphic conditions. Currently no radiometric ages are available to constrain the age of these tectonic phases. Since the Late Oligocene the Alpine metamorphic units were juxtaposed on the South-Alpine ones, lacking in Alpine metamorphic imprint, through the Canavese Line (CL in Fig. 3), a first-order regional tectonic discontinuity (Schmid et al., 1989; 2004). Even if in the analysed area (Fig. 3) this tectonic contact is buried beneath the Plio-

Quaternary deposits of the Po Plain, some authors (Bigi et al., 1990; Mosca et al., 2009) on the basis of subsurface data prolonged the CL in the South-western Po Plain.

The development of a complex network of semi-brittle to brittle regional faults, characterized by a strong strike-slip component of movement (Balestro et al., 2009b; Perrone et al., 2009), is related to the late- to post-metamorphic tectonic evolution of the Cottian Alps. Available zircon (ZFT) and apatite (AFT) fission track data (see Fig. 3; Bernet et al., 2001; Cadoppi et al., 2002; Balestrieri et al., 2004; Malusà et al., 2005; Tricart et al., 2007) indicate that the activity of these faults started since the Oligocene.

The major semi-brittle to brittle tectonic feature of this area corresponds to a N–S, sub-vertical structure that extends, for about 35 km, from the Lower Lanzo to the Lower Sangone valley, named Lis–Trana Deformation Zone (LTZ in Fig. 3; Balestro et al., 2009 a,b). In map-view the LTZ is 1-1.5 km wide and is characterized by a roughly nested geometry, formed by N-S major faults linked by minor NNW–SSE fault segments. The LTZ juxtaposes the Lanzo Ultramafic Complex with other units belonging to the Piedmont Zone, in its northern part, and with the Dora-Maira Unit, in its southern part. Approaching to the LTZ both a steepening and a clockwise rotation (from the E-W to the N-S direction) of the lithological contacts and the syn-metamorphic structures is observed. These features suggest a strong dextral component of displacement for this structure. The right-lateral sense of displacement is also confirmed by the mesoscale fault-slip data. N-S trending reverse faults and folds indicate also a minor shortening component of displacement for the LTZ. These data allowed to interpret the LTZ (Fig. 3) as a flower structure (*sensu* Harding 1985). A seismic section carried out in the Po plain for oil exploration south of the LTZ (Cassano et al., 1986; Mosca, 2006) shows that the metamorphic basement is displaced by roughly N-S steep faults. This suggests that the LTZ may extend southwards, beneath the Plio-Quaternary deposits of the Po Plain. On the basis of its structural features the LTZ may be considered, at a regional scale, as a sub-parallel minor fault strand of the postulated prolongation of the Canavese Line (Balestro et al., 2009a).

West of the LTZ two E-W striking, steep faults are also present (Perrone, 2006; Perrone et al., 2009; 2010), named the Sangone Fault system (SFS) and the Chisone fault (CF). Fault-slip data indicate that the SFS is characterized by strong sinistral component of movement whereas currently no kinematic data are available for the CF. Between the CF and SFS are moreover developed some other minor faults, including N-S right-lateral faults (Pinasca-Gran Dubbione Fault System, PGFS in Fig. 3), NE-SW oblique (normal-left) faults and NW-SE reverse faults. The development of NNW-SSE to N-S trending folds are also associated to these structures.

Regarding the post-metamorphic tectonic evolution, geometrical, kinematic data and overprinting relations allowed to distinguish two different structural associations in the analysed area. These two structural associations correspond to different faulting stages characterizing the brittle tectonic evolution of the inner Cottian Alps (Balestro et al., 2009a; Perrone et al., 2009; 2010). Available zircon and apatite fission track data may allow to constrain the age of the faulting events.

The first faulting stage (**faulting stage A** in Fig. 4) is related to the development of a complex strike-slip fault network. The major tectonic feature is represented by the LTZ, characterized by right-lateral movements, while the CF and SFS, characterized by strong sinistral component of movement, are interpreted as second-order antithetical structures. The faults developed between the CF and SFS would represent, hence, third-order structures (Fig. 4). Their geometry and kinematics indicate that these structures formed under a bulk regional NE-SW shortening and a NW-SE extension (Balestro et al., 2009a; Perrone et al., 2009). Paleostrain analysis of mesoscale fault-slip data also confirms a NE-SW shortening direction (Fig. 4). The development of foliated cataclasites and cataclasites indicates that this faulting stage may have occurred at 4-10 km depth (see Sibson, 1977; Scholz, 1988). Assuming a normal geothermal gradient (25-30°C/km), this depth range is compatible with that of closure temperature of the zircon (Rahn et al., 2004; Reiners and Brandon, 2006), which in the analysed area dates between 34,6-29,7 Ma (Oligocene-Early Miocene). On the regional scale, the faulting stage A may be roughly coeval with the dextral activity of the Canavese Line (Schmid et al., 1989).

A subsequent faulting stage (**faulting stage B** in Fig. 4), is indicated by the normal/transtensive movements observed along the LTZ minor structures, in some cases cross-cutting or overprinting the right-lateral ones. Also along the PGFS some N-S normal faults, cross-cutting the earlier strike-slip structures, have been observed. Normal faults, moreover, are associated to different types of fault-rocks (tectonic microbreccias and gouge) with respect to the transcurrent ones (cataclasites and foliated cataclasites). These data suggest that, as for the LTZ, also in this sector normal movements along N-S faults post-date strike-slip ones (Perrone et al., 2009). Kinematic analysis of fault-slip data indicates a sub-vertical shortening direction with an WNW-ESE to NW-SE extension (Fig. 4). The development of incoherent fault rocks (tectonic breccias and gouge) indicates that this faulting stage may have occurred at very shallow crustal levels (1-4 km depth). This depth is compatible with that of the closure temperature of the apatite (Reiners and Brandon, 2006), ranging between 27 and 13,1 Ma. Faulting stage B is therefore considered as post-Early Miocene and may be coeval with the extensional regime outlined by several authors in the adjoining sectors of the Western Alps (Sue et al., 2007; Champagnac et al., 2006; Sue and Tricart, 2003).

This kinematic evolution fits well with a model of dextral-transtension in the inner Western Alps (Fig. 4a), as proposed by some authors (Sue and Tricart, 2003; Delacou et al., 2008; Malusà et al. 2009; Perrone et al., 2010).

Plio-Quaternary tectonic activity

Clear field evidences of Plio-Quaternary tectonics are not observed in the analysed area, due to a number of factors, as already stressed. Nevertheless some geological features, described by Collo (1996) and by Collo and Giardino (1997), can be related to the tectonic activity of some of the faults that dissect this part of Western Alps.

The most important of these features is represented by the occurrence of Early Pleistocene lacustrine deposits (Fig. 5 and 6), reaching a thickness of 250 mt, in the Lower Chisone and Lower Pellice valleys bottom. Transversal profiles to these valleys (Fig. 6), based on borehole stratigraphies, reveal how the lacustrine successions unconformably rest onto the Alpine basement. Lacustrine deposits are separated from the Western Po Plain by a twofold rocky threshold localized at the Chisone and Pellice valley mouths. Field mapping of Quaternary deposits and landforms showed that the Pleistocene glaciers never reached the lower Pellice and Chisone valleys (Sereno Regis, 1985; Giraud, 1985), suggesting that these lacustrine basins are not of glacial origin. In the Chisone valley the lacustrine deposits generally dip 10°-20° to N-NE and show soft-sediment deformations (include both metric scale folds and faults) (Collo, 1996; Collo and Giardino, 1997). As well in the Pellice valley soft-sediment deformations were observed inside lacustrine succession probably due to liquefaction phenomena (Collo, 1990). On the basis of these data, Collo (1996) proposed that differential uplift occurred in the transition mountain-plain area between Susa and Po valleys hampering the drainage at the valley mouths. At present the geometry of these threshold is still not known in detail, even if it can be reasonably assumed that these structures may be represented by faults transversal to the valley axis. A roughly N-S fault system, bordering the Alpine chain, is shown in the interpretation of the seismic lines carried out in the Westernmost Po Plain (Mosca, 2006; Bertotti and Mosca, 2009). In the Pleistocene times the activity of these faults (Fig. 5), that could correspond to the southern prolongation of the LTZ, may have caused the uplift of both the bedrock at the Pellice and Chisone valley mouths and the inselbergs of the Rocca di Cavour and Madonna di Monte Bruno (two outcrops of metasediments and metagranitoids, belonging to the Dora Maira Unit, aligned along a N-S direction).

By contrast, no clear anomalies in the longitudinal profile of the Lower Susa valley can be observed (Carraro et al., 2005; Cadoppi et al., 2007) that could suggest a differential uplift transversal to the valley in the Quaternary times. In the subsoil of the Susa valley mouth and in the adjoining western Po Plain, beneath the Quaternary glacial and fluvial deposits, a thick succession of fluvio-lacustrine “Villafranchian” deposits (*sensu* Caramiello et al., 1996), referred to the Middle Pliocene-Early Pleistocene times, is found. These deposits represent a regressive succession with a typical aggradational character, widespread in the whole western Po Plain, which ended the Tertiary sedimentation and preceded the typical fluvial and glaciofluvial Pleistocenic succession. In the Middle-Late Pleistocene several glacial pulses reached the Susa valley mouth and formed a wide morainic amphitheatre (Rivoli-Avigliana Morainic Amphitheatre). In the lower segment of the Susa valley the Alpine glaciers, which strongly deepened the valley, almost completely removed the Pliocene-Early Pleistocenic fluviolacustrine succession.

Possible evidences of a recent activity of the LTZ also derive from the observations of mesoscale brittle deformations in the Plio-Quaternary deposits covering the Lanzo Ultramafic Complex. Coarse grained conglomerate of supposed Lower Pleistocene age displaced by faults were found in three sites. The first two outcrops (sites A, B in Fig. 5) are located along the LTZ, in the left side of the Lower Susa valley, whereas the third (C in Fig. 5) is located east of the LTZ, along a minor fault strand.

In the site A a N-S striking fault displaces these deposits; striae on fault surface indicate an almost pure dip-slip component, even if a clear sense of movement is not observed (Fig. 7a,b). A tectonic origin for this structure is supported by the occurrence of sub-parallel brittle shear zones that dissects the bedrock and by the absence of glacial deposits and related landforms near this site. In the site B ENE-WSW striking faults juxtaposes the deposits over the bedrock (Fig. 7c). Kinematic indicators suggest a strike-slip movement for these structures, even if slickensides indicate reverse movements as well. These movements seem not compatible with that of the glaciers that filled the Susa valley in the Plio-Pleistocene times. For this reason a glaciotectonic origin is improbable also for these deformations. Finally, in the site C a NNE-SSW normal fault displaces Lower Pleistocene alluvial fan deposits. The fault juxtaposes diamicton, in the hanging-wall, with coarse-grained conglomerate, in the footwall (Fig. 7d). The location of this site at the eastern margin of the Lanzo Ultramafic Complex strongly supports a tectonic origin even if a possible gravitational origin, related to the collapse of a thickened alluvial fan, may be yet not excluded.

Evidence for a recent tectonic activity of the Pinasca-Gran Dubbione Fault system (PGFS) derives by both geomorphological and geological observations. Collo and Giardino (1997), in fact, found Pleistocene deposits displaced by a N-S reverse fault in the Gran Dubbione valley. Moreover the PGFS strongly influences the river drainage because straight valleys, at times with asymmetric transversal profiles, are developed along these structures. In correspondence of the PGFS also steep scarps are present, suggesting a possible interaction between tectonic uplift and fluvial erosion.

Seismological data: seismicity and focal mechanisms

Relations between seismic activity and faults were investigated by selecting the best located earthquakes from the database of the instrumental seismicity recorded by the Seismic Network of the Western Italy (RSNI) for 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, LDS Paris, Sismalp Grenoble, Renass Strasbourg). Earthquakes were located with the Hypo-Ellipse program (Lee and Lahr, 1980) using several one-dimensional (1-D) layered velocity models along the path to take into account the different crustal structures beneath the seismic stations. The magnitude spans from Ml 2.0 to 4.8. The distribution of the hypocentres, with maximum horizontal and vertical location errors of 3 km, were compared with the fault pattern in the analysed area both in map view and cross-section. The location errors used for the selection represent 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.

Four new focal mechanisms have also been calculated where epicentres join the traces of the mapped faults in order to constrain: *i)* the geometry and kinematics of the activated faults *ii)* the present-day stress regime.

The map of Figure 8 shows the distribution of well-located epicentres in the Northern Cottian Alps.

Except for some deep earthquakes concentrated in the Westernmost Po Plain (Fig. 1, 8) that reach 30-40 km of depth, most of seismicity is localized at relatively shallow crustal levels (in the first 10-15 km). Figure 8 shows how most of the present seismicity is aligned along a NNE-SSW direction joining the northern segment of the LTZ while, moving southwards, the epicentres are aligned along the PGFS. Other earthquakes appear to define short fault segments oriented sub-parallel to the strikes of the major faults. It is worth noting that epicentres along the Canavese Line are very few or absent.

The four new focal solutions (Fig. 9; tab. 2) include two earthquakes (mainshock with aftershock event) occurred during the seismic sequence that struck the lower Susa valley in May 2004. The other two correspond to the events of April 18th, 1999 and April 1st , 2000. Seismic events were selected and weighted on the basis of their magnitude (Ml > 2.8), number of polarities on the focal sphere (> 20) and azimuthal coverage of stations (gap < 70°). The FPFIT program (Reasenberg and Oppenheimer, 1985) was used to calculate the focal mechanisms and the orientation of P and T axes of each seismic event. The uncertainties of fault parameters (strike, dip and rake uncertainty) for the fault plane solutions do not exceed 10°-20°. These new data update the catalogue of the focal mechanisms already published for this sector of the Western Alps (Eva et al., 1997; Eva & Solarino, 1998; Sue et al., 1999; Delacou et al., 2004; Bethoux et al., 2007).

In Figure 8 the fault plane solutions are plotted on the tectonic scheme of the study area. The focal solutions of the May 2004 seismic sequence show strike-slip mechanisms with one NNE-SSW right-lateral nodal plane. P axes are sub-horizontal and trend ENE-WSW to NE-SW with sub-horizontal NW-SE to NNW-SSE striking T axes. The other two events (4/18/99 and 4/1/2000) show transtensive solutions; P axes are E-W oriented and moderately dipping, whereas T axes are sub-horizontal and trend almost N-S.

Data Integration and analysis

By merging surface geology and seismological data, either in map view (Fig. 8) and cross-section (Fig. 10), we are able to investigate the connection between faults and seismicity: this linkage is then used for the comparison between the focal mechanisms of recent earthquakes and the kinematics data relative to the LTZ and minor associated structures.

A good correspondence between the faults and the distribution of the epicentres can be observed in Figure 8. In particular epicentres resemble, within the location errors and presumed dip of the faults, the trace of the Lis-Trana Deformation Zone (LTZ) and, westward, of the N-S faults of the Pinasca-Gran Dubbione Fault System (PGFS). Historical earthquakes (Ms> 4.5; Fig. 8) are also mostly located along the trace of the LTZ (1914, 1969 and 1980 events) and its southern prolongation (1311, 1808 and 1858 events). Some historical events (1449, 1507 and 1886) also occurred close to the Pinasca-Gran Dubbione Fault system.

Two geological cross-sections have been drawn, perpendicular to these faults (Fig. 10). The width of the cross sections is 10 km. Focal mechanisms, calculated in this work and obtained by published data, are projected along the sections. Black lines are traced where hypocentres are considered to lie onto the activated fault plane.

Section A-A’ crosses the northern part of the LTZ, where a good correspondence between the trend of the epicentres and the faults is observed (Fig. 10). In cross-section, the projected hypocenters resemble an alignment steeply dipping to the west, roughly coincident with the LTZ towards the surface. Near the LTZ most of focal mechanisms (seismic sequence of May 2004 and 8/2/1986 seismic event) show roughly N-S striking, steeply dipping nodal planes. West of the LTZ these nodal planes are characterized by right-lateral movements (Fig. 8).

Section B-B’ crosses the Pinasca-Gran Dubbione Fault system (Fig. 10). In this section the hypocentres seem to define a nearly vertical rupture that is aligned with the PGFS towards the surface. The seismicity, as observed also in section A-A’, is mostly limited to the upper 20 km. No focal mechanisms are available along this section.

Comparing structural data collected along the mapped faults with focal mechanisms calculated for this sector (Eva et al., 1997; Eva and Solarino, 1998; Sue et al., 1999; Delacou et al., 2004; Bethoux et al., 2007), it is also possible to investigate the kinematic compatibility between geological structures and seismological data. Fault-slip data collected along the N-S striking faults indicate a polyphasic tectonic activity for these structures. The earlier right-lateral movements, associated to the faulting stage A, are consistent with a bulk NE-SW regional shortening direction and with a NW-SE extension. Subsequent normal-transtensive movements, associated to the faulting stage B, are instead consistent with a bulk steep shortening direction and with a bulk WNW-ESE extension (Fig. 4). Focal mechanisms show strike-slip, transtensive and extensional solutions (Fig. 8), usually with a roughly N-S nodal plane, west of the LTZ. Focal solutions also indicate for this sector NW-SE to NNE-SSW sub-horizontal T axes and both sub-horizontal, with trend ranging from ENE-WNW to E-W, and steeply dipping P axes. Transpressive solutions, mostly consistent with a sub-horizontal ENE-WSW to E-W shortening direction, are instead mostly widespread east of the LTZ, in the westernmost Po Plain (see also Eva et al., 1997).

Thus, the comparison between structural and seismological data shows a good consistency in terms of both kinematics and geometry.

Based on these data, we interpret the polyphasic kinematic evolution of the mapped faults as induced by a bulk transtensive regime, active since the Late Oligocene-Early Miocene in the inner Western Alps, as already proposed by Sue and Tricart (2003). This transtensive regime may have caused the switching between the maximum and intermediate shortening direction (Hu and Angelier, 2004) of the two faulting stages with a roughly constant extension direction. This permutation may have been induced by the coexistence of two driving forces acting inside the chain: the counterclockwise rotation of the Adria plate (Collombet et al., 2002), which induced dextral strike-slip movements along the major faults bounding the inner Western Alps (Canavese Line and Penninic Front; Schmid et al., 1989; Perello et al., 1999), and gravitational forces, which induced extensional collapse (see also Sue and Tricart, 2003; Delacou et al., 2004 with reference therein; 2008). Focal mechanisms of present-day seismicity, characterised both by strike-slip and extensional solutions, indicate that this transtensional regime is still active in the inner Cottian Alps, as also pointed out by some recent works in the rest of the inner Western Alps (Delacou et al., 2004; 2008; Sue et al., 2007).

Summarizing, we observe a geometric and kinematic correspondence between the N-S striking faults and the trend of seismicity both in map and cross-section. The misfit between the nodal planes of focal solutions and the hypocentres alignment is also relatively low. The E-W striking nodal planes observed for some events may instead be possibly related to the reactivation of the E-W faults (SFS in Fig. 8), where some seismicity is observed.

Discussion

In this chapter we first propose a new seismotectonic model for the inner Cottian Alps and afterwards we discuss the possible implications for the current tectonics of the Western Alps.

Inferences on the seismotectonics of the inner Cottian Alps

The synthesis of geological and seismological data indicates a possible dependence of the seismicity of the inner Cottian Alps from the current tectonic activity of the LTZ and its associated structures. The LTZ has been interpreted as a minor, sub-parallel fault-strand of the southern prolongation of the Canavese Line (Balestro et al., 2009a).

The major evidences supporting this hypothesis are:

1) the distribution of instrumental and historical seismicity lines up with the LTZ and, southwards, with the PGFS; this includes the alignments of hypocentres that, in section view, show how the activated surfaces point towards these faults;

2) the fault-slip data for the N-S faults, showing both strike-slip and extensional movements, are consistent with the focal mechanisms of instrumental seismicity;

3) geological data (development of Pleistocenic lacustrine basins in the Chisone and Pellice valleys, mesoscale faults displacing Quaternary deposits) suggest that the activity of the LTZ may be prolonged up to the Quaternary times;

4) also E-W minor structures may have been reactivated in accordance with the present-day stress field.

Moreover, interferometry data indicate that the westernmost Po Plain is currently uplifting with respect to the inner Western Alps (Morelli et al., 2008). This uplifting could be induced, in the analyzed area, by the current activity of roughly N-S faults, like the LTZ, bordering the Alpine chain.

It must be remarked that the LTZ does not show unequivocal evidence of Holocene activity (deformations are observed only in the Pleistocene deposits). However, the focal mechanisms of the Susa Valley suggest that the faults activated during the May 2004 seismic sequence could be interpreted as the continuation at depth of the LTZ. Although there is a little discrepancy between the average strike and dip of the LTZ and the nodal planes of some focal mechanisms (seismic events of 14 and 17 May 2004), as also stressed in other structural contexts (Chiaraluce et al., 2005), fault models used in comparing seismological and geological data assume a simple fault geometry, with a single planar fault surface. By contrast, in the reality both seismic data (Harding, 1985) and mechanical models (Riedel, 1929; Naylor et al., 1986) reveal a complex geometry at depth for strike-slip faults, with differently oriented fault strands branching from a single major fault. In our hypothesis, this may be the case of the Lis-Trana Deformation Zone, where the mapped faults show a complex geometry represented at the surface by several steeply dipping major fault planes with different orientation (see Balestro et al., 2009a). Unfortunately, at present, no seismic reflection profile is available to constrain the geometry at depth of the LTZ and associated minor structures.

Summarising, we propose that in the inner Northern Cottian Alps the present-day seismic activity may be connected to the LTZ and its associated minor structures (Fig. 11). The kinematics of these structures is consistent with the focal mechanisms calculated for this area. Structural and seismological data indicate that LTZ is active under a bulk dextral-transtensive regime since the late Oligocene in the inner Cottian Alps, in agreement with the data published for the adjacent domain of the chain (Sue and Tricart, 2003; Sue et al., 2007). Deep geophysical data (Paul et al. 2001), moreover, show that the western side of the high velocity anomaly of the Ivrea Body overlaps with the LTZ. This may suggest a relation between the seismic activity and the Ivrea Body, as already shown by Bethoux et al. (2007) for the South-Western Alps. By contrast, east of the Canavese Line in the low-elevated Western Po Plain, focal solutions indicate that a transpressive regime currently prevails. Our data, thus, suggest that the Canavese Line may divide two adjacent sectors with different stress regimes, as also proposed by Bethoux et al. (2007). Transtensive regime is, in fact, observed west of the CL whereas transpressive regime is observed east of this structure. The geometry and the kinematics of the faults analysed in this work are illustrated in the interpretative cross-section of figure 12.

Our results are consistent with the geodynamic model of the evolution of mountain ranges that predicts extensional deformation, with normal faulting, across the crests of the range, while crustal shortening takes place along the flanks and lowlands, as recently proposed for the Western Alps (Eva et al., 1998; Sue and Tricart, 2003; Delacou et al., 2004, 2008). This suggests that, in this area, convergence between the Adria and Europe plates is still ongoing, even if at a very low deformation rates as both the low-magnitude of recent earthquakes and GPS data indicate (Calais et al., 2002; Delacou et al., 2004; 2008). Inside the chain, where extensional/transtensive stress regime is present, the mountain evolutionary model (see Delacou et al., 2004) predicts that gravitational body forces tend to equilibrate the belt by balancing the gravitational potential energy between its core, characterized by high crustal thickness, and its margins. Uplift is therefore expected at the core of the belt, as isostatic response to this equilibration. Champagnac et al. (2007), however, suggested that much of the present-day vertical motion of the Western Alps results from climatic change, manifested in part by ice melting and in part by enhanced erosion rates, in the Plio-Quaternary times. Therefore climatic change and erosion should also be considered important factors driving uplift in the mountain ranges.

The role of current tectonics of the Western Alps with respect to the study area

The available structural and seismological data indicate that in the inner Cottian Alps N-S regional faults are characterized by normal and right-lateral movements. Despite the small size of the analyzed area, these data could help to support a model for the current tectonics of the Western Alps among those previously discussed. Normal and dextral strike-slip movements along faults bordering the innermost part of the chain, like the LTZ, are consistent with geodynamic models that postulate a counterclockwise rotation of the Adria plate (Calais et al., 2002; Nocquet and Calais, 2003), possibly combined with body forces acting inside the chain (Delacou et al., 2004; 2008). This interpretation is supported also by the paleomagnetic data, indicating counterclockwise rotations both in the Western Alps (Collombet et al., 2002) and the Western Po Plain (Bormioli and Lanza, 1995). The counterclockwise rotation of the Adria plate, in fact, could cause a dextral component of movement along the LTZ whereas the normal component may be related to the body forces inside the chain. The counterclockwise rotation of the Adria, according to Calais et al. (2002), results in increasing convergence rates across the Alps from west to east. In fact about 2 mm/yr of N-S shortening in the Eastern Alps (Grenerczy et al., 2005; D’agostino et al., 2008) are observed whereas baselines crossing the Western Alps do not show significant shortening, in agreement with the seismological informations already described above (Calais et al. 2002; Sue et al. 1999, Delacou et al. 2004; 2008; Thouvenot and Fréchet, 2006). Geodetic data indicate a rotation pole for the Adria plate located between the Po valley and the French Alps (Anderson and Jackson, 1987; Ward, 1994; Calais et al., 2002).

Recently some works proposed that the Adria region is further fragmented in minor crustal blocks. D’Agostino et al. (2008), on the basis of space geodetic and seismological data, describe the kinematics of the Adriatic region in terms of two relative microplates with opposite sense of rotation: the Adria, with counterclockwise rotation, and the Apulia, with clockwise rotation. Mantovani et al. (2009), instead, proposed that the Adria plate separated from its northwestern (Padanian) protuberance, which was stuck into the European foreland, through the reactivation of the Giudicarie sinistral fault system (Castellarin and Cantelli, 2000), in the Miocene (Tortonian). D’Agostino et al. (2008) proposed that the end of the convergence in the Western Alps may be associated with the fragmentation of the Adria plate. According to these models, this fragmentation could have therefore induced the change in the LTZ kinematics (from transcurrent to extensional).

Our data do not support, instead, the southward extrusion of the inner Western Alps, proposed by Champagnac et al. (2006), as this model postulates sinistral movements along major faults parallel to the trend of the chain (like the LTZ), not observed in this study.

Neither the westward extrusion, proposed by Giglia et al. (1996), seems to be supported by our data, as transcurrent movement along the faults bounding the inner part the chain (LTZ) are not consistent with this model. Giglia et al. (1996) interprets the Stura “couloir” (Ricou, 1981; Laubscher, 1991; Collombet et al., 2002) as an important sinistral transfer fault that is accompanying the westward extrusion of the Western Alps. Giglia et al. (1996) considered the Stura couloir an active structure, on the basis of the distribution of instrumental seismicity.

However geological evidence of Quaternary activity are not known for this fault. Morever the more recent and detailed seismotectonic investigations did not show (Sue et al., 1999; Delacou et al., 2004; Sue et al., 2007) a geometrical and kinematic relation between this fault and the current seismicity. Mosca et al. (2009) indicate some E-W sinistral regional faults, which could be interpreted as the the Stura colouir eastward prolongation in the adjacent Langhe domain, as structures active in the Oligocene times. This tectonic reconstruction agrees also with that of Castellarin (1992, 2001).

Summary and conclusions

This work investigates the seismotectonic setting of the inner Cottian Alps (Italian Western Alps) coupling structural geology, seismology, neotectonics and geomorphology. The integration of all these data indicates that the seismic activity in the study area may be mainly related with the Lis-Trana Deformation Zone (LTZ), where normal and strike-slip movements are observed.

The dextral-normal movement along the LTZ is in agreement with a tectonic model that foresees a transtensive regime in the Western Alpine chain and shortening at its borders (Eva and Solarino, 1998; Eva et al., 1998; Sue and Tricart, 2003; Delacou et al., 2004; 2008). At the crustal scale the counterclockwise rotation of the Adria plate may be considered the geodynamic mechanism that induces a dextral component along the LTZ. The normal component may be instead related to the buoyancy forces acting inside the chain.

Recent geodetic studies about the kinematics of Adria, provide Adria-Eurasia Eulerian poles mostly located in the central-western Po Plain (Calais et al., 2002 and D’Agostino et al., 2008). The proximity of the Eulerian poles determines, in the Western Alps, relatively low GPS velocities (1-1.5 mm/yr; Calais et al., 2002), especially if compared with those observed in Central Italy (3-4 mm/yr; Calais et al., 2002). Such velocities, in our opinion, are compatible with the low magnitude of the current instrumental seismicity (minor than 3.5 - 4 Ml) observed in the inner Cottian Alps, in comparison with the higher magnitude activity of the central Italy. We stress that also the buoyancy forces, which actually seem to be active inside the chain, play an important role in the earthquake mechanism, as evidenced by the high number of extensional/transtensive solutions.

This study shows that even in regions characterized, at present, by low-deformation rates and where evidences of recent tectonic deformations are poor, the integration between accurate field surveys and seismological analysis may contribute to understand the location and evolution of active deformations. In turn, these informations may shed some light on the occurrence of higher magnitude events in adjoining sectors (Camassi and Stucchi, 1997).

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Figure captions

Table 1. Locations and parametres of the focal mechanisms in Fig. 2. Yr: year; Mo: month; Dy: day; Hr: hours; Mn: minutes; sec: seconds; Long.: longitude; Lat.: latitude; ML: local magnitude ; Az1(2), Dip1(2), Rake1(2): azimuth, dip, rake of fault plane 1 (2), in degrees; AzP(T), DipP(T): azimuth and dip of P(T) axes, in degrees. Ref.: B, Bethoux et al., 2007 ; E, Eva et al., 1997; N, Nicolas et al., 1990; S, Sue et al., 1999 ; U, unpublished data.

Table 2. Locations and parameters of the focal solutions computed in this study. Abbreviations as in table 1.

Figure 1. Map of the instrumental and historical seismicity in the Northern Cottian Alps. Instrumental seismicity (gray circles) from the database of the seismic network of the North-Western Italy (RSNI). Dark and light gray circles represent shallow seismicity (hypocentral depth

less than 20 km) and deep seismicity (hypocentral depth more than 20 km) respectively. Historical events (solid squares and triangles) from the Catalogue of strong earthquakes in Italy (Boschi et al., 2000).

Figure 2. Map of the focal mechanisms of the inner Cottian Alps (after Eva et al., 1997; 1998; Sue et al., 1999; Delacou et al., 2004). Numbering corresponds to that of table 1.

Figure 3. Tectonic sketch map of the inner Cottian Alps (a), the thick grey rectangle indicates the area shown in figure 5; WNW-ESE cross-section transversal to the main faults (b). CL: Canavese Line; CF: Chisone Fault; CFZ: Colle delle Finestre Deformation Zone; LTZ: Lis-Trana Deformation Zone; PGFS: Pinasca-Gran Dubbione Fault System; PTF: Padan Thrust Front; SFS: Sangone Fault System. From Perrone et al. (2010).

Figure 4. Tectonic sketch of the Western Alps (a); Oligocene to early Miocene (b) and post-Early Miocene (c) tectonics in the Northern Cottian Alps. Equal-area, lower hemisphere projections represent fault-slip data relative to the two faulting stages. Small contoured plots represent P axes obtained by fault slip data for each fault. Abbreviations as in Figure 3.

Figure 5. Map of the main faults with the Plio-Quaternary deposits of the inner Cottian Alps and western Po Plain (after Collo, 1995). A, B and C represents the sites where faulted deposits are observed (see details in the text). Abbreviations as in Figure 3.

Figure 6. Geological sections transversal to the Chisone and Pellice valleys. Trace of the sections in fig. 5. After Collo (1996).

Figure 7. (a) Early Pleistocene stream deposits displaced by a N-S striking fault (Messa stream); near the fault plane the clasts are parallelized to the fault surface, the dashed line indicate the track of the fault plane and the rectangle indicate the area shown in figure B; (b) detail of the striated

fault surface. (c) ENE-WSW striking faults juxtaposing Early Pleistocene deposits (1) over the bedrock (2, peridotites and serpentinites). (d) N-S striking fault juxtaposing coarse fine grained deposits, in the hanging-wall (1), to coarse-grained deposits, in the footwall (2).

Figure 8. (a) Seismotectonic map (seismicity with location error minor than 3 km) of the inner Cottian Alps; (b) equal-area projection (lower hemisphere) showing the distribution of the P axes and (c) the T axes of the focal mechanisms in the analysed area. Focal mechanisms computed in this work are represented with black compressional quadrants; numbering as in table 2. Focal mechanisms with grey compressional quadrants are from Bethoux et al. (2007); Eva et al. (1997), Nicolas et al. (1990), Sue et al. (1999). Instrumental seismicity from the database of the RSNI. Abbreviations as in Figure 3.

Figure 9. Focal mechanisms, with related parameters, computed in this study

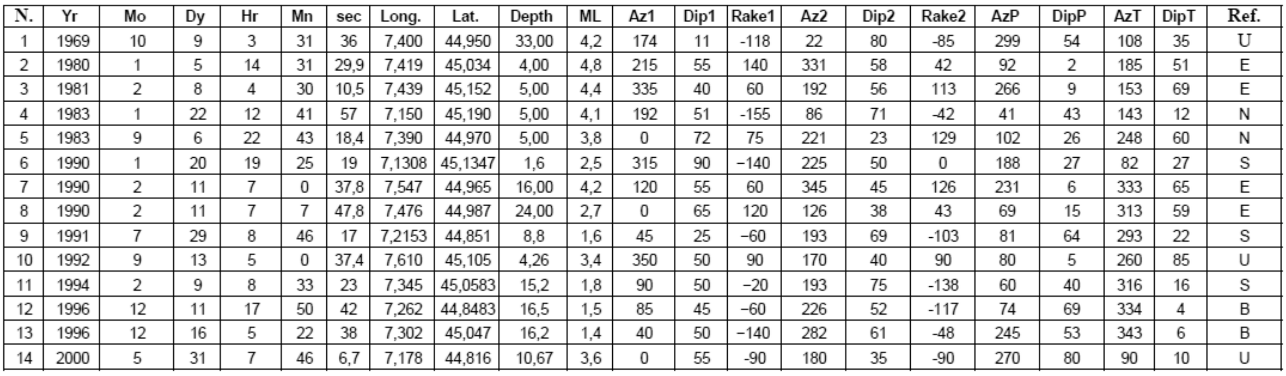
Figure 10. Seismic cross-sections transversal to the LTZ (a) and the PGFS (b). Traces of the section in fig. 8. Locations and near-surface orientations of faults, as interpreted by field geological data, are shown as solid black lines. Dashed black lines indicate the possible prolongation of the faults at depth as constrained by the trend of the hypocenters. Grey rectangles indicate the areas where hypocentres may be considered to lay on the fault plane.

Figure 11. Interpretative geological crustal section transversal to the main structures of the inner Cottian Alps. LTZ is interpreted as a minor fault strand of the CL. No attempt to infer the kinematics of the CL is proposed. Modified from the ECORS-CROP profile (Schmid and Kissling, 2000). Abbreviations as in Figure 3.

Figure 12. Updated seismotectonic model for inner Cottian Alps as inferred by the data presented in this work. Inside the chain, the transtensive stress regime is accommodated by steep faults (LTZ and minor faults). In the Po Plain a transpressive regime is observed. The Canavese Line is

interpreted as the structure that could separate these two sectors. LTZ: Lis-Trana Deformation Zone; CL: Canavese Line.

Table 1



N.	Yr	Mo	Dy	Hr	Mn	sec	Long.	Lat.	Depth	ML	Az1	Dip1	Rake1	Az2	Dip2	Rake2	AzP	DipP	AzT	DipT	Ref.
1	1969	10	9	3	31	36	7,400	44,950	33,00	4,2	174	11	-118	22	80	-85	299	54	108	35	U
2	1980	1	5	14	31	29,9	7,419	45,034	4,00	4,8	215	55	140	331	58	42	92	2	185	51	E
3	1981	2	8	4	30	10,5	7,439	45,152	5,00	4,4	335	40	60	192	56	113	266	9	153	69	E
4	1983	1	22	12	41	57	7,150	45,190	5,00	4,1	192	51	-155	86	71	-42	41	43	143	12	N
5	1983	9	6	22	43	18,4	7,390	44,970	5,00	3,8	0	72	75	221	23	129	102	26	248	60	N
6	1990	1	20	19	25	19	7,1308	45,1347	1,6	2,5	315	90	−140	225	50	0	188	27	82	27	S
7	1990	2	11	7	0	37,8	7,547	44,965	16,00	4,2	120	55	60	345	45	126	231	6	333	65	E
8	1990	2	11	7	7	47,8	7,476	44,987	24,00	2,7	0	65	120	126	38	43	69	15	313	59	E
9	1991	7	29	8	46	17	7,2153	44,851	8,8	1,6	45	25	−60	193	69	-103	81	64	293	22	S
10	1992	9	13	5	0	37,4	7,610	45,105	4,26	3,4	350	50	90	170	40	90	80	5	260	85	U
11	1994	2	9	8	33	23	7,345	45,0583	15,2	1,8	90	50	−20	193	75	-138	60	40	316	16	S
12	1996	12	11	17	50	42	7,262	44,8483	16,5	1,5	85	45	−60	226	52	-117	74	69	334	4	B
13	1996	12	16	5	22	38	7,302	45,047	16,2	1,4	40	50	−140	282	61	-48	245	53	343	6	B
14	2000	5	31	7	46	6,7	7,178	44,816	10,67	3,6	0	55	-90	180	35	-90	270	80	90	10	U

Table 2

N.	Yr	Mo	Dy	Hr	Mn	sec	Long.	Lat.	Depth	ML	Az1	Dip1	Rake1	Az2	Dip2	Rake2	AzP	DipP	AzT
1	1999	4	18	15	4	23,3	44,923	7,22	10,97	2,9	230	60	-150	124	64	-34	85	41	178
2	2000	4	1	1	21	37	45,101	7,312	10,37	3,4	314	41	-49	85	60	-120	306	62	196
3	2004	8	14	0	30	35	45,101	7,328	6,23	3,9	210	75	170	303	80	15	76	4	167
4	2004	5	17	6	9	17	45,108	7,334	10,6	3,2	20	70	-150	279	62	-23	242	35	148

Fig.1

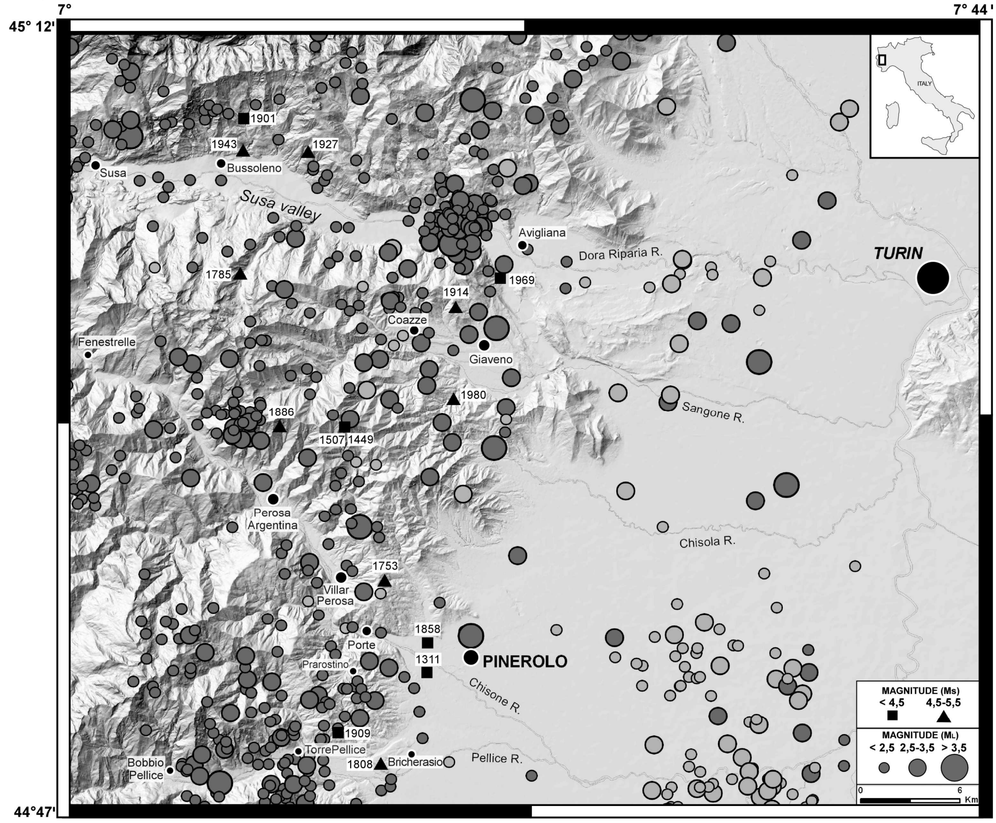

7°
7° 44'
45° 12'
44°47'
1901
1943
1927
Susa
Bussoleno
Susa valley
Avigliana
Dora Riparia R.
TURIN
1785
1914
1969
Coazze
Fenestrelle
Giaveno
1980
Sangone R.
1886
1507
1449
Perosa
Argentina
Chisola R.
1753
Villar
Perosa
1858
PINEROLO
Porte
1311
Prarostino
Chisone R.
1909
TorrePellice
Bobbio
Pellice
1808
Bricherasio
Pellice R.
ITALY
MAGNITUDE (Ms)
< 4,5
4,5-5,5
MAGNITUDE (ML)
< 2,5
2,5-3,5
> 3,5
0
6
Km

Fig.2

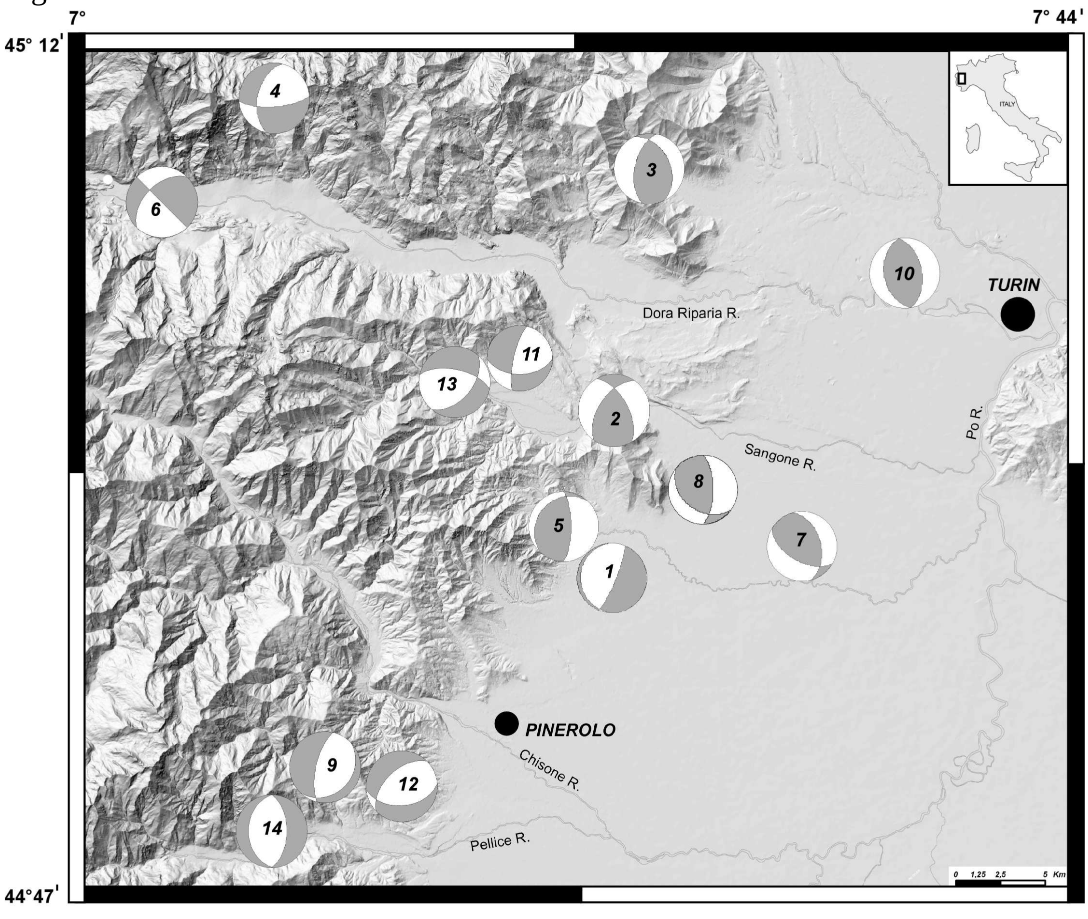

7°
7° 44'
45° 12'
44°47'
4
3
6
10
TURIN
Dora Riparia R.
11
13
2
Po R.
Sangone R.
8
5
7
1
PINEROLO
9
12
Chisone R.
14
Pellice R.
ITALY
0
1,25
2,5
5
Km

Fig.3

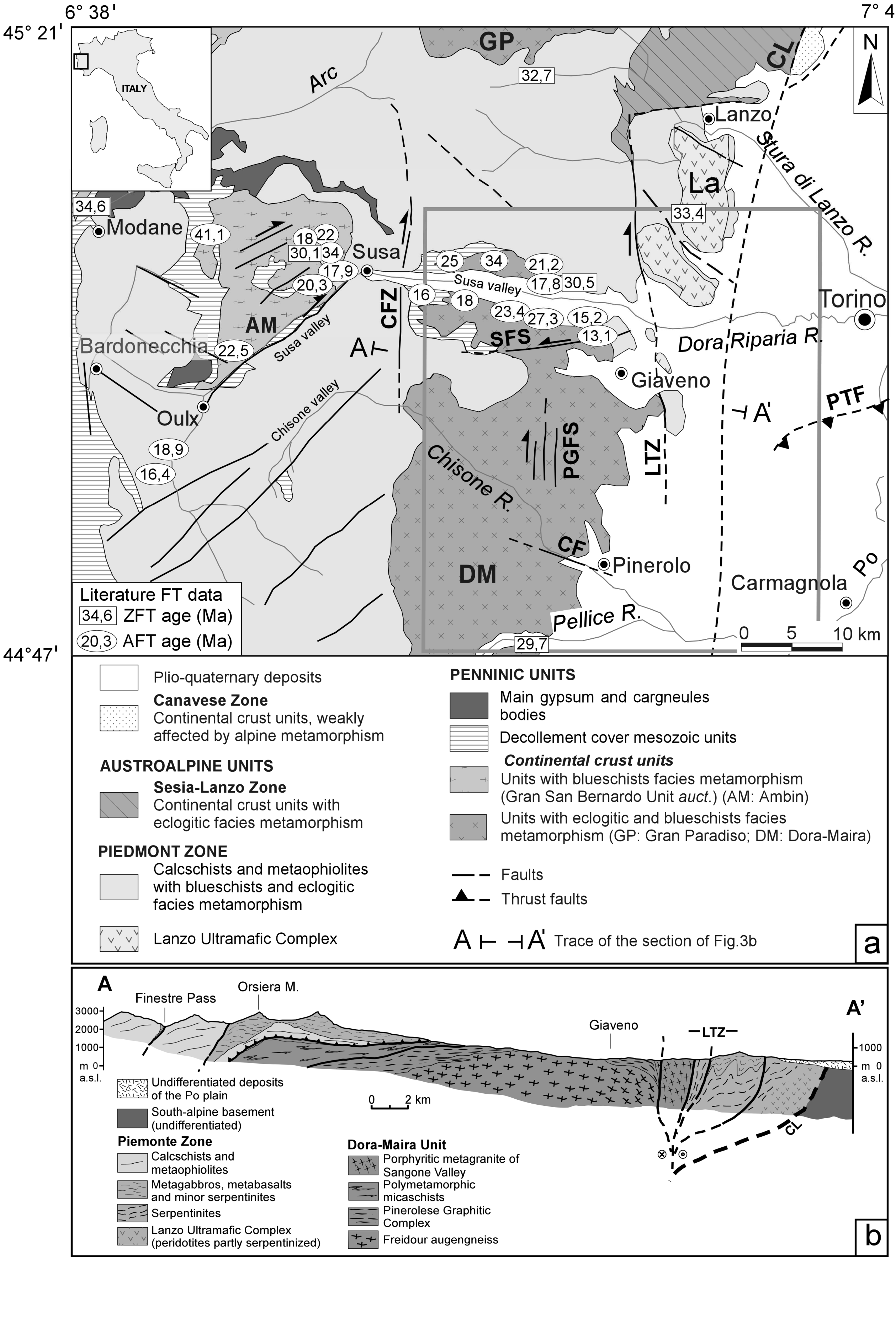

6° 38'
7° 43'
45° 21'
44°47'
ITALY
N
GP
Arc
32,7
CL
Lanzo
Stura di Lanzo R.
La
34,6
Modane
41,1
18
22
30,1
34
Susa
17,9
20,3
33,4
25
34
21,2
17,8
30,5
Susa valley
16
18
23,4
27,3
15,2
13,1
Torino
AM
Susa valley
CFZ
SFS
Dora Riparia R.
Bardonecchia
22,5
A
Giaveno
Oulx
Chisone valley
A'
PTF
18,9
16,4
Chisone R.
PGFS
LTZ
CF
Pinerolo
DM
Carmagnola
Po
Pellice R.
29,7
0
5
10 km
Literature FT data
34,6 ZFT age (Ma)
20,3 AFT age (Ma)
Plio-quaternary deposits
Canavese Zone
Continental crust units, weakly affected by alpine metamorphism
AUSTROALPINE UNITS
Sesia-Lanzo Zone
Continental crust units with eclogitic facies metamorphism
PIEDMONT ZONE
Calcschists and metaophiolites with blueschists and eclogitic facies metamorphism
Lanzo Ultramafic Complex
PENNINIC UNITS
Main gypsum and cargneules bodies
Decollement cover mesozoic units
Continental crust units
Units with blueschists facies metamorphism (Gran San Bernardo Unit auct.) (AM: Ambin)
Units with eclogitic and blueschists facies metamorphism (GP: Gran Paradiso; DM: Dora-Maira)
Faults
Thrust faults
A ⊢ ⊣ A' Trace of the section of Fig.3b
a
A
Finestre Pass
Orsiera M.
A'
3000
2000
1000
m 0
a.s.l.
Giaveno
LTZ
1000
m 0
a.s.l.
CL
0 2 km
Undifferentiated deposits of the Po plain
South-alpine basement (undifferentiated)
Piemonte Zone
Calcschists and metaophiolites
Metagabbros, metabasalts and minor serpentinites
Serpentinites
Lanzo Ultramafic Complex (peridotites partly serpentinized)
Dora-Maira Unit
Porphyritic metagranite of Sangone Valley
Polymetamorphic micaschists
Pinerolese Graphitic Complex
Freidour augengneiss
b

Fig. 4

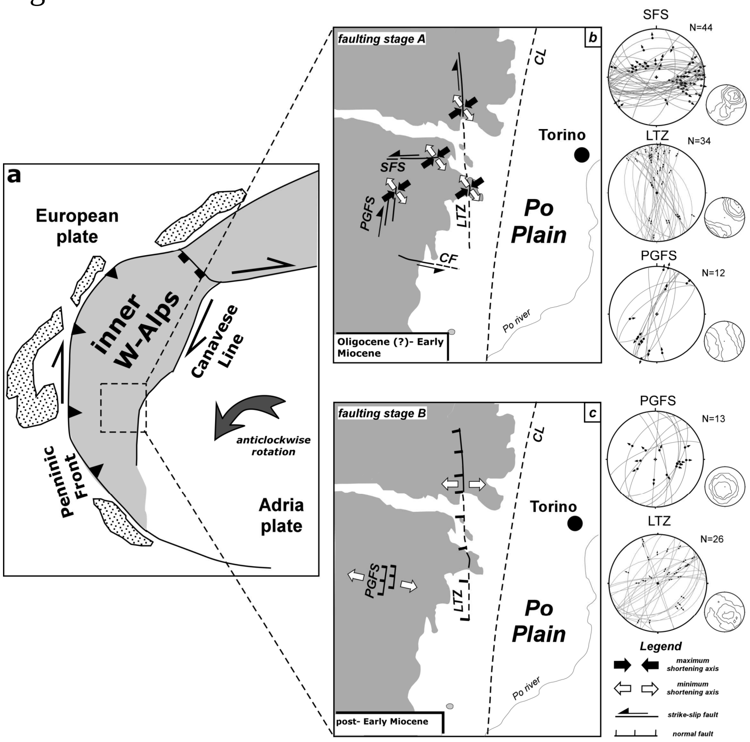

a
European plate
inner W-Alps
Canavese Line
Penninic Front
anticlockwise rotation
Adria plate
faulting stage A
b
CL
Torino
SFS
PGFS
LTZ
CF
Po Plain
Po river
Oligocene (?)- Early Miocene
SFS
N=44
LTZ
N=34
PGFS
N=12
faulting stage B
c
CL
Torino
PGFS
LTZ
Po Plain
Po river
post- Early Miocene
PGFS
N=13
LTZ
N=26
Legend
maximum shortening axis
minimum shortening axis
strike-slip fault
normal fault

Fig. 5

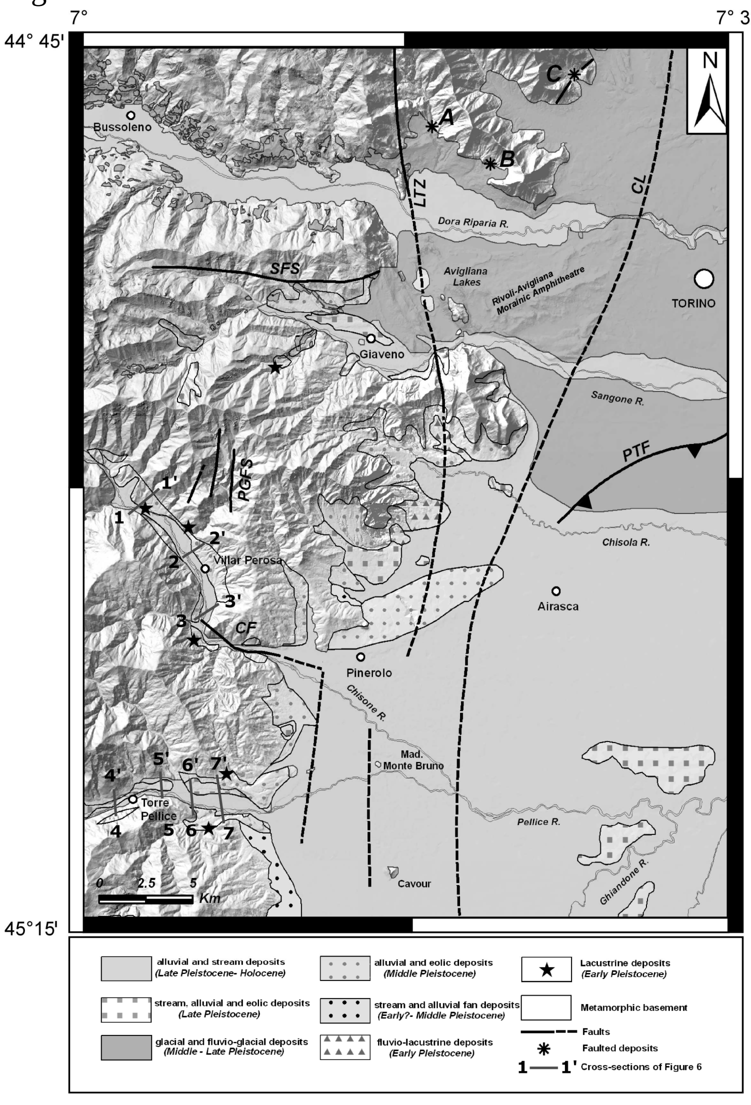

7°
7° 32'
44° 45'
45°15'
N
C
A
B
Bussoleno
LTZ
CL
Dora Riparia R.
SFS
Avigliana Lakes
Rivoli-Avigliana Morainic Amphitheatre
TORINO
Giaveno
Sangone R.
PTF
PGFS
1'
1
2'
2
Villar Perosa
3'
3
CF
Chisola R.
Airasca
Pinerolo
Chisone R.
Mad. Monte Bruno
4'
5'
6'
7'
Torre Pellice
4
5
6
7
Pellice R.
Cavour
Ghiandone R.
0
2.5
5
Km
alluvial and stream deposits (Late Pleistocene- Holocene)
stream, alluvial and eolic deposits (Late Pleistocene)
glacial and fluvio-glacial deposits (Middle - Late Pleistocene)
alluvial and eolic deposits (Middle Pleistocene)
stream and alluvial fan deposits (Early?- Middle Pleistocene)
fluvio-lacustrine deposits (Early Pleistocene)
Lacustrine deposits (Early Pleistocene)
Metamorphic basement
Faults
Faulted deposits
1 — 1' Cross-sections of Figure 6

Fig. 6

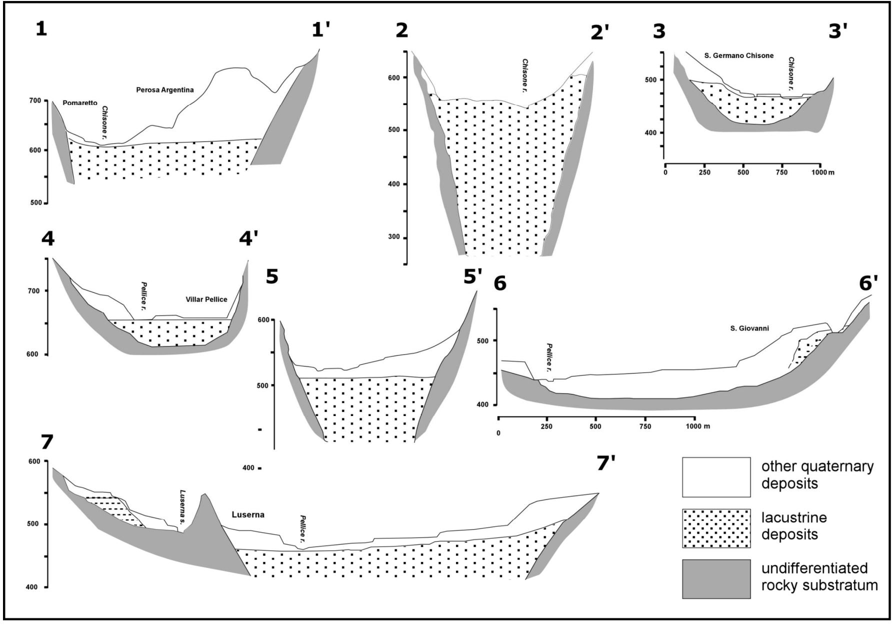

1
1'
700
600
500
Pomaretto
Chisone r.
Perosa Argentina
2
2'
600
500
400
300
Chisone r.
3
3'
S. Germano Chisone
Chisone r.
500
400
0
250
500
750
1000 m
4
4'
700
600
Pellice r.
Villar Pellice
5
5'
600
500
400
6
6'
S. Giovanni
Pellice r.
500
400
0
250
500
750
1000 m
7
7'
600
500
400
Luserna s.
Luserna
Pellice r.
other quaternary deposits
lacustrine deposits
undifferentiated rocky substratum

Fig. 7

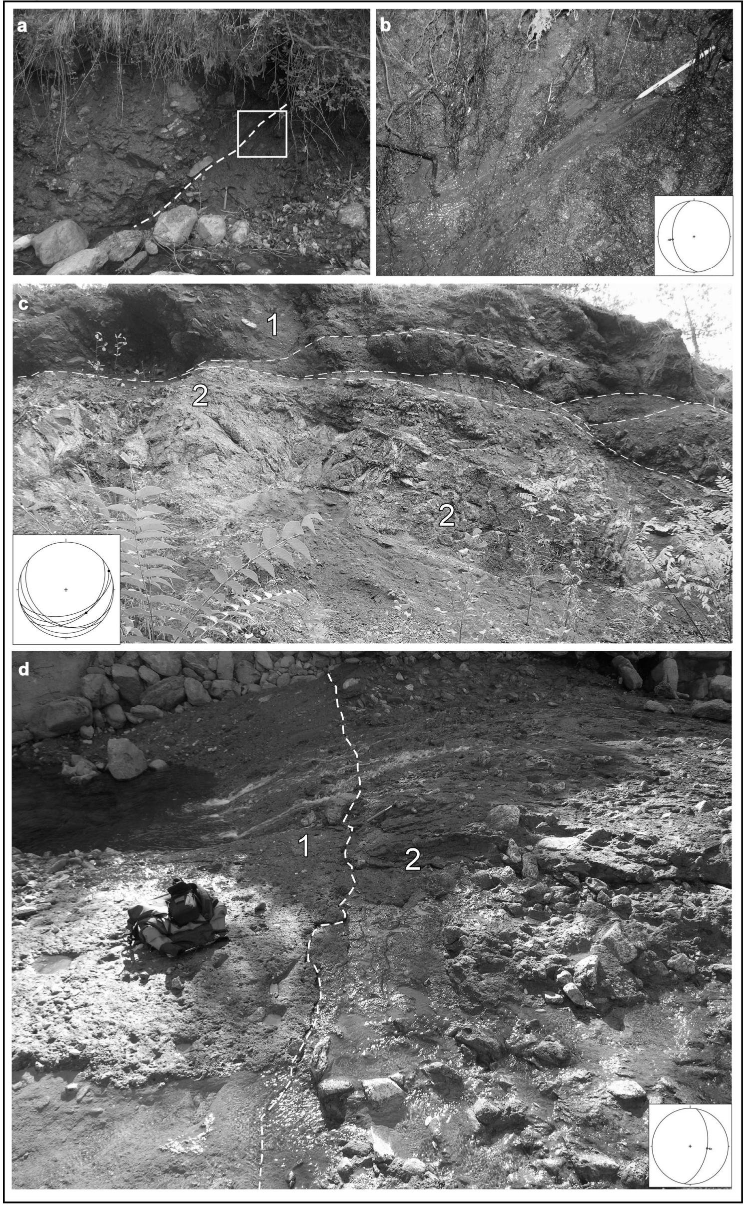

a
b
c
1
2
2
d
1
2

Fig. 8

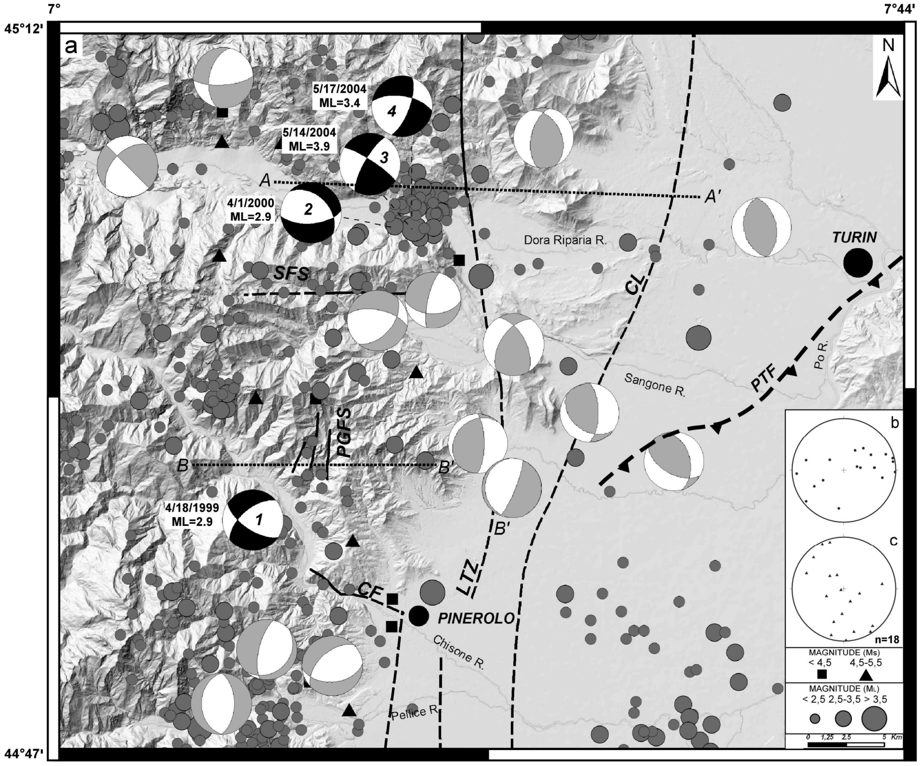
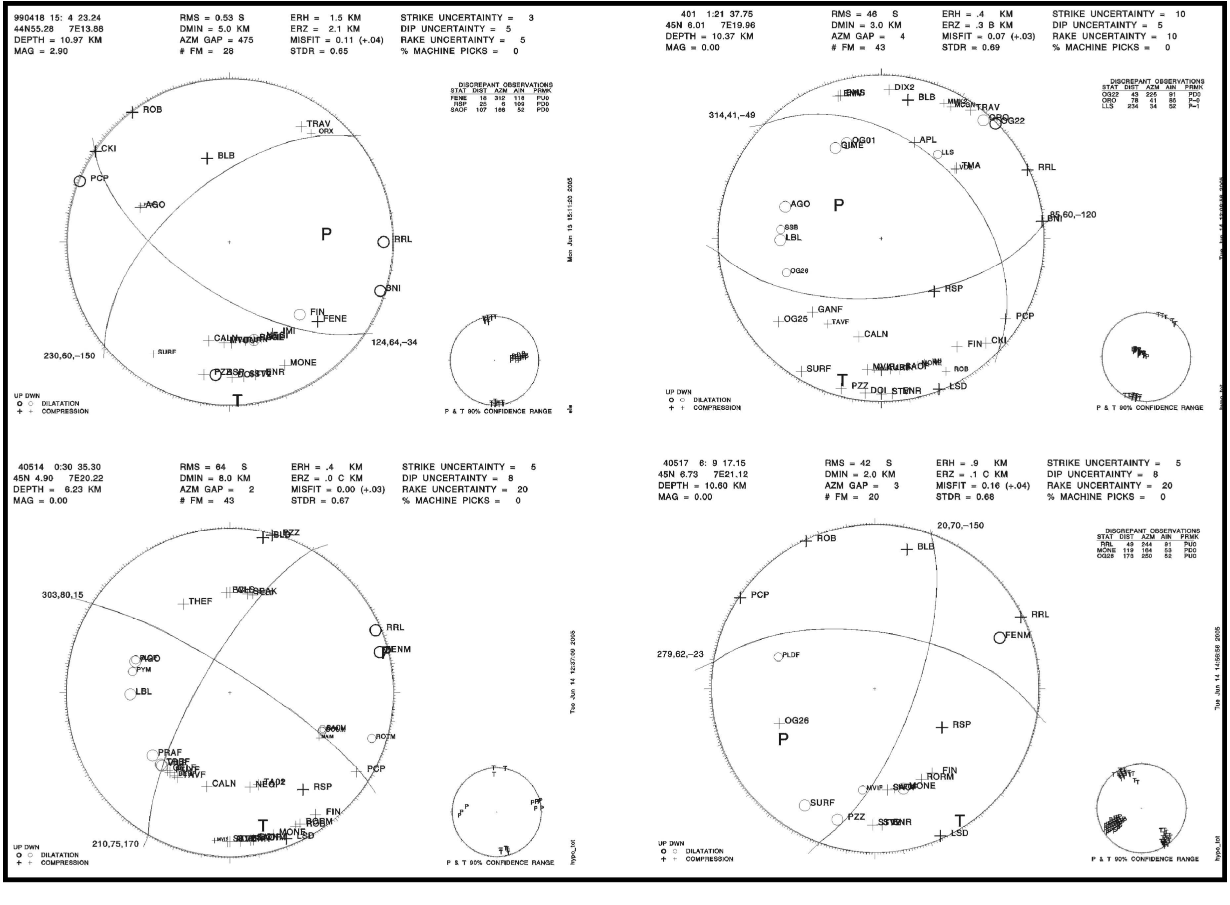


Fig. 9



```
990418 15: 4 23.24          RMS = 0.53 S        ERH =  1.5 KM            STRIKE UNCERTAINTY =   3
44N55.28    7E13.88         DMIN = 5.0 KM       ERZ =  2.1 KM            DIP UNCERTAINTY =  5
DEPTH = 10.97 KM            AZM GAP = 475       MISFIT = 0.11 (+.04)     RAKE UNCERTAINTY =   5
MAG = 2.90                  # FM =  28          STDR = 0.65              % MACHINE PICKS =   0

          DISCREPANT OBSERVATIONS
        STAT  DIST  AZM  AIN  PRMK
        FENE    18  312  118  PU0
         RSP    25    6  109  PD0
        SAOF   107  166   52  PD0
```

```
  401   1:21 37.75          RMS = 46    S       ERH = .4    KM           STRIKE UNCERTAINTY =  10
45N 6.01    7E19.96         DMIN = 3.0 KM       ERZ = .3 B KM            DIP UNCERTAINTY =  5
DEPTH = 10.37 KM            AZM GAP =    4      MISFIT = 0.07 (+.03)     RAKE UNCERTAINTY =  10
MAG = 0.00                  # FM =  43          STDR = 0.69              % MACHINE PICKS =   0

          DISCREPANT OBSERVATIONS
        STAT  DIST  AZM  AIN  PRMK
        OG22    43  225   91  PD0
        ORO     78   41   85  P-0
        LLS    234   34   52  P-1
```

```
 40514   0:30 35.30         RMS = 64    S       ERH = .4    KM           STRIKE UNCERTAINTY =   5
45N 4.90    7E20.22         DMIN = 8.0 KM       ERZ = .0 C KM            DIP UNCERTAINTY =  8
DEPTH =  6.23 KM            AZM GAP =   2       MISFIT = 0.00 (+.03)     RAKE UNCERTAINTY =  20
MAG = 0.00                  # FM =  43          STDR = 0.67              % MACHINE PICKS =   0
```

```
 40517   6: 9 17.15         RMS = 42    S       ERH = .9    KM           STRIKE UNCERTAINTY =   5
45N 6.73    7E21.12         DMIN = 2.0 KM       ERZ = .1 C KM            DIP UNCERTAINTY =  8
DEPTH = 10.60 KM            AZM GAP =    3      MISFIT = 0.16 (+.04)     RAKE UNCERTAINTY =  20
MAG = 0.00                  # FM =  20          STDR = 0.68              % MACHINE PICKS =   0

          DISCREPANT OBSERVATIONS
        STAT  DIST  AZM  AIN  PRMK
         RRL    49  244   91  PU0
        MONE   119  164   53  PD0
        OG26   173  250   52  PU0
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Fig. 10

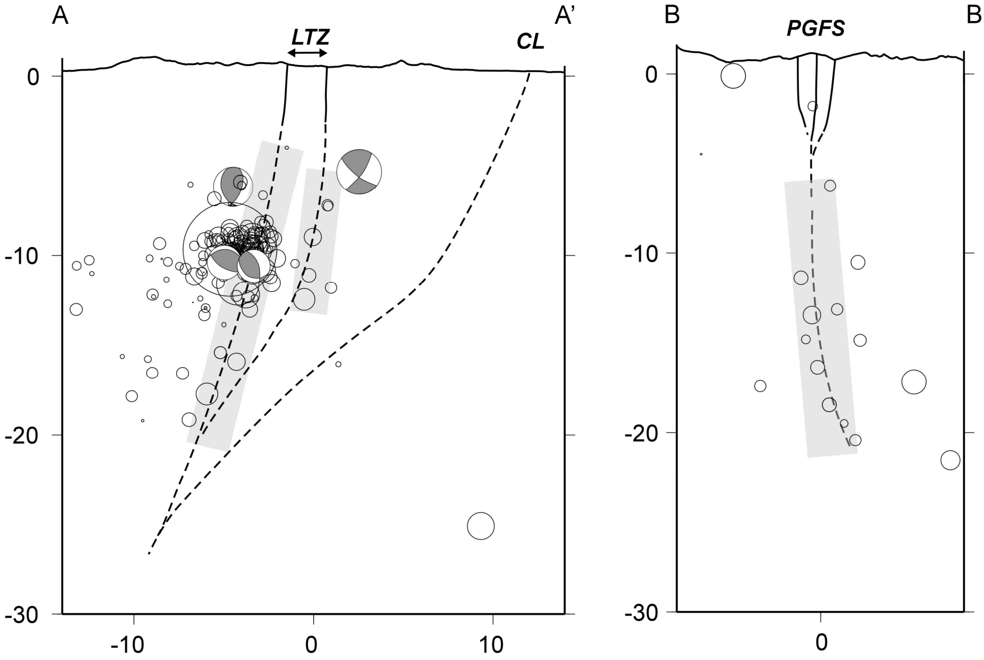

Fig. 11

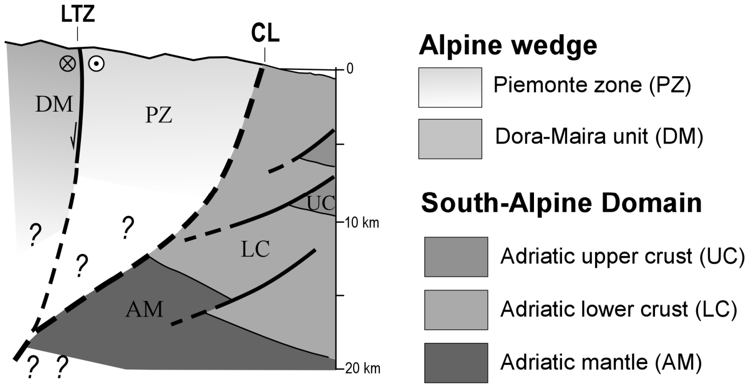

Fig. 12