

Miocene lateral extrusion in the inner western Alps revealed by dynamic fault analysis

Jean-Daniel Champagnac, Christian Sue, Bastien Delacou, Pierre Tricart, Cécile Allanic, Martin Burkhard

▶ To cite this version:

Jean-Daniel Champagnac, Christian Sue, Bastien Delacou, Pierre Tricart, Cécile Allanic, et al.. Miocene lateral extrusion in the inner western Alps revealed by dynamic fault analysis. Tectonics, 2006, 25, pp.TC3014. 10.1029/2004TC001779. hal-00130576

HAL Id: hal-00130576 https://hal.science/hal-00130576v1

Submitted on 4 May 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Miocene lateral extrusion in the inner western Alps revealed by dynamic fault analysis

J. D. Champagnac, ^{1,2} C. Sue, ¹ B. Delacou, ¹ P. Tricart, ³ C. Allanic, ¹ and M. Burkhard ¹

Received 16 December 2004; revised 2 February 2006; accepted 17 February 2006; published 8 June 2006.

[1] From early Miocene to the present-day the core parts of the western European Alps experienced brittle extensional deformations, mostly in a strike-parallel direction. Here we present new data constraining the brittle deformation of the Vanoise area (French Alps) and a synthesis of 312 paleostress tensors in the whole arc of the internal western Alps. The data show a continuous change in the direction of extension, from N065° (Simplon area), to N-S (Vanoise area) and to NNW-SSE (Briançon area). The abundance of orogenperpendicular σ_3 axes increases from the north to the south. In the Brianconnais area, an extensional reactivation of the Basal Penninic Thrust seems to be the origin of the E-W to NE-SW oriented σ_3 . In light of these new data and the regional paleostress synthesis, we propose a predominant orogen-parallel extension in the internal zone as a whole. This orogen-parallel extension is related to the indentation/rotation of the Apulian microplate and to the opening of the Ligurian Sea during the lower-middle Miocene. The locally observed orogen-perpendicular extension is interpreted as an effect of the exhumation of the Internal Crystalline massifs, the uplift of the External Crystalline massifs and/or the present-day geodynamics (postorogenic gravitational collapse). Some transcurrent tectonics, older than the extension in the Valais area and younger than the extension farther south is observed in the entire inner western Alps; strike-slip movements are correlated with the Apulian rotation and local permutation of stress axes. Citation: Champagnac, J. D., C. Sue, B. Delacou, P. Tricart, C. Allanic, and M. Burkhard (2006), Miocene lateral extrusion in the inner western Alps revealed by dynamic fault analysis, Tectonics, 25, TC3014, doi:10.1029/2004TC001779.

1. Introduction

[2] The Alpine belt results from the subduction of the Tethyan and Valaisan ocean seafloors and the subsequent collision between the European and Apulian margin since the upper Cretaceous [e.g., *Tricart*, 1984; *Lemoine et al.*, 1986; *Schmid and Kissling*, 2000]. At the plate scale, Africa currently continues to converge with Europe at a rate of 3–8 mm/yr at the longitude of the western Alps [*DeMets et al.*, 1994; *Albarello et al.*, 1995; *Nocquet and Calais*, 2004]. Alpine tectonics have been studied in great detail, in terms of nappe emplacement history and geometry [e.g., *Tricart*, 1984; *Escher and Beaumont*, 1997; *Pfiffner et al.*, 2000] as well as metamorphism and thermal evolution through time [*Steck and Hunziker*, 1994; *Desmons et al.*, 1999; *Brouwer et al.*, 2004]. Another important part of Alpine research focused on the arcuate shape of the belt and counterclockwise rotation of the Apulian promontory [e.g., *Vialon et al.*, 1989; *Collombet et al.*, 2002; *Lickorish et al.*, 2002].

- [3] In the past 10 years, emphasis has been placed on the study of late Alpine extensional tectonics under ductile to brittle conditions. Extension has been first described in the eastern Alps from the lower Miocene onward, with an E-W direction of extension, parallel to the Alpine trend [Selverstone, 1988; Ratschbacher et al., 1991; Frisch et al., 2000]. Ductile extension has also been locally observed in the central and western Alps [Ballèvre et al., 1990; Mancktelow, 1992; Steck and Hunziker, 1994; Rolland et al., 2000; Wawrzyniec et al., 2001; Tricart et al., 2004b]. In the western Alps, late Alpine brittle extension has been observed within inner parts of the belt [Aillères et al., 1995; Cannic et al., 1999; Sue and Tricart, 1999; Bistacchi et al., 2000; Champagnac et al., 2003, 2004; Grosjean et al., 2004; Tricart et al., 2004b]. Moreover, extension is currently active, as demonstrated by seismotectonics studies [Eva et al., 1998; Sue et al., 1999; Delacou et al., 2004; Kastrup et al., 2004, Delacou, 2005].
- [4] In this paper we present a series of 66 new paleostress tensors from the Vanoise area (French Alps, Figure 1a), computed from fault striations measurements, and presented in section 2.2. This new data set fills an important gap in the large-scale paleostress map of the inner western Alps, which is now based on a total of 312 paleostress tensors (presented and analyzed in the section 3). These data provide tight constraints about the evolution of the prevailing principal stress axis directions σ_1 and σ_3 through time, from Miocene to Recent for the inner western Alps. It appears that paleostress axis directions deviate significantly from the current state of stress as revealed by earthquake focal plane mechanisms.

2. Vanoise Area

2.1. Geological and Tectonic Setting

[5] The study area, the so-called "massif de la Vanoise", is located in the western Alps (Figure 1a), between the

Copyright 2006 by the American Geophysical Union. 0278-7407/06/2004TC001779

TC3014 1 of 26

¹Geological Institute, University of Neuchâtel, Neuchâtel, Switzerland.
²Now at Department of Geological Sciences and Cooperative Institute for Research in Environmental Science, University of Colorado, Boulder, Colorado, USA.

³Laboratoire de Géodynamique des Chaînes Alpines, Maison des Géosciences, Université de Grenoble, St Martin D'Hères, France.

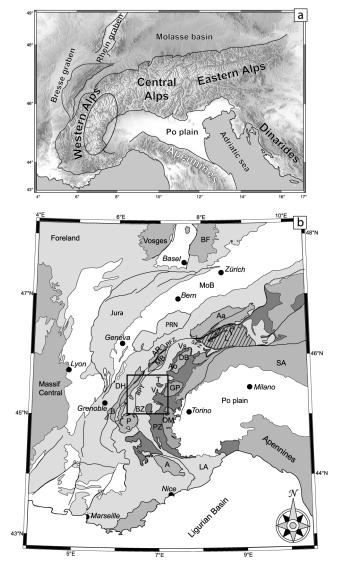


Figure 1. Location of the study area. (a) DEM (GTOPO30 database) of the Alps and surrounding areas. (b) Tectonic sketch map of the western and central Alps. A, Argentera; Aa, Aar; Ao, Aosta Valley; AR, Aiguilles Rouges; B, Belledonne; BPT, Basal Penninic Thrust; BR, Black forest; BZ, Briançonnais zone; DB, Dent Blanche nappe; DH, Dauphiné/Helvetic zone; DM, Dora Maira; GP, Gran Paradiso; L, Lepontine dome; LA, Ligurian Alps; MoB, Molasse Bassin; MB, Mont Blanc; PZ, Piémont zone; P, Pelvoux; PRN, Prealpine Nappes; RFZ, Rhône Fault Zone; SA, southern Alps; SFZ, Simplon Fault Zone; T, Tarentaise valley; V, Vanoise; Vs, Valais.

Tarentaise and Maurienne valley (Figure 1b). The two valleys crosscut most of the geological units of the western Alps, namely, from bottom to top: continental units from the European margin (Belledonne external crystalline massif and corresponding Dauphinois and ultra-Dauphinois cover units), parts of the Briançonnais microcontinent, (including, Subbriançonnais cover units and the Gran Paradiso Internal

Crystalline massif), and, highest in the nappe pile, Piémont oceanic units (Cretaceous "Schistes-Lustrés" calcschists and ophiolites). The tectonometamorphic history of this area is highly complex, and includes polyphase Alpine folding and back folding under moderate to ultrahighpressure metamorphism from the Cretaceous to the Miocene [e.g., *Desmons et al.*, 1999; *Rolland et al.*, 2000].

[6] Extension under greenschist facies to brittle conditions has been described in the Upper Maurienne valley and attributed to the vertical indentation induced by the doming of the Gran Paradiso massif during convergence in front of the Apulian mantle buttress [Rolland et al., 2000]. Because of the large varieties of geological units, fault populations have been measured in numerous lithologies, especially schists, granites, and gneisses of the crystalline basement (Ambin, Gran Paradiso, and Briançonnais basement), quartzites, sandstones, and dolomites of thick Briançonnais Triassic series, and Cretaceous Piémont calcschists.

2.2. Brittle Deformation

2.2.1. Field Observations

[7] The brittle deformation observed in the field is mostly extensional: normal faults ranging in size from centimeters to hundreds of meters are most frequently observed, and no reverse faults have been identified. Locally, transcurrent faults are observed, as well as horizontal striations on normal fault planes (reactivation). Our field work is based on fault and striation measurements (quantitative analyses, see below) and a qualitative determination of the fault orientation, size and aspect. Figure 2 shows a multiscale analysis of a faulted area near the Iseran pass, between the Tarentaise and Maurienne valleys (site NEIGE, n41 and n42, and Table 1) in the Cretaceous Schistes Lustrés. In the panoramic view shown in Figure 2a, a large-scale normal fault is observed, together with several minor ones; the large fault dips to the SW and defines a reverse slope in the topography. Springs are found along the fault trace. Figure 2b shows a large striated fault plane, SW dipping, and Figure 2c is a close-up showing two families of striations associated with this fault system. These observations and the measurement of about 40 couples of plane/striations at this site allow us to calculate two paleostress tensors with a reliable relative chronology (Figure 2d). From crosscutting relationships, the normal component clearly appears to be older than the transcurrent component. Note that the extensional axis (σ_3) remains in the NNE-SSW orientation for both tensors (see Figure 2 caption for further details).

2.2.2. Paleostress Computations

[8] Field work includes the systematic measurement of fault populations, including fault plane orientation, striation orientation and shear sense, as well as a reliability criterion of the shear sense (certain, probable, uncertain). Resolved shear stress orientation on each fault surface is assumed to be parallel to the measured striation with the correct shear sense [Wallace, 1951; Bott, 1959]. We used a systematic collection of minor faults to determine paleostress axis direction using the "direct inversion method" of Angelier [1990]. About 1500 faults planes and their slickenlines were

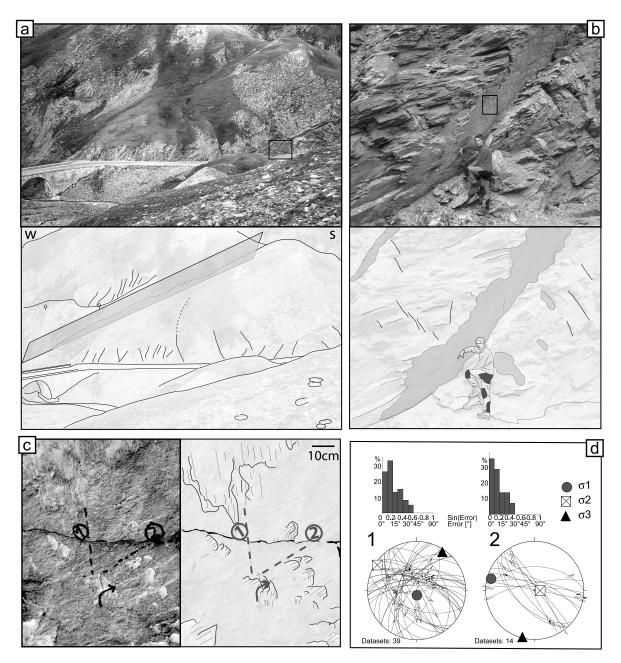


Figure 2. Fault analysis between Maurienne and Tarentaise valleys (site NEIGE N159°/N160°, close to the Iseran pass) with field views and their interpretations. (a) Morphological expression of a large normal fault viewed from the NE. The large west dipping fault is associated with smaller ones, east or west dipping. The bridge gives the scale. (b) Outcrop-scale view of one the minor fault (box in Figure 2a). The Cretaceous Schistes Lustrés limestones in the vicinity of the fault surface are broken into fault breccia. The geologist shows one of the striations of the fault surface. (c) Close-up of the same fault surface (box in Figure 2b) showing two directions of calcite slickenfibers; both directions have been drawn directly on the fault plane. Chronologically, the first direction is a downdip (normal fault), and the second one is subhorizontal (left lateral). (d) Measurement of several fault planes in this sector allows calculation of two paleostress tensors with a reliable relative chronology. For the computations and graphic representation of our data we used the "Tectonics FP" software [Sperner et al., 1993]. Plot of the calculated main stress axes (circle for σ_1 , square for σ_2 , and triangle for σ_3) are represented with fault planes and striations in lower hemisphere Schmidt stereograms. Also provided is the associated histogram of the misfit angle. The first tensor (extensional) and the second one (transcurrent) have the same σ_3 axis orientation. Furthermore, curved slickenfibers demonstrate a progressive transition between extensive and transcurrent movements.

measured at 58 sites covering the entire Vanoise massif and the Maurienne valley. Results include the orientation of major, intermediate and minor stress axes (σ_1 , σ_2 , and σ_3 , respectively), the ellipsoid form parameter $\Phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$ and the average misfit angle α (the angle between the computed optimum slickenline and the measured one). We estimated the quality of our paleotress tensors by way of several criteria:

- [9] 1. The number of faults used in the calculation, their spatial coverage and the accuracy of the slickenline measurements. Sites with less than 10 faults were not considered. We also discarded some 10% of faults from our initial database.
- [10] 2. The coherence between the inversion and the results from the geometrical solution (right dihedra method after *Angelier* [1979]).
- [11] 3. The average misfit angle α , which should be as low as possible, and its histogram repartition. The histogram should show a narrow half Gaussian distribution.
- [12] 4. The visualization of the inverse function with Ginko software [*Yamaji*, 2000] to determine the stability of the inversion.
- [13] The quality of stress tensors was classified from 1 (excellent) to 3 (low quality). According to this ranking system, 20 tensors (30%) are of low quality, 33 tensors (50%) are of medium quality while 13 tensors (20%) are excellent. Note that 5 tensors (n24, n31, n35, n51, and n65) have been calculated from fault populations without striations and classified with the lower quality criterion. In these cases, the most likely slip direction was deduced from drag folds and "en echelon" tension gashes, or simply by assuming a dip slip movement in the case of conjugate sets of normal faults. In several sites, two crosscutting sets of slickenline families have been observed, allowing us to determine two paleostress tensor (e.g., Figure 2).

2.2.3. Data Analysis

[14] Geometrical results (fault planes and striations, and paleostress tensors) of the 66 new paleostress tensors are shown in Figure 3. Numerical results of the inversions are integrated to the global database (Table 1), numbered N119 (n1 in Figures 3 and 4) to N184 (n66 in Figures 3 and 4). In map form (Figure 4), the coverage of our paleostress tensor data set is concentrated in the internal zones of the western Alps, except for tensors n17, n34, n63, n34, n51, and n57, located between the External Crystalline massif (ECM) of Belledonne and the Basal Penninic Thrust (BPT). The arrows represent the projected σ_3 axes onto the horizontal plane for both transcurrent (white arrows) and extensional (black arrows) paleostress tensors. A first overview reveals a N-S to NNE-SSW general direction of σ_3 axes, as highlighted with the rose diagram on the upper right part of the map. Seventy-one percent (51 out of 66) of our tensors are extensional (i.e., σ_1 steep, σ_3 subhorizontal) and the other 29% (15 out of 66) are transcurrent (i.e., σ_2 steep, σ_1 subhorizontal). On the basis of crosscutting relationships, some local chronologies have been observed: for most of the studied sites, transcurrent movements are younger than extensional ones (e.g., Figure 2). This relative chronology is obvious in the Mont Cenis area (tensors n9 to n16), and

consistent with the chronology all along the left side of the Maurienne valley, where conjugate normal faults bear clear evidence for a more recent reactivation with horizontal striations.

[15] The directions of principal stress axes are represented with rose diagrams (circular histograms, Figure 5a), with azimuth (Figure 5a, top) and plunge (Figure 5a, bottom) of axes. The majority of σ_1 axes are steep, with some random scatter around the vertical axis. A minor part of the population of σ_1 axes is subhorizontal, and related to transcurrent paleostress tensors; the σ_2 orientation is either subhorizontal (extensional stress state) or subvertical (transcurrent stress state), without any main direction. The most frequently observed direction of σ_3 axes is N-S to NNE-SSW, with some exceptions in an E-W orientation. All σ_3 axes are subhorizontal; this means that we did not calculated any compressional paleostress orientations. The plot of the entire data set of σ_1 and σ_3 axes on a Schmidt stereonet shows the spatial distribution of the stress axes (Figure 5b). The σ_1 axes (small circles) are predominantly in a nearvertical position (except for the transcurrent tensors), in a gently diffuse shape. The σ_3 axes (black triangles) are positioned horizontally. The contouring of σ_3 axes for the extensional and transcurrent states of stresses (Figure 5c) indicates coaxial direction for both transcurrent and extensional paleostress tensors. The global data set has also been used to calculate an "overall average" tensor for the entire area; we used all of the measured faults, even the fault planes discarded during stress inversion (but not the fault planes without lineation). The whole data set is composed of 1543 faults and their lineations. We applied the "right dihedra" (RD) method [Angelier, 1979] as well as "numerical-dynamical analysis" (NDA) [Sperner et al., 1993] to the entire data set. Because of the methods used and the size of the considered area, this calculation could be considered as a mean strain tensor for the entire region. The results are very similar and agree with the mean direction of extension determined by paleostress inversion: the minimum strain axis (the direction of extension) is oriented 021°/00° (RD) and 198°/01° (NDA). We also performed the same calculation for normal faults (i.e., with less than 45° between fault dip and lineation plunge, 86% of the data set) and for transcurrent faults (14% of the data set). Extensional axes are oriented with a very good correlation, 027°/00° (RD) and 200°/01° (NDA) for transcurrent faults, and 193°/07° (RD) and 196°/04° (NDA) for normal faults (Figure 5d). These strain analyses confirm the highly coaxial orientation of extensional axes for extensional stress/strain state and transcurrent stress/strain state. Despite local variations of orientations, the overall strain/stress state appears to be very stable, with a NNE-SSW direction of minimum stress/strain axis, for both transcurrent and extensional tensors.

[16] The analysis of the dip of fault planes and their associated striations (Figure 5e) demonstrates the predominance of dip slip normal faults: 50% of our data set is characterized by donwdip slip vectors, with less than 10° difference between the plunge of the striation and the dip of the fault plane. The very low number of faults with a high angle between fault plunge and lineation plunge is taken as

Table 1. Database of the 312 Paleostress Tensors Synthesized in This Paper^a

	1	Name			Location			C	r ₁	C	σ_2	C	₃		Paran	neters	
N	n	Site	Lon	Lat	ρ	τ	γ	az	Dip	az	Dip	az	Dip	Data	Φ	α	Conf
1	1	anniv (1)	7.5641	46.2645	184166	56.87	62.9	271	71	82	17	174	9	12	0.52	6	1
2	2	anniv (2)	7.5641	46.2645	184166	56.87	58.9	283	37	68	47	178	18	10	0.49	5.7	3
3	3	artsin	7.4279	46.1166	177390	51.07	61.9	8	61	207	27	113	8	18	0.47	11.5	1
4 5	4 5	cargn	7.5589 7.4318	46.2326 46.0181	181472 168956	56.13 48.75	29.1 78.2	285 214	73 69	118 38	17 21	27 307	4 1	18 11	0.08 0.2	6.5 5.5	2 2
6	6	chevre cleus1	7.3219	46.1148	182626	49.06	29.9	315	69	38 172	17	79	12	12	0.2	2.9	2
7	7	cleus2	7.327	46.1094	181913	49.02	18.0	355	53	148	33	247	13	11	0.32	3.2	1
8	8	couta	7.4913	46.0824	171335	51.50	12.5	26	87	154	2	244	2	22	0.22	9.4	1
9	9	danger	7.3227	46.0212	246457	31.64	5.6	320	48	101	35	206	20	16	0.95	6.7	1
10	10	dix	7.4073	46.0887	176077	50.02	41.0	182	9	69	67	271	21	33	0.97	7.3	2
11	11	emdd (1)	7.8388	46.223	169136	61.94	21.9	210	71	309	3	40	19	22	0.06	4.8	2
12	12	emdd (2)	7.8388	46.223	169136	61.94	80.9	250	12	88	78	341	3	13	0.24	7.8	3
13	13	emmd2	7.8609	46.2319	169192	62.61	29.6	202	81	303	2	33	8	16	0.07	7.6	1
14	14	ergi1	7.7082	46.2959	181165	60.40	18.4	250	74	134	7	42	14	11	0.4	5.3	2
15	15	ergi2	7.7062	46.2898	180655	60.25	37.8	226	64 53	2 131	19	98	17 25	9	0.93	9.8	3 1
16 17	16 17	evole findel	7.5043 7.7856	46.1085 46.0126	172950 151398	52.37 56.30	0.6 19.7	2 179	36	326	25 49	233 76	23 17	28 21	0.26 0.77	4.3 9.7	2
18	18	forel	7.4563	46.0302	168689	49.54	30.5	20	64	164	21	260	14	15	0.77	7.7	1
19	19	furi (1)	7.7326	45.9992	152567	54.71	56.3	178	63	26	25	291	11	21	0.08	6.3	1
20	20	furi (2)	7.7326	45.9992	152567	54.71	40.3	5	1	107	83	275	7	9	0.91	5	2
21	21	gallen	7.7891	46.0486	154558	57.22	22.2	53	59	309	8	215	30	9	0.79	4.3	2
22	22	gorner	7.7867	45.9847	148807	55.65	79.4	130	75	227	2	315	15	16	0.04	10	2
23	23	grime	7.5604	46.1609	174930	54.67	14.3	129	82	340	7	249	4	29	0.32	8.6	1
24	24	ires	7.2418	46.0733	183526	46.66	75.7	261	49	48	36	151	17	9	0.24	7.6	3
25	25	leuker	7.6603	46.3134	184732	59.72	86.3	129	58	344	27	146	16	18	0.23	7	2
26	26	moiry (1)	7.5769	46.1122	169823	53.94	14.1	2	32	124	40	248	34	28	0.45	10.3	1
27 28	27 28	moiry (2)	7.5769 7.3596	46.1122 45.9852	169823 170160	53.94 46.53	45.9 69.5	277 48	3 69	151 204	84 19	8 296	4 8	24 13	0.63 0.11	16.5 6.3	3
29	29	monv1 monv2	7.3415	46.005	170100	46.71	17.3	334	13	196	72	64	11	25	0.11	9.6	1
30	30	nax	7.4597	46.2412	186725	54.38	6.6	318	82	151	8	61	2	9	0.22	6.1	3
31	31	nikla	7.7879	46.1638	165410	59.65	3.4	152	5	34	79	243	10	22	0.49	12.5	2
32	32	randa1	7.7751	46.0878	158787	57.76	77.8	105	59	241	24	340	19	13	0.78	13.6	3
33	33	randa2	7.7615	46.0847	159077	57.38	40.4	107	73	287	17	17	0	27	0.13	7.5	1
34	34	rech1 (1)	7.4992	46.2461	185361	55.24	62.8	22	23	326	62	118	14	9	0.78	2	2
35	35	rech1 (2)	7.4992	46.2461	185361	55.24	89.8	209	68	58	19	325	10	13	0.13	5	2
36	36	rech2	7.4953	46.2416	185132	55.07	48.1	173	76	276	3	7	14	19	0.03	8.9	1
37	37	rotba	7.8215	46.0656	154772	58.38	3.6	350	46	138	39	242	16	14	0.04	2.4	2
38 39	38 39	roten	7.7674 7.2593	45.9866 46.0606	149845 181582	55.22 46.65	68.2 20.3	258 353	8 51	19 148	75 37	167 247	12 12	12 16	0.75 0.87	5.5 4.8	2 1
40	40	sarray schler	7.2715	46.0697	181636	47.09	2.1	239	65	137	5	45	24	8	0.16	3.8	3
41	41	solay1	7.5481	46.0653	167081	52.25	14.8	329	22	195	60	67	19	8	0.06	6.2	3
42	42	solay2	7.5385	46.0743	168330	52.26	24.7	150	71	349	18	257	6	16	0.17	8.6	2
43	43	solay3	7.534	46.0761	168705	52.21	57.8	0	50	212	36	110	16	11	0.98	3.5	3
44	44	stlu1	7.5939	46.2312	179813	56.81	8.2	178	67	331	21	65	10	13	0.23	3.3	1
45	45	stlu2	7.6029	46.2182	178222	56.73	12.3	151	37	353	51	249	11	15	0.6	6.3	2
46	46	tdela	7.3743	46.1571	183602	50.94	56.9	238	61	91	25	354	14	16	0.08	3.9	3
47	47	thyon	7.3709	46.1787	185505	51.40	2.4	262	70	142	10	49	17	14	0.29	6.3	2
48 49	48 49	trift	7.4505 7.7096	46.0245 46.1496	154479 167301	55.51 57.60	37.5 27.4	123 49	81 89	288 175	9 1	18 265	2	35 15	0.33 0.83	8.7 10.4	1
50	50	turgl turtm	7.6913	46.1714	170108	57.65	9.3	22	57	147	21	247	25	27	0.83	7.5	2 1
51	51	verc1	7.4558	46.2582	184385	56.39	36.4	147	73	287	13	20	11	19	0.01	11.4	2
52	52	verc2	7.5433	46.2479	183553	56.13	3.1	122	73	325	16	233	6	18	0.3	10.6	2
53	53	veyso	7.3321	46.194	188733	51.03	2.0	118	65	323	23	229	9	9	0.14	3.8	2
54	54	vingt	7.3956	46.0752	175547	49.48	33.5	271	81	173	1	83	9	16	0.57	3.8	1
55	55	visso	7.5809	46.2344	180668	56.61	61.4	205	8	91	71	298	17	17	0.85	5.6	3
56	56	zeneg	7.871	46.2795	173517	63.66	37.7	300	19	82	67	206	13	20	0.59	6.2	3
57	57	AVISE	7.1526	45.7059	162847	34.75	9.3	5	63	128	16	224	22	17	0.05	7.3	1
58	58	BAUCHE	6.7464	45.5394	182164	24.36	63.6	9	75 59	177	15	268	3	18	0.62	5.9	1
59 60	59 60	BISELX	7.2227	46.0058	179337	44.64	62.4	218	58	107	13	107	13	16	0.99	2.8	2
60 61	60 61	BUTHIER CARLO	7.2713 7.003	45.7845 45.7136	160510 173143	39.21 32.86	26.2 29.1	273 50	49 65	111 150	40 5	13 242	9 24	16 20	0.323	5.1 8.1	1 1
62	62	CHAP	6.7318	45.6937	190460	28.99	58.0	343	8	249	30	87	59	16	0.89	10.1	2
63	63	CHAT1	6.858	45.6178	177868	28.03	40.0	183	72	79	5	348	17	15	0.264	7.8	3
64	64	CHAT2	6.8628	45.4148	177384	27.99	1.0	218	61	119	5	27	28	18	0.008	1.8	1
65	65	ECHEV	7.2638	45.8026	162140	39.61	76.4	31	61	205	29	296	2	28	0.518	4	1
66	66	FERRE	7.1212	45.911	178314	40.44	19.4	273	28	149	47	21	30	12	0.06	#	3
67	67	FRETE (1)	6.8085	45.5709	179118	25.99	55.0	268	55	51	29	151	17	17	0.068	4	1

Table 1. (continued)

Name]	Location				71		⁵ 2		53		Paran	neters		
N	n	Site	Lon	Lat	ρ	τ	γ	az	Dip	az	Dip	az	Dip	Data	Φ	α	Conf
68	68	FRETE (2)	6.8085	45.5709	179118	25.99	4.0	291	8	147	80	22	6	8	0.565	10.2	3
69	69	GSB1	7.1877	45.8865	172592	40.82	33.8	101	11	215	65	7	22	21	0.91	7.7	3
70	70	GSB2	7.1896	45.8995	173407	41.22	5.8	313	24	159	64	47	10	19	0.577	16.9	2
71	71 72	GSBIT	7.1512	45.8598	172949	39.46	21.5	347 359	25 75	108	48	241	32 9	15 24	0.37 0.234	4.6	2
72 73	73	GURRAZ ISERAN	6.9033 7.021	45.6249 45.4317	175081 157752	28.78 23.38	25.2 58.6	339 84	75 84	142 352	12 0	234 262	6	34	0.234	6.1 9.4	1 1
74	74	LACPLAG	6.845	45.488	172856	23.60	27.4	319	65	141	25	51	1	14	0.07	3.7	2
75	75	MALAT	7.1313	45.8409	172881	38.60	25.6	271	32	129	52	13	19	15	0.18	4.7	2
76	76	MALAT2	7.1113	45.8408	174114	38.29	30.3	275	21	117	67	8	8	14	0.252	4.3	2
77	77	MARTI	7.0814	46.0918	193850	44.48	73.5	325	22	231	10	118	65	11	0.576	9.7	3
78	78	MICOEUR	7.2449	46.1183	186956	47.79	14.8	136	73	302	16	33	4	10	0.55	6.8	3
79	79	MONAL (1)	6.9009	45.5687	172471	26.91	48.1	48	85	165	2	255	4 0	20	0.25 0.539	11.8	1
80 81	80 81	MONAL (2) NIORD	6.9009 7.2035	45.5687 45.9589	172471 176910	26.91 43.08	2.1 51.1	119 261	36 2	298 168	54 59	29 352	31	11 16	0.539	6.2 9.2	2 2
82	82	PEIPOU	6.818	45.5253	176399	24.59	36.4	142	76	142	76	241	2	22	0.25	13	1
83	83	PLAN	6.9258	45.6244	173501	29.03	24.0	284	16	39	55	185	30	14	0.603	9	2
84	84	RECUL	6.9618	45.4669	163528	24.04	87.0	171	69	31	17	297	13	19	0.16	10.1	1
85	85	RIDD	7.2233	46.1551	191076	48.27	50.3	119	68	264	19	358	12	22	0.815	8.8	2
86	86	SAPIN	7.1486	46.1063	191226	45.89	17.1	352	73	151	16	243	6	15	0.77	7.8	2
87	87 88	SEIGNE STEOV (1)	6.8091	45.7528	188335	31.61 27.58	23.6 59.4	308 91	48 56	82 359	32 2	188 267	24 34	17 16	0.779 0.701	7.1 4	2
88 89	89	STFOY (1) STFOY (2)	6.9313 6.9313	45.5787 45.5787	170819 170819	27.58	45.4	157	11	48	61	253	27	14	0.701	7.1	2
90	90	THUIL	6.8991	45.7203	180467	31.73	36.7	88	71	265	19	355	1	10	0.53	4	3
91	91	TIGNES1	6.9199	45.5054	168218	24.97	15.0	32	73	129	2	220	17	17	0.127	5.1	1
92	92	TIGNES2	6.9254	45.4539	167310	24.62	89.6	195	25	60	56	295	21	13	0.418	7.3	2
93	93	TIGNES3	6.9442	45.4977	166841	24.84	16.8	65	75	280	12	188	8	11	0.812	4.3	2
94	94	TOULJE	7.1882	45.922	174777	41.70	2.3	300	47	145	40	44	13	24	0.87	6.5	2
95	95	VALDER1	7.1055 7.1119	45.54 45.546	156734	28.37 29.03	81.6	316 272	51	209	13	110	36 5	12	0.07 0.33	3.6	2
96 97	96 97	VALDER2 VALDER3	7.1119	45.5882	157102 158115	30.31	5.0 46.3	83	78 50	115 248	11 39	24 344	3 7	13 11	0.33	6.6 6.5	3
98	98	VALDER4 (1)	7.0259	45.6242	158809	31.85	0.2	79	79	303	8	212	8	10	0.05	14.7	2
99	99	VALDER4 (2)	7.0259	45.6242	158809	31.85	56.8	247	3	343	63	155	26	12	0.65	2.9	2
100	100	VALGR1	7.1562	45.6978	162121	34.54	36.5	36	73	271	10	178	14	12	0.09	4.1	2
101	101	VALGR25	7.0482	45.6041	164006	29.88	67.1	16	56	183	33	277	6	22	0.74	10.5	2
102	102	VALGR3	7.0632	45.6206	163870	30.63	5.4	228	87	126	1	36	3	12	0.5	5.1	2
103	103	VALGR4 VALP1 (1)	7.1008	45.679	164637	33.11 42.25	55.9	319	39	204	28	89 296	38	20	0.95 0.76	4.5 8.8	2 2
104 105	104 105	VALP1 (1) VALP1 (2)	7.2974 7.2974	45.8715 45.8715	165025 165025	42.25	73.7 56.7	26 117	5 78	168 9	84 4	279	4 11	17 21	0.76	9.6	3
106	106	VALP2 (1)	7.4924	45.9007	156241	46.80	2.2	161	57	312	30	49	13	12	0.345	11.4	2
107	107	VALP2 (2)	7.4924	45.9007	156241	46.80	36.8	98	31	188	59	190	4	11	0.949	5.1	3
108	108	VALP3	7.4628	45.8881	156868	45.85	36.8	196	85	99	1	9	5	13	0.707	6.1	2
109	109	VALP4 (1)	7.437	45.8782	157530	45.05	41.0	94	4	294	86	184	1	14	0.256	6.8	3
110	110	VALP4 (2)	7.437	45.8782	157530	45.05	21.0	359	75	155	13	246	6	17	0.07	8	1
111	111	VALP5	7.3534 7.2008	45.8323	161924	41.17	10.2	301	38	122	55	31	0	17	0.548	7	3
112 113	112 113	VALSA1 (1) VALSA1 (2)	7.2008	45.5295 45.5295	149591 149591	29.27 29.27	0.7 2.3	88 101	45 35	319 322	32 47	210 207	27 21	11 10	0.13 0.511	8.6	2 3
114	114	VALSA1 (2)	7.2115	45.5228	150088	30.29	2.3	91	36	327	38	208	32	11	0.48	4.1	3
115	115	VALSA3	7.2032	45.6525	156315	33.73	15.3	28	79	139	4	229	11	10	0.16	4.2	2
116	116	VALSA4	7.2051	45.6742	157494	34.50	3.5	93	70	304	17	211	10	16	0.773	14.4	2
117	117	VELAN	7.2591	45.9267	171307	43.15	13.1	300	1	201	85	30	5	16	0.499	8	2
118	118	VENS	7.1241	46.0865	191048	45.03	34.0	278	8	165	70	11	19	26	0.635	19.9	3
119	119	AMBIN	6.8738	45.1858	161203	12.79	16.8	67	70 73	269	19	176	7	75 14	0.12	10.5	1
120 121	120 121	ARPON1 ARPON2	6.6961 6.7123	45.3295 45.3169	178459 176865	16.96 16.63	87.0 20.4	220 131	73 59	18 306	16 31	110 37	6	14 38	0.21 0.55	7.2 9.3	2 2
122	122	AVERO1	7.0884	45.2918	147746	18.57	64.4	335	75	174	14	83	5	20	0.49	9.3	1
123	123	AVERO2	7.0306	45.3236	153136	19.33	69.7	29	85	179	4	269	2	45	0.49	12.4	1
124	124	BARDO	6.7172	45.0895	171680	8.49	2.5	237	75	103	10	11	10	31	0.06	13.5	1
125	125	BOZEL	6.6236	45.4446	187619	20.27	25.7	135	53	317	37	226	1	31	0.55	14.9	2
126	126	CELS	6.9431	45.1048	154282	9.91	3.1	302	33	72	45	193	27	14	0.51	10.9	3
127	127	CENIS1	6.9271	45.2269	158077	14.72	24.3	325	79	129	10	219	3	31	0.21	10.9	2
128 129	128 129	CENIS2(1) CENIS2(2)	6.9614 6.9614	45.2292 45.2292	155519 155519	15.03 15.03	18.0 4.0	264 107	68 6	87 4	22 66	357 199	1 23	17 18	0.23 0.63	11.2 7.4	1 2
130	130	CENIS2(2)	6.9243	45.2831	159833	16.88	13.1	314	65	107	22	210	10	16	0.63	8.8	2
131	131	CENIS4	6.9822	45.1886	152919	13.53	73.5	346	83	178	6	87	1	19	0.52	10.3	2
132	132	CENIS5	6.8634	45.2473	163465	15.09	55.9	333	76	161	14	71	2	17	0.37	8.2	2
133	133	CENIS6(1)	6.9695	45.2137	154500	14.47	8.5	1	74	111	6	203	15	32	0.19	8.3	1
134	134	CENIS6(2)	6.9695	45.2137	154500	14.47	76.5	181	11	337	78	91	5	29	0.92	6.6	2

Table 1. (continued)

		Name			Location			_ 0	⁵ 1	_ 0	⁵ 2	_ 0	· 3		Paran	neters	
N	n	Site	Lon	Lat	ρ	τ	γ	az	Dip	az	Dip	az	Dip	Data	Φ	α	Conf
135	135	CHAMB	6.2788	45.3873	211715	16.32	29.7	317	24	133	65	226	1	18	0.49	11.5	2
136	136	CHAMPA	6.7087	45.4599	181892	21.44	11.4	278	7	171	68	10	21	26	0.35	11.7	2
137	137	CHAMPA2	6.7167	45.4566	181179	21.40	17.4	276	8	40	75	184	12	17	0.54	12.8	2
138	138	ECOT	7.0927	45.3807	150651	22.20	66.8	340	66	183	22	89	8	23	0.16	4.2	2
139 140	139 140	ETACHE EXTRA	6.8136 6.7986	45.1613 45.2186	165347 167718	11.55 13.62	2.5 19.4	9 145	73 66	104 299	1 22	194 33	16 10	35 10	0.05 0.26	4.7 3.5	2
141	141	FONDS	6.6524	45.3089	181183	15.02	40.0	10	69	142	14	236	15	43	0.17	11.5	1
142	142	FONT	6.5006	45.4514	197002	19.59	5.6	296	59	100	30	194	7	24	#	#	3
143	143	FOUR	7.0167	45.3945	156765	21.95	24.0	101	78	318	10	226	7	28	0.29	8.5	1
144	144	FREJUS	6.665	45.1386	176473	10.09	23.9	254	85	124	3	34	4	26	0.21	14.9	2
145	145	GALIB	6.4096	45.065	195495	6.86	2.9	281	12	30	57	184	30	35	0.13	14.1	2
146	146	GIAGLI	7.0171	45.143	149237	11.86	10.9	7	79	271	1	181	10	17	0.56	15.5	3
147 148	147 148	GENEP LANSLEV	6.9191 6.9287	45.4192 45.2998	164884 160007	21.91 17.55	64.1 8.6	225 155	81 82	355 278	6 4	86 9	7 7	24 19	0.47 0.26	9.1 11	1 3
149	140	LLBOURG	6.8697	45.2852	164031	16.56	48.4	156	54	335	36	65	1	30	#	#	3
150	149	LLBOURG2	6.8671	45.2829	164161	16.45	86.5	301	85	193	2	103	5	22	0.38	10	2
151	150	LORES	6.9429	45.4013	162442	21.49	74.5	335	76	188	12	96	8	17	0.43	8.5	1
152	151	MAD	6.368	45.4403	206547	18.38	20.6	127	27	320	62	219	5	26	0.46	13.3	2
153	152	MASSE	6.6984	45.2596	176388	14.54	67.5	342	38	187	49	82	12	20	#	#	3
154	153	MASSE2	6.6974	45.2598	176472	14.54	5.5	127	75	277	13	9	7	19	0.56	7.9	2
155 156	154 155	MENU MICHE	6.5822 6.4865	45.3168 45.2184	186741 191768	15.82 12.10	22.8 17.1	290 278	82 29	83 54	7 52	173 175	4 22	17 27	0.46 0.57	5.4 17.8	2 3
157	156	MODAN2	6.6658	45.198	182780	12.10	21.7	36	58	170	23	269	21	17	0.57	8.4	3
158	157	MODAN	6.6004	45.2091	177506	12.20	76.8	155	68	300	18	34	12	24	0.53	12.3	3
159	158	NEIGE(1)	7.0328	45.4064	156054	22.57	11.4	174	82	303	5	34	6	39	0.13	12.7	1
160	159	NEIGE(2)	7.0328	45.4064	156054	22.57	7.6	285	9	92	81	195	2	14	0.3	14.4	2
161	160	OREL(1)	6.5565	45.2223	186443	12.53	32.5	102	78	316	10	225	6	12	0.15	8.8	3
162	161	OREL(2)	6.5565	45.2223	186443	12.53	57.5	165	9	273	63	70	25	9	0.06	5.9	3
163 164	162 163	OREL(3) ORGIE	6.5565 6.65	45.2223 45.2135	186443 179048	12.53 12.67	2.5 0.7	105 305	5 72	295 100	85 17	195 192	1 7	12 10	0.47 0.36	18.9 7.9	3
165	164	OULX	6.8577	45.0425	162728	7.02	22.0	43	76	300	3	209	14	17	0.50	13.5	3
166	165	PARTIE(1)	6.6722	45.2584	178363	14.35	7.7	108	36	300	54	202	6	19	0.46	8.9	2
167	166	PARTIE(2)	6.6722	45.2584	178363	14.35	56.3	316	85	48	0	138	5	10	0.44	10.8	3
168	167	PRIOUX	6.6941	45.348	179163	17.58	56.4	355	61	140	24	236	15	11	0.13	5.8	3
169	168	PUIT	6.5093	45.4674	196908	20.14	12.1	283	68	97	22	188	2	34	#	#	3
170	169	RIBON(2)	6.9941	45.3104	155426	18.49	25.5	56	70	182	12	275	16	31	0.64	8.9	1
171 172	170 171	RIBON(1) RIBON(3)	6.9941 6.9941	45.3104 45.3104	155426 155426	18.49 18.49	76.5 3.5	256 104	87 1	105 12	3 77	15 195	2 13	21 20	0.49 0.16	11 7.2	2 2
173	172	ROCHEU	6.9818	45.3804	158791	21.08	78.1	79	73	211	12	303	12	15	0.10	7.6	2
174	173	ROMOL	6.7638	45.1324	168689	10.24	64.2	52	71	214	18	306	5	22	0.27	14.4	3
175	174	SALIN	6.528	45.4678	195531	20.29	49.7	3	64	155	23	250	11	15	0.93	8.6	3
176	175	SARRA	6.6038	45.158	181559	10.54	22.5	131	80	303	9	33	1	28	0.26	21.6	2
177	176	TELEG	6.4442	45.1977	194645	11.26	49.7	168	72	329	18	61	6	14	0.57	10.2	2
178	177	TERMI	6.8373 6.8407	45.2859	166502 167144	16.36 17.50	33.6	300	67	143	21	50 154	8	20	0.01	9.1	2
179 180	178 179	TERMI2 VALLO	6.4273	45.3164 45.1594	195311	9.96	43.5 83.0	21 298	70 86	247 197	14 1	107	14 4	24 25	0.02 0.14	4.8 11.6	2 1
181	180	VALMO	6.4333	45.4306	201344	18.50	4.5	300	51	94	36	194	13	19	0.11	2.1	2
182	181	VALTHO1	6.5781	45.2825	186157	14.66	9.3	233	80	115	5	24	9	22	0.59	18.7	3
183	182	VALTHO2	6.5669	45.308	187669	15.44	81.6	52	82	187	6	277	6	20	#	#	3
184	183	VILLARO	7.0023	45.3313	155510	19.38	49.6	146	87	339	3	249	1	21	0.05	6.9	3
185	S1	Innri Alpa	8.107	46.2143	159306	68.31	32.3	312	69	125	21	216	2	13	0.273	5.8	2
186	S2	Schwarzi Balma	8.1074	46.2174	159619	68.37	9.6	124	72	351	12 10	258	13	13 10	0.296	10.3	2 3
187 188	S3 S4	Innri Biela Sirwoltensee	8.1041 7.9962	46.2105 46.2151	159003 162835	68.17 65.54	30.2 63.5	300 348	80 74	129 222	10	38 129	2 13	9	0.591 0.159	6.9 5.8	3
189	S5	Obers Fulmoos	7.9689	46.2085	163081	64.76	8.2	357	63	159	26	253	7	10	0.589	7.9	2
190	S6	Alte Kaserne	8.0967	46.1894	157060	67.66	11.7	149	82	326	8	56	1	17	0.401	5.8	2
191	S7	Hopschusee	8.0242	46.2543	165906	66.85	14.9	110	81	322	7	232	5	10	0.629	6.4	3
192	S8	Hopschusee	8.0222	46.2546	165990	66.81	3.8	128	70	336	17	243	9	13	0.9	6.2	2
193	S9	Staldhorn	8.0213	46.2582	166385	66.84	6.8	135	63	334	26	240	8	11	0.459	12.0	3
194	S10	Hopsche	8.0206	46.253	165882	66.75	18.7	39	87	138	1	228	3	15	0.767	7.2	2
195	S11	Engiloch Possbodestafel	8.0203	46.2256	163110	66.30	8.3	90	80 80	329	5	238 224	9 8	46 21	0.508	11.5	1
196 197	S12 S13	Rossbodestafel Gali Egga	8.0249 8.0112	46.1956 46.1919	159939 160006	65.93 65.52	21.9 22.5	10 240	80 85	134 133	6 1	43	8 4	21 18	0.439 0.29	11.8 18.2	1 2
198	S14	Egga	8.0366	46.2034	160352	66.35	74.7	303	73	50	5	141	17	29	0.404	9.7	1
199	S15	Glatthorn	8.0714	46.212	160142	67.36	11.4	174	75	325	13	56	7	21	0.625	8.5	2
200	S16	Bodme	8.052	46.1923	158738	66.56	27.6	219	83	309	0	39	7	16	0.346	6.0	2
200	S17	Walderuberg		46.213					82		7	246	3		0.52		2

Table 1. (continued)

		Name]	Location			c	5 1	c	₅₂	c	₃		Paran	neters	
N	n	Site	Lon	Lat	ρ	τ	γ	az	Dip	az	Dip	az	Dip	Data	Φ	α	Conf
202	S18	Homatta	8.0526	46.2171	161232	66.97	10.0	128	67	352	17	257	15	13	0.192	5.7	2
203	S19	Hübschhorn W	8.0374	46.2437	164414	67.01	15.0	101	74	325	12	232	11	17	0.686	9.7	2
204	S20	Biel	8.0703	46.1724	156146	66.70	35.7	0	69	117	10	211	18	42	0.16	10.8	1
205 206	S21 S22	Furggu Guggilihorn	8.0904 8.0871	46.1766 46.1696	155946 155339	67.29 67.09	11.3 58.9	161 356	75 56	324 222	15 18	56 126	4 17	9 14	0.655 0.048	13.6 8.8	3 2
207	S23	Bodmerhorn	8.0413	46.1908	158924	66.26	37.3	70	72	302	12	209	14	17	0.323	6.9	2
208	S24	Ochseläger	7.9523	46.2302	165808	64.73	50.7	66	77	285	10	194	8	31	0.244	10.0	1
209	S25	Lawigrabe	8.0485	46.1951	159125	66.51	32.5	54	73	186	12	279	14	43	0.113	10.3	1
210	S26	Bodmerhorn	8.0397	46.1881	158705	66.17	9.2	103	73	329	12	237	14	31	0.218	9.0	1
211	S27	Bodmer	8.0312	46.1839	158551	65.89	17.9	85	75	320	9	228	14	27	0.283	9.4	1
212	S28	Blauseewji	8.0445	46.1847	158208	66.24	15.8	16	81	171	8	262	4	12	0.187	14.5	2
213 214	S29 S30	Alte Kaserne Chaltwasser	8.0902 8.0559	46.1872 46.249	157031 164387	67.45 67.55	22.5 5.5	151 81	83 76	315 333	7 5	45 242	2 14	26 47	0.513 0.343	9.8 9.4	1 1
215	S31	Simplon - Kulm	8.0345	46.252	165350	67.07	13.1	106	77	325	10	234	8	12	0.519	6.2	3
216	S32	Stockji	7.9694	46.2528	167506	65.51	47.5	66	86	288	3	198	3	15	0.365	5.1	2
217	S33	Antonius	8.062	46.1824	157416	66.65	10.4	93	77	348	4	257	12	30	0.337	14.0	1
218	S34	Färicha	8.0515	46.1721	156707	66.21	31.2	308	79	125	11	215	1	27	0.437	7.9	2
219	S35	Laggin Biwak	8.0452	46.1654	156228	65.93	46.1	72	74	200	10	292	12	21	0.136	9.9	2
220	S36	Hübschhorn S	8.0547	46.2256	162039	67.16	5.2	67	73	332	2	242	17	34	0.192	8.6	1
221 222	S37 S38	Breithorn Chesselhorn	8.0781 8.0818	46.2345 46.221	162233 160737	67.88 67.77	4.9 22.2	83 150	73 64	335 6	5 21	243 270	16 14	27 15	0.325 0.388	5.7 8.9	1 2
223	S39	Casermetta	8.1149	46.1962	157221	68.24	21.2	12	87	137	2	227	3	17	0.388	7.2	2
224	S40	Waira	8.1328	46.153	152248	68.03	13.0	257	71	350	1	81	19	34	0.266	12.7	2
225	S41	Stalden	7.8937	46.2785	172630	64.16	9.2	56	76	325	1	235	14	15	0.24	12.7	2
226	S42	Furgghalte	8.0214	46.2055	161052	66.00	19.0	166	76	316	12	47	7	24	0.501	9.9	1
227	S43	Schilthorn	8.0127	46.2105	161836	65.87	0.9	242	73	334	1	65	17	15	0.138	6.8	2
228	S44	Wyssbode	8.0179	46.2121	161824	66.02	50.0	284	70	24	4	116	20	12	0.361	9.5	3
229 230	S45 S46	Obre Stossbode Holiecht	8.0181 8.0535	46.2022 46.2067	160819 160153	65.87 66.83	5.1 14.8	238 174	85 85	341 322	1 5	71 52	5 3	9 26	0.28 0.396	9.6 8.3	3 1
231	S47	Gärtjini	8.046	46.1487	154525	65.67	3.7	148	76	332	14	242	1	27	0.390	11.2	2
232	S48	Weissmies	8.0408	46.1416	153976	65.40	8.6	180	80	344	9	74	2	19	0.253	7.6	1
233	S49	Schafnuwald	8.1245	46.1629	153514	67.97	11.0	337	74	147	15	237	3	21	0.241	9.1	1
234	S50	Tannuwald	8.1082	46.154	153095	67.39	47.6	190	77	26	12	295	3	10	0.589	7.2	3
235	S51	Sera	8.1219	46.171	154425	68.02	2.0	5	80	160	10	250	4	9	0.529	8.0	3
236	S52	Ramserna	8.1292	46.2007	157259	68.68	24.7	30	76 72	134	4	224	14	19	0.423	7.5	2
237 238	S53 S54	Altes Hospiz Nidristi Alp	8.0162 7.9548	46.2337 46.2578	164063 168490	66.33 65.24	16.3 10.2	121 130	73 75	322 325	16 15	230 235	6 4	27 21	0.166 0.785	10.0 7.9	1 1
239	S55	Gampisch	8.0055	46.2333	164365	66.06	14.1	9	75 75	140	0	232	11	11	0.763	6.6	3
240	S56	Zwischbergen	8.0544	46.1174	151100	65.33	5.7	165	56	340	34	71	3	10	0.227	12.2	3
241	S57	Galaberr	8.0778	46.151	153737	66.53	46.5	24	72	203	18	293	1	19	0.253	7.9	2
242	S58	Glis	7.963	46.2983	172294	66.08	65.1	356	69	91	2	181	21	11	0.337	8.9	3
243	S59	Mäderhitta	7.9583	46.2838	170985	65.74	54.7	12	75	281	1	191	15	18	0.114	11.3	2
244	S60	Mäderhitta	7.9568	46.2763	170277	65.59	87.6	114	86	248	3	338	3	26	0.292	13.0	2
245 246	S61 SD	Griewald Staldhorn	7.959 8.0227	46.2868 46.2645	171268 166983	65.81 66.97	71.2 12.0	1 145	87 4	227 357	2 85	137 235	2 2	13	0.163 0.737	15.8 9.7	3
247	1	BDTNO	6.5208	44.7313	186998	-4.29	82.3	143	7	349	18	258	6	11 30	0.737	4.7	1
248	2	BDTSU	6.529	44.7147	186555	-4.88	89.9	108	83	356	3	265	6	25	0.4	4.8	1
249	3	RUBUR	6.9732	44.3968	160292	-18.99	68.0	2	3	260	76	93	13	12	0.8	17.8	2
250	4	BOUCH	6.9492	44.6902	153907	-7.28	25.7	64	69	236	21	327	3	30	0.2	7.5	1
251	5	CERVI	6.7505	44.8862	167829	0.91	43.1	208	76	313	4	44	14	18	0.3	9.7	2
252	6	CHABE	6.759	44.973	167323	4.22	37.2	193	83	58	5	327	5	21	0.4	9.5	1
253 254	7 8	CHAMB CHENO	6.8347 6.753	44.5413 44.9253	166085 167637	-12.45 2.40	43.5 43.6	32 111	67 76	214 317	23 13	124 226	1 6	23 10	0.3 0.4	11.4 14	2 3
255	9	CHESU	6.7527	44.9233	167646	1.91	3.1	261	73	97	17	5	4	10	0.4	11	3
256	10	MALAM	6.6433	44.7118	177599	-5.32	49.7	287	81	34	3	125	8	36	0.2	9.2	1
257	11	COLRI	6.5333	44.9342	184994	2.64	6.6	234	71	89	16	356	1	19	0.3	7.2	2
258	12	PEYGU	6.7403	44.8252	168851	-1.38	85.6	66	78	182	5	273	11	13	0.2	14.6	2
259	13	LONGE	6.9487	44.65	154686	-8.92	30.9	81	70	296	17	202	11	16	0.2	12.9	2
260	14	COLSN	6.841	44.4888	167107	-14.44	61.6	202	3	354	57	104	13	15	0.6	8.6	2
261	15	CPEYR	6.6245	44.7763	178355	-2.97	20.0	84	82	247	7	337	3	30	0.2	11.7	1
262 263	16 17	CROUS CROUS	6.6552 6.6552	44.7238 44.7238	176505 176505	-4.92 -4.92	23.9 73.1	62 15	67 16	294 157	15	199 282	17 11	8 10	0.4	15 16.5	3
264	17 18	CRXSA	6.5508	44.7238	183762	-4.92 -0.75	57.8	15 143	16 82	327	7 8	282	1	10	0.5 0.4	16.5 10.3	3 2
265	19	CRXSA	6.5508	44.8363	183762	-0.75	80.8	169	32	353	58	260	2	20	0.5	7.3	2
266	20	FOUIL	6.8003	44.5537	168416	-11.77	74.2	130	82	4	5	274	6	11	0.4	10.4	3
267	21	GROOU	6.6755	44.6593	175878	-7.30	35.7	218	68	48	22	317	4	27	0.2	11	1
268	22	GROOU	6.6755	44.6593	175878	-7.30	44.7	219	39	37	5	128	1	27	0.8	11.3	3

Table 1. (continued)

Name		Location					C	r ₁	c	σ_2	C	r ₃	Parameters				
N	n	Site	Lon	Lat	ρ	τ	γ	az	Dip	az	Dip	az	Dip	Data	Φ	α	Conf
269	23	JANES	6.7385	44.9338	168797	2.71	39.7	236	70	53	19	143	1	11	0.5	5	3
270	24	JANES	6.7385	44.9338	168797	2.71	79.3	172	4	43	83	262	5	8	0.7	14.5	3
271	25	JANOU	6.7535	44.9382	167624	2.89	22.9	343	81	250	0	160	9	13	0.4	9.8	2
272	26	LCORD	6.7688	44.841	166517	-0.82	12.2	204	84	77	4	347	5	13	0.4	10.5	2
273	27	NEUFC	6.7725	44.5713	170132	-10.96	68.0	281	70	150	13	57	15	20	0.3	10.6	2
274	28	NEUFC	6.7725	44.5713	170132	-10.96	61.0	16	20	208	70	108	4	12	0.6	11.4	3
275	29	LAUSE	6.6652	44.8558	174642	-0.17	82.2	55	84	172	3	262	5	17	0.3	8.8	2
276	30	LAVAL	6.8773	44.935	157846	2.84	8.8	175	75	84	0	354	15	22	0.4	11.7	2
277	31	MROYN	6.7297	44.6923	171090	-6.31	52.7	32	18	204	72	301	2	10	0.8	9.4	3
278	32	ORECE	6.5042	44.8017	187647	-1.87	67.1	200	2	310	83	111	7	17	0.8	8.5	3
279	33	ORCEA	6.5047	44.8017	187608	-1.88	85.1	195	77	3	15	93	4	23	0.3	12	1
280	34	ORCEB	6.5043	44.8017	187639	-1.88	85.1	199	75	2	14	93	4	16	0.1	11.4	1
281	35	OREES	6.5112	44.7963	187134	-2.07	88.9	15	77	178	13	269	4	10	0.2	12.6	1
282	36	OREES	6.5112	44.7963	187134	-2.07	62.9	203	5	96	73	295	16	10	0.2	17.8	2
283	37	OREOU	6.5115	44.7967	187107	-2.06	74.9	192	15	18	75	283	1	26	0.5	13.5	3
284	38	OROUA	6.5215	44.7952	186329	-2.12	74.1	122	8	343	7	252	6	31	0.3	9.5	1
285	39	OROUB	6.5213	44.7952	186345	-2.12	89.9	144	75	0	12	268	8	32	0.2	11.2	1
286	40	PARPA	6.6775	44.4968	179417	-13.02	82.0	176	74	337	15	69	5	13	0.2	14	2
287	41	PTPUY	6.6457	44.8325	176283	-0.99	42.0	298	85	47	1	137	4	15	0.4	9	1
288	42	BEAUD	6.689	44.8187	170203	-0.55	48.4	142	80	41	2	310	1	26	0.4	15.5	1
289	43	HOUER	6.7825	44.5877	168969	-1.33 -10.42	45.6	207	29	62	56	304	18	16	0.3	14.8	2
290	44	MLZOU	6.6318	44.8422	177335	-0.63	28.4	91	52	232	32	331	14	30	0.7	8.6	2
291	45	MLZSU	6.6363	44.8327	177025	-0.03 -0.97	10.0	97	62	258	28	349	28	12	0.2	9	2
291	46	PSTRL	6.7918	44.5793	168443	-0.97 -10.78	6.2	218	71	76	15	343	11	14	0.1	8.5	2
292	47	PCHAT	6.7878	44.54	169738	-10.78 -12.20	17.8	210	69	64	18	330	11	29	0.2	14.3	1
293 294	48	PCHAT	6.7878	44.54	169738	-12.20 -12.20	69.8	187	2	13	69	278	2	15	0.1	7.5	2
											19		6	20		9	2
295	49	PRORE	6.5642	44.9053	182531	1.64	45.4	154	70	315		47	-		0.2	-	
296	50	RMOES	6.6122	44.8347	178919	-0.87	10.9	252	72	102	16	10	8	19	0.2	7.7	1
297	51	RMOOU	6.6175	44.84	178474	-0.69	1.7	245	75	93	14	1	6	26	0.3	8.7	1
298	52	ROBAR	6.5698	44.808	182424	-1.76	70.8	15	86	159	3	249	2	20	0.4	10	1
299	53	RBLES	6.5543	44.9083	183313	1.74	21.7	101	72	247	15	340	9	45	0.5	9.3	1
300	54	RBLOU	6.5423	44.9083	184260	1.75	40.7	312	71	50	3	141	18	22	0.4	9.7	1
301	55	TURGE	6.7807	44.8288	165640	-1.30	7.7	181	76	82	2	351	14	25	0.5	8.8	2
302	56	ESCPE	6.677	44.6393	176119	-8.02	75.0	16	10	118	60	277	27	25	0.2	7.6	1
303	57	ESCRI	6.6898	44.6428	175053	-7.95	62.0	205	38	10	52	110	7	34	0.9	6	1
304	58	ESCNO	6.7003	44.635	174379	-8.28	63.7	19	1	276	83	108	7	30	0.4	9	1
305	59	ESCSU	6.7163	44.6295	173235	-8.55	67.4	15	2	111	73	284	17	29	0.4	7.3	1
306	60	FREIS	6.5357	44.7608	185505	-3.32	62.3	213	83	329	3	59	7	15	0.3	15.8	2
307	61	FOURN	6.5443	44.7962	184521	-2.13	64.9	290	80	33	0	113	10	25	0.4	11.7	2
308	62	BARAI	6.8263	44.5552	166367	-11.88	45.1	256	83	33	5	123	5	15	0.4	14.4	2
309	63	BARAI	6.8263	44.5552	166367	-11.88	61.1	21	33	188	57	287	6	21	0.7	15.7	2
310	64	VMARY	6.8625	44.5702	163187	-11.55	50.5	50	73	206	16	298	7	17	0.4	10.5	2
311	65	VHOUE	6.8242	44.5788	165942	-10.99	56.0	24	40	203	50	293	1	17	0.8	9.8	2
312	66	VLAUG	6.7508	44.5945	171279	-9.99	10.0	325	79	89	6	180	9	6	0.4	10.3	3

^aNumber of the tensor in this database (N), the number of the tensor in previous publications (n), and their names (site), the location and altitude (lon, lat in decimal degrees and z in meters), the polar coordinates (r, τ) , and the angle with respect to the Alpine belt (γ) , the σ_1 , σ_2 , and σ_3 orientation (azimuth and plunge) and the Φ ratio, with $\Phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$. Also given are the number of faults used in the inversion (data), the average misfit angle α , and the quality criterion ("conf").

an indicator for the lack of neoformed transcurrent faults. Figure 5f shows rose diagrams of azimuth and plunge of normal faults (top) and transcurrent faults (bottom) describing the geometrical relationship between fault orientations and kinematics.

3. Synthesis of Brittle Deformations in the Inner Western Alps

3.1. Presentation of the Data

[17] This synthesis is based on the new paleostress database presented in this paper (see section 2.2) as well

as four other previously published data sets [Champagnac et al., 2003; Sue and Tricart, 2003; Champagnac et al., 2004; Grosjean et al., 2004]. The same tools for inversion were used in these studies: right diedra [Angelier, 1979] and direct inversion [Angelier, 1990], implemented in the tectonics FP [Sperner et al., 1993] and Stress [Villemin and Charlesworth, 1992] software. This provides a wide and homogenous database (312 paleostress tensors) for the entire arc of the inner western Alps, covering a surface greater than 10,000 km² (average density of tensors: 3 tensors/100 km²). The whole data set is presented in Table 1 and split into five zones: paleostress tensors numbered from N1 to N56 come from the south Valais (zone B, [Champagnac et al., 2003]).

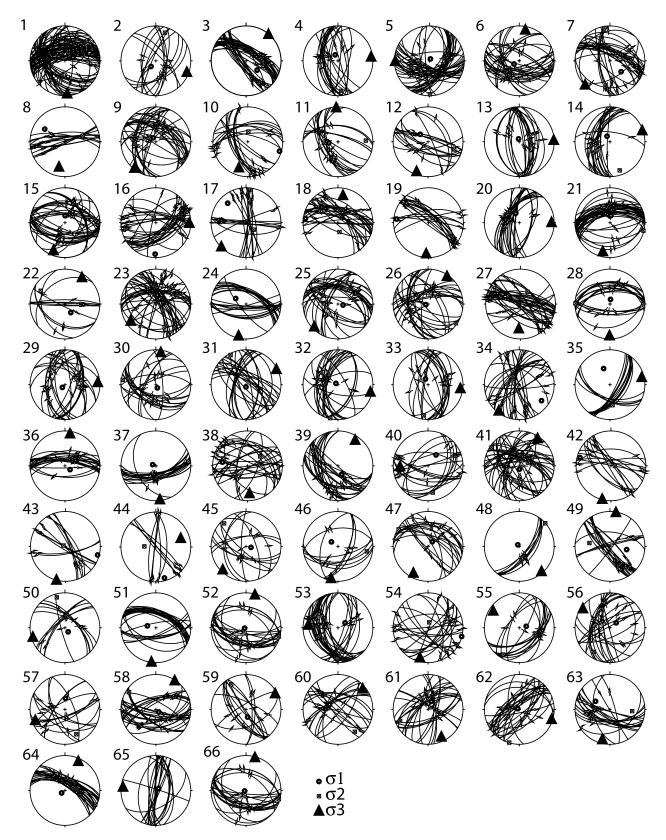


Figure 3. Stereonets of the 66 unpublished paleostress tensors. As for all of the stereonets used in this paper, data are projected in a Schmidt stereogram, lower hemisphere with circles for σ_1 axes, squares for σ_2 axes, and triangles for σ_3 axes. Faults and striations used for the calculation are also plotted. On average, 23 fault planes and their slickenlines were used for the calculation of each tensor.

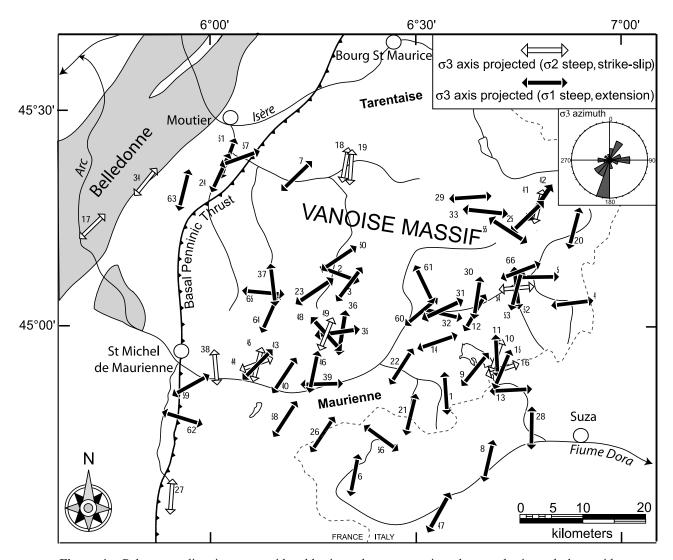


Figure 4. Paleostress direction map, with subhorizontal σ_3 axes projected onto a horizontal plane with white arrows for transcurrent tensors (subhorizontal σ_1 axis) and black arrows for extensional tensors (subvertical σ_1 axis). The dotted line represents the borders between Italy, Switzerland, and France; tensors are numbered from 1 to 66 beside the arrow.

Paleostress tensors numbered N57 to N118 come from the Aosta and Tarentaise valleys (zone C [Champagnac et al., 2004]). Tensors N119 to N184 are unpublished (zone D, section 2.2). Tensors numbered N187 to N246 come from the Simplon area (zone A [Grosjean et al., 2004]), and tensors N247 to N312 come from the Briançonnais area (zone E [Sue and Tricart, 2003]).

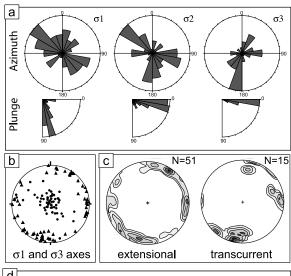
[18] In order to demonstrate the homogeneity and the large prevalence of extensional features in the inner parts of the western Alps, five examples of outcrops (one for each zone) and their associated paleostress tensors are presented in Figure 6. As in the Vanoise area, normal faulting is the most striking brittle deformation feature of the whole inner western Alps. The deformation is often penetrative (e.g., Figures 6a and 6d), with or without the prevalence of one of the conjugated fault families. Normal faults range from

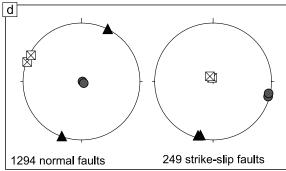
kilometer scale with a dacametric offset (e.g., Figure 6b and 6c), with a clear geomorphic expression (e.g., in the form of passes in the crest line, Figure 6c), to centimeter scale, with a millimetric offset (smallest faults in Figure 6a). Figure 6e shows metric conjugated normal faulting tilted of about 30° during extension. The directions of faulting observed from the landscape (or satellite) view are usually in good agreement with the general directions of the measured fault planes [Sue and Tricart, 2002; Champagnac et al., 2003].

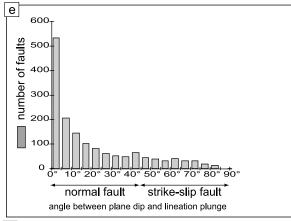
3.2. Synthesis and Interpretation of the Data

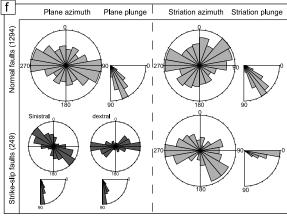
3.2.1. Directional Analyses of the Extensional Axes

[19] Five zones are defined, corresponding to each individual study. These studies have been performed within a









relative small area. Before carrying out a global analysis, the most remarkable features of each zone are pointed out individually (Figure 7).

3.2.1.1. Zone A, Simplon Area

[20] The data set from Grosjean et al. [2004] is located in the vicinity of the Simplon fault zone. This fault zone is a major NW-SW striking low-angle detachment, active during the Miocene [Mancktelow, 1992; Steck and Hunziker, 1994]. The total southwestward displacement of the hanging wall has been estimated to be 36 km, with a vertical offset of about 15 km [e.g., Steck and Hunziker, 1994]. Brittle deformation along the Simplon fault has been documented to be active during the upper Miocene [Zwingmann and Mancktelow, 2004]. Its footwall is made of a metamorphic pile of nappes (Lepontine dome), whereas its hanging wall is composed of upper Penninic nappes, overridden by the Austroalpine low methamorphic Dent Blanche Klippe. Grosjean et al. [2004] examined the brittle deformation features associated with the Simplon fault and calculated a total of 62 paleostress tensors form some 1000 faults/striation couples. The tensors are distributed in a relatively small area, providing a very high density of data (20 tensors/100 km²). All tensors are extensional (except N246/SD), with a stable ENE-WSW direction of extension. This orientation is identical to the pervasive stretching lineation observed within the

Figure 5. Directional analyses of the 66 tensors. (a) The 20° class size rose diagram and 10° class size quarter rose representing the σ_1 , σ_2 , and σ_3 azimuth and plunge for the 66 tensors. (b) Plot of σ_1 and σ_3 axis in a Schmidt lower hemisphere stereogram. (c) Comparison between σ_3 orientation for (left) extensional tensors and (right) transcurrent tensors using axes contouring mode; the major NNE-SSW directions are almost the same for both extensional and transcurrent paleostress tensors. (d) Global analysis based on the whole faults data set. Direction of extensional axis is very close for both normal faults and transcurrent faults. Calculations performed with "right dihedra" [Angelier, 1979] and dynamical-numerical methods [Sperner et al., 1993] are equivalent. (e) Histogram of the angle between fault plane dip and its striation plunge and the cumulated percentage. The 0° indicates a pure dip-slip normal fault, whereas 90° indicates a pure transcurrent fault. The low amount of high-angle faults indicates transcurrent movement along nonvertical fault planes (reactivated normal fault) as well as oblique striations along steep fault planes. (f) Orientation of (left) planes and (right) striations of the fault measured in the Vanoise area; (top) normal faults and (bottom) transcurrent faults are separated to determine the orientations of the faults in this area. Normal fault planes are scattered around the E-W orientation, with 50° to 80° dipping. Related striations are slightly extended, without clear direction; plunges vary between 40° and 70°. Transcurrent faults are sorted by their kinematic criterion: sinistral faults are NW-SE oriented, whereas dextral faults are E-W oriented, both with subvertical dip. Striations are in agreement with plane orientations, with NW-SE and E-W main direction; plunges are subhorizontal.

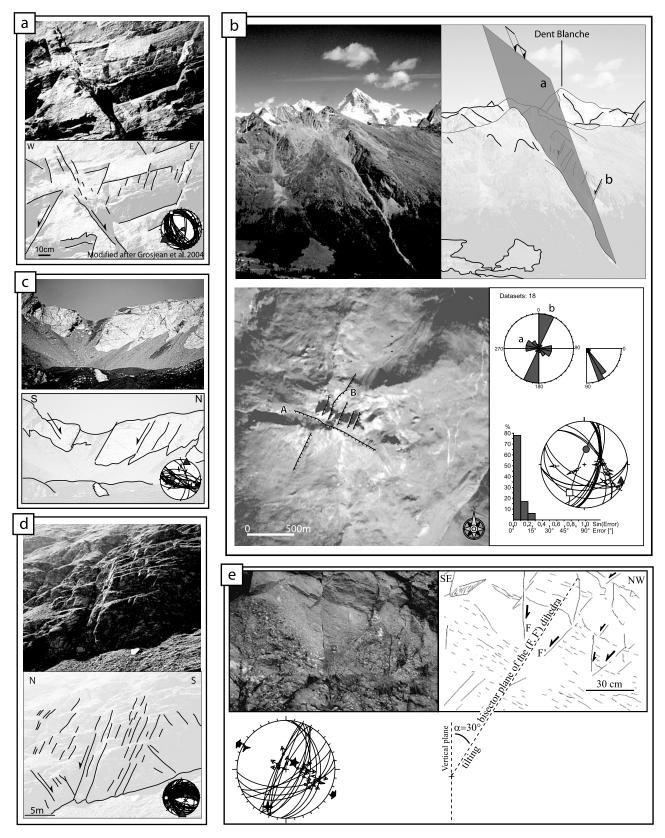


Figure 6

Simplon mylonites by *Mancktelow* [1992], indicating a temporal continuum of the kinematics from ductile to brittle conditions.

3.2.1.2. Zone B, Southern Valais

[21] This zone is located immediately to the west of the Simplon area and is limited to the north by the major Rhône fault (which follows closely the present-day Basal Penninic Thrust and the Rhône valley) and to the west by the northern tip of the Mont Blanc massif. The crest line of the Combin, Dent Blanche and Monte Rosa massifs, with many summits over 4000m in altitude, constitutes the southern border of this zone. The south Valais area belongs to the internal zones of the Alps and is made up of south dipping middle Penninic nappes, overridden by the main Alpine Piémont suture zone and the lower Austroalpine Dent Blanche nappe. The Brianconnais nappes consist of slices of pre-Carboniferous basement rocks, with their sedimentary cover. The Piémont suture zone is a melange of ophiolitic rocks and associated oceanic "Schistes Lustrés" calcschists. The overriding Dent Blanche nappe is the highest nappe in this part of the western Alps. It is mainly a crystalline basement unit with some isolated remnants of sedimentary cover [Steck and Hunziker, 1994; Escher and Beaumont, 1997; Steck et al., 1997]. The metamorphic history of the Penninic units is complex. Parts of the Piémont suture zone have experienced high- to ultrahigh-pressure metamorphisms, while most of the basement units have undergone only moderate pressure, middle to upper greenschist facies methamorphism [Desmons et al., 1999].

[22] Brittle deformation within this area has been examined recently [Champagnac et al., 2003]. Paleostress tensors are mainly extensional, and the mean σ_3 axis is oriented N065°, in a stable "Simplon-like" orientation. One third of the calculated tensors are transcurrent, with a coaxial orientation of σ_3 axis. Relative chronologies indicate a transcurrent/transtensive stress field followed by a purely extensional stress field.

3.2.1.3. Zone C, Aosta

[23] The geological structure of this area is very similar to that of the southern Valais, with a general dip of structures to the SE. Nevertheless, slices of Valaisan units (Cretaceous flyschs) and subriançonnais units (Mesozoic marls) are squeezed between the penninic pile of nappes and the Mont Blanc External Crystalline massif. The southern part of this zone is made of internal crystalline basement of the Gran Paradiso metamorphic dome. This gneissic dome (derived from the European margin) has been metamorphosed under eclogite facies and retromorphosed under greenshist facies (see *Rolland et al.* [2000] for details). In the core of this zone, the large north dipping Aosta-Ranzola Oligocene normal fault [*Diamond*, 1990] extends from the Piccolo San Bernardo pass in the west to the Ranzola pass, more than 100 km to the east. Its vertical offset ranges from 0.5 to 2 km. This major fault is described as left-lateral during Quaternary [*Carraro et al.*, 1994].

[24] Brittle deformation analyses of this area have been published and discussed by *Champagnac et al.* [2004]. The stress axes orientations are quite dispersed in space, but display a main NNE-SSW orientation of σ_3 axis. This orientation of extension has been interpreted in terms of orogen-parallel extension. The ratio between transcurrent and extensional paleostress tensors is 1/4, with varying the relative chronology.

3.2.1.4. Zone D, Vanoise

[25] This zone is presented in section 2. The ratio between transcurrent and extensional tensors is about 1/4. The mean directions of σ_3 axes for extensional and transcurrent stress field are coaxial, N-S oriented. A minor part of extensional axes are E-W oriented, and are interpreted as an orogen perpendicular stress field, according to *Champagnac et al.* [2004]. N-S extension is consistent with the results of *Malusa et al.* [2005] in the Val di Suza, farther east.

3.2.1.5. Zone E, Briançon Area

[26] The data used in this synthesis come from *Sue and Tricart* [2003]. Calculated tensors and late normal faulting observations are located in the southwestern Alps, between Pelvoux and Argentera External Crystalline massif. Four major features of large-scale brittle deformation have been observed in this area: the inversion as normal fault of the former Basal Penninic Thrust, the coexistance of transverse and longitudinal normal faults, related to orogen-parallel and orogen-perpendicular extensions, respectively, and a late dextral reactivation of NNW-SSE faults. 75% of the 66 computed paleostress tensors are extensional, the remaining

Figure 6. Fieldwork example of normal faulting all around the inner Alpine belt. (a) Close-up to penetrative normal fracturation close to the Simplon pass (site N195); the inversion of the fault population measured in the vicinity of the picture site indicates a NNE-SSW direction of σ_3 axis. (b) Multiscale analyses of the Pic d'Artsinol area (Valais, site n3). From the NW, a large south dipping normal fault is suspected; satellite imagery (IRS image, pixel size of 6 m) and field observations allow us to recognize two fault directions, a large E-W fault (south dipping, "a") and smaller NNE-SSW faults (east dipping, "b"). The 20° class size rose diagram of the measured fault plane shows both "a" and "b" directions. A good quality paleostress inversion (see misfit angle histogram) demonstrates a WNW-ESE direction of extension associated with this fault pattern. (c) Large-scale E-W normal faults at the Col de Malatra (Val d'Aoste, site N75), view from the east. Normal faults cut across the limestone cliff, and create a pass about 100 meters wide between the Gran San Bernardo valley and the Val Ferret (Italy). The small-scale measured faults are also E-W oriented and the calculated σ_3 axis is N-S oriented. (d) Large and close spaced normal fracturation in the Val d'Ambin (site 119). Both flanks of this small valley are dissected by normal faults. The great number of fault measurements (stereoplot) allows calculation of a well-constrained paleostress tensor with its extensional axis (σ_3) N-S oriented. (e) Conjugated normal faults in High Ubaye (site 310). Diedra is tilted of 30° toward the NW (around the σ_2 axis). The direction of extension σ_2 is NW-SE oriented.

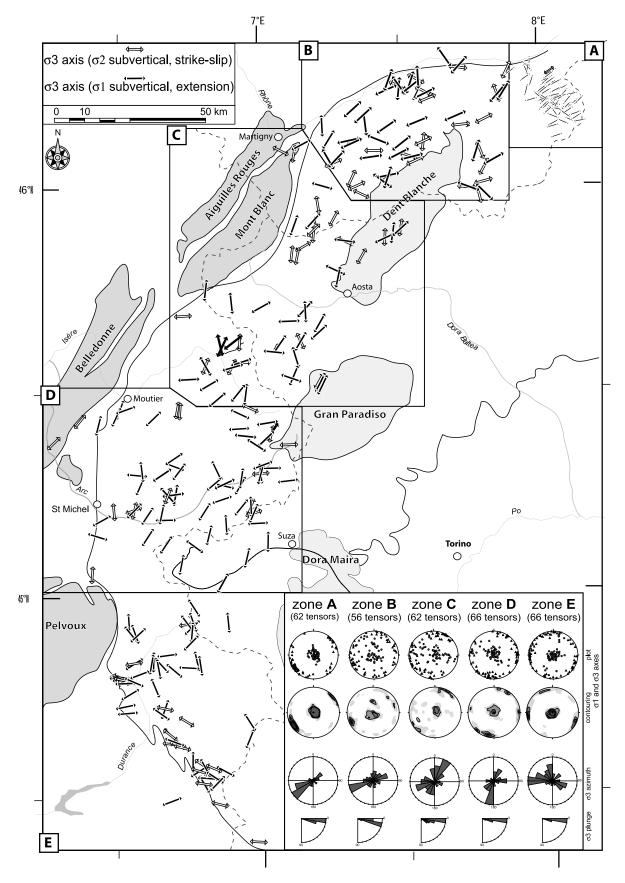


Figure 7

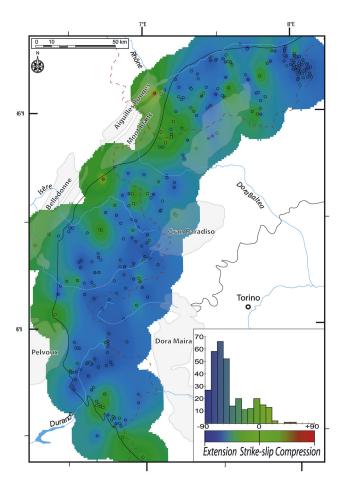


Figure 8. Contouring of the stress tensor orientation in the inner western Alps, based on the plunge of σ_1 and σ_3 axes. Color coding corresponds to the tectonic regime: compression in red, extension in blue, and strike slip in green. Small circles locate the site where paleostress inversion was performed, with their own color. The background colors come from the interpolation between data points. The blue color (extensional tectonics) largely prevails within our area of interest. The colored histogram shows the repartition of deformation regime in the belt. See text for discussion.

25% being transcurrent. The transcurrent stress field postdates the extensional one, as demonstrated by clear crosscutting relationships. The direction of extension is E-W (perpendicular to the BPT and the general trend of Alpine structures) and N-S to NNW-SSE (parallel to the BPT and the Alpine structures). *Sue and Tricart* [2003] interpreted both directions in terms of what they called a "multitrend extension", based on field evidence of simultaneous faulting activity and a low Φ ratio of the calculated tensors [Sue and Tricart, 1999, 2002, 2003]. One of the more striking tectonic features of this area is the large amount of orogen-perpendicular extension.

3.2.1.6. Entire Data Set

[27] Directional and statistical results of our synthesis around the Alpine belt are presented in Figure 7. We observe a continuous change in σ₃ direction from N065° in the Simplon area, to N-S in the Vanoise area and to NNW-SSE in the Briançon area. The dispersion of the σ_3 axes is very small in the Simplon area, probably because of the kinematic control of the major Simplon Fault Zone. The dispersion of σ_3 axes is greater in the Valais area, but the direction of extension is still very well constrained. The dispersion of the σ_3 axes increases in the Aosta/Tarentaise valleys and decreases again farther south. Another striking characteristic is the increasing amount of orogen-perpendicular σ_3 axes from north to south; in the Briançonnais area, the inversion of the BPT [Sue and Tricart, 1999, 2002] seems to be the origin of the E-W to NE-SW oriented σ_3 . The σ_1 axes are mainly subvertical. The dispersion of σ_1 axes increase from zone A to zone C and decrease from zone C to zone E; the σ_1 axes dispersion in the Briançonnais area is comparable to the dispersion in the Simplon area.

3.2.2. Transcurrent Versus Extensional Tectonics

[28] The percentage of transcurrent versus extensional paleostress tensors varies from 2% (zone A) to 33% (zone B), with a mean of 25% for the whole data set. The amount of transcurrent faults is about 15% of the global data set (about 800 faults out of more than 5000). Accordingly, the transcurrent stress field appears to be a slighter signal recorded by the brittle deformation, superimposed through time onto the first-order extensional regime. In order to represent the relative importance of the different types of tectonic regimes within the internal western Alps, we calculated a variable r that depends on the plunges of the σ_1 and σ_3 axes (r is plunge of σ_1 minus plunge of σ_3). For each tensor, the r parameter is calculated and varies linearly from -90 (red, purely compressive) to 0 (green, pure strike slip) and +90 (blue, purely extensional). Intermediate values are represented by transpressive (-90 < r < 0), and transtensive $(0 \le r \le 90)$ states of stress. We plotted every tensor with its own color code, while areas between observation points are filled with interpolation (GMT continuous curvature spline in tension [Smith and Wessel, 1990]). The map shown in Figure 8 provides an overview of the prevailing faulting styles observed all along the inner zone of the

Figure 7. Paleostress field synthesis of the inner western Alps. The map of the inner parts of the western Alps outlines some geological units (Dent Blanche, Gran Paradiso, and Dora Maira internal massifs, and Mont Blanc, Aiguilles Rouge, Belledonne and Pelvoux External Crystalline massifs). The studied area is subdivided in five parts: zone A, the Simplon pass area (with smaller arrows because of the high density of tensors), zone B, the south Valais, zone C, the Aosta and Tarentaise valleys, zone D, the Vanoise massif and the Maurienne valley and zone E, the Briançon and High Durance area (see text for details about origin of data). Arrows represent the minimum principal stress axes (σ_3) projected on horizontal plane (white arrows for transcurrent tensors, black arrows for extensional tensors). The insert gives the directional analyses of paleostress orientations for the five zones separately. From top to bottom the plots of σ_3 (triangle) and axes (circle), the contouring of the σ_1 (vertical) and σ_3 (horizontal) axes, rose diagram and plunge of the σ_3 orientation.

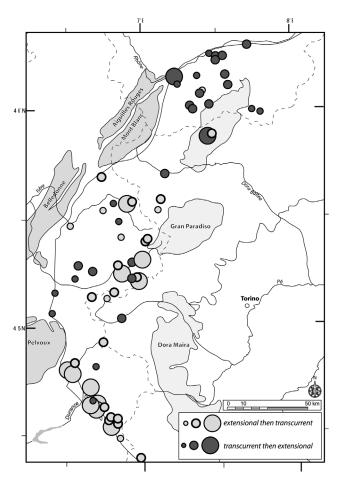


Figure 9. Chronological evidences based on field observations. The size of circles represents the reliability of the chronology (large circles for high-quality chronology evidences, small circles for lower quality). Dark grey circles symbolize locations where transcurrent deformation is older than extensional deformation. Light grey circles symbolize location where transcurrent deformation is younger than extensional deformation. The chronological orders are the opposite in the south Valais than elsewhere southward in the belt. Younger transcurrent motions are well developed in the southern branch of the arc (from the Gran Paradiso southward).

western Alps. The most striking characteristic is the predominance of an extensional state of paleostress, shown in blue. Strike slip (in green) is observed in some places, especially on the eastern side of the Mont Blanc massif, close to the Gran San Bernardo pass. This zone of transcurrent deformation separates the western Alpine belt into two parts, the Simplon and Valais areas to the north, and the Vanoise and Briançon area to the south. Southward of the Briançon area, the amount of transcurrent deformations gently increases again. Other transcurrent tensors are located on the external side of the belt, from the northern tip of the Mont Blanc massif to the central parts of the Belledonne massif. Nevertheless, site coverage in the external zones is poor, and the interpolated green colors should be regarded with some caution here.

[29] However, both transcurrent and extensional tectonic regimes are recorded by brittle deformation. In the Valais area, an older transfensive stress field, with high Φ ratio (i.e., close relative magnitudes of σ_1 and σ_2 axes, see below) is followed by a multitrend extensional stress field, with low Φ ratio (i.e., similar σ_2 and σ_3 axes) [Champagnac et al., 2003]. In contrast, the Maurienne and Briançonnais areas are characterized by younger transcurrent faults and horizontal striations superimposed on older normal faults (i.e., Figure 2c) [Sue and Tricart, 2002; Champagnac, 2005]. To better understand the spatial pattern of these chronologies, we plotted every site with the known relative chronology onto a map (Figure 9). Different circle sizes have been used to express the reliability of our observation (big circles indicate a well-established chronology, small circles indicate a low degree of confidence). This map confirms the intuitive observation of opposite chronologies between the Valais and all the surrounding areas. For most of the inner western Alps, the chronology is clear: extension is older than strike slip. The Valais area is however an exception where strike slip movements are followed by extension. The transition between the two regimes is located to the east side of the Mont Blanc massif, an area characterized by a predominance of transcurrent paleostress tensors, as highlighted in Figure 8. Despite these differences along strike, the σ_3 axes orientations for extensional and transcurrent stress fields show no statistical differences; moreover, an orientation analysis performed with the entire data set of normal faults and transcurrent faults within zones B, C and D show less than 10° difference between the transcurrent σ_3 axis and the extensional σ_3 axis (e.g., Figures 5c and 5d and Champagnac [2005]). Accordingly, we suggest a swapping between σ_1 and σ_2 axes in a single "deformation phase," with instabilities in space and time modifying the overall stress field [Champagnac et al., 2003; Sue and Tricart, 2003; Champagnac et al., 2004]. A part of such stress axes permutations could also be induced by rock heterogeneity and anisotropy, as demonstrated by *Hu and Angelier* [2004]; this phenomenon could be important, and needs to be considered. Nevertheless, chronological evidence (Figure 9) indicates opposite chronologies between the Valais and remaining parts of the inner western Alps, and the chronologies probably have a geological significance.

3.3. Ellipsoid Shape Form Parameter Φ

[30] Beyond the stress orientation, paleostress inversion allows one to determine the relative magnitude of σ_1 , σ_2 and σ_3 of the stress ellipsoid, the Φ ratio; $\Phi = [\sigma_2 - \sigma_3]/[\sigma_1 - \sigma_3]$) and $0 < \Phi < 1$ [e.g., *Angelier*, 1979]. A low Φ ratio (similar σ_2 and σ_3) indicates a multitrend (i.e., symmetric around the vertical axis) extension or transpression (for extensional or transcurrent tensor, respectively), and high Φ ratio (similar σ_1 and σ_3) indicates a transtensional stress field. According to our calculations, the Φ parameter provides a powerful and sensitive tool to investigate subtle differences in paleostress data, but needs to be used with caution, because of its high sensitivity to heterogeneous

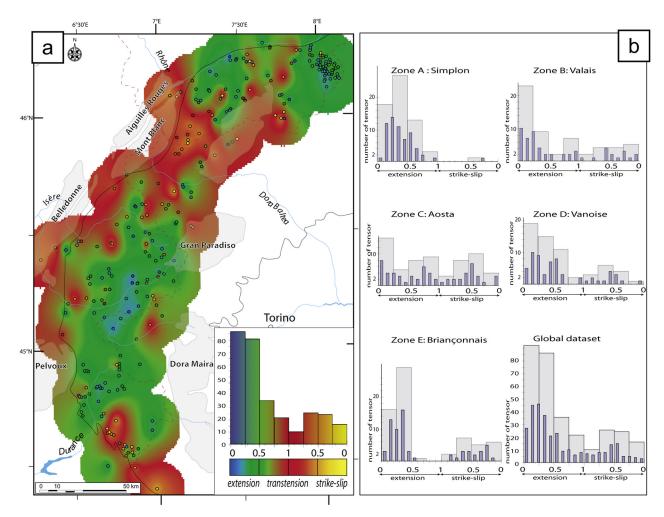


Figure 10. Map of the Φ ratio in the inner western Alps. (a) Map with interpolated Φ ratio for the entire data set. Color code is used between $\Phi=0$ (blue) and $\Phi=1$ (red), via $\Phi=0.5$ (green), for extensional tensors and between $\Phi=1$ (red) and $\Phi=0$ (yellow) via $\Phi=0.5$ (orange) for transcurrent tensors. Colored histogram gives the repartition of Φ ratio of the inner western Alpine belt. (b) Histogram presentation of the Φ ratio for each of the five zones separately, and for the entire data set, within 10° and 25° class size. The meaning of Φ ratio differs according to the plunge of σ_1 , the histograms are split into two parts: from 0 to 1 for extensional tensors and then from 1 to 0 for transcurrent tensors.

data sets. We present this parameter on a map (Figure 10a) and some further statistical analyses we performed (Figures 10b). Given the fact that the significance of a low Φ ratio is different for extensional or transcurrent tensors, we used a different color coding scheme: a blue-green-red scale is used for extensional tensors $\Phi=0$ (blue) and $\Phi=1$ (red), through $\Phi=0.5$ (green), whereas a red-orange-yellow scale is used for the representation of transcurrent tensors $\Phi=1$ (red) and $\Phi=0$ (yellow) through $\Phi=0.5$ (orange).

[31] Spatial interpolation has been performed between the documented sites (same interpolator as for r parameter, compare Figure 8). The map (Figure 10a) appears with large green areas, revealing pure extension. Some zones appear with blue tones, especially in the western Valais, the Simplon and the Vanoise area. A striking feature is the large reddish area in the Aosta valley, at the eastern side of the

Mont Blanc massif. A large transtensive to transcurrent region has recorded strike slip rather than the extensional tectonics prevailing in surrounding areas. This transcurrent/ transtensive area coincides with the transitions in the relative chronology described above (Figure 9). The position of this area (Val d'Aosta and surrounding) with respect to the Mont Blanc massif and/or the arc of the Alps (transition between central Alps and western Alps) could have reduced the extensional processes and thus increase the transcurrent tectonic. Such geodynamical process(es) remains open to debate. Other red/orange areas are located at the western flank of our studied area, along the External Crystalline massifs, and in the southernmost areas, close to the Basal Penninic Thrust. To better understand the spatial patterns and the relative values of the Φ ratio, we also plotted them in histograms, one for each zone and one for

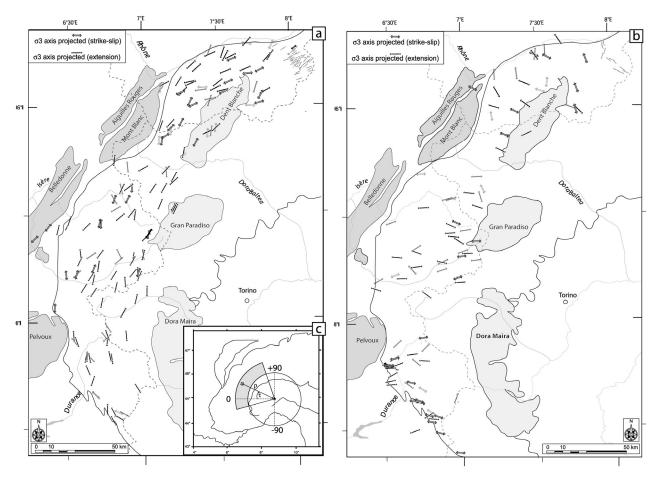


Figure 11. Spatial repartition of the extensional axes with respect to the Alpine belt. (a) Orogen-parallel extensional axes ($\beta < 30^{\circ}$, see text for details) plotted onto an Alpine map with white arrows for transcurrent and black arrows for extensional paleostress tensors. Also are plotted tensors with $30^{\circ} < \beta < 45^{\circ}$, in light grey. (b) Orogen-perpendicular extensional axes ($\beta > 60^{\circ}$) plotted onto Alpine map, with the same color code as Figure 12a ($90^{\circ} > \beta > 60^{\circ}$) in light grey. Outline of western Alps and circles used to convert geographical coordinates into polar coordinates are shown. The grey bend represents the area where we performed paleostress calculation ($-19^{\circ} < \tau < 69^{\circ}$ and 147.8 km < r < 246.5 km).

the whole data set (Figure 10b). Histograms (number of observations versus Φ ratio) were again plotted separately for extensional and transcurrent tensors. We further arranged the abscissas of the histograms (Φ) in order to show a continuum from multitrend extension to transpressive tensor, via pure extension, transtension and pure strike slip. The histogram of the global data set shows a peak for extensional low Φ ratio (0 < Φ < 0.5, multitrend extension) and a minimum for high Φ ratio (0.75 < Φ < 1, transtension) for both extensional and transcurrent tensors. A small second-order mode appears for transcurrent medium Φ ratios (close to 0.5). In the zone A (Simplon area), the tensors are exclusively extensional, and the Φ ratio is close to 0.5 (pure extension). In zone B (Valais area), most of the tensors have a low Φ ratio (less than 0.3, multitrend extension), with a second-order mode for high Φ ratios (transtension). Zone C (Aosta area) is characterized by a

wide range of Φ ratios and with three small maxima (multitrend extension, transtension and pure strike lip). The Vanoise area (zone D) presents a relatively wide distribution of extensional tensors ($0 < \Phi < 0.75$), with a peak of low values, and another ample maximum for transcurrent medium Φ value (pure strike lip). The southernmost area (Briançonnais area, zone E) is characterized by a bimodal histogram, with a first peak of medium to low Φ ratio within extensional tensors ($0.1 < \Phi < 0.4$) and a second, more diffuse maximum for transcurrent tensors ($0.7 > \Phi > 0.2$).

[32] To sum up, the Φ ratio analysis shows mostly bimodal distributions, clearly visible for zone D, E and the whole data set. For extensional tensors, Φ ratios are shifted to minor values, except in the Simplon area. The most impressive shift is observed in the Valais area, with very a low Φ ratio. This shift could be related to partly

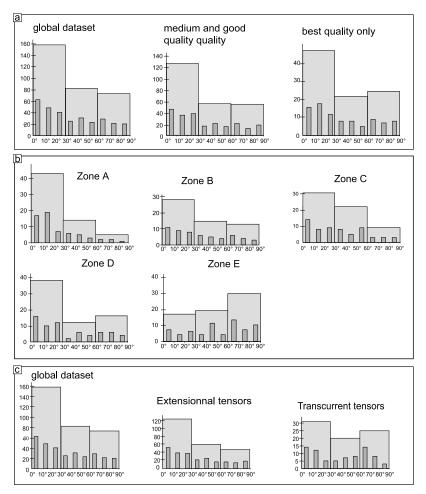


Figure 12. Histograms of the angular relationship between the Alpine trend and σ_3 orientations. (a) Angles are plotted within 10° and 30° class size for (left) the whole data set, (middle) medium and good quality criterion tensors, and (right) only best quality tensors. Despite the ever-predominant orogen-parallel tensors, best quality tensors appear to be slightly more "orogen-perpendicular" than lower quality. (b) Histograms of β angles for each zone separately, within 10° and 30° class size. See text for discussion. (c) Angular relationship between extensional axes (σ_3) plotted into histograms with 10° and 30° class size histograms for (left) global data set, (middle) extensional tensors, and (right) transcurrent tensors. See text for details.

heterogeneous data set, but probably reflects two directions of extension occurring in the same time (transition between two tectonic regime, see below).

3.4. Stress Axes in "Polar Alpine" Coordinates

[33] Given the arcuate shape of the western Alpine belt, the directional analyses of extensional axes, such as shown in Figure 6, as well as the choice of subsets (5 areas) is always biased with respect to the continuously changing strike direction of the bend of the NW Alps. For instance, a N-S direction in the Valais area has the same meaning as an E-W direction in the Vanoise area, if we consider the stress directions with respect to the strike of the Alps. In order to take this problem into account, we adopted a new coordinate system of polar coordinates. The shape of the northwestern Alpine belt can indeed be approximated with a portion of a circle, matching closely the changes in strike

observed both at the internal and external side of the Alps, as well as all first-order structures (External Crystalline massifs and Basal Penninic Thrust) as seen in map view. We have chosen a centre for our circle located in the middle of the Po plain (longitude 45°N, latitude 8.87°E, Figure 11a). Polar coordinates have been determined for all measurement sites with ρ the radius in kilometers from the center and τ the angular position in the Alpine belt, in degrees (measured positively in a clockwise sense from the west, Table 1).

[34] In order to examine the angular relationships between the arc of the NW Alps and paleostress axes orientations, we considered the three following angles: β the σ_3 axis azimuth (with $0^\circ < \beta < 180^\circ$), τ the angular position of the tensor in the Alpine belt (with $-19^\circ < \tau < 69^\circ$ here) and γ the angular position of the σ_3 axis with respect to the Alpine belt (with $(\gamma = abs (\beta - \tau))$) and (if $\gamma > 90^\circ$, then $\gamma = 180 - \gamma$)).

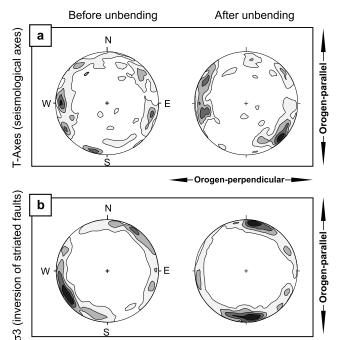


Figure 13. Contouring plot of seismotectonic T axes and σ_3 orientation calculated from fault measurements (Gauss counting method with k=100 [Robin and Jowett, 1986], contours at 1, 2, 3, and 4). (a) T axes from Delacou et al. [2004] database within our area of interest (grey bend of the Figure 11c). (left) Stereoplot of a classical contouring of T axes, in the geographical coordinates. (right) Stereoplot of the orientation of T axes with respect to the Alpine structures ("Alpine polar" coordinates). E-W to NW-SE orientations indicate an orogen-perpendicular direction of extensional axes. (b) The σ_3 (this paper) contouring (left) in geographical coordinates and (right) with respect to the Alpine structures ("Alpine polar coordinates"). The main orogen-parallel signal ("N-S") appears clearly, whereas the orogen-perpendicular ("E-W") is less expressed.

[35] The angular results are provided in Table 1 (ρ and τ entries), and the pattern of σ_3 axes with respect to the Alpine belt is plotted onto maps (Figure 11). On the basis of these angles, it is now possible to compare the direction of the extensional axis (for each tensor) with respect to its position within the Alpine belt. We adopt the following terminology: "orogen-parallel extension" is characterized by $0^{\circ} < \sigma_3 < 30^{\circ}$; "orogen-perpendicular extension" is characterized by $90^{\circ} > \gamma > 60^{\circ}$ and "oblique extension" is characterized by $30^{\circ} < \gamma < 60^{\circ}$. As shown in Figure 11a, the NW Alps are dominated by an orogen-parallel extension, prevailing within a wide belt of the inner Alps. Additionally, a large fan of orogen-perpendicular σ_3 axes is apparent from Figure 11b. This tendency is especially significant in the southern part of the belt (from the Vanoise area southward). Histograms (Figure 12c) give details of the distribution of σ_3 axes orientations with respect to the Alpine structures. The distribution for all the tensors is roughly 50% for orogen-parallel extensional axes, 27% and 23% for oblique and orogen-perpendicular extensional axes, respectively. With histogram classes of 10° , the mode is within the 0° - 10° class (orogen-parallel) with more than 60 tensors (20%). The distribution for extensional tensors is almost the same, with a mode in the $0^{\circ}-10^{\circ}$ class. In contrast, there is a bimodal distribution for transcurrent tensors; a first mode lies in the $0^{\circ}-10^{\circ}$ class and a second one in the $60^{\circ}-70^{\circ}$ class; the relative importance of orogen-perpendicular extensional axes is about 35%. In order to test the robustness of our tensor directions, we established an additional series of histograms (Figure 12a) with the angular distribution of extensional axes for good tensors (quality criterion of 1 or 2) and for the best tensors exclusively (quality criterion of 1). There is no noticeable change in the histogram shape, but the relative importance of orogen-perpendicular tensors increases, whereas the number of oblique tensors gently decreases. This could lead us to consider some oblique tensors as orogen-parallel (or -perpendicular) shifted by measurement (or calculation) imprecisions or block rotations. Of course, oblique tensors could also be regarded as true local direction of extension. The angle between the Alpine structures and extensional axes distribution of the stress axes for the five Alpine zones defined above is presented in Figure 12b. Zone A (Simplon area) presents many orogen-parallel σ_3 axes (more than 2/3) and very few orogen-perpendicular tensors; zone B and C have almost the same distribution as the global data set. As already seen in Figure 6b, zone D presents a bimodal distribution with a small maximum for orogen-perpendicular extensional axes. Zone E is the only area with more orogen-perpendicular than orogen-parallel extensional tensors; this has been interpreted by the normal reactivation of the Basal Penninic Thrust [Sue and Tricart, 1999, 2002]. From a global perspective, the relative amount of orogen-perpendicular paleostress tensors increases from north to south.

[36] In order to compare the paleostress results with the current direction of extension based on the inversion of focal plane mechanisms of earthquakes [Delacou et al., 2004], we used the same polar coordinates to analyze seismotectonic extensional axes. T axes come from Delacou et al. [2004] and have been chosen only within the area of our fault analysis $(-19^{\circ} < \tau < 69^{\circ})$ and 147.8 km $< \rho <$ 246.5 km). We then plotted the orientation of T axes (seismotectonics) and σ_3 axes (brittle deformation) in geographic coordinates (β) and in Alpine angular coordinates (γ) , with N-S orientation corresponding to orogen-parallel extension and E-W orientation corresponding to orogenperpendicular (Figure 13). The seismotectonic T axes contouring (Figure 13a) shows no obvious direction of extension, because of the curved shape of the NW Alps. In polar coordinates, however, a systematic pattern appears, oriented almost E-W to WNW-ESE, that is to say, perpendicular to the Alpine structures. In contrast, the contouring of σ_3 axes (Figure 13b) shows a NE-SW general trend of extension, which becomes "N-S" in polar coordinates, that is to say, orogen-parallel, with a minor portion E-W oriented.

[37] To sum up, the polar representation of extensional axes in the western Alps indicates major orogen-parallel (and a minor orogen-perpendicular) extension for Neogene

brittle deformation, whereas current seismotectonics T axes are clearly orogen-perpendicular oriented.

4. Discussion

4.1. Overview of Present-Day Deformation

[38] While convergence between Africa and Europe is well established on the larger scale, with a rate of 3 to 8 mm/yr at the longitude of the western Alps [DeMets et al., 1994; Nocquet and Calais, 2004], recent geodetic surveys [Sue et al., 2000; Calais et al., 2002; Oldow et al., 2002; Serpelloni et al., 2005] failed to demonstrate any convergence across the western Alps. Rather, the present-day deformation along the Lyon-Torino baseline is extensional, with a very low rate (<1 mm/yr) [Calais et al., 2002]. Relative movements between the northern part of the Apulian microplate and stable Europe appear to be insignificant [Oldow et al., 2002, Serpelloni et al., 2005]. The large-scale Africa-Europe convergence is consumed elsewhere, most likely south of Tyrrhenian Sea [Serpelloni et al., 2005], and within the Magrebides, as well as partly within the Dinarides, Appenines, and eastern Alps [Serpelloni et al., 2005].

[39] Seismological studies have been performed in the Alpine belt for decades [Pavoni, 1980; Béthoux et al., 1988; Deichmann and Rybach, 1989], but the extensional regime has been discovered only recently [Eva et al., 1998; Sue et al., 1999; Baroux et al., 2001; Delacou et al., 2004; Kastrup et al., 2004]. This extensional regime is well developed all along the core of the western Alps. As demonstrated by Delacou et al. [2004], this extensional deformation is associated with overthickened crust and a negative Bouguer anomaly. The directions of seismological T axes, as well as σ_3 axes (from the inversion of earthquake populations) describe a regular fan-shaped pattern, perpendicular to the Alpine belt (Figure 13). Only few compressional earthquakes have been recorded, and they are mainly located at the transition of the Alps with the foreland/lowland. The orogen-perpendicular extension is directionally consistent with the orogen-perpendicular extension we determined with our fault analysis (Figure 11b).

4.2. Neogene Brittle Deformation

[40] In this paper, we examined the brittle extensional tectonics in the inner western Alps. The majority (\sim 80%) of the calculated paleostress tensors are extensional with only few transcurrent tensors. More than 85% of all measured faults are normal, 15% are transcurrent. Transcurrent tectonics is the last event in the southern parts of the inner western Alps, whereas it is preceding extension in the Valais area (see section 3.2.2). The limit between these contrasting chronologies is located in the Aosta area (Figure 9). The orientation of σ_3 axes, however, remains identical for the transcurrent and extensional regimes and we only observe swapping between σ_1 and σ_2 .

[41] Extensional tectonics are well expressed throughout the inner western Alpine Arc, from the Simplon pass to the northern tip of the Argentera massif. The main direction of extensional axes is parallel to the structural grain of the Alps (Figures 4, 6, and 11), as observed in the eastern Alps. Only a minor part of σ_3 axes are oriented perpendicular to the Alpine structures. From a directional viewpoint, the orogenperpendicular extensional axes agree with the current stress regime inferred from seismotectonics. However, it could also be locally related to older extensional structures induced by the relative uplift of large Alpine units, such as the extensional reactivation of the Basal Penninic Thrust behind the Pelvoux massif [Sue and Tricart, 1999], ductile to brittle E-W extension along the western flank of the Gran Paradiso metamorphic dome [Rolland et al., 2000] or large west dipping normal faults on the western side of the Dora Maira and Viso massifs [Schwartz, 2002; Tricart et al., 2004b] during the Miocene. Given the brittle nature of faults, the extension characterized in this paper is postmetamorphic. Faults crosscut (and thus postdate) folds, schistosities and nappe-related ductile structures, even if some extensional movements occurred earlier, at the ductile-brittle transition [Champagnac, 2005, Malusa et al., 2005]. Furthermore, the large diversity of fault plane mineralizations (e.g., calcite, quartz, hematite, talc, amphibole, chlorite), the variety of movement-related lineations (slickenfibers, striations, wear marks) and the aspect of rocks in the vicinity of the fault plane (cataclasite, unconsolidated cataclasite, fault breccias and fault gouges) suggest a very large variation of faulting conditions (temperature, depth, strain rate, fluid pressure and composition) and therefore a long brittle history. Indeed, the fault population observed in the western Alps for this study is the result of a temporal integration of all brittle deformations which occurred in this area, from ductile-brittle transition to the present-day.

4.3. Geodynamical Interpretations

[42] Extensional processes are a common feature in evolved orogens and have been widely described [e.g., Dewey, 1988; Molnar and Lyon-Caen, 1988; England and Houseman, 1989; Le Pichon and Chamot-Rooke, 1991; Rey et al., 2001]. Widespread extension in evolved mountain belts has mostly been interpreted in terms of orogenic collapse and/or lateral extrusion (see Rey et al. [2001] and Sue and Tricart [2002] for a review). The onset of such extensional regimes is due to subtle changes in a complex equilibrium, such as a decreasing rate of convergence, increasing erosion rates, temperature-/time-dependent internal strength variations or isostatic reequilibration due to lower crust and/or lithospheric mantle behavior [Avouac and Burov, 1996; Molnar and Lyon-Caen, 1988; Molnar et al., 1993]. In the western Alps, the location of extensional tectonics, the orientation of extensional axes, as well as the lack of current convergence along the Lyon-Torino baseline have led to the proposal that the western Alps are currently in a state of postorogenic collapse [Delacou et al., 2004; Selverstone, 2005; Delacou et al., 2005; Jiménez-Munt et al., 2005], dominated by buoyancy and gravitational forces. This collapse involves an extension perpendicular to the axis of maximal crustal thickness of the belt.

[43] In contrast, extensional deformations described in the eastern Alps [Selverstone, 1988; Frisch et al., 2000] and the central Alps [Mancel and Merle, 1987; Mancktelow,

1992; Steck and Hunziker, 1994; Nievergelt et al., 1996; Wawrzyniec et al., 2001] have mostly been interpreted in terms of a syncollisional extension, with a main direction of extension oriented along the strike of the belt, and perpendicularly to the main shortening direction. Thus this orogen-parallel extension has been interpreted (at least for the eastern Alps) as lateral extrusion toward the east [e.g., Ratschbacher et al., 1991]. As recently supported by numerical modeling [Seyferth and Henk, 2004], lateral extrusion largely prevails in any evolved orogen; a free boundary and overthickened crust are described as favoring factors, however, the plate convergence remains the principal cause.

[44] In the western Alps, we have suggested that the orogen-parallel extension to be due to lateral extrusion toward the south [Champagnac et al., 2004]. The opening of the Ligurian Sea during the lower and middle Miocene [Carminati et al., 1998; Rollet et al., 2002; Rosenbaum et al., 2002] would act as a free boundary for the development of a large-scale lateral extrusion system. However, the transition between the inner extensional zones of the Alps and the Ligurian Basin is not straightforward: the southernmost part of the Alpine belt is bent into a tight arc, with the presence of the Argentera massif and Ligurian Alps. Nevertheless, as suggested by fission tracks studies, exhumation of the southern part of the west Alpine belt started in the late Miocene, with a rapid uplift since the Pliocene [Bigot-Cormier et al., 2000; Foeken et al., 2003]. This uplift started at a time, when the Ligurian Sea stopped opening (upper Miocene). Therefore the lower Miocene Alpine arc must have probably been less pronounced than it appears today [Collombet et al., 2002].

[45] In the eastern Alps, lateral extrusion is accommodated by a set of large conjugate dextral and sinistral faults. In the western Alps, large and long-lived dextral transcurrent faults are observed all along the belt, [e.g., *Ménard*, 1988], but only very few sinistral faults are known (exceptions are the Ospizio Sottile fault [*Bistacchi et al.*, 2000] and some faults within the Schistes Lustrés of the Queyras Ubaye area [*Tricart et al.*, 2004a]). Many authors consider this curved and predominantly dextral strike slip to be due to the counterclockwise rotation of the northern tip of the Apulian indenter [*Anderson and Jackson*, 1987; *Ménard*, 1988; *Vialon et al.*, 1989; *Collombet et al.*, 2002]. The scarcity of sinistral faults nicely fits with this interpretation.

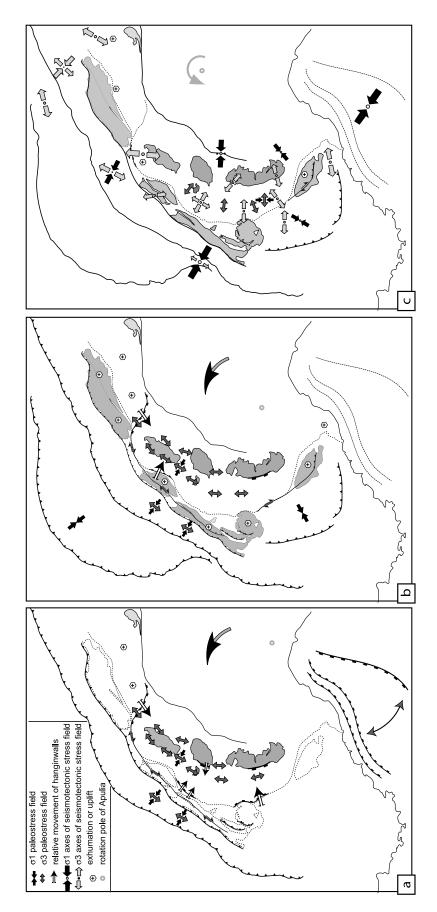
[46] We propose that the inner western Alps suffered a large-scale lateral extrusion toward the opening of the Ligurian Sea, at least during lower to middle Miocene. This lateral extrusion would be the origin of the main part of the brittle west Alpine tectonics. A significant part of the extension, however differs significantly from the expected orogen-parallel orientation: orogen-perpendicular or oblique extensional axes are in fact observed all around the belt. An important part of this extension is located in the hanging wall of large normal faults, and occurs under ductile-brittle transition and brittle conditions. This extension is induced by the up-doming and exhumation of basement nappes. It has been observed close to the Simplon pass [Mancktelow, 1992], in the vicinity of the Gran Paradiso and Ambin

Dôme [Rolland et al., 2000; Ganne et al., 2004], and in the Viso and Dora Maira massifs [Schwartz, 2002; Tricart et al., 2004b]. Extension has also been observed in the hanging wall of the reactivated BPT, in the Brianconnais area [Sue and Tricart, 2003] and on the eastern side of the Mont Blanc massif [Seward and Mancktelow, 1994; Aillères et al., 1995; Cannic et al., 1999]. Because of the dynamics of such relative uplift, this extensional tectonics is intimately linked to large-scale compressional deformation ("deep indenter" [e.g., Schwartz, 2002]). The orogen-parallel extrusion described above is also the consequence of shortening within the limits of the Alpine orogeny. Therefore Miocene extensional tectonics can result of the interaction between a major Alpine-scale orogen-parallel extension and a regional-scale "dome-related" extension. This could explain the local multitrend extension (low Φ ratio) observed.

[47] In summary, our preferred interpretation of the observed extension patterns is shown in Figure 14 which presents three snapshots of Neogene Alpine history: Figure 14a presents the main stage of orogen-parallel extension, directly related to extrusion toward the Ligurian basin, under brittle conditions. This stage predates the end of the Ligurian Basin opening, at 11 Ma [e.g., Rollet et al., 2002]. The external zones still undergo compressive deformation. Figure 14b presents the state of stress and strain after the end of the Ligurian Basin opening. Some orogen-parallel extension could be still active. This upper Miocene -Pliocene stage is characterized by rapid uplift of the External Crystalline massif, thrusting in the Jura and Dignes nappe systems as well as dextral motion all along the belt. Figure 14c presents the orogen-perpendicular extension related to recent paleostress field [Sue and Tricart, 2003; this study] and current strain and stress fields (seismotectonics inversions [Delacou et al., 2004]). The orientation of extensional axes is perpendicular to the belt, whereas compression is limited to a few localities in the external zone. Rotation of the Apulian microplate continue until the present-day [e.g., Anderson and Jackson, 1987; Serpelloni et al., 2005].

5. Conclusions

[48] This work fills a gap on brittle deformation analysis left by previous studies. 66 new paleostress tensors have been calculated using the direct inversion method in the Vanoise/Maurienne area (French Alps), between the Aosta Valley [Champagnac et al., 2004] and the Briançonnais area [Sue and Tricart, 2003]. The observed tectonic regime is largely extensional, with $\frac{1}{4}$ of transcurrent paleostress tensors. The main direction of σ_3 axes, for both transcurrent and extensional paleostress tensors, is N-S oriented, parallel to the Alpine structures. A minor part of σ_3 axes is E-W oriented, perpendicular to the Alpine structures. We also performed a synthesis of brittle deformation analyses for the entire arc of the inner western Alps, based on inversion of fault populations. This synthesis highlights the constant presence of an orogen-parallel direction of extension for the complete internal bend of the western Alps: the σ_3 axes are oriented parallel to the Alpine structures, from N065° in



motion all along the belt and uplift of the external crystalline massifs. Extensional orogen-parallel deformation still occurs in parallel extension, directly related to extrusion toward the Ligurian Basin and the indentation/rotation of the Apulian microplate. The external zones still undergo compression. Data from are from Dewey et al. [1989]; Mancktelow [1992]; Steck [2002], Schwartz [2002], Grosjean et al. [2004], and Tricart et al. [2004b]. (b) Tectonic regime after the end of the Ligurian internal zones, but seems to decrease toward the south. Data from are from Burkhard [1988; Dewey et al. [1989], Mancktelow 2000], Collombet et al. [2002], and Foeken et al. [2003]. (c) Orogen-perpendicular extension related to recent paleostress field Sue and Tricart 2003; this study] and current stress fields from Delacou et al. [2004] inferred from seismotectonic inversions. The orientation of extensional axes is perpendicular to the belt, whereas there is only little compression in the external zone. basin opening, characterized by propagation of the Alpine front toward the NW (Jura) and the SW (Digne nappe), dextral [1992], Seward and Mancktelow [1994], Burkhard and Sommaruga [1998], Bigot-Cormier et al. [2000], Bogdanoff et al. Three snapshots of proposed Alpine history for the western Alps, from the Neogene to present-day. (a) Orogenand Hunziker [1994], Carminati et al. [1998], Cannic et al. [1999], Bistacchi et al. [2000], Collombet et al. [2002], Rollet et al. This fan-shaped extensional axis is also related to the lack of geodetic shortening in the western Alps.

the Simplon and Valais area (Swiss Alps) to N-S in the Vanoise massif, and to NW-SW southward, in the Briançon area. We consider this extension to be related to an extrusion phenomenon toward the south during the Apulian indentation. The opening of the Ligurian Sea during lower to middle Miocene provided a free boundary, which should have promoted this extrusion.

[49] A minor group of σ_3 axes is oriented perpendicularly or obliquely to the Alpine structural trend. This direction of extension becomes more important toward the south, and is prominent in the Briançon area. The origin of this extension seems to be induced by uplift or updoming of External or Internal Crystalline massifs, and/or related to the current postorogenic state of stress [Delacou et al., 2004; Selverstone, 2005; Delacou et al., 2005; Jiménez-Munt et al., 2005].

- [50] Last, but not least, a transcurrent regime predates the extension in the Valais area, and postdates it in the other parts of the belt. The σ_3 axes related to the transcurrent paleostress tensors are consistent with σ_3 axes related to extensional paleostress tensors. Stress axes permutations induced by local or regional perturbations and counterclockwise rotational tectonics of the Apulian Microplate explain transcurrent tectonics in the inner western Alps, which is blended with extensional tectonics in the belt.
- [51] Acknowledgments. This work was supported by the Neuchâtel and Grenoble (UJF) universities and by the Swiss National Science Fund (grant 21-61684.00, 200020-101625/1, and PBNE2-106764). Authors thank the Associate Editor, Giulio Viola, and an anonymous reviewer for their constructive comments. We are grateful to Tehani Pestalozzi for English corrections of the manuscript.

References

- Aillères, L., J. Bertrand, J. Macaudière, and M. Champenois (1995), New structural data from the "Zone Houillere Brianconnaise" (French Alps), neoalpine tectonics and consequences for the interpretation of the Pennine Front., C. R. Acad. Sci., 321, 247–254.
- Albarello, D., E. Mantovani, D. Babbucci, and C. Tamburelli (1995), Africa-Eurasia kinematics: Main constraints and uncertainties, *Tectonophysics*, 243, 25–36.
- Anderson, H., and J. Jackson (1987), Active tectonics in the Adriatic region, Geophys. J. R. Astron. Soc., 91, 937–983
- Angelier, J. (1979), Determination of the mean principal direction of stress for a given fault population, *Tectonophysics*, 56, 17–26.
- Angelier, J. (1990), Inversion of field data in fault tectonics to obtain the regional stress: A new rapid direct inversion method by analytical means, *Geo*phys. J. Int., 103, 363–376.
- Avouac, J. P., and E. B. Burov (1996), Erosion as a driving mechanism of intracontinental mountain growth, J. Geophys. Res., 101, 17,747–17,769.
- Ballèvre, M., Y. Lagabrielle, and O. Merle (1990), Tertiary ductile normal faulting as a consequence of lithospheric stacking in the western Alps, Mem. Soc. Geol. Fr., 156, 27–236.
- Baroux, E., N. Béthoux, and O. Bellier (2001), Analyses of the stress field in southeastern France from earthquake focal mechanisms, *Geophys. J. Int.*, 145, 336–348.
- Béthoux, N., M. Cattaneo, P. Y. Delpech, C. Eva, and J.-P. Réault (1988), Mécanismes au foyer de séismes en mer Ligure et dans le sud des Alpes occidentales: Résultats et interprétation, C. R. Acad. Sci., 307, 71–77.
- Bigot-Cormier, F., G. Poupeau, and M. Sosson (2000), Déudations différentielles du massif Cristallin Externe alpin de l'Argentera (Sud-Est de la France) répérés par thermochronologie traces de fission (apatites, zircons): Differential denudations of the Argentera Alpine external crystalline massif (SE France) revealed by fission track thermochronology (zircons, apatites), C. R. Acad. Sci., 330, 363–370.
- Bistacchi, A., E. Eva, M. Massironi, and S. Solarino (2000), Miocene to Present kinematics of the NW-Alps: Evidences from remote sensing, structural analysis, seismotectonics and thermochronology, J. Geodyn., 30, 205–228.
- Bogdanoff, S., A. Michard, M. Mansour, and G. Poupeau (2000), Apatite fission track analysis in the Argentera massif: Evidence of contrasting denudation rates in the External Crystalline massifs of the western Alps, Terra Nova, 12, 117–125.

- Bott, M. H. (1959), The mechanism of oblique slip faulting, *Geol. Mag.*, *96*, 109-117.
- Brouwer, F. M., D. M. A. van de Zedde, M. J. R. Wortel, and R. L. M. Vissers (2004), Late-orogenic heating during exhumation: Alpine PTt trajectories and thermomechanical models, *Earth Planet. Sci. Lett.*, 220, 185–199.
- Burkhard, M. (1988), L'helvétique de la bordure occidentale du massif de l'Aar (évolution tectonique et métamorphique), Eclogae Geol. Helv., 81, 63– 114.
- Burkhard, M., and A. Sommaruga (1998), Evolution of the western Swiss Molasse basin: Structural relations with the Alps and the Jura belt, in Cenozoic Foreland Basins of Western Europe, edited by A. Mascles et al., Geol. Soc. Spec. Publ., 134, 270–298
- Calais, E., J. M. Nocquet, F. Jouanne, and M. Tardy (2002), Current strain regime in the western Alps from continuous Global Positioning System measurements, 1996–2001, Geology, 30, 651–654.
- Cannic, S., J.-L. Mugnier, and J.-M. Lardeaux (1999), Neogene extension in the western Alps, *Mem. Sci. Geol. Padova*, 51, 33–45.
- Carminati, E., M. J. R. Wortel, P. T. Meijer, and R. Sabadini (1998), The two-stage opening of the western-central Mediterranean basins: A forward modeling test to a new evolutionary model, *Earth Planet. Sci. Lett.*, 160, 667–679.
- Carraro, F., G. Guibaudo, M. Giardino, and A. Perotto (1994), Intense deformazioni in depositi fluvioglacustri olocenici nella media valle d'Aosta, *Atti Tic. Sci. Terra*, 1, 123–136.
- Champagnac, J. D. (2005), Tectonique cassante de l'arc interne des Alpes occidentales; implications geodynamiques, Ph.D. thesis, 222 pp., Neuchâtel and J. Fourier Grenoble 1 Univ., Grenoble, France
- Champagnac, J. D., C. Sue, B. Delacou, and M. Burkhard (2003), Brittle orogen-parallel extension in the internal zones of the Swiss Alps (south Valais), Eclogae Geol. Helv., 96, 325–338.
- Champagnac, J. D., C. Sue, B. Delacou, and M. Burkhard (2004), Brittle deformation in the inner northwestern Alps: From early orogen-parallel extrusion to late orogen-perpendicular collapse, *Terra Nova*, 16, 232–242.
- Collombet, M., J. C. Thomas, A. Chauvin, P. Tricart, J. P. Bouillin, and J. P. Gratier (2002), Counterclockwise rotation of the western Alps since the Oligocene: New insights from paleomagnetic data, *Tectonics*, 21(4), 1032, doi:10.1029/ 2001TC901016.
- Deichmann, N., and L. Rybach (1989), Earthquakes and temperatures in the lower crust below the

- northern Alpine Foreland of Switzerland, in *Properties and Processes of Earth's Lower Crust, Geophys. Monogr. Ser.*, vol. 51, edited by R. F. Mereu, S. Mueller, and D. M. Fountain, pp. 197–213, AGU, Washington, D. C.
- Delacou, B. (2005), Tectonique et gédynamique actuelle de l'arc alpin: Approche sismotectonique et modéisation numéique, Ph.D. thesis, 249 pp, Neuchâtel and Sophia Antipolis Univ., Nice, France.
- Delacou, B., C. Sue, J. D. Champagnac, and M. Burkhard (2004), Present-day geodynamics in the bend of the western and central Alps as constrained by earthquake analysis, *Geophys. J. Int.*, 158, 753–774.
- Delacoi, B., C. Sue, J. D. Champagnac, and M. Burkhard (2005), Origin of the current stress field in the western/central Alps: Role of gravitational reequilibration constrained by numerical modelling, in *Deformation, Rheology and Tec*tonics: From Minerals to the Lithosphere, edited by D. Gapais et al., Geol. Soc. Spec. Publ., 243, 295–310
- DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein (1994), Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions, *Geophys. Res. Lett.*, 21, 2191– 2194.
- Desmons, J., J. Aprahamian, R. Compagnoni, L. Cortesogno, M. Frey, L. Gaggero, G. Dallagiovanna, S. Seno, and L. Radelli (1999), Alpine metamorphism of the western Alps: Middle to high P/T metamorphism., Schweiz. Mineral. Petrogr. Mitt., 79, 89–110.
- Dewey, J. F. (1988), Extensional collapse of orogens, *Tectonics*, 7, 1123–1139.
- Dewey, J. F., M. L. Helman, E. Turco, D. W. H. Hutton, and S. D. Knott (1989), Kinematics of the western Mediterranean., in *Alpine Tectonics*, edited by M. Coward et al., *Geol. Soc. Spec. Publ.*, 45, 265–283.
- Diamond, L. W. (1990), Fluid inclusion evidence for P-V-T-X evolution of hydrothermal solutions in Late-Alpine gold-quartz veins at Brusson, Val d'Ayas, northwest Italian Alps., Am. J. Sci., 290, 912–958.
- England, P., and G. Houseman (1989), Extension during active convergence, with application to the Tibetan Plateau, J. Geophys. Res., 94, 17,561–17,579.
- Escher, A., and C. Beaumont (1997), Formation, burial and exhumation of basement nappes at crustal scale: A geometric model based on the western Swiss-Italian Alps, *J. Struct. Geol.*, 19, 955–974.
- Eva, E., S. Pastore, and N. Deichmann (1998), Evidence for ongoing extensional deformation in the

- western Swiss Alps and thrust-faulting in the southwestern Alpine foreland, *J. Geodyn.*, 26, 27-43.
- Foeken, J. P. T., T. J. Dunai, G. Bertotti, and P. A. M. Andriessen (2003), Late Miocene to present exhumation in the Ligurian Alps (southwest Alps) with evidence for accelerated denudation during the Messinian salinity crisis, Geology, 31, 797–800.
- Frisch, W., I. Dunkl, and J. Kuhlemann (2000), Postcollisional orogen-parallel large-scale extension in the eastern Alps, *Tectonophysics*, 327, 239–265.
- Ganne, J., J.-M. Bertrand, and S. Fudral (2004), Geometry and kinematics of early Alpine nappes in a Brianconnais basement (Ambin massif, western Alps), C. R. Geosci., 336, 1219–1226.
- Grosjean, G., C. Sue, and M. Burkhard (2004), Late Neogene brittle extension in the vicinity of the Simplon fault zone, central Alps, Switzerland, *Eclogae Geol. Helv.*, 97, 33–46.
- Hu, J. C., and J. Angelier (2004), Stress permutations: Three-dimensional distinct element analysis account for a common phenomenon in brittle tectonics, J. Geophys. Res., 109, B09403, doi:10.1029/2003JB002616.
- Jiménez-Munt, I., D. Garcia-Castellanos, A. M. Negredo, and J. P. Platt (2005), Gravitational and tectonic forces controlling postcollisional deformation and the present-day stress field of the Alps: Constraints from numerical modeling, Tectonics, 24, TC5009, doi:10.1029/2004TC001754.
- Kastrup, U., M. L. Zoback, N. Deichmann, K. Evans, and D. Giardini (2004), Stress field variations in the Swiss Alps and the northern Alpine foreland derived from inversion of fault plane solutions, J. Geophys. Res., 109, B09403, doi:10.1029/ 2003JB002616.
- Lemoine, M., et al. (1986), The continental margin of the Mesozoic Tethys in the western Alps, Mar. Pet. Geol., 3, 179–199.
- Le Pichon, X., and N. Chamot-Rooke (1991), Extension of continental crust, in Controversies in Modern Geology: Evolution of Geological Theories in Sedimentology, Earth History and Tectonics, edited by D. W. Müller, J. A. McKenzie, and H. J. Weissert, pp. 313–338, Elsevier, New York.
- Lickorish, W. H., M. Ford, J. Bürgisser, and P. R. Cobbold (2002), Arcuate thrust systems in sandbox experiments: A comparison to the external arcs of the western Alps, Geol. Soc. Am. Bull., 114, 1089– 1107.
- Malusa, M. G., R. Polino, M. Zattin, G. Bigazzi, S. Martin, and F. Piana (2005), Miocene to Present differential exhumation in the western Alps: Insights from fission tracks thermochronology, *Tectonics*, 24, TC3004, doi:10.1029/2004TC001782.
- Mancel, P., and O. Merle (1987), Kinematics of the northern part of the Simplon line (central Alps), *Tectonophysics*, 135, 265–275.
- Mancktelow, N. S. (1992), Neogene lateral extension during convergence in the central Alps: Evidence interrelated faulting and backfolding around the Simplon pass (Switzerland), *Tectonophysics*, 215, 295–317.
- Ménard, G. (1988), Structure et cinéatique d'une chaîne de collision: Les Alpes occidentales et centrales, thèse de Doctorat d'Etat, 278 pp., Univ. Joseph Fourier, Grenoble, France.
- Molnar, P., and H. Lyon-Caen (1988), Some simple physical aspects of the support, structure, and evolution of mountain belts, Geol. Soc. Am. Bull., 218, 179–207.
- Molnar, P., P. England, and J. Martinod (1993), Mantle dynamics, the uplift of the Tibetan Plateau and the Indian monsoon, Rev. Geophys., 31, 123-153.
- Nievergelt, P., M. Liniger, N. Froitzheim, and R. F. Maehlmann (1996), Early to mid Tertiary crustal extension in the central Alps: The Turba mylonite zone (eastern Switzerland), *Tectonics*, 15, 329– 340
- Nocquet, J. M., and E. Calais (2004), Geodetic measurements of crustal deformation in the western

- Mediterranean and Europe, *Pure Appl. Geophys.*, 161, 661–681.
- Oldow, J. S., L. Ferranti, D. S. Lewis, J. K. Campbell, B. D'Argenio, R. Catalano, G. Pappone, L. Carmignani, P. Conti, and C. L. V. Aiken (2002), Active fragmentation of Adria, the north African promontory, central Mediterranean orogen, Geology, 30, 779–782.
- Pavoni, N. (1980), Comparison of focal mechanisms of earthquakes and faulting in the Helvetic zone of the central Valais, Swiss Alps, Eclogae Geol. Helv., 73, 551–558.
- Pfiffner, O. A., S. Ellis, and C. Beaumont (2000), Collision tectonics in the Swiss Alps: Insight from geodynamic modeling, *Tectonics*, 19, 1065–1094.
- Ratschbacher, L., W. Frisch, H.-G. Linzer, and O. Merle (1991), Lateral extrusion in the eastern Alps: 2, Structural analysis, *Tectonics*, 10, 257–271.
- Rey, P., O. Vanderhaeghe, and C. Teyssier (2001), Gravitational collapse of the continental crust: Definition, regimes and modes, *Tectonophysics*, 342, 435–449.
- Robin, P.-Y. F., and E. C. Jowett (1986), Computerized density contouring and statistical evaluation of orientation data using counting circles and continuous weighting functions., *Tectonophysics*, 121, 207–233.
- Rolland, Y., J. M. Lardeaux, S. Guillot, and C. Nicollet (2000), Syn-convergence extension, vertical pinching and contrasted metamorphic units on the western edge of the Gran Paradise massif (French-Italian Alps), Geodyn. Acta, 13, 133–148.
- Rollet, N., J. Deverchere, M. O. Beslier, P. Guennoc, J. P. Rehault, M. Sosson, and C. Truffert (2002), Back are extension, tectonic inheritance, and volcanism in the Ligurian Sea, western Mediterranean, Tectonics, 21(3), 1015, doi:10.1029/2001TC900027.
- Rosenbaum, G., G. S. Lister, and C. Duboz (2002), Reconstruction of the tectonic evolution of the western Mediterranean since the Oligocene, *J. Vir-tual Explor.*, 8, 107–130.
- Schmid, S. M., and E. Kissling (2000), The arc of the western Alps in the light of geophysical data on deep crustal structure, *Tectonics*, 19, 62–85.
- Schwartz, S. (2002), La zone piéontaise des Alpes occidentales: Un paléo-complexe de subduction. Arguments métamorphiques, géochronologiques et structuraux, Ph.D. thesis, 341 pp, Univ. Claude Bernard, Lyons, France.
- Selverstone, J. (2005), Are the Alps collapsing?, *Annu. Rev. Earth Planet. Sci.*, 33, 1–20.
- Selverstone, S. M. (1988), Evidences for east-west crustal extension in the eastern Alps: Implication for the unroofing history of the Tauern window, *Tectonics*, 7, 87–105.
- Serpelloni, E., M. Anzidei, P. Baldi, G. Casual, and A. Galvani (2005), Crustal velocity and strain-rate fields in Italy and surrounding regions: New results from the analysis of permanent and non-permanent GPS networks, Geophys. J. Int., 161, 861–880, doi:1111/j.1365-264X.2005.02618.x.
- Seward, D., and N. S. Mancktelow (1994), Neogene kinematics of the central and western Alps: Evidence from fission-track dating, *Geology*, 22, 803–806.
- Seyferth, M., and A. Henk (2004), Syn-convergent exhumation and lateral extrusion in continental collision zones: Insights from three-dimensional numerical models, *Tectonophysics*, 382, 1–29.
- Smith, W. H. F., and P. Wessel (1990), Gridding with continuous curvature splines in tension, *Geophysics*, 55, 293–305.
- Sperner, B., R. Ott, and L. Ratschbacher (1993), Faultstriae analysis: A turbo Pascal program package for graphical presentation and reduced stress-tensor calculation, Comput. Geosci., 19, 1361–1388.
- Steck, A., and J. Hunziker (1994), The tertiary structure and thermal evolution of the central Alps: Compressional and extensional structures in an orogenic belt, *Tectonophysics*, 238, 229–254.
- Steck, A., J. L. Epard, A. Escher, R. Marchant, and F. Masson (1997), Geological interpretation

- of the seismic profiles through western Switzerland: Rawil (W1), Val d'Annivier (W2), Mattertal (W3), Zmutt-Zermatt-Findelen (W4), and Val de Bagnes (W5), in *Results of NRP 20: Deep Structure of the Swiss Alps*, edited by O. A. Pfiffner et al., Springer, New York.
- Sue, C., and P. Tricart (1999), Late Alpine brittle extension above the Frontal Pennine Thrust near Briancon, western Alps, Eclogae Geol. Helv., 92, 171–181.
- Sue, C., and P. Tricart (2002), Widespread post-nappe normal faulting in the internal western Alps: A new constrain on arc dynamic, J. Geol. Soc. London, 159, 61 – 70.
- Sue, C., and P. Tricart (2003), Neogene to ongoing normal faulting in the inner western Alps: A major evolution of the late alpine tectonics, *Tectonics*, 22(5), 1050, doi:10.1029/2002TC001426.
- Sue, C., F. Thouvenot, J. Frechet, and P. Tricart (1999), Widespread extension in the core of the western Alps revealed by earthquake analysis, J. Geophys. Res., 104, 25,611–25,622.
- Sue, C., J. Martinod, P. Tricart, F. Thouvenot, J. F. Gamond, J. Frechet, D. Marinier, J. P. Glot, and J. R. Grasso (2000), Active deformation in the inner western Alps inferred from comparison between 1972-classical and 1996-GPS geodetic surveys, *Tectonophysics*, 320, 17–29.
- Tricart, P. (1984), From passive margin to continental collision: A tectonic scenario for the western Alps, Am. J. Sci., 284, 97–120.
- Tricart, P., S. Amaudric du Chaffaut, C. Ayoub, M. Ballère, R. Caby, C. Gout, Y. Lagabrielle, D. Leblanc, O. P. P. Le Mer, and P. Saby (2004a), Carte géologique de la France au 1/50000eme, feuille 848 Aiguille-Col Saint Martin, Bur. de Rec. Geol. et Min., Orléans, France.
- France.
 Tricart, P., S. Schwartz, C. Sue, and J.-M. Lardeaux (2004b), Evidence of synextension tilting and doming during final exhumation from analysis of multistage faults (Queyras Schistes lustrés, western Alps), *J. Struct. Geol.*, 26, 1633–1645.
- Vialon, P., P. Rochette, and G. Ménard (1989), Indentation and rotation in the Alpine arc., in Alpine Tectonics, edited by M. Coward et al., Geol. Soc. Spec. Publ., 45, 329–338.
- Villemin, T., and H. Charlesworth (1992), Stress: A program to analyze data from Striated fault. International Union of Geological Science Commission on Tectonics, Shorts Course on Some Applications of IBM-PC Compatible Micro-computer in Structural Geology, Cent. Am. Sch. of Geol., Univ. de Costa Rica, San Jose.
- Wallace, R. E. (1951), Geometry of shearing stress and relation to faulting, *J. Geol.*, *59*, 118–130.
- Wawrzyniec, T. F., J. Selverstone, and G. J. Axen (2001), Style of footwall uplift along the Simplon and Brenner normal fault system, central and eastern Alps, *Tectonics*, 20, 748–770.
- Yamaji, A. (2000), The multiple inverse method: A new technique to separate stresses from heterogeneous fault-slip data, *J. Struct. Geol.*, 22, 441– 452.
- Zwingmann, H., and N. Mancktelow (2004), Timing of Alpine fault gouges, Earth Planet. Sci. Lett., 223, 415–425
- C. Allanic, M. Burkhard, B. Delacou, and C. Sue, Geological Institute, University of Neuchâtel, Rue Argand 11, CP2, CH-2000 Neuchâtel, Switzerland.
- J. D. Champagnac, Department of Geological Sciences/CIRES, Benson Earth Sciences Building, University of Colorado, Boulder, CO 80309, USA. (champagn@colorado.edu)
- P. Tricart, Laboratoire de Géodynamique des Chaînes Alpines (LGCA), Maison des Géosciences, Université de Grenoble, F-38400 St Martin D'Hères, France.