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The active fault system of SW Alps

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Abstract

Historical and active seismicity in the south-western Alps (France and Italy) shows the recurrence of relatively high magnitude earthquakes ($M \geq 5.8$), like the one that recently affected the Italian Apennine range ($M=6.3$ on the 30th March 2009). However, up-to-date detailed mapping of the active fault network has been poorly established. The evaluation of seismological hazard in particular in the highly populated French and Italian coastal region cannot be done without this. Here, we present a detailed study of the main active fault system, based on geological observations along the south-western flank of the Alpine arc. This N140° right-lateral strike-slip active fault system runs along the edge of the Argentera-Mercantour range and can be followed down to the Mediterranean Sea. It is evidenced by (1) Holocene offsets of glacial geomorphology witnessing ongoing fault activity since 10 ka, (2) widespread recent (10-20 Ma) pseudotachylytes featuring long term activity of the faults, (3) active landslides along the main fault zone, (4) geothermal anomalies (hot springs) emerging in the active faults, (5) ongoing low-magnitude seismic activity and (6) localization of the main historical events. In the light of our investigations, we propose a new tectonic pattern for the active fault system in the south-western Alps.

Key words: Active fault, historical seismicity, neotectonics, seismic hazard, SW Alps.

1. Introduction

The greatest seismic hazard in France is located at the transition between the south-western Alps and the Ligurian basin (Ritz et al., 1992; Sébrier et al., 1997; Eva & Solarino, 1998; Baroux et al., 2001; Larroque et al., 2001; Terrier, 2006). However, the active fault network sparking off the regional seismic activity is not clearly identified. Thus, the (mapping) definition of active fault systems is crucial and requires detailed structural and chronologic analysis.

The active fault system in the south-western Alps is largely controlled by inherited alpine faults. Indeed, alpine tectonic displacements within the south-alpine N140°E dextral and N90°E thrust fault network were established on syn-kinematic phyllosilicates by the single-grain $^{40}\text{Ar}/^{39}\text{Ar}$ laser method (Corsini et al., 2004 ; Sanchez et al., 2009a ; Simon-Labric et al., 2009).

A first set of thrust motions with “top-towards west” kinematics is recognized at ~33-34 Ma and is related to burial of the European plate below the Penninic Frontal Thrust (PFT) and the orogenic wedge of the Internal Alps (Fig.1; Simon-Labric et al., 2009).

Further, right-lateral strike-slip displacements were initiated at ~26 Ma (Corsini et al., 2004) and followed at 20-22 Ma (Sanchez et al., 2009a) witnessing the onset of transcurrent motions accommodated by N140 trending faults in response to sub-meridian shortening in the south-western Alps. These dated shear zones were formed at mid crustal depths ($5 < P < 7$ kb – 15-20 km), at temperature conditions of $350 \pm 50^\circ\text{C}$ (Sanchez et al., 2009a), at the front of the mantle wedge indenter of the Ivrea Body, which is located underneath the internal Alpine zone, north of the surface trace of the Penninic Frontal Thrust (Roure et al., 1996; Paul et al., 2001; Bethoux et al., 2007; Schreiber et al., 2008).

From Middle Miocene to Pliocene, these N140°E dextral strike-slip faults were connected to a sub-meridian extensional High Durance fault system and the N140°E dextral Serenne

fault at the south-eastern boundary of the Pelvoux massif (Tricart et al., 1996; Sue and Tricart, 2003) (Fig.1).

In this study, we focus on the south-western slope of the Argentera-Mercantour massif where we have observed recent reactivation of the N140 right-lateral faults.

2. Field investigations

A field transect was performed along the major active N140E regional fault (the Tinée Fault; Fig.1; Fig. 2a) on which evident geological markers have witnessed recent activity. This fault is characterised by horizontal striae (Fig. 2b) and featured by significant fracturing with N-S vertical joints spaced of 20-40 cm (Fig. 2c). Some of these joints are filled by pseudotachylytes (detailed in Fig. 2d-h) which are connected to the fault plan showing dextral movement (Horizontal striae and tension gash “en echelon”; Fig. 2b,g). As widely evoked, the presence of pseudotachylytes related to fault zone records fossil earthquakes which nucleate at the base of brittle seismogenic zone ($<10\text{-}15\text{km}$; Lin et al., 2005; Sibson and Toy, 2006). In our case, this corresponds to a temperature $< 200 \pm 100^\circ\text{C}$ from the present-day Alpine geotherm (Crouzet et al., 1999) and allows estimating the exhumation age of this deep part of the seismogenic zone between 10 and 20 Ma according to fission track dates (Bigot et al., 2006). This age range shows that the Tinée N140° dextral fault is active between 10 and 20 Ma as also suggested by the brecciation and offset of the joints observed in several places, which show late deformation in relation to seismic activity (Fig. 2i).

Ongoing activity of this fault is also shown by the most recent Holocene slip events inferred from the offset of geomorphological features (Fig. 3). Aerial photographs and field investigation of the Argentera-Mercantour massif reveal a consistent 50 m dextral offset of crests and glacially polished surfaces, nearby the pseudotachylyte zone (Fig.2a; Fig. 3a,b). Further north in Le Pra area, along the Tinée fault, Sanchez et al. (2009b) reported similar geomorphological observations. Glacially polished bedrock outcrops dated around 12 ka are

offset by up to 15m by some of the Tinée active fault scarps dated at 8-11 ka (Sanchez et al., 2009b). Moreover, in the neighbouring La Clapière and Le Pra landslides located along the Tinée active fault (Fig. 1; Fig. 2a), are dated between 10, 7 and 5 ka (Bigot et al., 2005; Sanchez et al., 2009b). Therefore, According to the damaged zone near the Tinée fault, featured by a dense network of opened fractures (Fig. 3c), it is obvious that such displacements can only be related to seismic activity. Moreover, in the le Pra area, we can state that the 15m right-lateral offset could result from a series of post-glacial seismic events post-dating 12 ka.

3. Interpretation-Discussion

3.1 Active faults in SW Alps

These structural and geochronological investigations have provided evidence for the active character of the studied south-western Alps strike-slip system and allow the construction of a new regional map of active faults, presented in Fig. 1. The observed morphological offsets are in lateral continuation to the active Jausiers fault, whose N140°E orientation is defined by the alignment of epicentres determined after the 2004-2006 seismic crisis (Fig.4; Jenatton et al., 2007). The studied active fault is defined by ongoing low-magnitude seismic activity represented by more than 16,000 earthquakes of maximum magnitude $M_L=2.7$ during this two year period (see Figs 2b and 6 in Jenatton et al., 2007). The seismic activity was clustered along a 9 km long and 3 to 8 km-deep rupture zone trending in a 140°E direction (Fig.4). From focal mechanism analysis, fault motion is right-lateral strike-slip; more than half focal solutions show a strike-slip motion with a NW-SE dextral plane. Only a third is extensional with tension axes (T) trending NE-SW to E-W. These seismological data agree with field observations at the surface, showing the two different fault trends in the NW Argentera-Mercantour (Fig. 1). Inversion of fault-striae data measured in the field to determine the paleo-stress directions gave similar solutions in the same zone (Fig. 4). Two main tensors

were obtained. The first one is featured by horizontal strike slip along the N140° faults while the second one shows E-W extension along the N-S normal faults. Both are in agreement with a sub-meridian shortening. A third intermediate tensor is also obtained in the transition zones between the two fault types (Fig. 4). Therefore, field analysis and focal mechanisms show that the Jausiers and Tinée faults correspond to a single structure hereafter called the Jausiers-Tinée Fault (JTF). At a larger scale, this active fault network is outlined by numerous focal mechanisms showing strike-slip and normal solutions (Delacou et al., 2004; Béthoux et al., 2007). We ascribe the bimodality of focal mechanisms and paleo-stress inversions as the expression of a “pull-apart” system (Fig.1; Fig.5). Following this interpretation, E-W extension (Sue and Tricart, 2003; Sue et al., 2007) and 140°E right-lateral motion are reconciled within a single model.

By analogy, at the south-eastern boundary of the Argentera-Mercantour massif, instrumental seismicity is recorded along-side of the Saorge-Taggia Fault (STF) (Madeddu et al., 1997), which is parallel to the JTF. The focal mechanism solutions indicate dextral strike-slip motion of the STF with a N140° trending plane (Madeddu et al., 1997) in agreement with the JTF geometry and kinematics. The south-eastern part of the STF active fault merges into the Mediterranean (Ligurian) Sea near San Remo where the morphology of the Messinian surface is strongly offset by this fault (Bigot et al., 2004).

Regarding the JTF and STF, seismic activity has been reported since the 16th century, with earthquakes producing epicentral intensities > VIII, MSK (Sisfrance, 2008). The strongest events were located near the village of La Bollène-Vésubie (AD 1564 event). It destroyed most villages in the Vésubie and upper Roya Valleys and was estimated to have had a magnitude of ~ 5.8 (Fig.1; Cadiot, 1979). Its localization (Cadiot, 1979; Sisfrance, 2008) near the JTF (Fig. 1) allows us to attribute this event to JTF motion. Other major historical events occurred near San Remo and Menton including the 1887 earthquake, which reached intensity IX MSK (Sisfrance, 2008).

Thus, according to field investigations, seismological data and historical seismicity, it appears that the STF and the JTF represent an active “en echelon” faults system (JTF-STF), which localises most of the deformation in the area and on which high-magnitude earthquakes ($M > 6$) may occur.

At a regional scale, moderate but regular seismicity has also been recorded along the $N20^\circ$ sinistral Middle Durance Fault (MDF; Cushing et al., 2008) on which five significant seismic events with intensity $MSK \geq VIII$ occurred during these five last centuries (Sisfrance, 2008). The MDF is linked to the “Grand Vallon and Pont de Fossé-Eychauda” fault (GVF-PFEF), extending northwards into the Pelvoux massif, along which microseismicity has been measured (Terrier, 2006). These observations show that the MDF-GVF-PFEF comprises a unique $N20^\circ$ tectonic structure that branches into the main active fault system at the boundary between the internal and external Alps. Similarly, instrumental seismicity has revealed activity on other $N20^\circ$ sinistral faults, such as the Peille-Laguët (PLF; Courboulès et al., 2003), Vésubie (VF) and Rouaine (RF) faults (Terrier, 2006), which are truncated by the $N140^\circ$ JTF-STF (Fig.1). Deformation of Plio-Quaternary alluvial deposits has been described along the Digne (Jorda et al., 1992; Hippolyte et al., 2000) and Mont Férion (Campredon et al., 1977; Dubar et al., 1992) thrust, also demonstrating their recent reactivation with a dextral strike-slip component (Bès-MontDenier Fault: BMDF; St Blaise-Aspremont fault: BAF; Fig. 1).

Thus, the tectonic framework of the south-western external Alps exhibits a conjugate active fault system formed by $N140^\circ$ dextral and $N20^\circ$ sinistral faults compatible with a sub-meridian shortening context (Fig.1).

3.2 Seismic hazard evaluation

These new findings have implications for the evaluation of seismological and related
 (landslide, tsunami) hazards in one of the most populated regions of the Mediterranean Sea
 coast (the Riviera). Seismicity reported on the JTF-STF during the last decade is moderate
 ($M < 4$) and the historical earthquake catalogue (Sisfrance, 2008) does not report any
 significant event along the entire fault. However, the offset of topographic crests and glacial
 morphology observed along the JTF-STF imply a major paleoseismic event. As many authors
 have pointed out, different slips and stress drops can be observed from large earthquakes with
 similar sizes (Wells and Coppersmith, 1994; B. Romanowicz and Ruff, 2002; Manighetti et
 al., 2007). In particular, Manighetti et al. (2007) claimed that such variability of slips could be
 related to the fault geometry. Indeed, a segmented fault, breaking in shorter but more strongly
 energetic ruptures, may display higher slip than an un-segmented fault. Along the extremely
 segmented JTF-STF system, the maximum displacement observed (15m and 50m), can lead
 to magnitude overestimation with respect to a more mature un-segmented fault. Therefore, the
 offset morphologies could result from the recurrence of lower magnitude earthquakes ($M \approx 6$)
 and creeping processes also cannot be ruled out. In the same way, the seismic potential of the
 MDF-GV-PFEF, which corresponds to the major N20 conjugate fault, has been assessed by
 palaeoseismological investigations that suggest the possibility of a strong earthquake between
 27 and 9 ka (Sébrier et al., 1997). Concerning the seismic hazard related to the N20
 conjugated faults (RF, VF and PLF), the present-day seismicity remains lower than the main
 N140E fault system, even if nothing proves that a large earthquake along these minor faults
 could not occur though it is suggested by the AD 1618 and AD 1664 earthquakes (Sisfrance,
 2008). Thus, more work has to be done to estimate the motions on these smaller fault
 segments as they merge into the densely populated coastal zone. Even lower magnitude
 earthquakes ($M \leq 6$) on these minor faults could cause dramatic damage given their shallow
 hypocenter depth and local site effects.

4. Conclusions

Based on field investigations and seismicity, it is concluded that the south-western Alps has been subject to transcurrent deformations since at least the Holocene period, mainly accommodated by a > 100 km long, N140°E dextral segmented active fault system (JTF-STF), a conjugate N20 sinistral fault (MDF GV-PFEF) and minor conjugate N20 sinistral (RF, VF, PLF) and N-S extensional (HDF) or dextral faults (DF, BAF, BF, SF). These active faults share some general characteristics of intraplate faults, such as their relatively slow tectonic motions. Infrequent but large earthquakes ($M \approx 6$) may be expected near the densely populated French and Italian coastlines but the recurrence and magnitude of such events remains to be estimated.

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Figure caption

Fig. 1. Regional geological map of the active fault network in the south-western Alps (Hautes-Alpes to Alpes Maritimes, France), with the locations of key geological markers including faults, landslides (Jomard et al., 2007) and geothermal anomalies. Location of the AD 1564 historical seismic event is also shown. Focal mechanisms along the main fault have been taken from Courboux et al. (2003), Delacou et al. (2004) and Bethoux et al. (2007). The size represents the magnitude. PFT: Penninic Frontal Thrust; DCFT: Digne-Castellane Frontal Thrust, CT: Castellane Thrust; NT: Nice Thrust; JF: Jausier fault; TF: Tinée fault; STF: Saorge-Taggia fault; PLF: Peille-Laghet fault; VF: Vésubie fault; BAF: St Blaise-Aspremont fault; RF: Rouaine fault; BMDF: Bès-MontDenier fault; MDF: Middle Durance fault; GVF: Grand-Vallon fault; PFEF: Pont de Fossé-Eychauda fault; HDF: High Durance fault; SF: Serenne fault; BF: Bersézio fault.

Fig. 2. Pictures of field relationships in the Argentera-Mercantour crystalline massif (orthogneiss) along the Tinée Fault zone transect. a. General view of Clapière landscape showing the Tinée fault zone; b. Evidence of right-lateral motion along the Tinée fault with horizontal striae and schistosity deflection. c. Regularly spaced N-S joints in the damage zone along the Tinée fault. d,e. Pseudotachylyte veins infilling the N-S joints. f. Pseudotachylyte

joints containing pure quartz clasts and showing cataclastic features evolving locally to ductile stretching of clasts in the central part of the joints. g. Tension gash “en echelon” filled by pseudotachylytes showing dextral movement of the Tinée fault. h. Pseudotachylyte joints reaching several centimetres in width. i. Brecciation and offset of pseudotachylyte joints.

Fig. 3. Pictures showing evidence of right-lateral displacement of the ≥ 10 ka geomorphology. a, aerial photograph, with the main fault underlined in black; offset geomorphological markers include offset crests (✱) and slope break (●). b, landscape photograph showing the same markers. c, damaged zone along the fault located on b, featured by numerous cracks and fractures with a high angle to the fault strike.

Fig. 4. Relationship between focal mechanisms and paleostress axes along the JTF. The cartographic data correspond to field investigations locally filled out by 1/50 000 geological maps data. Focal mechanisms along the Jausier fault (JF) have been taken from Jenatton et al. (2007). Schmidt stereonets in lower hemisphere showing the distribution of more than 70 measured fault and striae and the computation of paleostress axes determined with Tector software (Angelier, 1990). Stars with 5,4,3 branches mark the principal stress axes of σ_1 , σ_2 and σ_3 respectively. Large grey arrows show directions of compression and extension with azimuthal confidence in grey. The contours around poles give the principal stress axes uncertainty during the inversion.

Fig. 5. Block diagram showing the active fault system in the north-western part of the south-western Alps. The picture represents the pull-apart system with the two major dextral Jausier-Tinée fault and Serennes-Bersézio fault and the extensional High Durance fault system.

Figure 4