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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 Lustrés 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 strenghtens 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.

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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 continued 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; Aillères *et al.*, 1995; Tricart *et al.*, 1996; Virlouvet *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).

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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 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 calcschists 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 internal crystalline massifs (e.g. Dora Maira massif; Chopin *et al.*, 1991), and 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

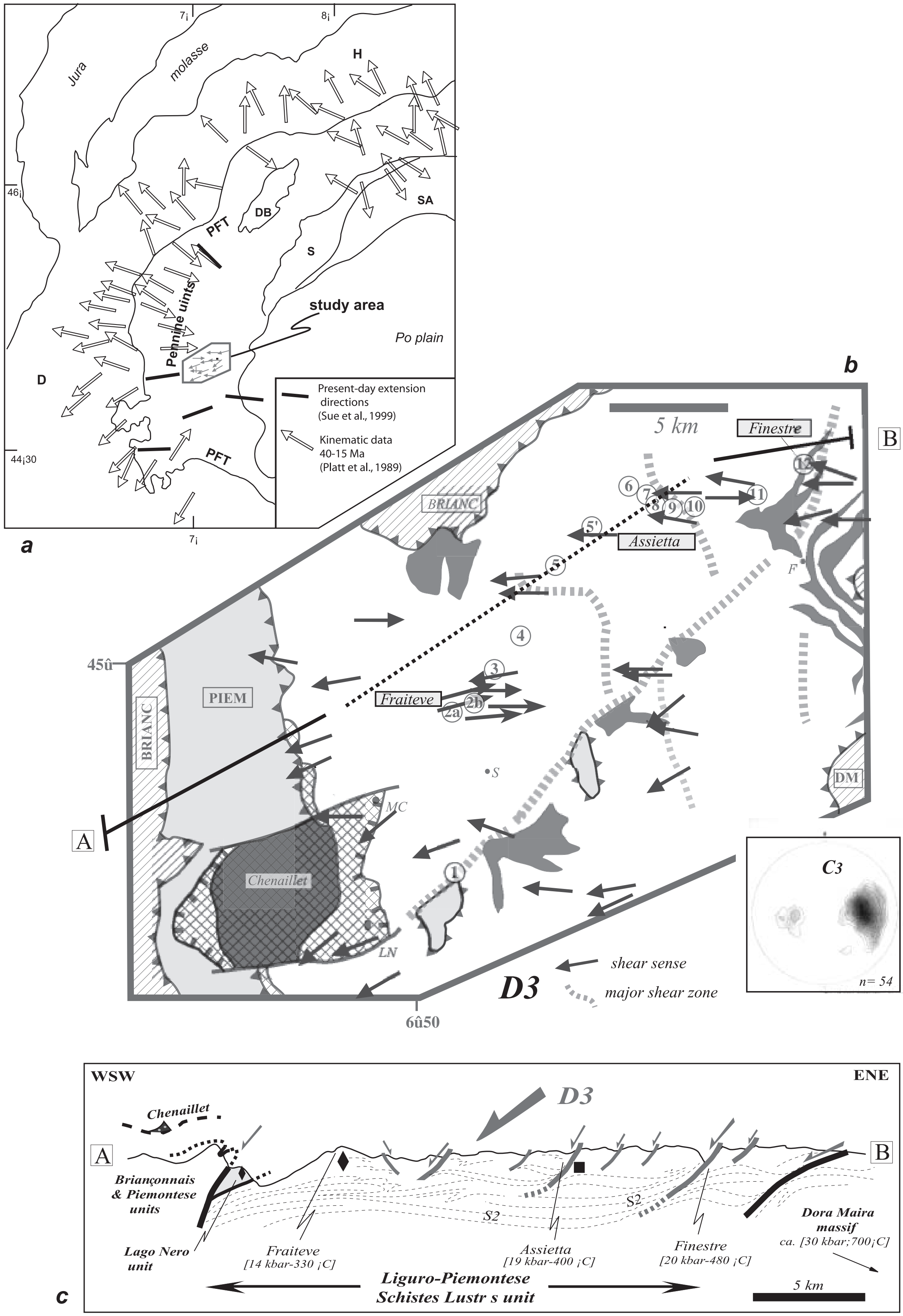
Jura
molasse
H
DB
SA
S
D
PFT
Pennine uints
study area
Po plain
Present-day extension directions (Sue et al., 1999)
Kinematic data 40-15 Ma (Platt et al., 1989)
46¡
44¡30
7¡
8¡
a
b
5 km
Finestre
Assietta
Fraiteve
BRIANC
PIEM
Chenaillet
MC
LN
DM
F
S
45û
6û50
A
B
C3
n= 54
shear sense
major shear zone
D3
WSW
ENE
Chenaillet
Briançonnais & Piemontese units
Lago Nero unit
Fraiteve [14 kbar-330 ¡C]
Assietta [19 kbar-400 ¡C]
Finestre [20 kbar-480 ¡C]
Dora Maira massif ca. [30 kbar;700¡C]
S2
Liguro-Piemontese Schistes Lustr s unit
5 km
c

Fig. 1 (a) Location of the study area in the inner Western Alps (within the framed box). The late ductile stretching directions shown in (b) (after Agard *et al*., 2001a) are schematically reported within the box and can be compared with the kinematic data compiled by Platt *et al*. (1989) on the one hand, and to present-day extension directions (Sue *et al*., 1999) on the other hand. D: Dauphinois zone; DB: Dent Blanche nappe; H: Helvetic zone; PFT: Pennine Frontal thrust; S: Sesia; SA: South-Alpine zone. (b) Simplified structural map of the study area. Numbers correspond to the fault measurement sites. Arrows: kinematic indicators associated with the late D3 ductile and ductile to brittle deformation (the strongly dis-symetrical character of the C3 shear planes is evidenced in the framed box to the lower right; lower hemisphere, Schmidt projection). Hatched: Briançonnais-type units (including the Dora Maira unit to the SE; DM); light grey: Piemontese zone; white: Liguro-Piemontese metasediments (Schistes Lustrés, SL hereafter) and main ophiolite bodies enclosed (dark grey); double hatching: Lago Nero oceanic unit (LN: Lago Nero; MC: Monte Cruzore); dark grey, double hatched: Chenaillet oceanic unit. S: Sestrières; F: Fenestrelle. (c) Schematic SW–NE section across the study area (see location in b) showing: the location of the main D3 shear zones (in grey) post-dating earlier D2 deformation (S2: D2 schistosity), and the range of P–T conditions (increasing eastward) reached by the SL metasediments. Symbols: first occurrence, from W to E, of carpholite (diamonds) and chloritoid (squares).

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 calcschists from the Queyras (south of our study area), Lazarre *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 (Ballèvre *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 Lazarre *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 Aillères *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 together taken as evidence for a tendancy 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-trending strike-slip motion) characterized by low values of the ϕ ratio (see definition below), which they interpreted as a multitrend 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 Solarino, 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 Sestrieres

The 10 sites selected for the measurements are scattered on a transect between Sestrieres 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

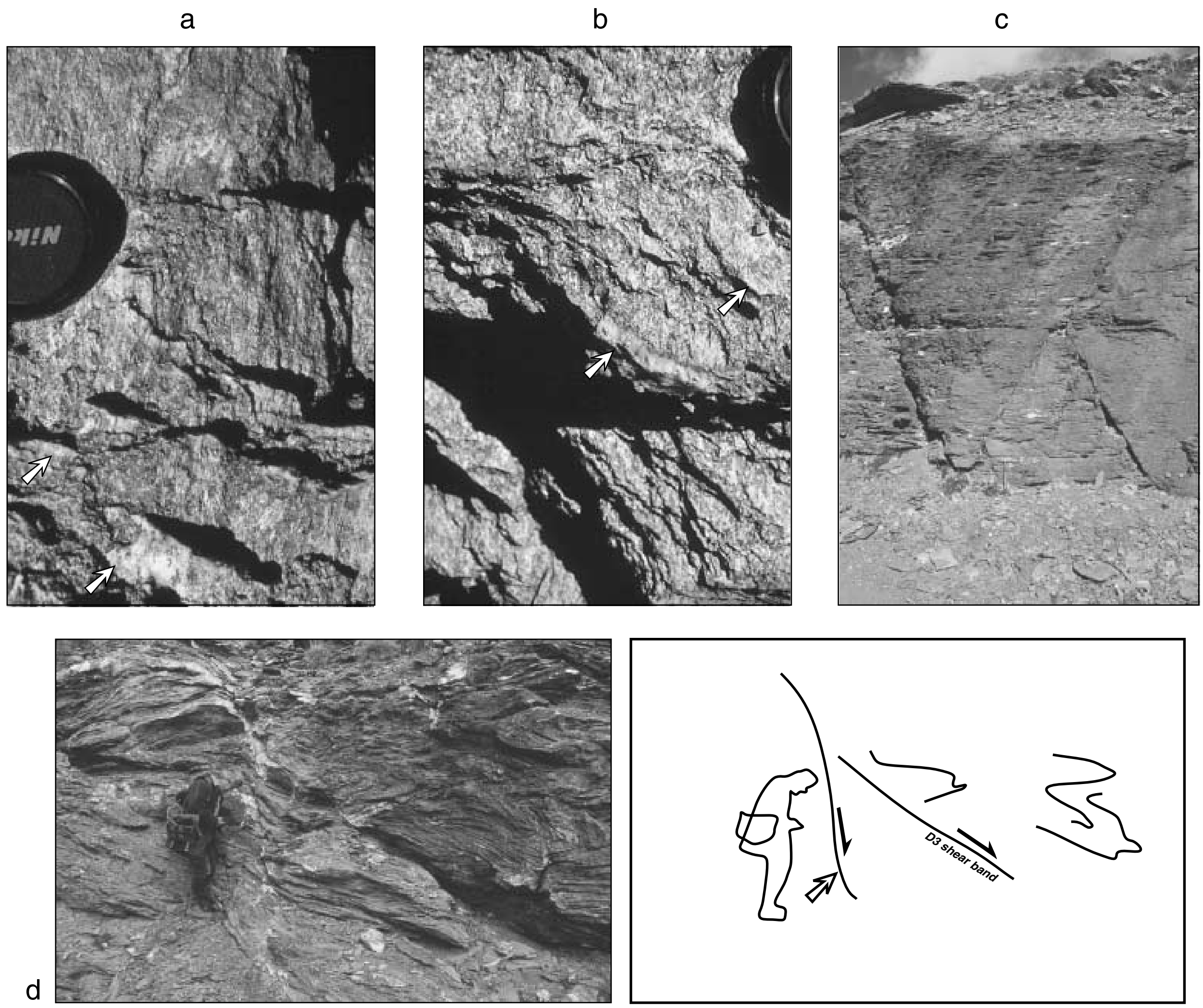

Fig. 2 Some aspects of brittle deformation in the Schistes Lustrés unit. (a) Late brittle calcite overgrowths growing upon, and slightly oblique to, the late ductile D3 structures (site 9, between Assieta and Finestre; location given on Fig. 1). (b) As (a), but closer to Finestre area (site 11). (c) 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).

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 palaeostress 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 posteriori* strenghtened 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 ($\phi = [(\sigma2 - \sigma3)/(\sigma1 - \sigma3)]$, $0 \leq \phi \leq 1$) 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-

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 ($\sigma2 - \sigma3$)/($\sigma1 - \sigma3$) 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

		σ1		σ2		σ3						
Site		(T)	(P)	(T)	(P)	(T)	(P)	Phi	Ang	%rup	*n*	Chronological constraints
1	1C	70	78	229	11	320	4	0.5	4	17	17	(C then D′)
	1D′	356	9	232	74	88	13	0.2	21	37	6	
2a	2AB	144	74	348	15	257	6	0.5	8	20	21	(A–B then C) and (A then C′)
	2A	26	74	296	0	206	16	0.5	12	27	6	
	2C	110	78	17	1	287	12	0.4	6	17	11	
	2D	137	80	277	8	7	6	0.4	5	16	6	
2b	2′A	66	86	334	0	244	4	0.4	4	8	5	(A then B)
	2′B	12	79	175	11	266	3	0.4	5	15	7	
3	3A	265	80	141	6	50	8	0.5	8	20	9	(A then C)
	3C	207	83	6	7	96	3	0.3	8	20	14	
4	4A	358	75	145	12	236	8	0.4	8	26	6	(A then B)
	4C	34	71	226	19	135	4	0.5	10	30	7	(D then D′)
	4D	317	76	82	8	174	11	0.5	4	14	8	
	4D′	306	39	63	29	177	37	0.4	22	55	5	
5	5B	117	79	357	5	266	9	0.6	4	12	6	(A-B then C) and (B then D′)
	5C	0	64	231	17	135	19	0.0	9	30	4	
	5D′	282	8	72	81	191	4	0.5	8	34	5	
6	6A	8	71	142	14	236	14	0.4	3	22	4	(A then C then D′)
	6C	23	85	208	5	118	0	0.4	7	35	6	
7	7A	39	81	146	3	236	9	0.4	3	10	5	(B then C) and (A then D′) and (A then D) and (A then C)
	7AB	29	82	167	6	258	5	0.4	6	18	8	
	7C	51	67	231	24	141	0	0.6	8	27	4	
	7D	29	88	291	0	201	2	0.3	3	10	6	
	7D′	145	87	303	3	33	1	0.8	21	41	11	
8	8A	336	76	159	14	68	1	0.5	9	24	22	(C then C′?)
	8A	201	82	53	7	323	4	0.4	1	33	16	
	8B	199	32	23	58	290	2	0.7	7	27	9	
	8C	6	74	244	9	152	13	0.4	4	37	9	
	8C	97	85	320	3	230	3	0.5	9	20	9	
	8C′	267	31	61	56	169	12	0.2	7	40	13	
	8D′	42	79	175	8	266	8	0.5	9	21	5	
9	9AB	324	88	179	1	89	1	0.4	9	26	17	(A–B then C then D)
	9C	108	85	222	2	312	5	0.6	13	30	23	
	9D	273	72	118	17	25	7	0.5	8	28	17	
10	10C	128	80	241	4	332	9	0.5	10	24	16	(A-B then C)
	10C′	85	44	187	13	290	44	0.5	14	59	6	
11	11B	71	76	178	4	269	13	0.4	11	26	8	(B then D)
	11C	79	7	44	2	34	2	0.7	1	34	8	
	11D	42	61	279	17	182	23	0.1	11	24	6	
12	12C	61	75	219	14	310	5	0.3	8	24	10	(A then C) and (C then D)
	12D	107	67	270	22	3	6	0.4	12	23	12	

to-brittle west-dipping D3 shear planes (Fig. 1c) or to a component of simple shear (Gapais *et al.*, 1991), which remains low because the average σ1 is nearly vertical within the error bars (Fig. 3).

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 pre-dated 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 coherently N–S. Other reports of

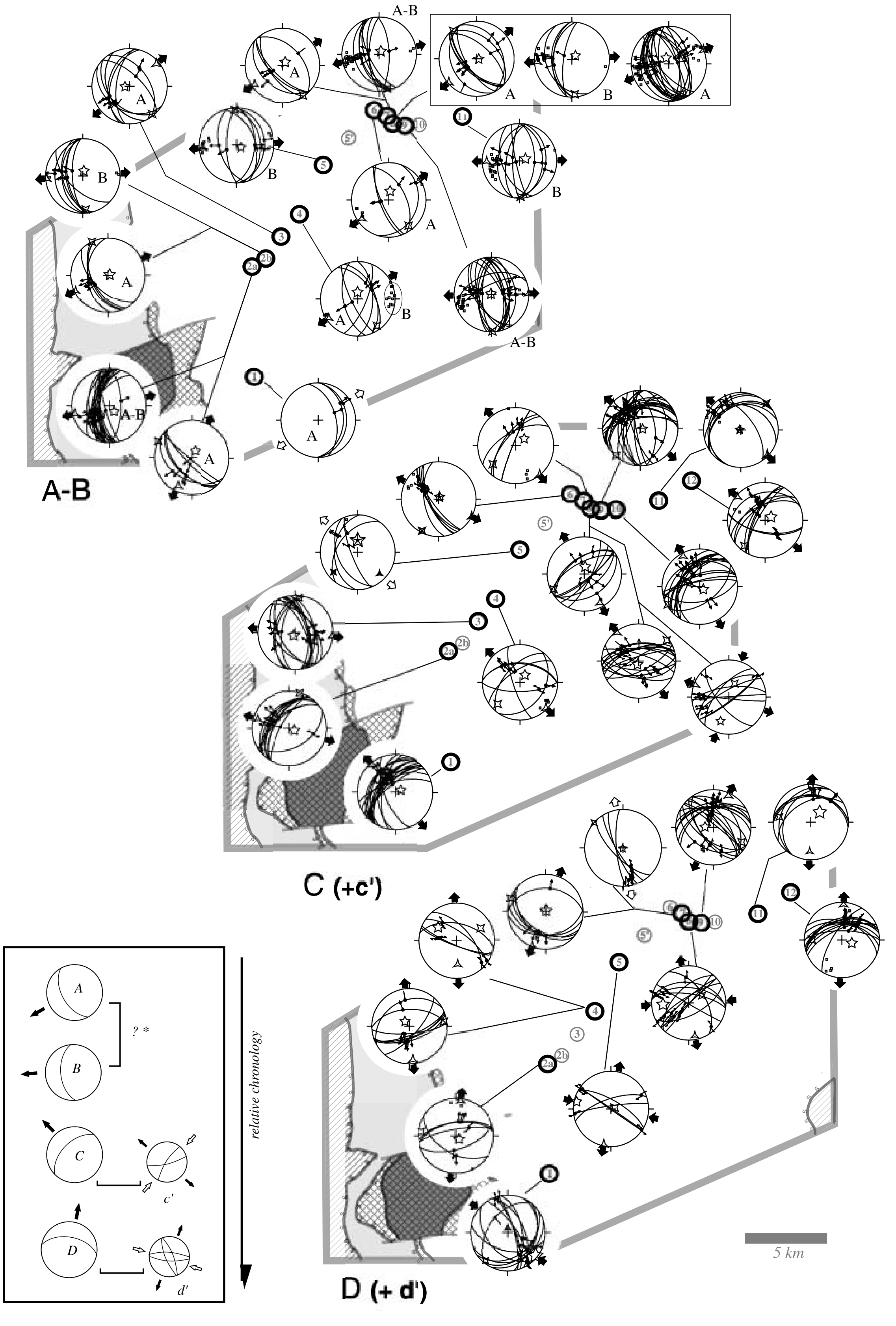
A-B
C (+c')
D (+ d')
5 km
relative chronology
? *
c'
d'

Fig. 3 Fault populations in the Schistes Lustrés 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.

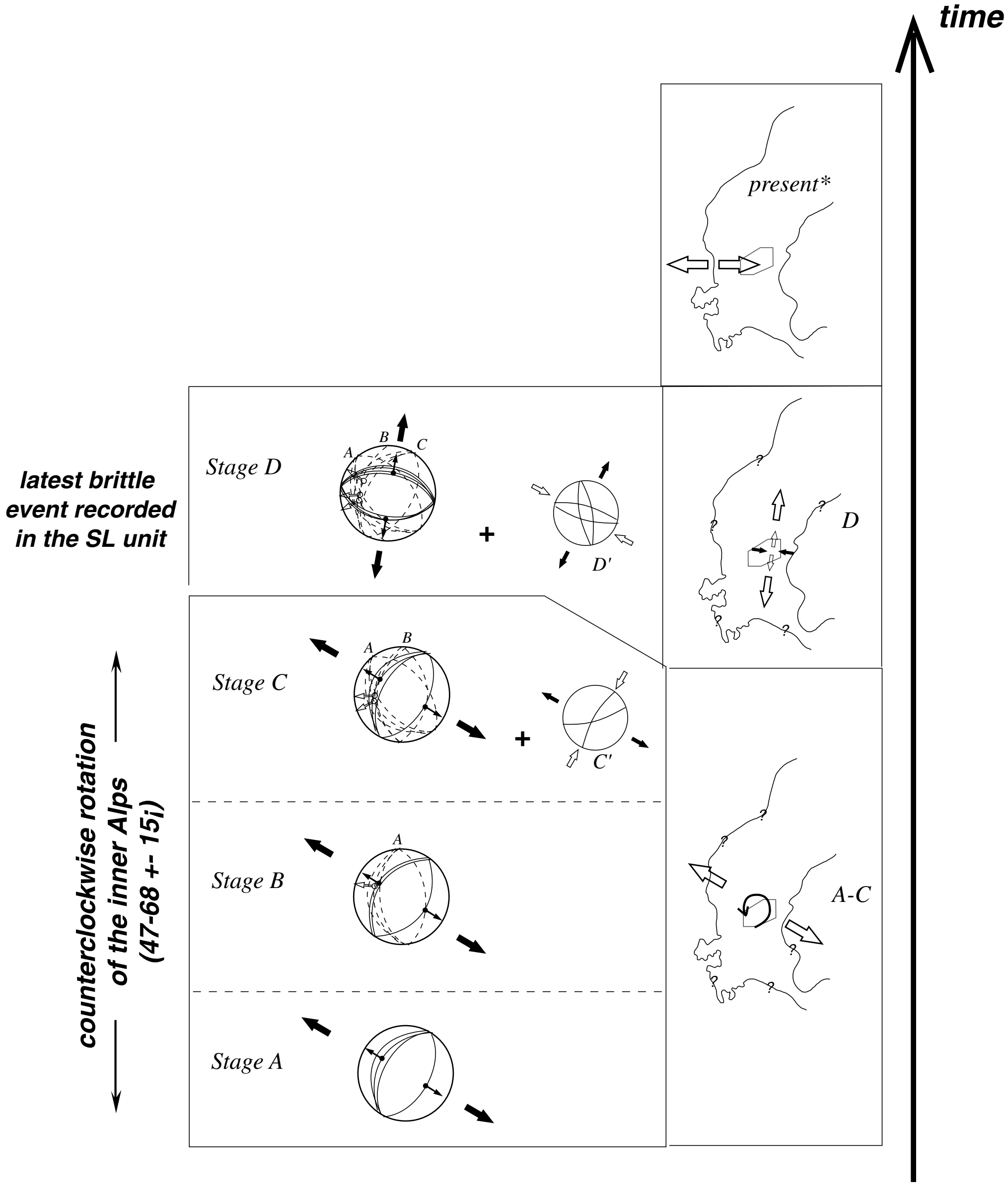

Fig. 4 Sketch depicting the possible evolution of the main stress directions with time in this part of the inner Western Alps. In this interpretation, the progressive clockwise rotation of the earliest directions of brittle extension (Fig. 3; stages A to C) was coeval and witnessed the anticlockwise 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 Lustrés unit (stage D) may reflect a short-lived stage of orogen-parallel extension (see text for further details). Astetrisk: 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.

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.

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 (Fig. 4), 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 strenghtens 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 respect 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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