Post-nappe brittle extension in the inner Western Alps (Schistes Lustrés) following late ductile exhumation: a record of synextension block rotation?

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ABSTRACT

Fault data collected from the Schistes Lustre's domain point to the existence of successive steps of deformation and indicate that extension is not multidirectional. This study underlines the continuity between the patterns of late brittle/ductile exhumation tectonics and brittle deformation, and strengthens the view that extensional movements dominate in shallow levels of the inner Western Alps since at least 35–30 Ma. The progressive clockwise rotation of the earliest directions of extension with time is compatible with the amount of anticlockwise rotation from c. 35 Ma determined by recent palaeomagnetic studies, whereas the last documented N–S extension may reflect a short-lived stage of orogen-parallel extension.


Introduction

Active extension is presently affecting most of the units in the inner Western Alps (e.g. Eva and Solarino, 1998; Sue et al., 1999). Some major thrusts are even thought to have been extensional since c. 20–15 Ma (Seward and Mancktelow, 1994; Sue and Tricart, 1999; Tricart et al., 2001), despite continuous convergence and ongoing collision during the last 30 Ma (Tricart, 1984; Coward and Dietrich, 1989).

In the past decade, several regional studies have focused on the description of extensional brittle tectonics in the inner French–Italian Western Alps, mainly in the Briançonnais zone (Lazarre et al., 1994; Allègres et al., 1995; Tricart et al., 1996; Virlovet et al., 1996; Sue and Tricart, 1999; Schwartz, 2002). Lazarre et al. (1994) suggested that successive stress regimes may have prevailed in the Liguro-Piemontese zone, whereas Sue and Tricart (2002) recently concluded on the occurrence of regional-scale multidirectional extension from 20 to 15 Ma to the present (despite nearly orthogonal directions of extension for the Briançonnais and Liguro-Piemontese zones). By contrast, the final ductile exhumation of the high-pressure low-temperature (HP-LT) Liguro-Piemontese metapelites was associated with west-vergent extensional movements that took place at c. 35 Ma (Agard et al., 2001a, 2002). The question then arises as to whether the late ductile and brittle extensional stages represent the record of a fairly continuous tectonic evolution.

We collected new data in order to complement available data on fault patterns in the Schistes Lustrés (SL) domain (close to Sestrieres, Italy) and study the transition between the late ductile extensional movements and the brittle deformation. The results presented below show successive steps of extensional faulting that are compatible with the 47–68° anticlockwise rotation of the inner Western Alps evidenced from palaeomagnetic data (at this latitude: Thomas et al., 1999; Collombet et al., 2002).

Post-nappe extension in the inner western alps: an overview

The inner parts of the arcuate Western Alpine belt represent palaeogeographical zones that suffered significant burial (c. > 30 km) related to the closure of the Alpine ocean, before the onset of collision at 30 Ma. In terms of palaeogeography, going outwards from the thinned, continental...
Post-nappe brittle extension in the inner Western Alps

Present-day extension directions (Sui et al., 1999)
Kinematic data 40-15 Ma (Platt et al., 1989)

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European margin one successively finds: the continental Briançonnais and Piemontese zones, and the Liguro-Piemontese zone (comprising the SL domain), which corresponds to metasediments (plus minor ophiolites) from the oceanic domain proper (e.g. Lemoine et al., 2000).

**Ductile exhumation of HP-LT rocks in the SL domain**

The Upper Jurassic to Upper Cretaceous SL calcshists and pelites were metamorphosed under contrasted HP-LT conditions corresponding to blueschist to eclogite facies conditions (12–20 kbar, between 350 and 500 °C; Agard et al., 2001b), as a result of the Alpine ocean closure. The early stages of deformation coeval with HP-LT metamorphism were almost completely overprinted by exhumation tectonics.

Two opposite vergence exhumation stages were recognized in the SL domain in the study area (Agard et al., 2001a): (i) a ductile, predominantly east-vergent D2 deformation event; and (ii) a conspicuous, highly asymmetric west-vergent event termed D3, taking place at depths of 15–20 km. Radiometric dating suggested an age of 48–43 Ma and 38–35 Ma for the D2 and D3 stages, respectively (Agard et al., 2002). In fact, D3 deformation in the SL domain compares well, in terms of both style and age, with the west-vergent deformation recognized on the borders of the continental Brianc¸ onnais and in the Piemontese zones, and the Liguro-Piemontese zone (comprising the SL domain), which corresponds to a major event taking place at the rear of the inner parts of the orogen at around 35 Ma.

D3 deformation patterns (directions and shear senses; Fig. 1) reveal a relatively constant strike throughout the study area between N240 (i.e. N120 °W) and N270. In fact, D3 shows a transitional character from ductile to brittle deformation, being more brittle in the west of the study area than in the east (Agard et al., 2001a). This latter characteristic was interpreted as the result of different temperature regimes prevailing at the onset of D3 deformation at the two ends of the study area (Agard et al., 2001a), although some of this deformation might be somewhat diachronous.

**Fault and stress patterns in the SL domain**

In calcshists from the Queyras (south of our study area), Lazarré et al. (1994) reported two main families of faults striking N160 and N070, and three different stress regimes, namely (i) a N160-directed extension followed by (ii) a nearly multidirectional extension (N070/N160) and (iii) a late strike-slip regime associated with a N030 compression accommodated by these two sets of faults. Although they suggest that brittle extension could be the continuation of the extensional ductile deformation recognized earlier (Bàllèvre et al., 1990; Philippot, 1990), they report that the various schistosities never seem to accommodate brittle deformation.

Schwartz (2002) also reported two fault families in the Queyras SL unit, orientated N155 and N75, respectively, the former being strongly asymmetric. In contrast to Lazarré et al. (1994), Schwartz (2002) put forward a significant tilting of the SL unit, and suggested that it could have been large enough to produce a strong asymmetry. Schwartz also assumes that extension is multidirectional.

**Fault and stress patterns in the Briançonnais zone and adjacent areas**

Tricart et al. (1996) first pointed out that dip-slip normal faulting actually pre-dated the present-day dextral strike-slip motion taking place along the N-S-trending Briançonnais Frontal Thrust (Barféty et al., 1968), a conclusion in line with similar findings by Ailléres et al. (1995) further north. In the adjacent Briançonnais blocks, Virlouvet et al. (1996) reported a set of mostly E-W-trending faults marking a N-S extension prior to strike-slip movements. These faults were taken together as evidence for a tendency towards multidirectional extension, and were thought to represent regional-scale crustal thinning in much the same way as on top of a thickened wedge (Platt, 1986).

Along the Pennine Frontal Thrust (PFT), Sue and Tricart (1999) described an E-W brittle extension (again followed by dextral N-S-trend strike-slip motion) characterized by low values of the φ ratio (see definition below), which they interpreted as a multistage extensional regime. They suggested that the eastward downthrow along the PFT (for which fission track data have shown to date back to c. 20 Ma; Tricart et al., 2001) might have controlled the whole brittle extension in the inner Western Alps. Sue and Tricart (2002) extended the database across the Briançonnais and in the Piemontese zones (and in part of the SL domain) and concluded that there was a multidirectional extension everywhere in the inner Alps along the Pelvoux–Viso transect.

**Active deformation in the inner Western Alps**

The seismic activity is low in the SL domain as compared with the adjacent Briançonnais domain (Eva and Salarino, 1998; Sue et al., 1999, 2000), where brittle extension is spectacularly prolonged by the present-day extensional seismic activity (Sue et al., 1999). Sue et al. (1999, 2000) recognized a dominant E–W extension with differential motions in the range 2–4 mm yr⁻¹ (i.e. very similar to the results of Calais et al., 2000, further south). These authors also defined three domains with different radial directions of extension (Fig. 1), which strikingly resemble Tertiary kinematic directions compiled by Platt et al. (1989).

**Fault analysis in the Liguro-Piemontese Schistes Lustres around Sestriere**

The 10 sites selected for the measurements are scattered on a transect between Sestriere and Fenestrelle (Italy). Brittle deformation is marked in the field by a dense network of metre-scale faults. Some major faults are visible, but rarely exceed 100 m in length (except close to site 1). Striated faults and veins all point to a dominant extensional behaviour. Interestingly, calcite slickensides frequently grow directly upon brittle/ductile D3 shear planes (Fig. 2), particularly in the east of the study area. In places, late, minor strike-slip faulting was also observed.

About 500 faults were measured (and fewer than 3% discarded). Not all fault sets are present in each measurement site. Yet, in each site, a
chronology was deduced from the analysis of the successive generations of slickensides on fault planes, which is consistent at the scale of the SL unit: phases A–B, then C, then D and strike-slip movements successively developed (see Fig. 2 and Table 1). For this reason, mechanically and geometrically consistent fault systems were assumed to have formed contemporaneously and were plotted together in order to retrieve the probable regional-scale stress regime at the time of faulting. This is justified because slip data were collected away from major fault zones (except site 1) and the palaeo-

stress reconstructions therefore meet the assumptions of stress homogeneity and low finite (hence nearly coaxial) strain (e.g. Twiss and Unruh, 1998) – this is also a posteriorem strengthened by the consistency of tensors from one site to another (see below).

Computation of palaeostress orientations (Table 1) was made by the direct inversion method of Angelier (1990), assuming that striation on a fault plane is parallel to the shear stress exerted on the plane. Although often computed from conjugate sets and therefore poorly constrained, values of the φ ratio (\(\phi = [\sigma_2 - \sigma_3]/(\sigma_1 - \sigma_3)\), 0 ≤ φ ≤ 1) are usually lower than 0.5 (the theoretical value for actual unidirectional extension), but frequently close to or above 0.4 (i.e. much larger than the expected null value for multidirectional extension). This result is consistent with the findings of Sue and Tricart (2002) for the sites they analysed in the Liguro-Piemontese zone.

Within a given fault set showing a similar strike, north/west-dipping faults are generally more numerous. This asymmetry is even more pronounced in the west of the study area (Fig. 3). It could either be due to the reactivation of late ductile-

Fig. 2 Some aspects of brittle deformation in the Schistes Lustres unit. (a) Late brittle calcite overgrowths growing upon, and slightly oblique to, the late ductile D3 structures (site 9, between Assieta and Finestre; location given on Fig. 1). (b) As (a), but closer to Finestre area (site 11). (c) An example of conjugate faults from stage D (site 2a). The width of the photograph is approximately 4 m (see hammer at the bottom of the outcrop for scale). (d) An example of a brittle fault directly branching upon a late ductile/brittle D3 shear band (site 3).
Table 1 Results of palaeostress determination using fault-slip data (only fault types represented by a sufficient number of faults are listed here: this explains why some fault types that are referred to in the Chronological constraints column are not listed in the Site column). For each stress orientation, trend (T) and plunge (P) are given; Phi: value of the \((\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)\) ratio; Ang and %rup: differences between the observed and calculated striae, in terms of angular variations and length, respectively (see Angelier, 1990, for further explanations); n: number of faults used to calculate palaeostress orientations. Relative chronology relationships observed in the field are given (extreme right column), where they were available.

<table>
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<th>Site</th>
<th>(\sigma_1) (T)</th>
<th>(\sigma_2) (P)</th>
<th>(\sigma_3) (P)</th>
<th>Phi</th>
<th>Ang</th>
<th>%rup</th>
<th>n</th>
<th>Chronological constraints</th>
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Discussion

Continuity of extension since c. 35 Ma

This study further confirms that extension largely dominates the late brittle evolution of the inner Western Alps (Tricart and co-workers). In fact, no evidence of reverse faulting was recognized in the field: the Oligo-Miocene backthrusting event (Tricart, 1984), already partly reappraised by Sue and Tricart (2002), seems to be virtually non-existent here.

In addition, several features suggest that this brittle extension directly follows the late ductile exhumation regime, termed D3 (Agard et al., 2001a): (i) brittle extension directions for phases A and B are subparallel (< 15°) to the kinematic directions inferred for D3, (ii) the growth of slickensides subparallel to L3 lineations on D3 shear planes (Fig. 2) is visible in several places and (iii) asymmetric fault patterns are observed as for D3 (except for phase A in the eastern part of the study area). This continuity of the ductile to brittle extension is thus comparable to the one evidenced by Rolland et al. (2000) further north and Schwartz (2002) further south.

Comparison with previous studies in the inner Western Alps

Our results show that brittle extension in the SL domain can be interpreted in terms of successive normal fault populations: A–B, then C, then D, C and D being sometimes associated with strike-slip faults (Table 1). This evolution corresponds to a clockwise rotation of apparent extension directions of approximately 90–105°, from N260 (phase A–B) to N315 (phase C) and N005 (phase D). This chronological sequence is, however, opposite to that of Lazarre et al. (1994), who assumed that N170 extension preceded N060 extension (i.e. those equivalent to stages C and A, respectively).

Our study underlines a possible diachronism of extension that contrasts with the multidirectional extension globally recognized by Sue and Tricart (2002). In fact, their extension directions in the SL domain, rather than being in fact multidirectional, strike...
Fig. 3 Fault populations in the Schistes Lustre’s unit. Stereodiagrams point to successive steps of brittle extension, from A to D (for justification see Table 1). Palaeostress orientations, calculated using the direct inversion method of Angelier (1990), are reported in Table 1 (see text for details). Square black symbols: poles to late brittle veins. Asterisk: only in two sites (sites 2b and 4) was a chronological criterion evidenced between one fault population striking N130 (A type) and another one striking approximately N180 (B type). At those two sites, the B type post-dated the A type. Elsewhere this distinction could not be ascertained. This is why we finally chose to keep only one single family – although, in the light of our interpretation (Fig. 4), A and B might well represent slightly diachronous steps of extension.
coherently N–S. Other reports of extension further north (e.g. Seward and Mancktelow, 1994; Cannic et al., 1999; Bistacchi et al., 2000; Rolland et al., 2000) did not show multidirectional extension.

Evolution of the stress regime through time

The successive directions of extension evidenced by this study may be interpreted either in terms of rotation of the stress axes through time or in terms of rotation of the SL unit itself (or in terms of a combination of both). The lack of age constraints for each set of faults makes it difficult to discriminate between these two interpretations.

Fig. 4 Sketch depicting the possible evolution of the main stress directions with time in this part of the inner Western Alps. In this interpretation, the progressive clockwise rotation of the earliest directions of brittle extension (Fig. 3; stages A to C) was coeval and witnessed the anticlockwise rotation of the inner Western Alps deduced from palaeomagnetic studies (right column of figure), while the boundary stress/strain conditions remained broadly unchanged. The last documented N–S extension in the Schistes Lustres unit (stage D) may reflect a short-lived stage of orogen-parallel extension (see text for further details). Astetisk: extension direction after Sue et al. (1999). NB: the interpretation in terms of stress or strain axes is almost equivalent if one considers separately the regional, vertical-axis rigid rotations and the local brittle deformation: away from major faults the assumptions of stress homogeneity and low finite (hence coaxial) strain for late brittle faulting (Twiss and Unruh, 1998) are indeed probably met.
Following Vialon et al. (1989), Thomas et al. (1999) demonstrated that the Briançonnais zone had been rotated anticlockwise 47 ± 13° since the late Eocene – early Oligocene (c. 35–30 Ma). This anticlockwise rotation of the inner Western Alps was recently confirmed by Collombet et al. (2002) for the Briançonnais (for Sesia-Lanzo, see Lanza, 1979), who showed that the amount of rotation increased southwards (up to c. 120°), with a value close to 47–68 ± 15° west of our study area.

We therefore propose that our apparent clockwise rotation of brittle extension directions recorded this anticlockwise rotation of the inner Western Alps identified by palaeomagnetic studies. According to this interpretation, the direction of extension would have been roughly constant (at N305°–315°) while the SL domain was being rotated: phases A–B would then represent the beginning or an early stage of rotation (because the directions of extension of early brittle faults A–B are almost parallel with those of D3 extension), whereas phase C would correspond to the last stages of nearly NW–SE extension before the onset of phase D and strike-slip movements. The asymmetry of fault patterns observed for both phases A and C further suggests they could have formed in a similar tectonic regime.

In this interpretation, phase D would then represent the last recorded brittle event in the SL domain, before the onset of the present-day seismic, E–W brittle extension documented in the Briançonnais zone. Phase D could be related to earlier stress regimes by stress permutation, perhaps representing a local tectonic pulse marked by a slight E–W shortening inducing strike-slip movements and orogen-parallel extension within the dominant extensional regime.

Conclusions

This study strengthens the view that extensional movements have dominated at shallow levels of the inner Western Alps since at least 35–30 Ma. The duration of this process is compatible with models of regional-scale thinning (e.g. Platt, 1986), but a discussion of the mechanisms at depth responsible for this behaviour (e.g. gravitational instability, whether or not indentation-driven, slab breakoff, rotation, etc.; see Sue and Tricart, 2002, for a review) is beyond the scope of the present paper.

The results of this study point to the existence of successive steps of deformation and strongly suggests that extension is not really multidirectional (Tricart et al., 2001; Sue and Tricart, 2002). In this regard, our results are in agreement with those of Lazarre et al. (1994), although our relative chronology differs. This study also underlines the continuity between the late brittle/ductile exhumation tectonics and brittle deformation in the SL domain.

Finally, the clockwise rotation of the extension directions over time is shown to be compatible with the anticlockwise rotation evidenced by several palaeomagnetic studies (e.g. Thomas et al., 1999; Collombet et al., 2002).

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