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

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[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  $\sigma_3$  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  $\sigma_3$ . 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

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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  $\sigma_1$  and  $\sigma_3$  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

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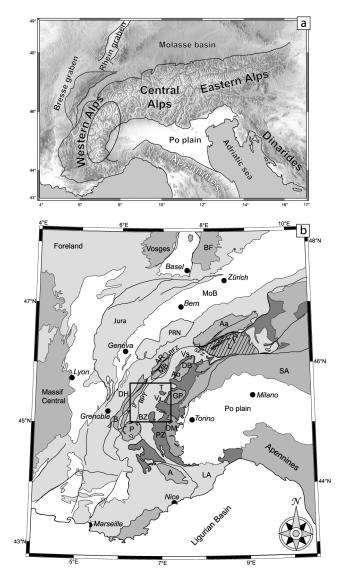


Figure 1. Location of the study area. (a) DEM (GTOPO30 database) of the Alps and surrounding areas. (b) Tectonic sketch map of the western and central Alps. A, Argentera; Aa, Aar; Ao, Aosta Valley; AR, Aiguilles Rouges; B, Belledonne; BPT, Basal Penninic Thrust; BR, Black forest; BZ, Briançonnais zone; 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 ultrahigh-pressure 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  $(\sigma_3)$ 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

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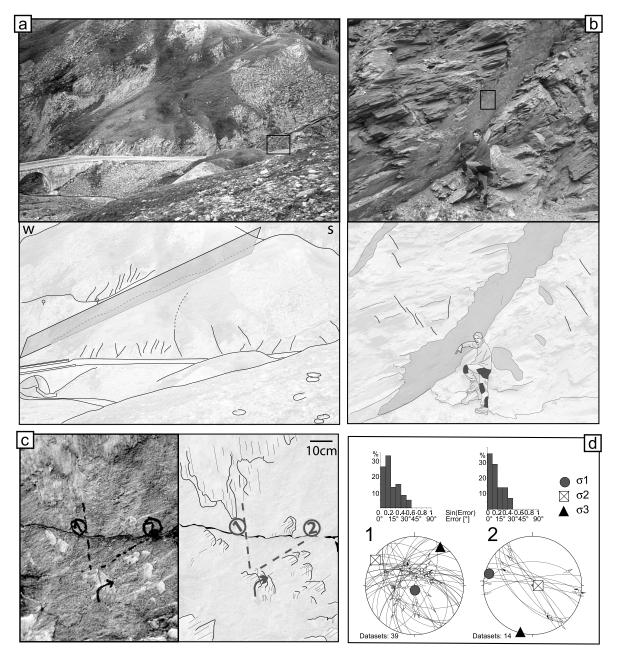


Figure 2. Fault analysis between Maurienne and Tarentaise valleys (site NEIGE N159°/N160°, close to the Iseran pass) with field views and their interpretations. (a) Morphological expression of a large normal fault viewed from the NE. The large west dipping fault is associated with smaller ones, east 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  $\sigma_1$ , square for  $\sigma_2$ , and triangle for  $\sigma_3$ ) 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  $\sigma_3$  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  $(\sigma_1, \sigma_2, \text{ and } \sigma_3, \text{ respectively})$ , the ellipsoid form parameter  $\Phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$  and the average misfit angle  $\alpha$  (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  $\alpha$ , 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  $\sigma_3$  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  $\sigma_3$  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.,  $\sigma_1$  steep,  $\sigma_3$  subhorizontal) and the other 29% (15 out of 66) are transcurrent (i.e.,  $\sigma_2$  steep,  $\sigma_1$  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  $\sigma_1$  axes are steep, with some random scatter around the vertical axis. A minor part of the population of  $\sigma_1$  axes is subhorizontal, and related to transcurrent paleostress tensors; the  $\sigma_2$  orientation is either subhorizontal (extensional stress state) or subvertical (transcurrent stress state), without any main direction. The most frequently observed direction of  $\sigma_3$  axes is N-S to NNE-SSW, with some exceptions in an E-W orientation. All  $\sigma_3$ axes are subhorizontal; this means that we did not calculated any compressional paleostress orientations. The plot of the entire data set of  $\sigma_1$  and  $\sigma_3$  axes on a Schmidt stereonet shows the spatial distribution of the stress axes (Figure 5b). The  $\sigma_1$  axes (small circles) are predominantly in a nearvertical position (except for the transcurrent tensors), in a gently diffuse shape. The  $\sigma_3$  axes (black triangles) are positioned horizontally. The contouring of  $\sigma_3$  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  $021^{\circ}/00^{\circ}$  (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  $10^{\circ}$  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<sup>a</sup>

Name			]	Location			c	<sup>7</sup> 1	C	<sup>5</sup> 2	c	3	Parameters				
Ν	n	Site	Lon	Lat	ρ	τ	γ	az	Dip	az	Dip	az	Dip	Data	$\Phi$	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	4	cargn	7.5589	46.2326	181472	56.13	29.1	285	73	118	17	27	4	18	0.08	6.5	2 2
5 6	5 6	chevre cleus1	7.4318 7.3219	46.0181 46.1148	168956 182626	48.75 49.06	78.2 29.9	214 315	69 69	38 172	21 17	307 79	1 12	11 12	0.2 0.06	5.5 2.9	2
7	7	cleus2	7.3219	46.1094	182020	49.00	18.0	355	53	148	33	247	12	12	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	ergil	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	2	19	98	17	9	0.93	9.8	3
16	16	evole	7.5043	46.1085	172950	52.37	0.6	2	53	131	25	233	25	28	0.26	4.3	1
17	17	findel	7.7856	46.0126	151398	56.30	19.7	179	36	326	49 21	76	17 14	21	0.77	9.7	2 1
18 19	18 19	forcl furi (1)	7.4563 7.7326	46.0302 45.9992	168689 152567	49.54 54.71	30.5 56.3	20 178	64 63	164 26	21	260 291	14	15 21	0.45 0.08	7.7 6.3	1
20	20	furi (2)	7.7326	45.9992	152567	54.71	40.3	5	1	107	83	275	7	9	0.08	5	2
20	20	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	27	moiry (2)	7.5769	46.1122	169823	53.94	45.9	277	3	151	84	8	4	24	0.63	16.5	3
28	28	monv1	7.3596	45.9852	170160	46.53	69.5	48	69	204	19	296	8	13	0.11	6.3	3
29	29	monv2	7.3415	46.005	172711	46.71	17.3	334	13	196	72	64	11	25	0.49	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 59	34	79	243	10	22	0.49	12.5	2
32 33	32 33	randa1 randa2	7.7751 7.7615	46.0878 46.0847	158787 159077	57.76 57.38	77.8 40.4	105 107	59 73	241 287	24 17	340 17	19 0	13 27	0.78 0.13	13.6 7.5	3 1
34	34	rech1 (1)	7.4992	46.2461	185361	55.24	62.8	22	23	326	62	118	14	9	0.13	2	2
35	35	rech1 $(1)$	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	38	roten	7.7674	45.9866	149845	55.22	68.2	258	8	19	75	167	12	12	0.75	5.5	2
39	39	sarray	7.2593	46.0606	181582	46.65	20.3	353	51	148	37	247	12	16	0.87	4.8	1
40	40	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 46	45	stlu2 tdela	7.6029 7.3743	46.2182 46.1571	178222 183602	56.73 50.94	12.3 56.9	151 238	37 61	353 91	51 25	249 354	11 14	15	0.6 0.08	6.3 3.9	2 3
40 47	46 47	thyon	7.3743	46.1787	185505	50.94 51.40	2.4	258	70	142	10	49	14	16 14	0.08	6.3	2
48	48	trift	7.4505	46.0245	154479	55.51	37.5	123	81	288	9	18	2	35	0.33	8.7	1
49	49	turgl	7.7096	46.1496	167301	57.60	27.4	49	89	175	1	265	1	15	0.83	10.4	2
50	50	turtm	7.6913	46.1714	170108	57.65	9.3	22	57	147	21	247	25	27	0.24	7.5	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	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 40	107	13	107	13	16	0.99	2.8	2
60 61	60 61	BUTHIER	7.2713	45.7845 45.7136	160510	39.21	26.2 29.1	273	49 65	111	40 5	13 242	9 24	16 20	0.323	5.1	1
61 62	61 62	CARLO CHAP	7.003 6.7318	45.7136 45.6937	173143 190460	32.86 28.99	29.1 58.0	50 343	65 8	150 249	5 30	242 87	24 59	20 16	0.89 0.36	8.1 10.1	1 2
62 63	62 63	CHAP CHAT1	6.858	45.6937 45.6178	190460	28.99	58.0 40.0	545 183	8 72	249 79	50 5	87 348	59 17	16	0.36	7.8	2 3
64	64	CHAT2	6.8628	45.4148	177384	28.03	1.0	218	61	119	5	27	28	13	0.204	1.8	1
65	65	ECHEV	7.2638	45.8026	162140	39.61	76.4	31	61	205	29	296	28	28	0.518	4	1
	66	FERRE	7.1212	45.911	178314	40.44	19.4	273	28	149	47	21	30	12	0.06	#	3
66																	

Table 1. (continued)

N         Site         Lat         ρ         τ         γ         vz         Dip         uz         Dip         Dip         Dip         Dip		]	Name		]	Location				1	0	52		53	Parameters		neters		
69         69         65B1         7.187         45.8865         17.292         40.82         33.8         101         11         215         64         7         12         10         19         0.577         16.9           71         71         GSB17         7.1512         45.898         172440         34.62         2.15         347         2.5         184         2.4         12.4         9         2.4         0.24         6.1         3.4         6.1         3.4         6.1         3.4         6.1         3.4         6.1         3.4         6.1         3.4         6.2         3.4         6.1         3.4         6.2         3.4         6.1         3.4         6.4         3.4         6.2         3.4         6.1         1.4         0.27         6.4         7.7         7.7         7.7         7.7         7.7         7.7         7.4         7.4         1.4         6.0         1.4         3.2         3.3         1.5         6.1         2.2         1.4         1.4         3.2         2.1         1.1         3.5         7.3         3.2         2.2         1.1         1.1         1.5         1.4         1.4         1.4         1.4         1.4	N	n	Site	Lon	Lat	ρ	τ	γ	az	Dip	az	Dip	az	Dip	Data	$\Phi$	α	Conf	
70         00         CSBE2         7,1896         45,8995         173407         41,22         5.8         313         2.4         159         64         47         10         0.577         16.9           71         TG         GURRAZ         6.903         45,6249         175081         25,15         347         252         359         75         145         12         24.4         9.4         0.23         4         0.23         4         0.23         4         0.23         4         0.23         4         0.23         4         0.23         57         14.4         14         0.11         4         0.07         3.7           77         75         MALAT         7.1134         45.480         172818         3.86.0         2.5         2.1         2.17         15         19         15         0.57         6.2           71         75         MALAT         7.1134         46.1133         19350         4.443         7.5         2.2         2.55         4         10         0.55         6.8         5.6         7.8         1.10         1.1         0.50         1.1         0.016         0.25         1.1         0.03         9.1         10	68	68	FRETE (2)	6.8085	45.5709	179118	25.99	4.0		8		80			8		10.2	3	
71       71       CKBHT       71.512       45.899       172949       39.46       21.5       347       25       108       88       24       92.4       92.4       02.3       61.1         73       73       ISERAN       70.01       45.8117       15752       23.38       58.6       84       84       352       02       02.6       6       44       0.23       9.4       0.23       9.7       7.7       7.7       MALAT       7.113       45.8449       172881       38.60       25.6       2.1       12       12       52       13       19       18       6.1       10.3       7.7       7.7       MART       7.113       45.8449       172841       38.60       25.6       2.1       117       67       8       14       10.057       5.7       7.7       MART       7.111       45.849       172841       38.03       2.2       2.1       119       8.6       5.4       10       10.5       0.5       1.8       10.0       0.5       5.8       8.8       10.0       10.0       0.5       14       10.0       0.7       9.2       12.1       10.0       10.0       10.0       10.0       10.0       10.0       10.0																		3	
P2         P2         CIURRAZ         6.0033         45.6249         175081         28.78         28.75         21         117         67         78         84.74         40.75         23.75         21         117         67         78         84.74         0.75         0.75         0.77         77         MARTI         70.844         46.791         72.71         24.71         24.71         14.81         78.75         33.83         80         MONAL(10         67.000         45.587         77.2471         25.91         11         16         39         32.2         31         11         0.10         73.75         78.88         81.71         13.82         33.83         11         20.81         11         10.77 <t< td=""><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>2</td></t<>																		2	
73       ISERAN       7.021       45.4317       157752       23.38       85.6       84       84       322       0       202       6       14       12         75       75       MALAT       7.1131       45.8400       172861       38.60       25.6       271       32       129       52       13       10       15       0.18       4.7         76       76       MALAT       7.1131       45.8400       172814       38.60       25.0       21       17       67       8       8       14       0.55       6.8       10       0.55       6.8       10       0.65       6.8       10       0.55       6.8       80       MONAL (1)       0.6000       45.5687       172471       26.01       48.1       48       86       15.2       25.2       15       10       0.55       5.5       58.8       17.1       14.8       16.6       29       55.2       11       16.0       0.25       1.8       10.0       0.55       2.5       13       10       0.45       1.8       10.0       0.55       2.5       13       10.0       0.55       2.5       13       10.0       0.55       2.5       1.8       10.0																		2 1	
44         74         LACPLAG         6.845         4.5488         17286         32.0         25.4         319         65         75         MALAT         7.1113         45.8408         172818         38.0         25.6         27.1         21.9         25         21         11.7         67         8         14         0.025         4.3           77         MACTT         7.1113         45.8408         17414         38.29         30.3         275         21         11.7         67         8         8         14         0.025         1.8           77         MACOEUR         7.2449         46.1183         18936         44.8         14         136         73         302         16         33         4         10         0.55         6.8           80         MONAL (1)         6.000         45.567         172471         2.69         1.1         2.1         2.1         2.1         2.1         2.1         2.1         2.1         2.1         2.1         2.1         2.2         2.1         2.2         2.1         3.1         4.0         0.5         4.1           81         81         MORAL         7.231         5.1         1.1         3.2																		1	
75         75         76         MALAT         71.113         45.8409         172.81         38.60         25.6         271         12         12         12         12         13         14         13.82           77         77         MALATZ         7.1113         45.8400         189385         44.48         73.5         322         12         10         18         8         14         0.55         6.8           87         MCNCLU         6.9009         45.5687         172471         26.91         48.1         48         56         6.2         2.55         1.6         0.57         9.2           282         PEPROU         6.818         45.5237         17699         24.9         36.4         14.2         16         9.3         15         18         0.16         10.1         10																		2	
77         77         78         MARTI         7.0814         40018         19389         44.48         73.5         22         23         10         11         0.376         9.7           79         79         MCNAL (1)         6.0009         45.587         172471         26.91         48.1         48         55         16.5         2         25         25         42         40         0.25         1.8           80         MONAL (2)         6.0009         45.587         172471         26.91         48.1         48         85         16.5         2         25         25         25         25         25         25         25         25         25         25         25         25         16         33         4         10         70         33         14         0.033         14         0.039         34         343         34         11         352         11         0.031         17         71         15         17         17         15         13         15         15         13         12         12         12         12         12         12         13         12         13         12         14         16	75	75	MALAT		45.8409	172881	38.60	25.6	271	32	129	52	13	19	15	0.18	4.7	2	
78         NICOEUR         7.2449         64.1183         18.968         64.779         14.8         13.67         73         302         16         33         4         10         0.55         6.8           80         MONAL (1)         6.9009         45.5687         172471         26.91         42.1         119         36         2285         45         29         352         31         6         0.57         9.2           81         81         NIORD         7.0354         455.985         17.309         24.0         28.4         142         76         142         76         24         0.60         0.7         7.8           82         PEIPOU         6.818         45.5253         17.6399         24.59         3.4         162         3.8         17         29         2         0.81         1.3         1.9         0.16         10.1           84         84         RECUL         6.958         45.4669         163.252         1.9         3.5         1.8         2         1.8         4         1.8         1.3         1.6         3.5         2         1.8         1.4         1.4         1.4         1.4         1.4         1.4         1.	76	76	MALAT2	7.1113	45.8408	174114	38.29	30.3	275	21	117	67	8	8	14	0.252	4.3	2	
P9         MONAL (1)         6.9009         45.5687         172471         26.91         48.1         48         85         165         2         25         4         20         0.25         11.8           81         NIORD         7.2035         45.9589         17610         43.08         51.1         261         2         168         59         32         10         10         0.57         9.2           82         82         PILAN         6.9258         45.6244         173.01         20.03         240         284         16         39         55         18         30         14         0.063         9         16         17         197         13         10         0.16         10.1         17         297         13         10         0.16         10.1         18         56         59         22         73         151         16         24.3         10         10.1         10         17																		3	
80         MONAL (2)         6.9009         45.5687         17241         2.911         1.1         3.6         2.98         5.4         2.9         0         1.1         0.539         6.2           81         81         NIGRD         7.0235         45.598         17610         3.0         51.1         24         168         53         53         51         3.0         1.2         2.2         2.0         2.5         1.8           81         84         RECUL         6.958         45.6469         16328         2.401         8.70         171         68         2.44         6         38         12         2.2         0.81         13         19         0.16         10.1           85         85         RTDV         1.486         64.1063         19126         45.89         17.1         18.8         88         2         18.335         10.10         1.3         13.1         14.6         13.1         1.40         0.41         7.73         1.41         4.4         1.40         1.25         7.3         1.41         1.40         1.4         1.40         1.40         1.40         1.40         1.40         1.40         1.40         1.40         1.40																		3	
81         81         NUCRD         7.203         45.9589         17690         43.08         51.1         261         2         168         59         32         11         16         0.57         92         13           82         82         PLAN         6.9258         45.6244         17300         29.03         240         284         16         39         55         183         0.14         0.060         9           85         85         RIDD         7.233         46.1551         191076         48.27         50.3         119         68         2.44         17         0.77         7.8           86         86         SAPIN         7.148         46.1551         191076         48.27         50.3         119         68         2.267         34         16         0.70         7.7           87         SEIGNE         6.8091         45.7281         17819         2.758         54.4         157         11         48         16         0.70         7.1         0.017         7.4           88         88         STEOY (2)         6.9313         45.5787         170819         2.758         45.4         157         11         48																		1 2	
R2         PEIPOU         6.818         45.523         17.699         24.59         36.4         142         76         142         76         142         76         142         76         142         76         142         76         142         76         141         97         13         19         06.6         10.1           84         84         RECUL         6.9618         45.4699         16.328         24.04         87.0         171         69         34.1         19         358         16         15.0         10         358         12         22         0.815         8.8           87         STEOY         0.6313         45.5787         170819         2.758         45.4         157         11         48         61         2.53         1         10         0.53         4         16         0.123         2.20         17         0.33         4.577         170819         2.758         45.4         157         11         48         61         2.35         1         10         0.53         4.17         0.717         7.11         0.727         7.1           90         THULL         6.8919         4.5.727 <th16818< th="">         30</th16818<>																		2	
84         84         RECUL         6.6618         45.4669         16528         24.04         87.0         171         69         31         17         327         13         19         0.61         0.11          85         85         85         85         87         77         222         0.815         8.8           86         86         SAPIN         7.1486         46.103         191226         45.87         17.1         352         73         151         16         23.8         16         0.70         7.1           87         87         STEOY         6.9313         45.5787         170819         27.58         54.4         157         11         48         61         23.5         1         10         0.33         4         171         0.22         22.0         17         70         1.17         71.7																		1	
85         85         RIDD         7.2233         46.151         191076         48.27         50.3         19         68         264         19         24         10         24.2         10         10.7         7.8           87         87         STFOY (1)         6.3013         45.5787         170819         2.78         50.4         10         48         82         32         27         14         10         0.012         4           88         88         STFOY (2)         6.313         45.5787         170819         2.78         50.4         18         71         14         86         12         22         17         14         0.402         7.1           90         90         TIGNES1         6.9194         45.303         18047         13.7         3.67         12         92         12         TIGNES3         6.9424         45.4971         16.641         2.44         15.0         32         73         12.9         2.30         17         13         0.41         7.3         3.00         47         14         4.4         14         0.42         4.5         4.5         4.5         17.1         4.5         4.5         17.1         17 <td>83</td> <td>83</td> <td>PLAN</td> <td>6.9258</td> <td>45.6244</td> <td>173501</td> <td>29.03</td> <td>24.0</td> <td>284</td> <td>16</td> <td>39</td> <td>55</td> <td>185</td> <td>30</td> <td>14</td> <td>0.603</td> <td>9</td> <td>2</td>	83	83	PLAN	6.9258	45.6244	173501	29.03	24.0	284	16	39	55	185	30	14	0.603	9	2	
86         86         SAPIN         7,1486         46,1063         91226         45,80         17.1         352         73         151         16         243         6         15         0.777         78.           87         87         SEIGNE         6.9913         45,5787         170819         27,58         59.4         15         16         82         32         188         267         34         16         0.701         4           90         90         THULL         6.9919         45,7203         180467         31,73         36.7         88         71         265         19         355         1         10         0.53         4           91         91         TIGNES1         6.9199         45,6024         186411         24.84         16.8         57         280         12         188         81         10.8         10.8         10.8         10.812         4.3           94         94         TOULLE         7.182         45.922         17417         12.3         300         47         15         11.4         13         0.41         13.0         36.           95         VALDER4         7.119         45.44         15																		1	
87         SEIGNE         6.8091         45.7528         188335         31.61         23.6         308         48         82         22         188         24         17         0.779         7.1           88         88         STFOY (1)         6.9113         45.5787         170819         27.88         54.4         157         1         48         62         23         27         1         0.053         4           90         90         THORES1         6.919         45.5054         168218         24.07         15.0         32         73         126         25         20         12         188         8         11         0.127         5.1           93         93         116NE32         6.924         45.054         167310         24.84         16.6         57         20         12         188         8         11         0.127         5.1           94         94         TOULIE         7.182         45.548         157102         20.3         30         47         33         33         43         35         56         56         50         71         73         33         43         35         56         21         22.0																		2	
88         88         STFOY (1)         6.913         45.5787         170819         27.58         59.4         91         56         359         2         267         34         16         0.701         4           90         90         THULL         6.8914         45.5787         170819         27.58         45.4         157         128         265         19         355         1         10         0.53         4           91         91         TIGNES1         6.9199         45.5034         168218         24.97         15.0         32         73         129         2         20         13         0.418         7.3           92         92         TIGNES3         6.9444         45.4977         166841         24.497         1.66         51         209         145         40         44         3         24         33         36         65         69         VALDER1         7.182         45.544         157013         21.38         30         41.5         115         112         14         22         0.07         3.6           96         VALDER4 (1)         7.0259         45.672         158809         31.85         50.2         279																		2 2	
98         99         STFOY (2)         6.991         45.787         107819         27.88         45.4         15.7         11         48         61         253         27         14         0.492         7.1           90         90         TIGNES1         6.9194         45.5054         188218         24.97         15.0         32         73         129         2         20         17         17         0.127         5.1           93         TIGNES3         6.9442         45.4977         166841         24.62         86.6         195         25         60         56         295         VALDER         7.188         45.922         17477         41.70         2.3         300         47         145         44         43         2.4         0.67         5.5           50         50         VALDER4         7.119         45.544         157102         29.03         5.0         272         78         115         11         24         5         13         0.33         6.6           79         VALDER4 (1)         7.0259         45.642         158809         31.85         5.6         271         10         33         212         8         10																		1	
90         90         THUL         6.8991         45.7203         180467         31.73         36.7         88         71         265         19         355         1         10         0.53         4           92         TIGNES1         6.9199         45.5044         16818         2.497         166841         2.4.82         86         195         2.5         60         56         2.95         2.1         13         0.418         7.3           93         TIGNES3         6.9442         45.4977         166841         2.4.84         16.8         65         75         2.80         14         44         43         2.4         0.87         4.5           95         VALDER1         7.1822         45.54         156734         2.8.37         81.6         31.6         51         2.09         31         110         36         12         0.07         3.6         0.33         6.6           97         VALDER3         7.1129         45.5461         158009         31.85         5.6.8         247         3         33         2.77         10         17.8         14         12         0.65         1.4.7           100         100         VALDER4(1)<																		2	
P2         92         TIGNES2         6.9242         4.5439         167310         2.462         89.6         195         2.5         60         25         50         25         21         13         0.418         7.3           94         94         TOULLE         7.1882         45.922         174777         41.70         2.3         300         47         145         40         44         13         24         0.87         3.6           95         VALDER1         7.1189         45.54         156734         2.8.7         81.6         316         51         200         13         110         36         12         0.07         3.6           96         VALDER4         7.1119         45.5464         157102         20.3         5.2         79         93         8         21.2         8         10         0.05         1.4.7           99         VALDER4(2)         7.0259         45.6242         158809         31.85         56.8         247         3         33         32         277         6         22         0.74         10.5           101         10         VALGR4         7.0632         45.6246         188.03         33																		3	
93       TIGNES3       6.942       45.4977       16.6841       24.84       16.8       65       75       280       12       188       8       11       0.812       4.3         94       94       TOULLE       7.1855       45.542       15777       41.70       2.3       300       71       145       40       44       13       40       87.6       6.5         95       VALDER2       7.119       45.546       157102       29.03       5.0       272       78       115       11       24       5       13       0.03       6.6         97       97       VALDER4       17.122       45.642       158009       31.85       0.2       79       79       304       7       11       0.92       2.0.74       14.5         100       100       VALDER4       7.152       45.6242       158009       31.85       0.2       87       334       63       327       6       2       0.74       10.5       10.5       10.1       17.16       14.5       16.1       13.6       33       12       0.65       1.4       10.6       18.5       31       18.7       18.6       15.1       10.7       10.5	91	91	TIGNES1	6.9199	45.5054	168218	24.97	15.0	32		129	2	220		17		5.1	1	
94         94         TOULE         7.1852         45.92         7.1777         41.70         2.3         300         47         145         40         44         13         24         0.87         6.5           96         96         VALDER2         7.1119         45.546         157102         29.03         5.0         272         78         115         11         24         5         10         0.35         6.6           97         97         VALDER3         7.122         45.5882         158115         30.31         46.3         83         50         248         39         344         7         11         0.922         6.5           99         VALDER4(2)         7.0259         45.642         158809         31.85         56.8         247         3         33         277         6         22         0.74         10.5           101         101         VALGR4         7.1008         45.697         164637         33.11         55.9         319         204         28         89         38         20         0.95         4.5           104         104         VALP1(1)         7.2974         45.8715         1650025         42.25																		2	
95         VALDER1         7.1055         45.546         156734         28.37         81.6         316         51         209         13         110         36         12         0.07         3.6           97         97         VALDER2         7.112         45.5882         158115         30.31         46.3         83         50         248         39         344         7         11         0.922         6.5           98         98         VALDER4 (1)         7.0259         45.6242         158809         31.85         56.8         271         3         343         61         155         62         12         0.05         14.7           100         100         VALDER4 (2)         7.052         45.626         163870         30.63         5.4         228         87         126         1         36         3         12         0.5         5.1           103         VALGR3         7.0632         45.626         163870         30.63         5.4         228         87         126         1         36         3         12         0.55         5.1           104         VALPIC1         7.2974         45.8715         165025         42.25 <td></td> <td>2</td>																		2	
96       VALDER2       7.1119       45.546       157102       29.03       5.0       272       78       115       112       12       45       51       0.03       6.6         98       98       VALDER4 (1)       7.0259       45.6242       158809       31.85       0.2       79       79       303       8       212       8       10       0.05       14.7         99       94       VALDER4 (2)       7.0259       45.6242       158809       31.85       56.8       247       3       343       63       155       26       12       0.65       2.9         101       101       VALCR25       7.0482       45.6078       16.6107       36.63       54       228       87       126       136       33       12       0.6       12       0.5       51         103       103       VALCR4       7.1008       45.679       164637       33.11       55.9       319       39       204       28       93       82       0.0       55.5       11.0       105       105       105       104       104       VALPR1(1)       7.2974       45.8715       166025       42.25       56.7       117       78																		2 2	
97         VALDER3         7.122         45.582         158115         30.31         46.3         83         50         248         39         344         7         11         0.922         6.5           99         99         VALDER4(1)         7.0259         45.6242         158809         31.85         56.8         247         3         343         63         155         26         12         0.05         1.47           100         100         VALGR4(2)         7.0452         45.6041         16406         29.8         67.1         16         56         183         3277         6         22         0.74         10.5           101         VALGR4         7.1063         45.679         164637         33.11         57.9         19         92         264         28         93         82         0.09.5         45.51           105         VALP1(1)         7.2974         45.8715         165025         42.25         56.7         117         78         9         4         279         11         21         0.62         9.6           106         106         VALP2 (2)         7.4924         45.9007         156241         46.80         3.68																		1	
98         VALDER4 (1)         7.0259         45.6242         158809         31.85         56.8         247         3         303         8         212         8         10         0.05         14.7           99         99         VALDER4 (2)         7.0259         45.6242         158809         31.85         56.8         247         3         343         63         155         26         12         0.65         2.9           101         101         VALGR1         7.152         45.6978         162121         34.54         36.5         73         271         10         178         14         12         0.09         4.1           102         102         VALGR4         7.1084         45.600         163870         30.63         5.4         228         87         126         1         36         31         20         9.5         5.1           103         03         VALCR4         7.1008         45.8715         165025         42.25         56.7         17         78         9         4         279         11         21         0.62         9.6           106         VALP2 (1)         7.4924         45.9007         156241         46.80<																		3	
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	98																	2	
101       VALGR25       7.0482       45.6041       164006       29.88       67.1       16       56       183       33       277       6       22       0.74       10.5       1.1         102       102       VALGR3       7.0632       45.6206       163870       30.63       5.4       228       87       126       1       36       3       12       0.05       5.1         104       104       VALP1 (1)       7.2974       45.8715       165025       42.25       56.7       117       78       9       4       279       11       21       0.62       9.6         105       105       VALP1 (1)       7.2974       45.8715       165025       42.25       56.7       117       78       9       4       279       11       21       0.62       9.6         106       106       VALP2 (2)       7.4924       45.9007       156241       46.80       2.2       161       57       312       30       49       13       12       0.345       1.4         107       VALP2 (2)       7.437       45.8782       157530       45.05       21.0       359       155       13       246       61 <t< td=""><td>99</td><td>99</td><td>VALDER4 (2)</td><td>7.0259</td><td>45.6242</td><td>158809</td><td></td><td>56.8</td><td>247</td><td>3</td><td>343</td><td>63</td><td>155</td><td>26</td><td></td><td></td><td>2.9</td><td>2</td></t<>	99	99	VALDER4 (2)	7.0259	45.6242	158809		56.8	247	3	343	63	155	26			2.9	2	
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$																		2	
103       103       VALGR4       7.1008       45.679       164637       33.11       55.9       319       39       204       28       89       38       20       0.95       4.5         104       104       VALP1 (1)       7.2974       45.8715       165025       42.25       56.7       117       78       9       4       279       11       21       0.62       9.6         106       106       VALP2 (1)       7.4924       45.9007       156241       46.80       3.6.8       98       31       188       59       190       4       11       0.949       5.1         107       VALP3       7.4628       45.8818       156684       45.85       3.6.8       196       85       99       1       9       5       13       0.707       6.1         108       VALP4 (1)       7.437       45.8782       157530       45.05       21.0       359       75       51       13       246       6       17       0.07       8       111       11       VALP4 (2)       7.373       45.8725       149591       29.27       2.3       101       35       22       47       10       0.51       8.6																		2	
104       104       VALPI (1)       7.2974       45.8715       165025       42.25       73.7       26       5       168       84       296       4       17       0.76       8.8         105       105       VALPI (2)       7.2974       45.8715       165025       42.25       56.7       117       78       9       4       296       4       17       0.62       9.6         106       107       VALP2 (2)       7.4924       45.9007       156241       46.80       36.8       98       31       188       59       190       4       11       0.949       5.1         108       108       VALP3       7.4628       45.8881       156668       45.05       41.0       94       4294       86       184       1       14       0.256       6.8         110       VALP4 (2)       7.437       45.8782       157530       45.05       21.0       359       75       155       13       246       6       17       0.07       8       11       11       VALS4       10.0       0.511       8.029       210       27       11       0.13       3       113       111       10.0       15.13       15.3 <td></td> <td>2 2</td>																		2 2	
105       VALP1 (2)       7.2974       45.8715       165025       42.25       56.7       117       78       9       4       279       11       21       0.62       9.6         106       106       VALP2 (1)       7.4924       45.9007       156241       46.80       36.8       98       31       188       59       190       4       11       0.949       5.1         108       108       VALP3       7.4628       45.8881       156868       45.85       36.8       196       85       99       1       9       5       13       0.707       6.1         109       VALP4 (1)       7.437       45.8782       157530       45.05       21.0       359       75       155       13       2.6       6       17       0.07       8         111       110       VALP4 (1)       7.437       45.8782       157530       45.05       21.0       359       75       155       13       0       17       0.548       7         112       VALSA1 (1)       7.2008       45.5295       149591       29.27       2.3       91       36       327       38       208       32       11       0.16       4																		2	
106       VALP2 (1)       7.4924       45.9007       156241       46.80       2.2       161       57       312       30       49       13       12       0.345       11.4         107       VALP2 (2)       7.4924       45.9007       156241       46.80       36.8       98       31       188       59       190       4       11       0.949       5.1         108       108       VALP4 (1)       7.437       45.8782       157530       45.05       21.0       939       75       155       13       246       6       17       0.07       8         110       VALP4 (2)       7.437       45.8782       157530       45.05       21.0       301       38       122       55       31       0       17       0.548       7         112       VALSA1 (2)       7.2008       45.5295       149591       29.27       2.3       101       35       322       47       207       21       10       0.511       8.6         114       VALSA1 (2)       7.2014       45.6725       156315       33.73       15.3       28       79       139       4       229       11       10       0.16       4.2																		3	
108       VALP3       7.4628       45.8881       156868       45.85       36.8       196       85       99       1       9       5       13       0.707       6.1         109       VALP4 (1)       7.437       45.8782       157530       45.05       41.0       94       4       294       86       184       1       14       0.256       6.8         110       VALP4 (1)       7.437       45.8782       157530       45.05       21.0       359       75       155       13       246       6       17       0.07       8         111       VALSA1 (1)       7.2008       45.5295       149591       29.27       0.7       88       45       319       32       210       27       11       0.13       3         113       VALSA1 (2)       7.2018       45.5295       156315       33.73       15.3       28       79       139       4       229       11       0       0.6       17       0.16       4.2         114       VALSA3       7.2051       45.672       157494       34.50       3.5       93       70       304       17       211       0       0.6       0.498       8	106	106			45.9007	156241			161		312	30	49	13	12	0.345	11.4	2	
109       VALP4 (1)       7.437       45.8782       157530       45.05       41.0       94       4       294       86       184       1       14       0.256       6.8         110       110       VALP4 (2)       7.437       45.8782       157530       45.05       21.0       359       75       155       13       246       6       17       0.07       8         111       111       VALP4 (2)       7.437       45.8782       157530       45.05       21.0       301       38       122       55       31       0       17       0.548       7         112       112       VALSA1 (1)       7.2008       45.5295       149591       29.27       0.7       88       45       319       32       210       27       11       0.13       3         113       113       VALSA1 (2)       7.2008       45.525       166315       33.73       15.3       28       79       139       4       229       11       10       0.16       4.2         116       116       VALSA4       7.2051       45.6742       157494       34.50       3.5       93       70       304       17       211       1																		3	
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$																		2	
111       111       VALP5       7.3534       45.8323       161924       41.17       10.2       301       38       122       55       31       0       17       0.548       7         112       112       VALSA1 (1)       7.2008       45.5295       149591       29.27       0.7       88       45       319       32       210       27       11       0.13       3         113       113       VALSA1 (2)       7.2008       45.5295       149591       29.27       2.3       101       35       322       47       207       21       10       0.511       8.6         114       114       VALSA2       7.2115       45.5228       156315       33.73       15.3       28       79       139       4       229       11       10       0.16       4.2         116       116       VALSA4       7.2051       45.6742       157494       34.50       3.5       93       70       304       17       211       10       16       0.4773       14.4         117       VELAN       7.2591       45.9267       171307       43.15       13.1       300       1       201       85       16       14																		3 1	
112       112       VALSA1 (1)       7.2008       45.5295       149591       29.27       0.7       88       45       319       32       210       27       11       0.13       3         113       113       VALSA1 (2)       7.2008       45.5295       149591       29.27       2.3       101       35       322       47       207       21       10       0.511       8.6         114       114       VALSA1 (2)       7.2015       45.5295       156315       33.73       15.3       28       79       139       4       229       11       0.16       4.2         116       116       VALSA3       7.2021       45.6722       157494       34.50       3.5       93       70       304       17       211       10       16       0.473       14.4         117       117       VELAN       7.2591       45.9267       171307       43.15       13.1       300       1       201       85       30       5       16       0.499       8         118       118       VENS       7.1241       46.0865       191048       45.03       20.7       73       18       16       110       6       1																		3	
113       113       VALSA1 (2)       7.2008       45.5295       149591       29.27       2.3       101       35       322       47       207       21       10       0.511       8.6         114       114       VALSA2       7.2115       45.5228       150088       30.29       2.3       91       36       327       38       208       32       11       0.48       4.1         115       VALSA3       7.2032       45.6525       156315       33.73       15.3       28       79       139       4       229       11       10       0.16       4.2         116       116       VALSA4       7.2051       45.6742       157494       34.50       3.5       93       70       304       17       211       10       0.6       0.73       14.4         117       IT       VELAN       7.2541       45.0855       191048       45.03       34.0       278       8       165       70       11       19       26       0.635       19.9       119         118       118       VENS       7.1241       46.0865       191048       45.03       34.0       278       8       165       70       11<																		2	
114       114       VALSA2       7.2115       45.5228       150088       30.29       2.3       91       36       327       38       208       32       11       0.48       4.1         115       115       VALSA3       7.2032       45.6525       156315       33.73       15.3       28       79       139       4       229       11       10       0.16       4.2         116       116       VALSA4       7.2051       45.6742       157494       34.50       3.5       93       70       304       17       211       10       0.16       0.773       14.4         117       IT       VELAN       7.2591       45.9267       171307       43.15       13.1       300       1       201       85       30       5       16       0.499       8         118       118       VENS       7.1241       46.0865       191048       45.03       34.0       278       8       165       70       11       19       26       0.635       19.9         119       119       AMBIN       6.8738       45.1858       161203       12.79       16.8       67       70       269       19       176																		3	
116       116       VALSA4       7.2051       45.6742       157494       34.50       3.5       93       70       304       17       211       10       16       0.773       14.4         117       117       VELAN       7.2591       45.9267       171307       43.15       13.1       300       1       201       85       30       5       16       0.499       8         118       118       VENS       7.1241       46.0865       191048       45.03       34.0       278       8       165       70       11       19       26       0.635       19.9         119       119       AMBIN       6.8738       45.1858       161203       12.79       16.8       67       70       269       19       176       7       75       0.12       10.5         120       120       ARPON1       6.6961       45.3295       178459       16.96       87.0       220       73       18       16       110       6       14       0.21       7.2         121       121       ARPON2       6.7123       45.3169       176865       16.63       20.4       131       59       306       31       37	114	114		7.2115	45.5228		30.29	2.3	91	36	327	38	208		11	0.48	4.1	3	
117       117       VELAN       7.2591       45.9267       171307       43.15       13.1       300       1       201       85       30       5       16       0.499       8         118       118       VENS       7.1241       46.0865       191048       45.03       34.0       278       8       165       70       11       19       26       0.635       19.9         119       119       AMBIN       6.8738       45.1858       161203       12.79       16.8       67       70       269       19       176       7       75       0.12       10.5         120       120       ARPON1       6.6961       45.3295       178459       16.96       87.0       220       73       18       16       110       6       14       0.21       7.2         121       121       ARPON2       6.7123       45.3169       176865       16.63       20.4       131       59       306       31       37       2       38       0.55       9.3         122       122       AVERO2       7.0306       45.3236       153136       19.33       69.7       29       85       179       4       269																		2	
118       118       VENS       7.1241       46.0865       191048       45.03       34.0       278       8       165       70       11       19       26       0.635       19.9         119       119       AMBIN       6.8738       45.1858       161203       12.79       16.8       67       70       269       19       176       7       75       0.12       10.5         120       120       ARPON1       6.6961       45.3295       178459       16.96       87.0       220       73       18       16       110       6       14       0.21       7.2         121       121       ARPON2       6.7123       45.3169       176865       16.63       20.4       131       59       306       31       37       2       38       0.55       9.3         122       122       AVERO1       7.0884       45.2918       147746       18.57       64.4       335       75       174       4       83       5       20       0.49       9.3         123       124       BARDO       6.7172       45.0895       171680       8.49       2.5       237       75       103       10       11																		2	
119       119       AMBIN       6.8738       45.1858       161203       12.79       16.8       67       70       269       19       176       7       75       0.12       10.5         120       120       ARPON1       6.6961       45.3295       178459       16.96       87.0       220       73       18       16       110       6       14       0.21       7.2         121       121       ARPON2       6.7123       45.3169       176665       16.63       20.4       131       59       306       31       37       2       38       0.55       9.3         122       122       AVERO1       7.0884       45.2918       147746       18.57       64.4       335       75       174       14       83       5       20       0.49       9.3         123       123       AVERO2       7.0306       45.3236       153136       19.33       69.7       29       85       179       4       269       2       45       0.49       1.4         124       124       BARDO       6.7172       45.0895       171680       8.49       2.5       237       75       103       10       11																		2 3	
120       120       ARPON1       6.6961       45.3295       178459       16.96       87.0       220       73       18       16       110       6       14       0.21       7.2         121       121       ARPON2       6.7123       45.3169       176865       16.63       20.4       131       59       306       31       37       2       38       0.55       9.3         122       122       AVERO1       7.0884       45.2918       147746       18.57       64.4       335       75       174       14       83       5       20       0.49       9.3         123       123       AVERO2       7.0306       45.3236       153136       19.33       69.7       29       85       179       4       269       2       45       0.49       12.4         124       BARDO       6.7172       45.0895       171680       8.49       2.5       237       75       103       10       11       10       31       0.06       13.5         125       BOZEL       6.6236       45.4446       187619       20.27       25.7       135       53       317       37       26       1       31																		1	
121       121       ARPON2       6.7123       45.3169       176865       16.63       20.4       131       59       306       31       37       2       38       0.55       9.3         122       122       AVERO1       7.0884       45.2918       147746       18.57       64.4       335       75       174       14       83       5       20       0.49       9.3         123       123       AVERO2       7.0306       45.3236       153136       19.33       69.7       29       85       179       4       269       2       45       0.49       12.4         124       BARDO       6.7172       45.0895       171680       8.49       2.5       237       75       103       10       11       10       31       0.06       13.5         125       BOZEL       6.6236       45.4446       187619       20.27       25.7       135       53       317       37       226       1       31       0.55       14.9         126       CELS       6.9431       45.1048       154282       9.91       3.1       302       33       72       45       193       27       14       0.51																		2	
123       123       AVERO2       7.0306       45.3236       153136       19.33       69.7       29       85       179       4       269       2       45       0.49       12.4         124       124       BARDO       6.7172       45.0895       171680       8.49       2.5       237       75       103       10       11       10       31       0.06       13.5         125       BOZEL       6.6236       45.4446       187619       20.27       25.7       135       53       317       37       226       1       31       0.55       14.9         126       126       CELS       6.9431       45.1048       154282       9.91       3.1       302       33       72       45       193       27       14       0.51       10.9         127       127       CENIS2(1)       6.9271       45.2269       158077       14.72       24.3       325       79       129       10       219       3       31       0.21       10.9         128       CENIS2(1)       6.9614       45.2292       155519       15.03       18.0       264       68       87       22       357       1       17 <td></td> <td>2</td>																		2	
124       124       BARDO       6.7172       45.0895       171680       8.49       2.5       237       75       103       10       11       10       31       0.06       13.5         125       125       BOZEL       6.6236       45.4446       187619       20.27       25.7       135       53       317       37       226       1       31       0.55       14.9         126       126       CELS       6.9431       45.1048       154282       9.91       3.1       302       33       72       45       193       27       14       0.51       10.9         127       127       CENIS1       6.9271       45.2269       158077       14.72       24.3       325       79       129       10       219       3       31       0.21       10.9         128       CENIS2(1)       6.9614       45.2292       155519       15.03       18.0       264       68       87       22       357       1       17       0.23       11.2         129       129       CENIS2(2)       6.9614       45.2292       155519       15.03       18.0       264       68       87       22       357       1<	122	122	AVERO1	7.0884	45.2918	147746	18.57	64.4	335	75	174	14	83		20	0.49	9.3	1	
125       125       BOZEL       6.6236       45.4446       187619       20.27       25.7       135       53       317       37       226       1       31       0.55       14.9         126       126       CELS       6.9431       45.1048       154282       9.91       3.1       302       33       72       45       193       27       14       0.51       10.9         127       127       CENIS1       6.9271       45.2269       158077       14.72       24.3       325       79       129       10       219       3       31       0.21       10.9         128       CENIS2(1)       6.9614       45.2292       155519       15.03       18.0       264       68       87       22       357       1       17       0.23       11.2         129       129       CENIS2(2)       6.9614       45.2292       155519       15.03       18.0       264       68       87       22       357       1       17       0.23       11.2         129       129       CENIS2(2)       6.9614       45.2929       155519       15.03       16.0       107       6       46       6       199 <td< td=""><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>1</td></td<>																		1	
126       126       CELS       6.9431       45.1048       154282       9.91       3.1       302       33       72       45       193       27       14       0.51       10.9         127       127       CENIS1       6.9271       45.2269       158077       14.72       24.3       325       79       129       10       219       3       31       0.21       10.9         128       128       CENIS2(1)       6.9614       45.2292       155519       15.03       18.0       264       68       87       22       357       1       17       0.23       11.2         129       129       CENIS2(2)       6.9614       45.2292       155519       15.03       18.0       264       68       87       22       357       1       17       0.23       11.2         129       129       CENIS2(2)       6.9614       45.2292       155519       15.03       4.0       107       6       4       66       199       23       18       0.63       7.4         130       130       CENIS3       6.9243       45.2831       159833       16.88       13.1       314       65       107       22 <td< td=""><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>1</td></td<>																		1	
127       127       CENIS1       6.9271       45.2269       158077       14.72       24.3       325       79       129       10       219       3       31       0.21       10.9         128       128       CENIS2(1)       6.9614       45.2292       155519       15.03       18.0       264       68       87       22       357       1       17       0.23       11.2         129       129       CENIS2(2)       6.9614       45.2292       155519       15.03       4.0       107       6       4       66       199       23       18       0.63       7.4         130       CENIS3       6.9243       45.2831       159833       16.88       13.1       314       65       107       22       210       10       16       0.67       8.8         131       131       CENIS4       6.9822       45.1886       152919       13.53       73.5       346       83       178       6       87       1       19       0.52       10.3         132       132       CENIS5       6.8634       45.2473       163465       15.09       55.9       333       76       161       14       71																		2	
128       128       CENIS2(1)       6.9614       45.2292       155519       15.03       18.0       264       68       87       22       357       1       17       0.23       11.2         129       129       CENIS2(2)       6.9614       45.2292       155519       15.03       4.0       107       6       4       66       199       23       18       0.63       7.4         130       130       CENIS3       6.9243       45.2831       159833       16.88       13.1       314       65       107       22       210       10       16       0.67       8.8         131       131       CENIS4       6.9822       45.1886       152919       13.53       73.5       346       83       178       6       87       1       19       0.52       10.3         132       132       CENIS5       6.8634       45.2473       163465       15.09       55.9       333       76       161       14       71       2       17       0.37       8.2         133       133       CENIS6(1)       6.9695       45.2137       154500       14.47       8.5       1       74       111       6       20																		3 2	
129129CENIS2(2)6.961445.229215551915.034.0107646619923180.637.4130130CENIS36.924345.283115983316.8813.1314651072221010160.678.8131131CENIS46.982245.188615291913.5373.5346831786871190.5210.3132132CENIS56.863445.247316346515.0955.93337616114712170.378.2133133CENIS6(1)6.969545.213715450014.478.5174111620315320.198.3																		1	
130       130       CENIS3       6.9243       45.2831       159833       16.88       13.1       314       65       107       22       210       10       16       0.67       8.8         131       131       CENIS4       6.9822       45.1886       152919       13.53       73.5       346       83       178       6       87       1       19       0.52       10.3         132       132       CENIS5       6.8634       45.2473       163465       15.09       55.9       333       76       161       14       71       2       17       0.37       8.2         133       133       CENIS6(1)       6.9695       45.2137       154500       14.47       8.5       1       74       111       6       203       15       32       0.19       8.3																		2	
132         132         CENIS5         6.8634         45.2473         163465         15.09         55.9         333         76         161         14         71         2         17         0.37         8.2           133         133         CENIS6(1)         6.9695         45.2137         154500         14.47         8.5         1         74         111         6         203         15         32         0.19         8.3			CENIS3	6.9243		159833				65			210	10		0.67		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			CENIS4															2	
																		2	
137 $137$ $CERTSU(2)$ $0.7073$ $43.2137$ $134300$ $14.47$ $(0.3 - 161 - 11 - 357)$ $(6 - 31 - 5)$ $29$ $0.92 - 0.0$																		1 2	
	134	134	CEN130(2)	0.9093	43.213/	154500	14.4/	/0.3	101	11	331	/0	91	3	29	0.92	0.0	2	

Table 1. (continued)

Name		Name		]	Location			σ	1	0	2		<sup>5</sup> 3	Parameters			
N	n	Site	Lon	Lat	ρ	τ	γ	az	Dip	az	Dip	az	Dip	Data	$\Phi$	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
138 139	138 139	ECOT ETACHE	7.0927	45.3807	150651	22.20	66.8	340 9	66 72	183 104	22	89 194	8	23 35	0.16	4.2 4.7	2 2
139	139	EXTRA	6.8136 6.7986	45.1613 45.2186	165347 167718	11.55 13.62	2.5 19.4	9 145	73 66	299	1 22	33	16 10	35 10	0.05 0.26	4.7 3.5	23
141	141	FONDS	6.6524	45.3089	181183	15.97	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
146 147	146 147	GIAGLI GENEP	7.0171 6.9191	45.143 45.4192	149237 164884	11.86 21.91	10.9 64.1	7 225	79 81	271 355	1 6	181 86	10 7	17 24	0.56 0.47	15.5 9.1	3 1
148	148	LANSLEV	6.9287	45.2998	160007	17.55	8.6	155	82	278	4	9	7	19	0.47	11	3
149	1.10	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
153 154	152 153	MASSE	6.6984 6.6974	45.2596 45.2598	176388 176472	14.54 14.54	67.5 5.5	342 127	38 75	187 277	49 13	82 9	12 7	20 19	# 0.56	# 7.9	3
154	155	MASSE2 MENU	6.5822	45.3168	186741	14.34	22.8	290	73 82	83	13 7	9 173	4	19	0.36	7.9 5.4	2 2
156	155	MICHE	6.4865	45.2184	191768	12.10	17.1	278	29	54	52	175	22	27	0.57	17.8	3
157	156	MODAN2	6.6658	45.198	182780	12.28	21.7	36	58	170	23	269	21	17	0.98	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 45.2223	186443	12.53	32.5 57.5	102	78 9	316 273	10	225 70	6 25	12 9	0.15 0.06	8.8 5.9	3
162 163	161 162	OREL(2) OREL(3)	6.5565 6.5565	45.2223	186443 186443	12.53 12.53	2.5	165 105	5	275	63 85	195	23 1	12	0.00	5.9 18.9	3 3
164	163	ORGIE	6.65	45.2135	179048	12.67	0.7	305	72	100	17	192	7	10	0.36	7.9	3
165	164	OULX	6.8577	45.0425	162728	7.02	22.0	43	76	300	3	209	14	17	0.67	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
169 170	168 169	PUIT RIBON(2)	6.5093 6.9941	45.4674 45.3104	196908 155426	20.14 18.49	12.1 25.5	283 56	68 70	97 182	22 12	188 275	2 16	34 31	# 0.64	# 8.9	3 1
171	170	RIBON(1)	6.9941	45.3104	155426	18.49	76.5	256	87	102	3	15	2	21	0.49	11	2
172	171	RIBON(3)	6.9941	45.3104	155426	18.49	3.5	104	1	12	77	195	13	20	0.16	7.2	2
173	172	ROCHEU	6.9818	45.3804	158791	21.08	78.1	79	73	211	12	303	12	15	0.48	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
176 177	175 176	SARRA TELEG	6.6038 6.4442	45.158 45.1977	181559 194645	10.54 11.26	22.5 49.7	131 168	80 72	303 329	9 18	33 61	1 6	28 14	0.26 0.57	21.6 10.2	2 2
178	177	TERMI	6.8373	45.2859	166502	16.36	33.6	300	67	143	21	50	8	20	0.01	9.1	2
179	178	TERMI2	6.8407	45.3164	167144	17.50	43.5	21	70	247	14	154	14	24	0.02	4.8	2
180	179	VALLO	6.4273	45.1594	195311	9.96	83.0	298	86	197	1	107	4	25	0.14	11.6	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
183 184	182 183	VALTHO2 VILLARO	6.5669 7.0023	45.308 45.3313	187669 155510	15.44 19.38	81.6 49.6	52 146	82 87	187 339	6 3	277 249	6 1	20 21	# 0.05	# 6.9	3 3
185	S1	Innri Alpa	8.107	46.2143	159306	68.31	32.3	312	69	125	21	249	2	13	0.03	5.8	2
186	S2	Schwarzi Balma	8.1074	46.2174	159619	68.37	9.6	124	72	351	12	258	13	13	0.296	10.3	2
187	S3	Innri Biela	8.1041	46.2105	159003	68.17	30.2	300	80	129	10	38	2	10	0.591	6.9	3
188	S4	Sirwoltensee	7.9962	46.2151	162835	65.54	63.5	348	74	222	10	129	13	9	0.159	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 87	Alte Kaserne	8.0967	46.1894	157060	67.66 66.85	11.7	149	82 81	326	8	56 232	1	17	0.401	5.8 6.4	2
191 192	S7 S8	Hopschusee Hopschusee	8.0242 8.0222	46.2543 46.2546	165906 165990	66.85 66.81	14.9 3.8	110 128	81 70	322 336	7 17	232 243	5 9	10 13	0.629 0.9	6.4 6.2	3 2
192	S9	Staldhorn	8.0222	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	8.0203	46.2256	163110	66.30	8.3	90	80	329	5	238	9	46	0.508	11.5	1
196	S12	Rossbodestafel	8.0249	46.1956	159939	65.93	21.9	10	80	134	6	224	8	21	0.439	11.8	1
197	S13	Gali Egga	8.0112	46.1919	160006	65.52	22.5	240	85	133	1	43	4	18	0.29	18.2	2
198	S14	Egga	8.0366	46.2034	160352	66.35	74.7	303	73 75	50 225	5	141 56	17	29 21	0.404	9.7	1
199 200	S15 S16	Glatthorn Bodme	8.0714 8.052	46.212 46.1923	160142 158738	67.36 66.56	11.4 27.6	174 219	75 83	325 309	13 0	30 39	7 7	16	0.625 0.346	8.5 6.0	2 2
	010	Dounte	0.054	10.1/45	120/20	00.00	<i>2</i> 7.0		05	507	0	246	3	10	0.0-10	0.0	2

#### Table 1. (continued)

N 202 203 204 205 207 208 209 210 211 212 213 214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 2230 221 229 2230 221 229 2230 221 229 220 221 229 220 221 220 220 220 220 220 220 220 220	n S18 S19 S20 S21 S22 S23 S24 S25 S26 S27 S28 S29 S30	Site Homatta Hübschhorn W Biel Furggu Guggilihorn Bodmerhorn Ochseläger Lawigrabe Bodmerhorn	Lon 8.0526 8.0374 8.0703 8.0904 8.0871 8.0413 7.0522	Lat 46.2171 46.2437 46.1724 46.1766	ρ 161232 164414 156146	т 66.97 67.01	γ 10.0	az 128	Dip	az	Dip	az	Dip	Data	Φ 0.102	α	Conf
203 204 205 206 207 208 209 210 211 212 213 214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 2230 231 232	<ul> <li>S19</li> <li>S20</li> <li>S21</li> <li>S22</li> <li>S23</li> <li>S24</li> <li>S25</li> <li>S26</li> <li>S27</li> <li>S28</li> <li>S29</li> </ul>	Hübschhorn W Biel Furggu Guggilihorn Bodmerhorn Ochseläger Lawigrabe	8.0374 8.0703 8.0904 8.0871 8.0413	46.2437 46.1724 46.1766	164414		10.0	129	(7	252	17	0.57	1.5	12	0.102		
204 205 206 207 208 209 210 211 212 213 214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 220 221 222 223 224 225 226 227 228 229 221 222 223 223 223 223 223 223 223 223	S20 S21 S22 S23 S24 S25 S26 S27 S28 S29	Biel Furggu Guggilihorn Bodmerhorn Ochseläger Lawigrabe	8.0703 8.0904 8.0871 8.0413	46.1724 46.1766		67.01		120	67	352	17	257	15	13	0.192	5.7	2
205 206 207 208 209 210 211 212 213 214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 220 221 222 223 224 225 226 227 228 229 230 231 232	S21 S22 S23 S24 S25 S26 S27 S28 S29	Furggu Guggilihorn Bodmerhorn Ochseläger Lawigrabe	8.0904 8.0871 8.0413	46.1766	156146		15.0	101	74	325	12	232	11	17	0.686	9.7	2
206 207 208 209 210 211 212 213 214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 220 221 222 223 224 225 226 227 228 229 230 231 232	<ul> <li>S22</li> <li>S23</li> <li>S24</li> <li>S25</li> <li>S26</li> <li>S27</li> <li>S28</li> <li>S29</li> </ul>	Guggilihorn Bodmerhorn Ochseläger Lawigrabe	8.0871 8.0413			66.70	35.7	0	69	117	10	211	18	42	0.16	10.8	1
207 208 209 210 211 212 213 214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 2230 231 232	<ul> <li>S23</li> <li>S24</li> <li>S25</li> <li>S26</li> <li>S27</li> <li>S28</li> <li>S29</li> </ul>	Bodmerhorn Ochseläger Lawigrabe	8.0413	16 1606	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
208 209 210 211 212 213 214 215 216 217 218 219 220 221 222 222 222 222 222 222 222 222	S24 S25 S26 S27 S28 S29	Ochseläger Lawigrabe		46.1696 46.1908	155559	66.26	37.3	550 70	30 72	302	18	209	17	14	0.048	o.o 6.9	2
209 210 211 212 213 214 215 216 217 218 219 220 221 222 222 222 222 222 222 222 222	S25 S26 S27 S28 S29	Lawigrabe	7.9523	46.2302	165808	64.73	50.7	66	77	285	10	194	8	31	0.244	10.0	1
211 212 213 214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 230 231 232	S27 S28 S29	Bodmerhorn	8.0485	46.1951	159125	66.51	32.5	54	73	186	12	279	14	43	0.113	10.3	1
212 213 214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 230 231 232	S28 S29		8.0397	46.1881	158705	66.17	9.2	103	73	329	12	237	14	31	0.218	9.0	1
213 214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 230 231 232	S29	Bodmer	8.0312	46.1839	158551	65.89	17.9	85	75	320	9	228	14	27	0.283	9.4	1
214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 230 231 232		Blauseewji	8.0445	46.1847	158208	66.24	15.8	16	81	171	8	262	4	12	0.187	14.5	2
215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 230 231 232	330	Alte Kaserne	8.0902	46.1872	157031	67.45	22.5	151	83	315	7 5	45	2	26	0.513	9.8	1
216 217 218 219 220 221 222 223 224 225 226 227 228 229 230 231 232	S31	Chaltwasser Simplon - Kulm	8.0559 8.0345	46.249 46.252	164387 165350	67.55 67.07	5.5 13.1	81 106	76 77	333 325	5 10	242 234	14 8	47 12	0.343 0.519	9.4 6.2	1 3
217 218 219 220 221 222 223 224 225 226 227 228 229 230 231 232	S31	Stockji	7.9694	46.2528	167506	65.51	47.5	66	86	288	3	198	3	12	0.365	5.1	2
218 219 220 221 222 223 224 225 226 227 228 229 230 231 232	S33	Antonius	8.062	46.1824	157416	66.65	10.4	93	77	348	4	257	12	30	0.337	14.0	1
<ul> <li>220</li> <li>221</li> <li>222</li> <li>223</li> <li>224</li> <li>225</li> <li>226</li> <li>227</li> <li>228</li> <li>229</li> <li>230</li> <li>231</li> <li>232</li> </ul>	S34	Färicha	8.0515	46.1721	156707	66.21	31.2	308	79	125	11	215	1	27	0.437	7.9	2
221 222 223 224 225 226 227 228 229 230 231 232	S35	Laggin Biwak	8.0452	46.1654	156228	65.93	46.1	72	74	200	10	292	12	21	0.136	9.9	2
<ul> <li>222</li> <li>223</li> <li>224</li> <li>225</li> <li>226</li> <li>227</li> <li>228</li> <li>229</li> <li>230</li> <li>231</li> <li>232</li> </ul>	S36	Hübschhorn S	8.0547	46.2256	162039	67.16	5.2	67	73	332	2	242	17	34	0.192	8.6	1
<ul> <li>223</li> <li>224</li> <li>225</li> <li>226</li> <li>227</li> <li>228</li> <li>229</li> <li>230</li> <li>231</li> <li>232</li> </ul>	S37	Breithorn	8.0781	46.2345	162233	67.88	4.9	83	73	335	5	243	16	27	0.325	5.7	1
224 225 226 227 228 229 230 231 232	S38	Chesselhorn	8.0818	46.221	160737	67.77	22.2	150	64	6	21	270	14	15	0.388	8.9	2
225 226 227 228 229 230 231 232	S39 S40	Casermetta Waira	8.1149 8.1328	46.1962 46.153	157221	68.24 68.03	21.2	12 257	87	137 350	2 1	227 81	3 19	17 34	0.482	7.2 12.7	2 2
226 227 228 229 230 231 232	S40 S41	Stalden	8.1328 7.8937	46.133	152248 172630	64.16	13.0 9.2	237 56	71 76	325	1	235	19	54 15	0.266 0.24	12.7	2
227 228 229 230 231 232	S42	Furgghalte	8.0214	46.2055	161052	66.00	19.0	166	76	316	12	47	7	24	0.501	9.9	1
229 230 231 232	S43	Schilthorn	8.0127	46.2105	161836	65.87	0.9	242	73	334	1	65	17	15	0.138	6.8	2
230 231 232	S44	Wyssbode	8.0179	46.2121	161824	66.02	50.0	284	70	24	4	116	20	12	0.361	9.5	3
231 232	S45	Obre Stossbode	8.0181	46.2022	160819	65.87	5.1	238	85	341	1	71	5	9	0.28	9.6	3
232	S46	Holiecht	8.0535	46.2067	160153	66.83	14.8	174	85	322	5	52	3	26	0.396	8.3	1
	S47	Gärtjini	8.046	46.1487	154525	65.67	3.7	148	76	332	14	242	1	27	0.311	11.2	2
233	S48	Weissmies	8.0408	46.1416	153976	65.40	8.6	180 337	80 74	344	9 15	74	2 3	19	0.253	7.6 9.1	1 1
233 234	S49 S50	Schafnuwald Tannuwald	8.1245 8.1082	46.1629 46.154	153514 153095	67.97 67.39	11.0 47.6	337 190	74 77	147 26	13	237 295	3	21 10	0.241 0.589	9.1 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	134	4	224	14	19	0.423	7.5	2
237	S53	Altes Hospiz	8.0162	46.2337	164063	66.33	16.3	121	73	322	16	230	6	27	0.166	10.0	1
238	S54	Nidristi Alp	7.9548	46.2578	168490	65.24	10.2	130	75	325	15	235	4	21	0.785	7.9	1
239	S55	Gampisch	8.0055	46.2333	164365	66.06	14.1	9	75	140	0	232	11	11	0.162	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
241 242	S57 S58	Galaberr Glis	8.0778 7.963	46.151 46.2983	153737 172294	66.53 66.08	46.5 65.1	24 356	72 69	203 91	18 2	293 181	1 21	19 11	0.253 0.337	7.9 8.9	2 3
242	S59	Mäderhitta	7.9583	46.2838	170985	65.74	54.7	12	75	281	1	191	15	18	0.337	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	S61	Griewald	7.959	46.2868	171268	65.81	71.2	1	87	227	2	137	2	13	0.163	15.8	3
246	SD	Staldhorn	8.0227	46.2645	166983	66.97	12.0	145	4	357	85	235	2	11	0.737	9.7	3
247	1	BDTNO	6.5208	44.7313	186998	-4.29	82.3	142	77	349	18	258	6	30	0.6	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 30	0.8	17.8	2
250 251	4 5	BOUCH CERVI	6.9492 6.7505	44.6902 44.8862	153907 167829	-7.28 0.91	25.7 43.1	64 208	69 76	236 313	21 4	327 44	3 14	30 18	0.2 0.3	7.5 9.7	1 2
252	6	CHABE	6.759	44.973	167323	4.22	37.2	193	83	58	5	327	5	21	0.3	9.5	1
253	7	CHAMB	6.8347	44.5413	166085	-12.45	43.5	32	67	214	23	124	1	23	0.3	11.4	2
254	8	CHENO	6.753	44.9253	167637	2.40	43.6	111	76	317	13	226	6	10	0.4	14	3
255	9	CHESU	6.7527	44.9123	167646	1.91	3.1	261	73	97	17	5	4	10	0.3	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 81	78 70	182	5	273	11	13	0.2	14.6	2
259 260	13 14	LONGE COLSN	6.9487 6.841	44.65 44.4888	154686 167107	$-8.92 \\ -14.44$	30.9 61.6	81 202	70 3	296 354	17 57	202 104	11 13	16 15	0.2 0.6	12.9 8.6	2 2
260 261	14	CPEYR	6.6245	44.4888	178355	-14.44 -2.97	20.0	202 84	3 82	247	7	337	3	30	0.8	8.0 11.7	1
262	16	CROUS	6.6552	44.7238	176505	-4.92	23.9	62	67	294	15	199	17	8	0.2	15	3
263	17	CROUS	6.6552	44.7238	176505	-4.92	73.1	15	16	157	7	282	11	10	0.5	16.5	3
264	18	CRXSA	6.5508	44.8363	183762	-0.75	57.8	143	82	327	8	237	1	19	0.4	10.3	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			a		1 ( 0 4 1 /	11 77	740	120									
267	20	FOUIL	6.8003	44.5537	168416	-11.77	74.2	130	82	4	5	274	6	11	0.4	10.4	3
268		FOUIL GROOU GROOU	6.8003 6.6755 6.6755	44.5537 44.6593 44.6593	168416 175878 175878	-11.77 -7.30 -7.30	74.2 35.7 44.7	130 218 219	82 68 39	4 48 37	5 22 5	274 317 128	6 4 1	11 27 27	0.4 0.2 0.8	10.4 11 11.3	3 1 3

indic i. (commutual)	Table	1. (	(continued	1)
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Name			]	Location			c	<sup>5</sup> 1	c	<sup>5</sup> 2	c	<sup>5</sup> 3	Parameters				
Ν	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	172941	-1.55	48.4	142	80	41	2	310	1	26	0.3	15.5	1
289	43	HOUER	6.7825	44.5877	168969	-10.42	45.6	207	29	62	56	304	18	16	0.7	14.8	2
290	44	MLZOU	6.6318	44.8422	177335	-0.63	28.4	91	52	232	32	331	14	30	0.2	8.6	2
291	45	MLZSU	6.6363	44.8327	177025	-0.97	10.0	97	62	258	28	349	28	12	0.1	9	2
292	46	PSTRL	6.7918	44.5793	168443	-10.78	6.2	218	71	76	15	343	11	14	0.2	8.5	2
293	40	PCHAT	6.7878	44.54	169738	-12.20	17.8	210	69	64	18	330	11	29	0.1	14.3	1
294	48	PCHAT	6.7878	44.54	169738	-12.20	69.8	187	2	13	69	278	2	15	0.4	7.5	2
295	49	PRORE	6.5642	44.9053	182531	1.64	45.4	154	70	315	19	47	6	20	0.4	9	2
295	50	RMOES	6.6122	44.8347	178919	-0.87	10.9	252	70	102	16	10	8	19	0.2	7.7	1
290	51	RMOOU	6.6175	44.84	178474	-0.87 -0.69	1.7	245	75	93	10	10	6	26	0.2	8.7	1
298	52	ROBAR	6.5698	44.808	182424	-1.76	70.8	15	86	159	3	249	2	20	0.5	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	183313	1.74	40.7	312	71	50	3	141	18	22	0.5	9.5	1
301	55	TURGE	6.7807	44.8288	165640	-1.30	7.7	181	76	82	2	351	14	25	0.4	8.8	2
301	56	ESCPE	6.677	44.6393	176119	-1.30 -8.02	75.0	16	10	02 118	60	277	27	25 25	0.3	0.0 7.6	1
302	57	ESCRI	6.6898			-8.02 -7.95	62.0	205	38	10	52	110	7	23 34	0.2	6	1
				44.6428	175053												
304	58	ESCNO	6.7003	44.635	174379	-8.28	63.7	19	1	276	83	108	7	30	0.4	9 7 2	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

<sup>a</sup>Number 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,  $\tau$ ), and the angle with respect to the Alpine belt ( $\gamma$ ), the  $\sigma_1$ ,  $\sigma_2$ , and  $\sigma_3$  orientation (azimuth and plunge) and the  $\Phi$  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  $\alpha$ , and the quality criterion ("conf").

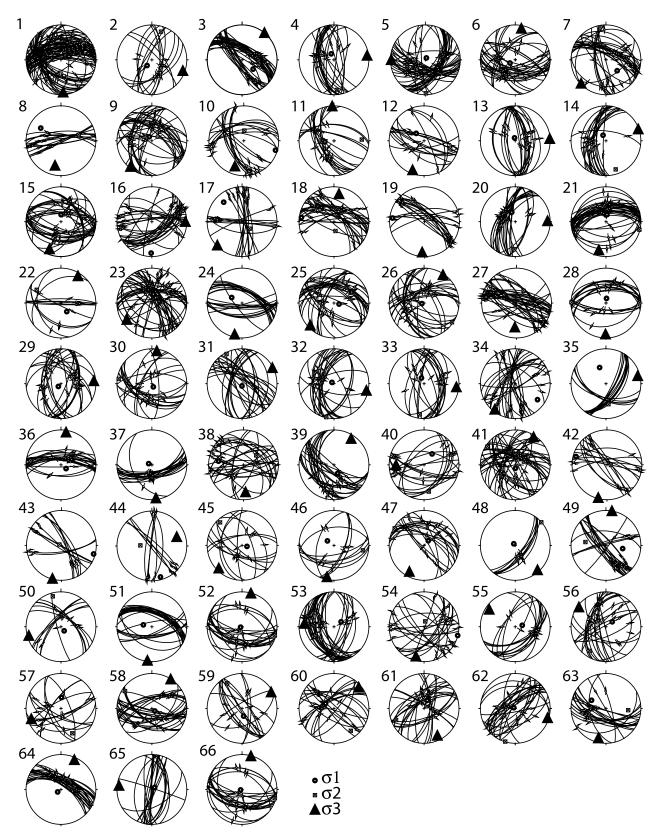
an indicator for the lack of neoformed transcurrent faults. Figure 5f shows rose diagrams of azimuth and plunge of normal faults (top) and transcurrent faults (bottom) describing the geometrical relationship between fault orientations and kinematics.

# **3.** Synthesis of Brittle Deformations in the Inner Western Alps

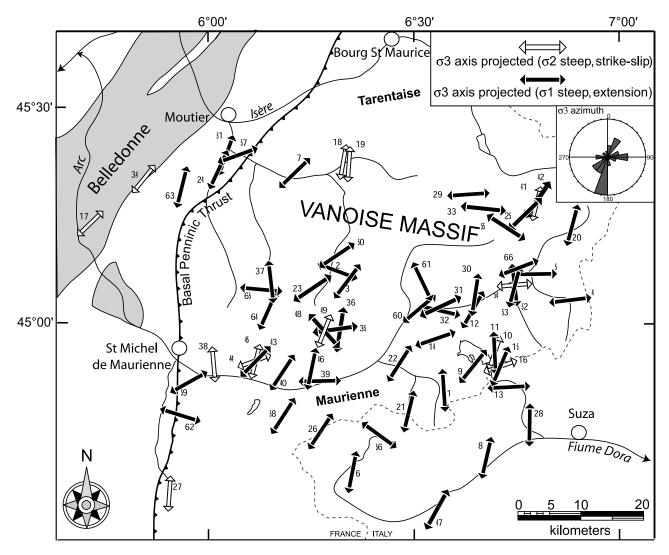
#### 3.1. Presentation of the Data

[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 km<sup>2</sup> (average density of tensors: 3 tensors/100 km<sup>2</sup>). 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  $\sigma_1$  axes, squares for  $\sigma_2$  axes, and triangles for  $\sigma_3$  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  $\sigma_3$  axes projected onto a horizontal plane with white arrows for transcurrent tensors (subhorizontal  $\sigma_1$  axis) and black arrows for extensional tensors (subvertical  $\sigma_1$  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]).

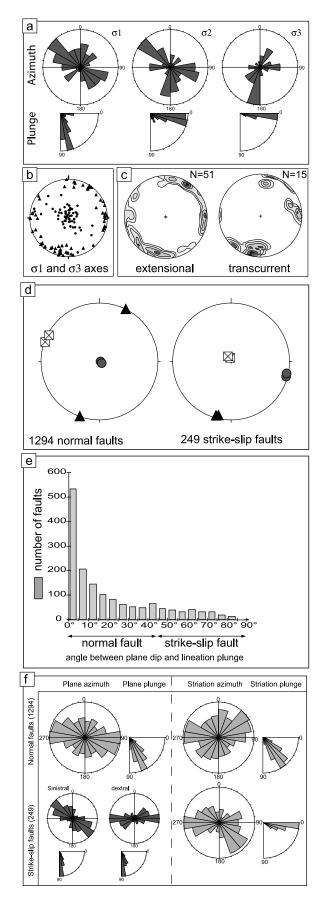
[18] In order to demonstrate the homogeneity and the large prevalence of extensional features in the inner parts of the western Alps, five examples of outcrops (one for each zone) and their associated paleostress tensors are presented in Figure 6. As in the Vanoise area, normal faulting is the most striking 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  $30^{\circ}$  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 km<sup>2</sup>). 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  $20^{\circ}$  class size rose diagram and  $10^{\circ}$  class size quarter rose representing the  $\sigma_1$ ,  $\sigma_2$ , and  $\sigma_3$  azimuth and plunge for the 66 tensors. (b) Plot of  $\sigma_1$  and  $\sigma_3$  axis in a Schmidt lower hemisphere stereogram. (c) Comparison between  $\sigma_3$ 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  $90^{\circ}$  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-Worientation, 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.

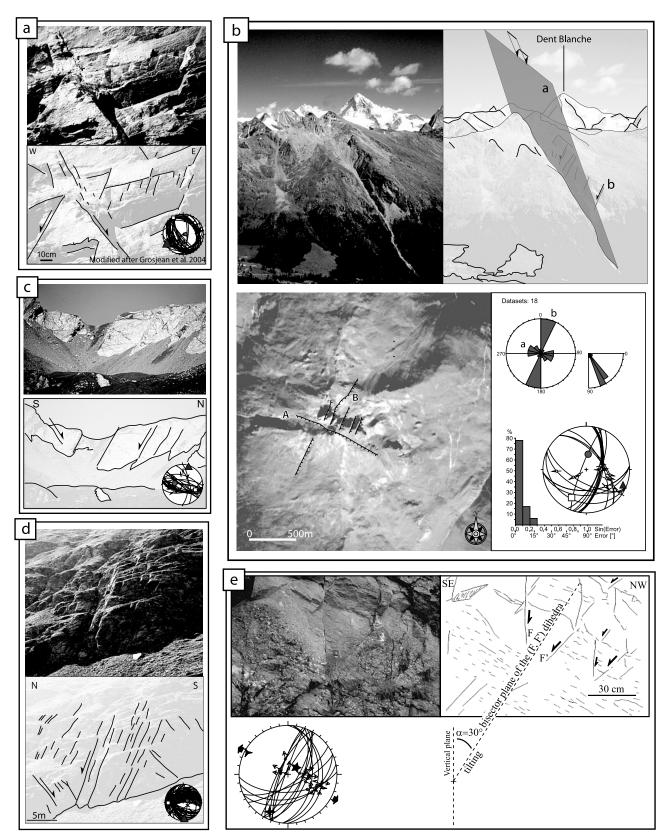


Figure 6

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 Briançonnais 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  $\sigma_3$  axis is oriented N065°, in a stable "Simplon-like" orientation. One third of the calculated tensors are transcurrent, with a coaxial orientation of  $\sigma_3$  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  $\sigma_3$  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.

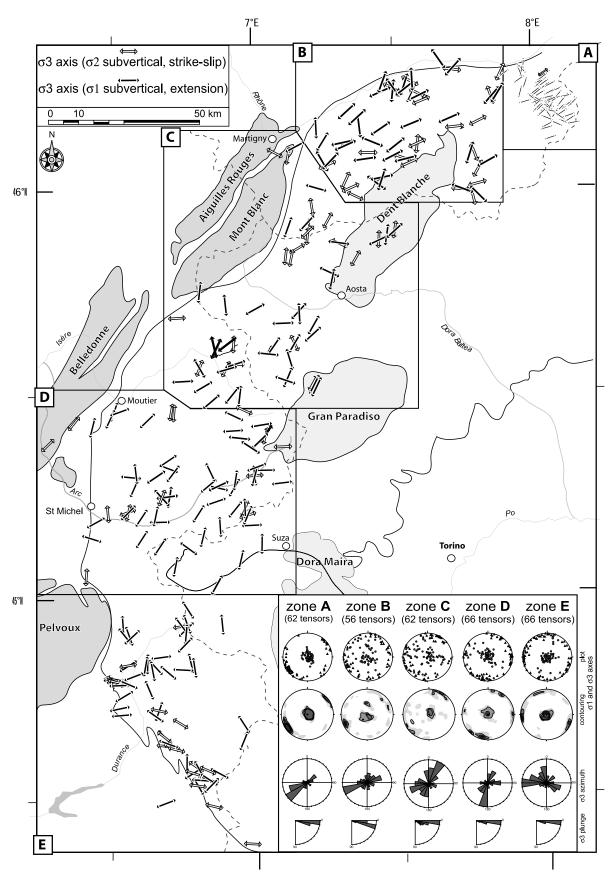
#### 3.2.1.4. Zone D, Vanoise

[25] This zone is presented in section 2. The ratio between transcurrent and extensional tensors is about 1/4. The mean directions of  $\sigma_3$  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

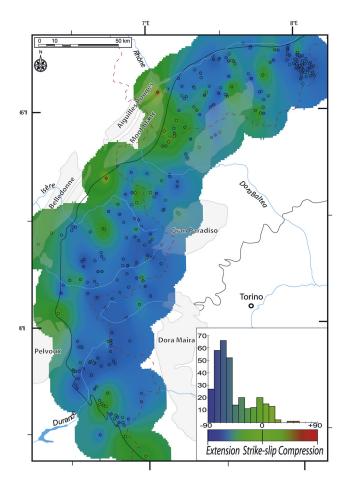
**Figure 6.** Fieldwork example of normal faulting all around the inner Alpine belt. (a) Close-up to penetrative normal fracturation close to the Simplon pass (site N195); the inversion of the fault population measured in the vicinity of the picture site indicates a NNE-SSW direction of  $\sigma_3$  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  $\sigma_3$  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 ( $\sigma_3$ ) N-S oriented. (e) Conjugated normal faults in High Ubaye (site 310). Diedra is tilted of 30° toward the NW (around the  $\sigma_2$  axis). The direction of extension of extension  $\sigma_2$  is NW-SE oriented.





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**Figure 8.** Contouring of the stress tensor orientation in the inner western Alps, based on the plunge of  $\sigma_1$  and  $\sigma_3$  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  $\Phi$  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 orogenperpendicular 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  $\sigma_3$  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  $\sigma_3$  axes is very small in the Simplon area, probably because of the kinematic control of the major Simplon Fault Zone. The dispersion of  $\sigma_3$ axes is greater in the Valais area, but the direction of extension is still very well constrained. The dispersion of the  $\sigma_3$  axes increases in the Aosta/Tarentaise valleys and decreases again farther south. Another striking characteristic is the increasing amount of orogen-perpendicular  $\sigma_3$  axes from north to south; in the Brianconnais area, the inversion of the BPT [Sue and Tricart, 1999, 2002] seems to be the origin of the E-W to NE-SW oriented  $\sigma_3$ . The  $\sigma_1$  axes are mainly subvertical. The dispersion of  $\sigma_1$  axes increase from zone A to zone C and decrease from zone C to zone E; the  $\sigma_1$  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  $\sigma_1$  and  $\sigma_3$  axes (r is plunge of  $\sigma_1$  minus plunge of  $\sigma_3$ ). 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 < r < 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 ( $\sigma_3$ ) 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  $\sigma_3$  (triangle) and axes (circle), the contouring of the  $\sigma_1$  (vertical) and  $\sigma_3$  (horizontal) axes, rose diagram and plunge of the  $\sigma_3$  orientation.

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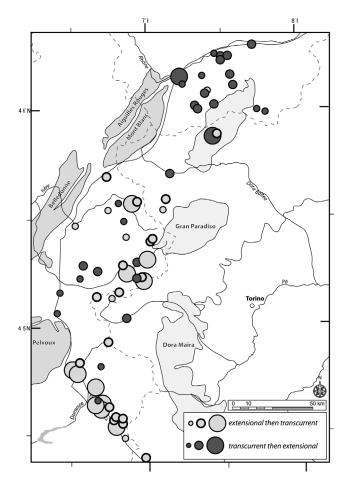


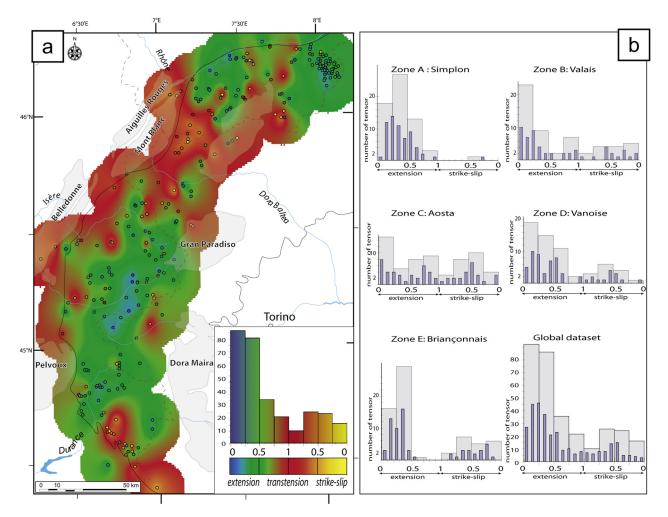
Figure 9. Chronological evidences based on field observations. The size of circles represents the reliability of the chronology (large circles for high-quality chronology evidences, small circles for lower quality). Dark grey circles symbolize locations where transcurrent deformation is older than extensional 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 transfersive stress field, with high  $\Phi$  ratio (i.e., close relative magnitudes of  $\sigma_1$  and  $\sigma_2$  axes, see below) is followed by a multitrend extensional stress field, with low  $\Phi$  ratio (i.e., similar  $\sigma_2$  and  $\sigma_3$  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  $\sigma_3$  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  $10^{\circ}$  difference between the transcurrent  $\sigma_3$ axis and the extensional  $\sigma_3$  axis (e.g., Figures 5c and 5d and Champagnac [2005]). Accordingly, we suggest a swapping between  $\sigma_1$  and  $\sigma_2$  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 $\Phi$

[30] Beyond the stress orientation, paleostress inversion allows one to determine the relative magnitude of  $\sigma_1$ ,  $\sigma_2$  and  $\sigma_3$  of the stress ellipsoid, the  $\Phi$  ratio;  $\Phi = [\sigma_2 - \sigma_3]/[\sigma_1 - \sigma_3])$  and  $0 < \Phi < 1$  [e.g., *Angelier*, 1979]. A low  $\Phi$  ratio (similar  $\sigma_2$  and  $\sigma_3$ ) indicates a multitrend (i.e., symmetric around the vertical axis) extension or transpression (for extensional or transcurrent tensor, respectively), and high  $\Phi$  ratio (similar  $\sigma_1$  and  $\sigma_3$ ) indicates a transtensional stress field. According to our calculations, the  $\Phi$  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

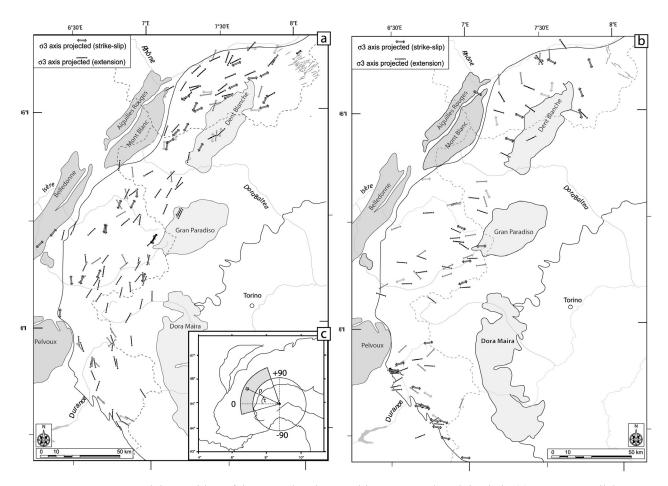


**Figure 10.** Map of the  $\Phi$  ratio in the inner western Alps. (a) Map with interpolated  $\Phi$  ratio for the entire data set. Color code is used between  $\Phi = 0$  (blue) and  $\Phi = 1$  (red), via  $\Phi = 0.5$  (green), for extensional tensors and between  $\Phi = 1$  (red) and  $\Phi = 0$  (yellow) via  $\Phi = 0.5$  (orange) for transcurrent tensors. Colored histogram gives the repartition of  $\Phi$  ratio of the inner western Alpine belt. (b) Histogram presentation of the  $\Phi$  ratio for each of the five zones separately, and for the entire data set, within 10° and 25° class size. The meaning of  $\Phi$  ratio differs according to the plunge of  $\sigma_1$ , 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  $\Phi$  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  $\Phi$  ratio, we also plotted them in histograms, one for each zone and one for

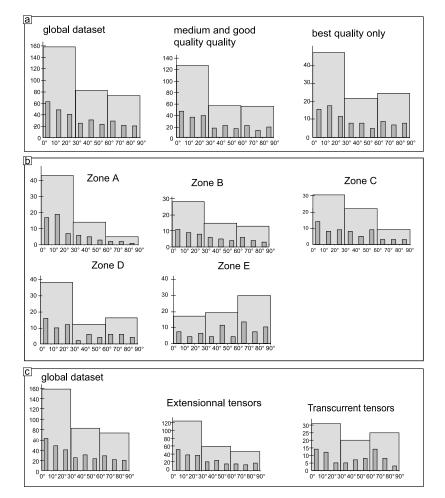


**Figure 11.** Spatial repartition of the extensional axes with respect to the Alpine belt. (a) Orogen-parallel extensional axes ( $\beta < 30^\circ$ , see text for details) plotted onto an Alpine map with white arrows for transcurrent and black arrows for extensional paleostress tensors. Also are plotted 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  $\Phi$  ratio) were again plotted separately for extensional and transcurrent tensors. We further arranged the abscissas of the histograms  $(\Phi)$  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  $\Phi$  ratio ( $0 < \Phi < 0.5$ , multitrend extension) and a minimum for high  $\Phi$  ratio (0.75 <  $\Phi$  < 1, transtension) for both extensional and transcurrent tensors. A small second-order mode appears for transcurrent medium  $\Phi$ ratios (close to 0.5). In the zone A (Simplon area), the tensors are exclusively extensional, and the  $\Phi$  ratio is close to 0.5 (pure extension). In zone B (Valais area), most of the tensors have a low  $\Phi$  ratio (less than 0.3, multitrend extension), with a second-order mode for high  $\Phi$  ratios (transtension). Zone C (Aosta area) is characterized by a

wide range of  $\Phi$  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  $\Phi$  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  $\Phi$  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  $\Phi$  ratio analysis shows mostly bimodal distributions, clearly visible for zone D, E and the whole data set. For extensional tensors,  $\Phi$  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  $\Phi$  ratio. This shift could be related to partly



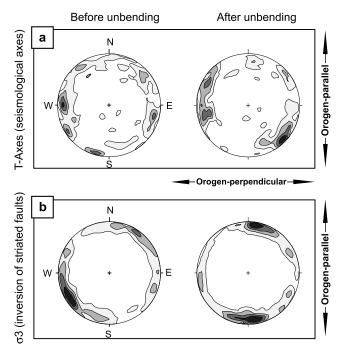
**Figure 12.** Histograms of the angular relationship between the Alpine trend and  $\sigma_3$  orientations. (a) Angles are plotted within 10° and 30° class size for (left) the whole data set, (middle) medium and good quality criterion tensors, and (right) only best quality tensors. Despite the ever-predominant orogen-parallel tensors, best quality tensors appear to be slightly more "orogen-perpendicular" than lower quality. (b) Histograms of  $\beta$  angles for each zone separately, within 10° and 30° class size. See text for discussion. (c) Angular relationship between extensional axes ( $\sigma_3$ ) 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  $\rho$  the radius in kilometers from the center and  $\tau$ 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:  $\beta$  the  $\sigma_3$ axis azimuth (with  $0^\circ < \beta < 180^\circ$ ),  $\tau$  the angular position of the tensor in the Alpine belt (with  $-19^\circ < \tau < 69^\circ$  here) and  $\gamma$  the angular position of the  $\sigma_3$  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  $\sigma_3$  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  $\sigma_3$  (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 ( $\rho$  and  $\tau$ entries), and the pattern of  $\sigma_3$  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  $\sigma_3$  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  $\sigma_3$  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  $10^{\circ}$ , the mode is within the  $0^{\circ}$ - $10^{\circ}$  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  $\sigma_3$  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  $\sigma_3$  axes (brittle deformation) in geographic coordinates  $(\beta)$  and in Alpine angular coordinates  $(\gamma)$ , 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  $\sigma_3$  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  $\sigma_3$  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 (~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  $\sigma_3$  axes, however, remains identical for the transcurrent and extensional regimes and we only observe swapping between  $\sigma_1$  and  $\sigma_2$ .

[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  $\sigma_3$  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 orogenparallel 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].

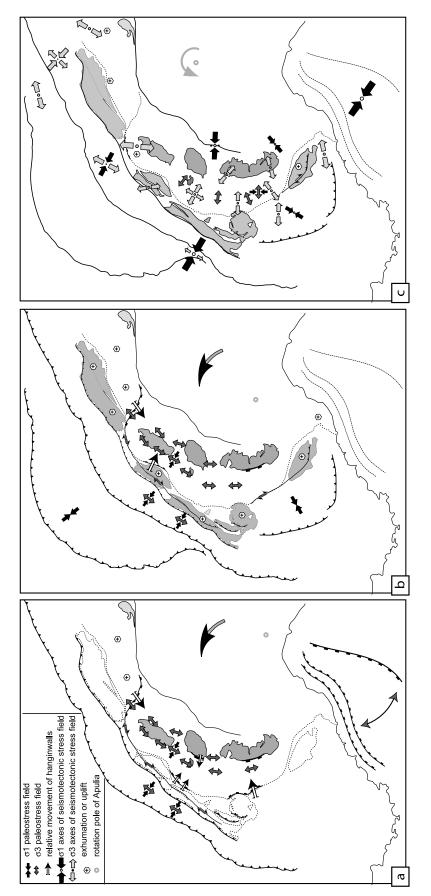
[45] In the eastern Alps, lateral extrusion is accommodated by a set of large conjugate dextral and sinistral faults. In the western Alps, large and long-lived dextral transcurrent faults are observed all along the belt, [e.g., *Ménard*, 1988], but only very few sinistral faults are known (exceptions 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  $\Phi$  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  $\sigma_3$  axes, for both transcurrent and extensional paleostress tensors, is N-S oriented, parallel to the Alpine structures. A minor part of  $\sigma_3$  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  $\sigma_3$  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 *Dewev 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. Figure 14.

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  $\sigma_3$  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  $\sigma_3$  axes related to the transcurrent paleostress tensors are consistent with  $\sigma_3$  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.

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