

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.

Clearly speaking, 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

If convergence between Africa and Europe is now well established on the global scale, with a rate from 3 to 8 mm/year at the longitude of the western Alps [Demets et al., 1994; Nocquet et al., 2001], recent geodetic survey [Sue et al., 2000; Calais et al., 2002; Oldow et al., 2002; Vigny et al., 2002] failed to demonstrate any convergence within the western Alps. Oppositely, the strain vector along a Lyon-Torino baseline is very low (less than 1mm/yr), maybe in EW extension [Calais et al., 2002; Vigny et al., 2002]; furthermore, movement between the northern part of the Apulian microplate and the stable Europe appears to be insignificant [Oldow et al., 2002]. Then the large scale convergence seems to be consumed in other orogens (Dinarides, Magrebides, Eastern Alps, Appenines...) in a complex manner. Geodetic surveys often locally agree with seismotectonic deformations [Martinod et al., 1996; Calais et al., 2000; Sue et al., 2000; Martinod et al., 2001; Calais et al., 2002].

Seismological studies have been performed in the alpine belt from decades ago [Rothé, 1941; Pavoni, 1961; Fréchet, 1978; Pavoni, 1980; 1986; Béthoux et al., 1988; Deichmann and Rybach, 1989], but the extensional tectonics has been observed since 10 years only [Maurer, 1993; Eva et al., 1998; Sue et al., 1999; Baroux et al., 2001; Kastrup, 2002; Sue et al., 2002; Delacou et al., 2004]. This extensional regime is widely developed in the inner part of the alpine belt (roughly the internal zones) and determine a large bow of extensional deformation. As demonstrated by Delacou et al. [2004], this extensional deformation is located over overthickened crust. Furthermore, the direction of T-axes (tensional axes of earthquakes), as well as calculated σ_3 axes (inversion of population of earthquakes) are fan-shaped oriented, perpendicular to the alpine belt (orogen-perpendicular extension, see figure 14 and Delacou et al. [Delacou et al.]). Only few compressional earthquakes has been recorded, and they are mainly located at the bottom of the alpine topography (and thick crust). The orogen-perpendicular extension is directionally consistent with the orogen-perpendicular extension we determined with faults analyses (figure 12b).

4.2. The neogene brittle deformation

In the present paper, we highlighted the large amount of brittle extensional tectonics in the inner western Alps. This is noticed with the amount of calculated extensional paleostress tensors *vs.* transcurrent paleostress tensors (almost 80% / 20%) as well as the amount of normal faults measured *vs.* transcurrent fault (almost 85% / 15 %). Fieldwork chronological evidences demonstrates an opposite chronology between the Valais area and the rest of the alpine belt : transcurrent tectonics is clearly younger in the south part of the inner western Alps, whereas it is older in the Valais area. The limit between these chronologies seems to be somewhere in the east side of the Mont-Blanc massif, in the Aosta area (figure 10). The orientation of extensional axes, however, is the same for transcurrent and extensive regimes and we observe only a swap between σ_1 and σ_2 .

The extensional tectonics is expressed in the whole inner western arc, from the Simplon

pass to the northern tip of the Argentera massif. Then, the main direction of extensional axes is parallel to the alpine structures (figure 5, figure 8 and figure 12), as observed in the eastern Alps. A minor part of σ_3 axes are oriented perpendicularly to the alpine structures; this part of orogen-perpendicular extension is more significant for good quality tensors and / or transcurrent tensor. From a directional point of view, this orogen-perpendicular extensional axes could be linked to current seismological regime. It could also be locally related to older extensional structures induced by relative uplift of large alpine units : inversion as detachment of the major BPT 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 W-dipping normal fault in the west side of the Dora-Maira and Viso massif [Schwartz et al., 2004; Tricart et al., 2004b] during the Miocene. Regrettably, an important limit of our work is the lack of absolute chronology for faulting. Nevertheless, given the brittle nature of faults, this extension is clearly post-metamorphic. Faults clearly crosscut (and thus postdate) folds, shistosity and ductile nappe related structures, even if some movements occur early, at the ductile-brittle transition. Furthermore, the large diversity of fault plane mineralisations (calcite, quartz, hematite, talc, amphibole, chlorite...), the variety of movement-related lineations (slikenfibers, scratches, striations) and the aspect of rocks in the vicinity of the fault plane (cataclasite, unconsolidated cataclasite, fault breccia and fault gouges) suggest a very large variation of faulting conditions (temperature, depth, fluid pressure and composition) and therefore a long brittle history. Indeed, the fault population observed in the western Alps for this study are a temporal integration of all brittle deformation occurred in this area, from ductile-brittle transition to the present-day, with several P-T-t final exhumation paths.

4.3. Geodynamical interpretations

Extensional processes are a common feature in evolved orogen and have been widely described [e.g. Wernicke and Burchfield, 1982; Dewey, 1988; Molnar and Lyon-Caen, 1988; Le Pichon and Chamot-Rooke, 1991; Doglioni, 1995; Rey et al., 2001]. Extension coaxial to the main direction of convergence as been observed in the Andes [Dalmayrac and Molnar, 1981; Sébrier et al., 1985; Deverchere, 1988], the Himalayans [Molnar and Tapponnier, 1978; Armijo et al., 1986; Herren, 1987; England and Houseman, 1989; Harrison et al., 1992] and the Basin and Range [Lister and Davis, 1989; Thatcher et al., 1999]. This coaxial extension (perpendicular to the trend of the belt) has mostly been interpreted in term of orogenic collapse. The beginning of such an extensional regime is due to subtle changes in a complex equilibrium, such as decreasing rate of convergence, increasing erosion rate, temperature / time-dependant internal strength variation or isostatic reequilibration due to slab behaviour [Avouac and Burov, 1996]. In the Western and Central 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 propose the western Alps deformation to be guided by buoyancy forces and then to be in a stage of post-orogenic collapse [Delacou et al., 2004; in press], driven by buoyancy and gravitational forces. This collapse involve extension perpendicular to the axis of maximal overthickness of the belt.

Oppositely, extensional deformation described in the eastern Alps [Selverstone, 1988; Ratschbacher et al., 1989; Peresson and Decker, 1997; Meyre et al., 1998; Frisch et al., 2000] and central Alps [Mancel and Merle, 1987; Mancktelow, 1992; Steck and Hunziker, 1994; Nievergelt et al., 1996] are interpreted in term of syncollisional extension, with a main direction of extension oriented along the strike of the belt, and perpendicularly to the main shortening direction. Thus, this orogen-parallel extension have been interpreted as lateral extrusion, from the Lepontine Dome toward the Pannonian basin. The back-arc extension behind the Carpatian

arc was proposed to be the main driving force for such mechanism [Seghedi et al., 1998]. As recently supported by numerical modelling [Seyferth and Henk, 2004], lateral extrusion largely prevails in an evolved orogen ; free boundary and overthickened crust are described as favoring factors, the plate convergence, however, remaining the principal cause.

In the western Alps, we have suggested the orogen-parallel extension to be due to lateral extrusion toward the South [Champagnac et al., 2004]. The opening of Ligurian sea during Lower and Middle Miocene [Vigliotti and Langenheim, 1995; Carminati et al., 1998a; 1998b; Rollet et al., 2002; Rosenbaum et al., 2002; Speranza et al., 2002] would be the free boundary for the development of large scale lateral extrusion. However, the passage between the inner extensional zones of the Alps and the Ligurian basin is not straightforward : the southernmost part of the alpine belt is highly arcuated, with the presence of the Argentera massif and Ligurian Alps. Nevertheless, as suggested by fission tracks studies, exhumation of the southern part of the W-alpine belt start in the late Miocene, with a rapid uplift since the Pliocene [Bigot-Cormier et al., 2000; Foeken et al., 2003]. This uplift began during the stop of the Ligurian sea opening (Upper Miocene). Therefore, the Lower Miocene alpine arc would be less arcuated than actually [c.f. Collombet et al., 2002], with a direct relationship between extensional inner Alps and the oceanic basin.

In the eastern Alps, lateral extrusion is accommodated by large conjugated dextral and sinistral faults. In the western Alps, large and long-lived dextral transcurrent faults are observed all along the belt, [e.g. Gurlay and Ricou, 1983; Ménard, 1988; Sartori, 1993; Tricart et al., 1996], but only few sinistral faults (except the Ospizio Sottile fault after Bistacchi et al. [2000] and within Schistes lustrés of the Queyras-Ubaye [Tricart et al., 2004a]). Several authors considered this curved and largely predominant dextral strike-slip to be due counterclockwise rotation of the northern tip of the Apulian indenter [Goguel, 1963; Gidon, 1974; Anderson and Jackson, 1987; Ménard, 1988; Vialon et al., 1989; Laubscher, 1991; Pavoni, 1991; Pavoni et al., 1997; Thomas et al., 1999; Collombet et al., 2002]. The scarcity of sinistral faults could therefore interpreted as a consequence of rotation of indenter.

Consequently, we propose in this paper that the inner western Alps suffered a large scale lateral extrusion toward the opening Ligurian sea, at least during Lower to Middle Miocene. This lateral extrusion is the origin of the main brittle deformation observed in the field, with large scale orogen-parallel extension.

A significant part of the extensional deformation, however differs significantly from orogen-parallel orientation : orogen-perpendicular or oblique extensional axes are observed all around the belt. The origin of orogen-perpendicular extension needs to be discussed: An important part of the extension previously observed in the western Alps is located in the hangingwall of large normal faults, and occurs under ductile-brittle transition and brittle conditions. This extension is induced by up-doming of basement nappe exhumation. 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 hangingwall of the reactivated BPT, in the Briançonnais area [Sue and Tricart, 2003] and in the east 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 et al., 1999]). The orogen-parallel extrusion described above is also the consequence of shortening in-between the limits of the alpine orogeny. Therefore, Miocene extensional tectonics can be the results of the interaction between major alpine-scale orogen-parallel extension and regional-scale “dome-related” extension. The consequence could explain the local multitrend extension (low Φ ratio) observed.

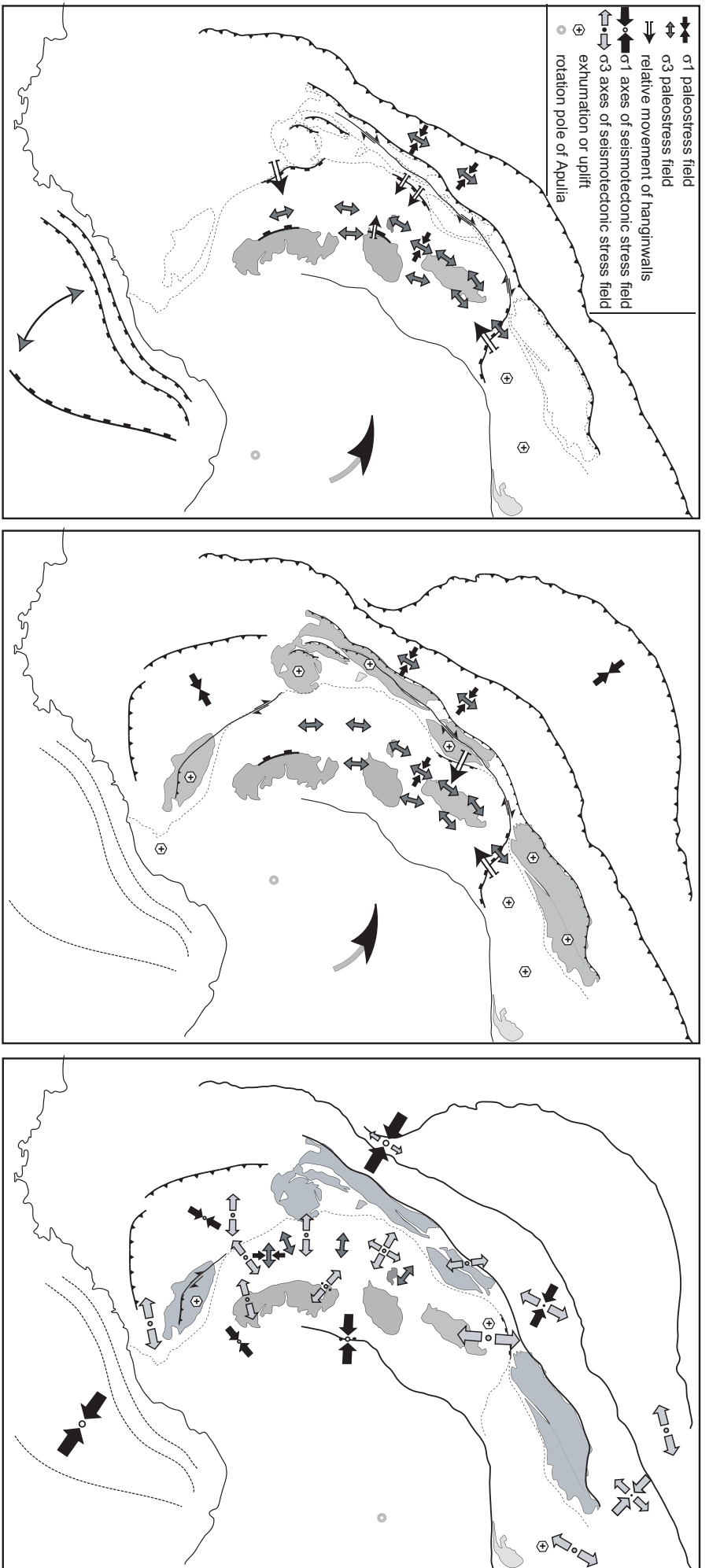


Figure 15: Three snapshots of Neogen to current alpine history.

(a) Orogen-parallel extension, directly related to extrusion toward the Ligurian basin and the indentation / rotation of the Apulian microplate. The external zones still underwent under compressive deformation [Dewey et al., 1989; Soom, 1990; Mancktelow, 1992; Steck and Hunziker, 1994; Tricart et al., 1996; Carminati et al., 1998a; Bistacchi et al., 2000; Dick, 2000; Collombet et al., 2002; Rollet et al., 2002; Grosjean et al., 2004; Malusa, 2004; Schwartz et al., 2004; Dumont et al., in press].

(b) Tectonic regime after the end of the Ligurian basin opening, characterized by propagation of the alpine front toward the NW (Jura) and the SW (Digne nappe), dextral motion all along the belt and uplift of the external crystalline massifs. Extensional orogen-parallel deformation still occurs in internal zones, but seems to decrease toward the South. [Mauffret et al., 1980; Burkhard, 1988; Dewey et al., 1989; Soom, 1990; Mancktelow, 1992; Seward and Mancktelow, 1994; Burkhard and Sommaruga, 1998; Bigot-Cormier et al., 2000; Bogdanoff et al., 2000; Collombet et al., 2002; Homberg et al., 2002; Foecken et al., 2003].

(c) Orogen-perpendicular extension related to recent paleostress field [this study, Sue and Tricart 2003] and current strain and stress fields from Delacou et al. [2004] inferred from seismotectonics inversion. The orientation of extensional axes is perpendicular to the belt, whereas there is only few compression in the external zone. This fan-shaped extensional axes is also related to the lack of geodetic shortening in the western Alps.

In summary, our preferred interpretation of the observed extension patterns is shown in figure 15 which presents 3 snapshots of Neogen alpine history:

Figure 15a 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 11Ma.. The external zones still undergoes compressive deformation.

Figure 15b 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 ECM, thrusting in the Jura and Dignes nappe systems and dextral motion all along the belt.

Figure 15c presents the orogen-perpendicular extension related to recent paleostress field [this study, Sue and Tricart 2003] and current strain and stress fields from Delacou et al. [2004] inferred from seismotectonics inversion. The orientation of extensional axes is perpendicular to the belt, whereas compression is limited to a few locales in the external zone

5. Conclusions

This work fill the gap of brittle deformation analyses between previous studies. From direct inversion method, 66 new paleostress tensors have been calculated in the Vanoise / Maurienne area (French Alps), inbetween the Aosta Valley [Champagnac et al., 2004] and the Briançonnais area [Sue and Tricart, 2003]. The observed tectonic regime is largely extensional, with $\frac{1}{4}$ of transcurrent paleostress tensors. The main direction of σ_3 axes, for both transcurrent and extensional paleostress tensors, is N-S oriented, parallel to the alpine structures. A minor part of σ_3 axes is E-W oriented, perpendicular to the alpine structures. We also performed a synthesis in the entire bend of the inner western Alps of brittle deformation analyses, based on inversion of fault populations. This synthesis highlight the major orogen-parallel direction of extension for the complete internal bend of the western Alps : the σ_3 axes are oriented like the alpine structures, from N065° in 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 is a free boundary, which could help this extrusion.

A minor part of σ_3 axes is oriented perpendicular or oblique to the alpine structures. This direction of extension increase toward the South, and is important in the Briançon area. The origin of this extension seems to be induced by uplift or updoming of External or Internal Crystalline Massifs (during apulian indentation), or related the current state of stress.

Last, but not least, a transcurrent regime predates the extension in the Valais area, and postdates it in the other parts of the belt. The σ_3 axes related to the transcurrent paleostress tensors are consistant with σ_3 axes related to extensional paleostress tensors. Stress axes permutations, induced by local or regional perturbations, and counterclockwise rotational tectonics of the Apulian microplate explain transcurrent tectonics in the inner western Alps, which is blended with extensional tectonics in the belt.

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8. Appendix A

name		location				σ_1		σ_2		σ_3		parameters					
N°	n°	site	lon	lat	ρ	τ	az	dip	az	dip	az	dip	data	ϕ	α	conf.	γ
1	1	anniv (1)	7,5641	46,2645	184166	56,87	271	71	82	17	174	9	12	0,52	6	1	62,9
2	2	anniv (2)	7,5641	46,2645	184166	56,87	283	37	68	47	178	18	10	0,49	5,7	3	58,9
3	3	artsin	7,4279	46,1166	177390	51,07	8	61	207	27	113	8	18	0,47	11,5	1	61,9
4	4	cargn	7,5589	46,2326	181472	56,13	285	73	118	17	27	4	18	0,08	6,5	2	29,1
5	5	chevre	7,4318	46,0181	168956	48,75	214	69	38	21	307	1	11	0,2	5,5	2	78,2
6	6	cleus1	7,3219	46,1148	182626	49,06	315	69	172	17	79	12	12	0,06	2,9	2	29,9
7	7	cleus2	7,327	46,1094	181913	49,02	355	53	148	33	247	13	11	0,32	3,2	1	18,0
8	8	couta	7,4913	46,0824	171335	51,50	26	87	154	2	244	2	22	0,22	9,4	1	12,5
9	9	danger	7,3227	46,0212	246457	31,64	320	48	101	35	206	20	16	0,95	6,7	1	5,6
10	10	dix	7,4073	46,0887	176077	50,02	182	9	69	67	271	21	33	0,97	7,3	2	41,0
11	11	emdd (1)	7,8388	46,223	169136	61,94	210	71	309	3	40	19	22	0,06	4,8	2	21,9
12	12	emdd (2)	7,8388	46,223	169136	61,94	250	12	88	78	341	3	13	0,24	7,8	3	80,9
13	13	emmd2	7,8609	46,2319	169192	62,61	202	81	303	2	33	8	16	0,07	7,6	1	29,6
14	14	ergi1	7,7082	46,2959	181165	60,40	250	74	134	7	42	14	11	0,4	5,3	2	18,4
15	15	ergi2	7,7062	46,2898	180655	60,25	226	64	2	19	98	17	9	0,93	9,8	3	37,8
16	16	evole	7,5043	46,1085	172950	52,37	2	53	131	25	233	25	28	0,26	4,3	1	0,6
17	17	findel	7,7856	46,0126	151398	56,30	179	36	326	49	76	17	21	0,77	9,7	2	19,7
18	18	forcl	7,4563	46,0302	168689	49,54	20	64	164	21	260	14	15	0,45	7,7	1	30,5
19	19	furi (1)	7,7326	45,9992	152567	54,71	178	63	26	25	291	11	21	0,08	6,3	1	56,3
20	20	furi (2)	7,7326	45,9992	152567	54,71	5	1	107	83	275	7	9	0,91	5	2	40,3
21	21	gallen	7,7891	46,0486	154558	57,22	53	59	309	8	215	30	9	0,79	4,3	2	22,2
22	22	gorner	7,7867	45,9847	148807	55,65	130	75	227	2	315	15	16	0,04	10	2	79,4
23	23	grime	7,5604	46,1609	174930	54,67	129	82	340	7	249	4	29	0,32	8,6	1	14,3
24	24	ires	7,2418	46,0733	183526	46,66	261	49	48	36	151	17	9	0,24	7,6	3	75,7
25	25	leuker	7,6603	46,3134	184732	59,72	129	58	344	27	146	16	18	0,23	7	2	86,3
26	26	moiry (1)	7,5769	46,1122	169823	53,94	2	32	124	40	248	34	28	0,45	10,3	1	14,1
27	27	moiry (2)	7,5769	46,1122	169823	53,94	277	3	151	84	8	4	24	0,63	16,5	3	45,9
28	28	monv1	7,3596	45,9852	170160	46,53	48	69	204	19	296	8	13	0,11	6,3	3	69,5
29	29	monv2	7,3415	46,005	172711	46,71	334	13	196	72	64	11	25	0,49	9,6	1	17,3
30	30	nax	7,4597	46,2412	186725	54,38	318	82	151	8	61	2	9	0,22	6,1	3	6,6
31	31	nikla	7,7879	46,1638	165410	59,65	152	5	34	79	243	10	22	0,49	12,5	2	3,4
32	32	randa1	7,7751	46,0878	158787	57,76	105	59	241	24	340	19	13	0,78	13,6	3	77,8
33	33	randa2	7,7615	46,0847	159077	57,38	107	73	287	17	17	0	27	0,13	7,5	1	40,4
34	34	rech1 (1)	7,4992	46,2461	185361	55,24	22	23	326	62	118	14	9	0,78	2	2	62,8
35	35	rech1 (2)	7,4992	46,2461	185361	55,24	209	68	58	19	325	10	13	0,13	5	2	89,8
36	36	rech2	7,4953	46,2416	185132	55,07	173	76	276	3	7	14	19	0,03	8,9	1	48,1
37	37	rotba	7,8215	46,0656	154772	58,38	350	46	138	39	242	16	14	0,04	2,4	2	3,6
38	38	roten	7,7674	45,9866	149845	55,22	258	8	19	75	167	12	12	0,75	5,5	2	68,2
39	39	sarray	7,2593	46,0606	181582	46,65	353	51	148	37	247	12	16	0,87	4,8	1	20,3
40	40	schler	7,2715	46,0697	181636	47,09	239	65	137	5	45	24	8	0,16	3,8	3	2,1
41	41	solay1	7,5481	46,0653	167081	52,25	329	22	195	60	67	19	8	0,06	6,2	3	14,8
42	42	solay2	7,5385	46,0743	168330	52,26	150	71	349	18	257	6	16	0,17	8,6	2	24,7
43	43	solay3	7,534	46,0761	168705	52,21	0	50	212	36	110	16	11	0,98	3,5	3	57,8
44	44	stlu1	7,5939	46,2312	179813	56,81	178	67	331	21	65	10	13	0,23	3,3	1	8,2
45	45	stlu2	7,6029	46,2182	178222	56,73	151	37	353	51	249	11	15	0,6	6,3	2	12,3
46	46	tdela	7,03723	46,1571	183602	50,94	238	61	91	25	354	14	16	0,08	3,9	3	56,9
47	47	thyon	7,3709	46,1787	185505	51,40	262	70	142	10	49	17	14	0,29	6,3	2	2,4
48	48	trift	7,4505	46,0245	154479	55,51	123	81	288	9	18	2	35	0,33	8,7	1	37,5
49	49	turgl	7,7096	46,1496	167301	57,60	49	89	175	1	265	1	15	0,83	10,4	2	27,4
50	50	turtm	7,6913	46,1714	170108	57,65	22	57	147	21	247	25	27	0,24	7,5	1	9,3
51	51	verc1	7,4558	46,2582	184385	56,39	147	73	287	13	20	11	19	0,01	11,4	2	36,4
52	52	verc2	7,5433	46,2479	183553	56,13	122	73	325	16	233	6	18	0,3	10,6	2	3,1
53	53	veyso	7,3321	46,194	188733	51,03	118	65	323	23	229	9	9	0,14	3,8	2	2,0
54	54	vingt	7,3956	46,0752	175547	49,48	271	81	173	1	83	9	16	0,57	3,8	1	33,5
55	55	visso	7,5809	46,2344	180668	56,61	205	8	91	71	298	17	17	0,85	5,6	3	61,4
56	56	zeneg	7,871	46,2795	173517	63,66	300	19	82	67	206	13	20	0,59	6,2	3	37,7
57	57	AVISE	7,1526	45,7059	162847	34,75	5	63	128	16	224	22	17	0,05	7,3	1	9,3
58	58	BAUCHE	6,7464	45,5394	182164	24,36	9	75	177	15	268	3	18	0,62	5,9	1	63,6
59	59	BISELX	7,2227	46,0058	179337	44,64	218	58	107	13	107	13	16	0,99	2,8	2	62,4
60	60	BUTHIER	7,2713	45,7845	160510	39,21	273	49	111	40	13	9	16	0,323	5,1	1	26,2
61	61	CARLO	7,003	45,7136	173143	32,86	50	65	150	5	242	24	20	0,89	8,1	1	29,1
62	62	CHAP	6,7318	45,6937	190460	28,99	343	8	249	30	87	59	16	0,36	10,1	2	58,0
63	63	CHAT1	6,858	45,6178	177868	28,03	183	72	79	5	348	17	15	0,264	7,8	3	40,0
64	64	CHAT2	6,8628	45,6148	177384	27,99	218	61	119	5	27	28	18	0,008	1,8	1	1,0
65	65	ECHEV	7,2638	45,8026	162140	39,61	31	61	205	29	296	2	28	0,518	4	1	76,4
66	66	FERRE	7,1212	45,911	178314	40,44	273	28	149	47	21	30	12	0,06		3	19,4
67	67	FRETE (1)	6,8085	45,5709	179118	25,99	268	55	51	29	151	17	17	0,068	4	1	55,0
68	68	FRETE (2)	6,8085	45,5709	179118	25,99	291	8	147	80	22	6	8	0,565	10,2	3	4,0
69	69	GSB1	7,1877	45,8865	172592	40,82	101	11	215	65	7	22	21	0,91	7,7	3	33,8
70	70	GSB2	7,1896	45,8995	173407	41,22	313	24	159	64	47	10	19	0,577	16,9	2	5,8
71	71	GSBIT	7,1512	45,8598	172949	39,46	347	25	108	48	241	32	15	0,37	4,6	2	21,5
72	72	GURRAZ	6,9033	45,6249	175081	28,78	359	75	142	12	234	9	24	0,234	6,1	1	25,2
73	73	ISERAN	7,021	45,4317	157752	23,38	84	84	352	0	262	6	34	0,2	9,4	1	58,6
74	74	LACPLAG	6,845	45,488	172856	23,60	319	65	141	25	51	1	14	0,07	3,7	2	27,4
75	75	MALAT	7,1313	45,8409	172881	38,60	271	32	129	52	13	19	15	0,18	4,7	2	25,6
76	76	MALAT2	7,1113	45,8408	174114	38,29	275	21	117	67	8	8	14	0,252	4,3	2	30,3
77	77	MARTI	7,0814	46,0918	193850	44,48	325	22	231	10	118	65	11	0,576	9,7	3	73,5

Table 1

Table 1 (continued)

78 78	MICOEUR	7,2449	46,1183	186956	47,79	136	73	302	16	33	4	10	0,55	6,8	3	14,8
79 79	MONAL (1)	6,9009	45,5687	172471	26,91	48	85	165	2	255	4	20	0,25	11,8	1	48,1
80 80	MONAL (2)	6,9009	45,5687	172471	26,91	119	36	298	54	29	0	11	0,539	6,2	2	2,1
81 81	NIORD	7,2035	45,9589	176910	43,08	261	2	168	59	352	31	16	0,57	9,2	2	51,1
82 82	PEIPOU	6,818	45,5253	176399	24,59	142	76	142	76	241	2	22	0,25	13	1	36,4
83 83	PLAN	6,9258	45,6244	173501	29,03	284	16	39	55	185	30	14	0,603	9	2	24,0
84 84	RECUL	6,9618	45,4669	163528	24,04	171	69	31	17	297	13	19	0,16	10,1	1	87,0
85 85	RIDD	7,2233	46,1551	191076	48,27	119	68	264	19	358	12	22	0,815	8,8	2	50,3
86 86	SAPIN	7,1486	46,1063	191226	45,89	352	73	151	16	243	6	15	0,77	7,8	2	17,1
87 87	SEIGNE	6,8091	45,7528	188335	31,61	308	48	82	32	188	24	17	0,779	7,1	2	23,6
88 88	STFOY (1)	6,9313	45,5787	170819	27,58	91	56	359	2	267	34	16	0,701	4	1	59,4
89 89	STFOY (2)	6,9313	45,5787	170819	27,58	157	11	48	61	253	27	14	0,492	7,1	2	45,4
90 90	THUIL	6,8991	45,7203	180467	31,73	88	71	265	19	355	1	10	0,53	4	3	36,7
91 91	TIGNES1	6,9199	45,5054	168218	24,97	32	73	129	2	220	17	17	0,127	5,1	1	15,0
92 92	TIGNES2	6,9254	45,4539	167310	24,62	195	25	60	56	295	21	13	0,418	7,3	2	89,6
93 93	TIGNES3	6,9442	45,4977	166841	24,84	65	75	280	12	188	8	11	0,812	4,3	2	16,8
94 94	TOULJE	7,1882	45,922	174777	41,70	300	47	145	40	44	13	24	0,87	6,5	2	2,3
95 95	VALDER1	7,1055	45,54	156734	28,37	316	51	209	13	110	36	12	0,07	3,6	2	81,6
96 96	VALDER2	7,1119	45,546	157102	29,03	272	78	115	11	24	5	13	0,33	6,6	1	5,0
97 97	VALDER3	7,122	45,5882	158115	30,31	83	50	248	39	344	7	11	0,922	6,5	3	46,3
98 98	VALDER4 (1)	7,0259	45,6242	158809	31,85	79	79	303	8	212	8	10	0,05	14,7	2	0,2
99 99	VALDER4 (2)	7,0259	45,6242	158809	31,85	247	3	343	63	155	26	12	0,65	2,9	2	56,8
100 100	VALGR1	7,1562	45,6978	162121	34,54	36	73	271	10	178	14	12	0,09	4,1	2	36,5
101 101	VALGR25	7,0482	45,6041	164006	29,88	16	56	183	33	277	6	22	0,74	10,5	2	67,1
102 102	VALGR3	7,0632	45,6206	163870	30,63	228	87	126	1	36	3	12	0,5	5,1	2	5,4
103 103	VALGR4	7,1008	45,679	164637	33,11	319	39	204	28	89	38	20	0,95	4,5	2	55,9
104 104	VALP1 (1)	7,2974	45,8715	165025	42,25	26	5	168	84	296	4	17	0,76	8,8	2	73,7
105 105	VALP1 (2)	7,2974	45,8715	165025	42,25	117	78	9	4	279	11	21	0,62	9,6	3	56,7
106 106	VALP2 (1)	7,4924	45,9007	156241	46,80	161	57	312	30	49	13	12	0,345	11,4	2	2,2
107 107	VALP2 (2)	7,4924	45,9007	156241	46,80	98	31	188	59	190	4	11	0,949	5,1	3	36,8
108 108	VALP3	7,4628	45,8881	156868	45,85	196	85	99	1	9	5	13	0,707	6,1	2	36,8
109 109	VALP4 (1)	7,437	45,8782	157530	45,05	94	4	294	86	184	1	14	0,256	6,8	3	41,0
110 110	VALP4 (2)	7,437	45,8782	157530	45,05	359	75	155	13	246	6	17	0,07	8	1	21,0
111 111	VALP5	7,3534	45,8323	161924	41,17	301	38	122	55	31	0	17	0,548	7	3	10,2
112 112	VALSA1 (1)	7,2008	45,5295	149591	29,27	88	45	319	32	210	27	11	0,13	3	2	0,7
113 113	VALSA1 (2)	7,2008	45,5295	149591	29,27	101	35	322	47	207	21	10	0,511	8,6	3	2,3
114 114	VALSA2	7,2115	45,5228	150088	30,29	91	36	327	38	208	32	11	0,48	4,1	3	2,3
115 115	VALSA3	7,2032	45,6525	156315	33,73	28	79	139	4	229	11	10	0,16	4,2	2	15,3
116 116	VALSA4	7,2051	45,6742	157494	34,50	93	70	304	17	211	10	16	0,773	14,4	2	3,5
117 117	VELAN	7,2591	45,9267	171307	43,15	300	1	201	85	30	5	16	0,499	8	2	13,1
118 118	VENS	7,1241	46,0865	191048	45,03	278	8	165	70	11	19	26	0,635	19,9	3	34,0
119 1	AMBIN	6,8738	45,1858	161203	12,79	67	70	269	19	176	7	75	0,12	10,5	1	16,8
120 2	ARPON1	6,6961	45,3295	178459	16,96	220	73	18	16	110	6	14	0,21	7,2	2	87,0
121 3	ARPON2	6,7123	45,3169	176865	16,63	131	59	306	31	37	2	34	0,55	9,3	2	20,4
122 4	AVERO1	7,0884	45,2918	147746	18,57	335	75	174	14	83	5	20	0,49	9,3	1	64,4
123 5	AVERO2	7,0306	45,3236	153136	19,33	29	85	179	4	269	2	45	0,49	12,4	1	69,7
124 6	BARDO	6,7172	45,0895	171680	8,49	237	75	103	10	11	10	31	0,06	13,5	1	2,5
125 7	BOZEL	6,6236	45,4446	187619	20,27	135	53	317	37	226	1	31	0,55	14,9	2	25,7
126 8	CELS	6,9431	45,1048	154282	9,91	302	33	72	45	193	27	14	0,51	10,9	3	3,1
127 9	CENIS1	6,9271	45,2269	158077	14,72	325	79	129	10	219	3	31	0,21	10,9	2	24,3
128 10	CENIS2(1)	6,9614	45,2292	155519	15,03	264	68	87	22	357	1	17	0,23	11,2	1	18,0
129 11	CENIS2(2)	6,9614	45,2292	155519	15,03	107	6	4	66	199	23	18	0,63	7,4	2	4,0
130 12	CENIS3	6,9243	45,2831	159833	16,88	314	65	107	22	210	10	16	0,67	8,8	2	13,1
131 13	CENIS4	6,9822	45,1886	152919	15,53	346	83	178	6	87	1	19	0,52	10,3	2	73,5
132 14	CENIS5	6,8634	45,2473	163465	13,09	333	76	161	14	71	2	17	0,37	8,2	2	55,9
133 15	CENIS6(1)	6,9695	45,2137	154500	14,47	1	74	111	6	203	15	32	0,19	8,3	1	8,5
134 16	CENIS6(2)	6,9695	45,2137	154500	14,47	181	11	337	78	91	5	29	0,92	6,6	2	76,5
135 17	CHAMB	6,2788	45,3873	211715	16,32	317	24	133	65	226	1	18	0,49	11,5	2	29,7
136 18	CHAMPA	6,7087	45,4599	181892	21,44	278	7	171	68	10	21	26	0,35	11,7	2	11,4
137 19	CHAMPA2	6,7167	45,4566	181179	21,40	276	8	40	75	184	12	17	0,54	12,8	2	17,4
138 20	ECOT	7,0927	45,3807	150651	22,20	340	66	183	22	89	8	23	0,16	4,2	2	66,8
139 21	ETACHE	6,8136	45,1613	165347	11,55	9	73	104	1	194	16	35	0,05	4,7	2	2,5
140 22	EXTRA	6,7986	45,2186	167718	13,62	145	66	299	22	33	10	10	0,26	3,5	3	19,4
141 23	FONDS	6,6524	45,3089	181183	15,97	10	69	142	14	236	15	43	0,17	11,5	1	40,0
142 24	FONT	6,5006	45,4514	197002	19,59	296	59	100	30	194	7	24	#	#	3	5,6
143 25	FOUR	7,0167	45,3945	156765	21,95	101	78	318	10	226	7	28	0,29	8,5	1	24,0
144 26	FREJUS	6,665	45,1386	176473	10,09	254	85	124	3	34	4	26	0,21	14,9	2	23,9
145 27	GALIB	6,4096	45,065	195495	6,86	281	12	30	57	184	30	35	0,13	14,1	2	2,9
146 28	GIAGLI	7,0171	45,143	149237	11,86	7	79	271	1	181	10	17	0,56	15,5	3	10,9
147 29	GENEP	6,9191	45,4192	164884	21,91	225	81	355	6	86	7	24	0,47	9,1	1	64,1
148 30	LANLEV	6,9287	45,2998	160007	17,55	155	82	278	4	9	7	19	0,26	11	3	8,6
149 31	LLBOURG	6,8697	45,2852	164031	16,56	156	54	335	36	65	1	30	#	#	3	48,4
150 32	LLBOURG2	6,8671	45,2829	164161	16,45	301	85	193	2	103	5	22	0,38	10	2	86,5
151 33	LORES	6,9429	45,4013	162442	21,49	335	76	188	12	96	8	17	0,43	8,5	1	74,5
152 34	MAD	6,368	45,4403	206547	18,38	127	27	320	62	219	5	26	0,46	13,3	2	20,6
153 35	MASSE	6,6984	45,2596	176388	14,54	342	38	187	49	82	12	20	#	#	3	67,5
154 36	MASSE2	6,6974	45,2598	176472	14,54	127	75	277	13	9	7	19	0,56	7,9	2	5,5
155 37	MENU	6,5822	45,3168	186741	15,82	290	82	83	7	173	4	17	0,46	5,4	2	22,8
156 38	MICHE	6,4865	45,2184	191768	12,10	278	29	54	52	175	22	27	0,57	17,8	3	17,1

Table 1 (continued)

157 39	MODAN	6,6004	45,2091	182780	12,28	155	68	300	18	34	12	24	0,53	12,3	2	21,7
158 40	MODAN2	6,6658	45,198	177506	12,20	36	58	170	23	269	21	17	0,98	8,4	3	76,8
159 41	NEIGE(1)	7,0328	45,4064	156054	22,57	174	82	303	5	34	6	39	0,13	12,7	1	11,4
160 42	NEIGE(2)	7,0328	45,4064	156054	22,57	285	9	92	81	195	2	14	0,3	14,4	2	7,6
161 43	OREL(1)	6,5565	45,2223	186443	12,53	102	78	316	10	225	6	12	0,15	8,8	3	32,5
162 44	OREL(2)	6,5565	45,2223	186443	12,53	165	9	273	63	70	25	9	0,06	5,9	3	57,5
163 45	OREL(3)	6,5565	45,2223	186443	12,53	105	5	295	85	195	1	12	0,47	18,9	3	2,5
164 46	ORGIE	6,65	45,2135	179048	12,67	305	72	100	17	192	7	10	0,36	7,9	3	0,7
165 47	OULX	6,8577	45,0425	162728	7,02	43	76	300	3	209	14	17	0,67	13,5	2	22,0
166 48	PARTIE(1)	6,6722	45,2584	178363	14,35	108	36	300	54	202	6	19	0,46	8,9	2	7,7
167 49	PARTIE(2)	6,6722	45,2584	178363	14,35	316	85	48	0	138	5	10	0,44	10,8	3	56,3
168 50	PRIOUX	6,6941	45,348	179163	17,58	142	78	345	11	254	5	11	0,15	25,7	3	56,4
169 51	PUIT	6,5093	45,4674	196908	20,14	283	68	97	22	188	2	34	#	#	3	12,1
170 52	RIBON(1)	6,9941	45,3104	155426	18,49	202	68	87	10	353	20	21	0,13	7,2	2	25,5
171 53	RIBON(2)	6,9941	45,3104	155426	18,49	56	70	182	12	275	16	31	0,64	8,9	1	76,5
172 54	RIBON(3)	6,9941	45,3104	155426	18,49	104	1	12	77	195	13	20	0,16	7,2	2	3,5
173 55	ROCHEU	6,9818	45,3804	158791	21,08	79	73	211	12	303	12	15	0,48	7,6	2	78,1
174 56	ROMOL	6,7638	45,1324	168689	10,24	52	71	214	18	306	5	22	0,27	14,4	3	64,2
175 57	SALIN	6,528	45,4678	195531	20,29	3	64	155	23	250	11	15	0,93	8,6	3	49,7
176 58	SARRA	6,6038	45,158	181559	10,54	131	80	303	9	33	1	28	0,26	21,6	2	22,5
177 59	TELEG	6,4442	45,1977	194645	10,26	168	72	329	18	61	6	14	0,57	10,2	2	49,7
178 60	TERMI	6,8373	45,2859	166502	16,36	300	67	143	21	50	8	20	0,01	9,1	2	33,6
179 61	TERMI2	6,8407	45,3164	167144	17,50	21	70	247	14	154	14	24	0,02	4,8	2	43,5
180 62	VALLO	6,4273	45,1594	195311	9,96	298	86	197	1	107	4	25	0,14	11,6	1	83,0
181 63	VALMO	6,4333	45,4306	201344	18,50	300	51	94	36	194	13	19	0,11	2,1	2	4,5
182 64	VALTHO1	6,5781	45,2825	186157	14,66	233	80	115	5	24	9	22	0,59	18,7	3	9,3
183 65	VALTHO2	6,5669	45,308	187669	15,44	52	82	187	6	277	6	20	#	#	3	81,6
184 66	VILLARO	7,0023	45,3313	155510	19,38	146	87	339	3	249	1	21	0,05	6,9	2	49,6
185 S1	Innri Alpa	8,107	46,2143	159306	68,31	312	69	125	21	216	2	13	0,273	5,8	2	32,3
186 S2	Schwarzl Balma	8,1074	46,2174	159619	68,37	124	72	351	12	258	13	13	0,296	10,25	2	9,6
187 S3	Innri Biela	8,1041	46,2105	159003	68,17	300	80	129	10	38	2	10	0,591	6,9	3	30,2
188 S4	Sirwoltensee	7,9962	46,2151	162835	65,54	348	74	222	10	129	13	9	0,159	5,8	3	63,5
189 S5	Obers Fulmoos	7,9689	46,2085	163081	64,76	357	63	159	26	253	7	10	0,589	7,9	2	8,2
190 S6	Alte Kaserne	8,0967	46,1894	157060	67,66	149	82	326	8	56	1	17	0,401	5,8	2	11,7
191 S7	Hopschusee	8,0242	46,2543	165906	66,85	110	81	322	7	232	5	10	0,629	6,4	3	14,9
192 S8	Hopschusee	8,0222	46,2546	165990	66,81	128	70	336	17	243	9	13	0,9	6,154	2	3,8
193 S9	Staldhorn	8,0213	46,2582	166385	66,84	135	63	334	26	240	8	11	0,459	12	3	6,8
194 S10	Hopsche	8,0206	46,253	165882	66,75	39	87	138	1	228	3	15	0,767	7,2	2	18,7
195 S11	Engiloch	8,0203	46,2256	163110	66,30	90	80	329	5	238	9	46	0,508	11,53	1	8,3
196 S12	Rosshodestafel	8,0249	46,1956	159939	65,93	10	80	134	6	224	8	21	0,439	11,76	1	21,9
197 S13	Gali Egga	8,0112	46,1919	160006	65,52	240	85	133	1	43	4	18	0,29	18,22	2	22,5
198 S14	Egga	8,0366	46,2034	160352	66,35	303	73	50	5	141	17	29	0,404	9,7	1	74,7
199 S15	Glatthorn	8,0714	46,212	160142	67,36	174	75	325	13	56	7	21	0,625	8,476	2	11,4
200 S16	Bodme	8,052	46,1923	158738	66,56	219	83	309	0	39	7	16	0,346	6	2	27,6
201 S17	Walderuberg	8,0584	46,213	160638	67,05	134	82	337	7	246	3	17	0,52	8,353	2	1,1
202 S18	Homatta	8,0526	46,2171	161232	66,97	128	67	352	17	257	15	13	0,192	5,692	2	10,0
203 S19	Hübschhorn W	8,0374	46,2437	164414	67,01	101	74	325	12	232	11	17	0,686	9,7	2	15,0
204 S20	Biel	8,0703	46,1724	156146	66,70	0	69	117	10	211	18	42	0,16	10,79	1	35,7
205 S21	Furggu	8,0904	46,1766	155946	67,29	161	75	324	15	56	4	9	0,655	13,56	3	11,3
206 S22	Guggilhorn	8,0871	46,1696	155339	67,09	356	56	222	18	126	17	14	0,048	8,786	2	58,9
207 S23	Bodmerhorn	8,0413	46,1908	158924	66,26	70	72	302	12	209	14	17	0,323	6,9	2	37,3
208 S24	Ochseläger	7,9523	46,2302	165808	64,73	66	77	285	10	194	8	31	0,244	10	1	50,7
209 S25	Lawigrabe	8,0485	46,1951	159125	66,51	54	73	186	12	279	14	43	0,113	10,28	1	32,5
210 S26	Bodmerhorn	8,0397	46,1881	158705	66,17	103	73	329	12	237	14	31	0,218	8,968	1	9,2
211 S27	Bodmerglatsche	8,0312	46,1839	158551	65,89	85	75	320	9	228	14	27	0,283	9,37	1	17,9
212 S28	Blauseewji	8,0445	46,1847	158208	66,24	16	81	171	8	262	4	12	0,187	14,5	2	15,8
213 S29	Alte Kaserne	8,0902	46,1872	157031	67,45	151	83	315	7	45	2	26	0,513	9,76	1	22,5
214 S30	Chaltwasser	8,0559	46,249	164387	67,55	81	76	333	5	242	14	47	0,343	9,447	1	5,5
215 S31	Simplon - Kulm	8,0345	46,252	165350	67,07	106	77	325	10	234	8	12	0,519	6,167	3	13,1
216 S32	Stockji	7,9694	46,2528	167506	65,51	66	86	288	3	198	3	15	0,365	5,1	2	47,5
217 S33	Antonius	8,062	46,1824	157416	66,65	93	77	348	4	257	12	30	0,337	13,97	1	10,4
218 S34	Färicha	8,0515	46,1721	156707	66,21	308	79	125	11	215	1	27	0,437	7,926	2	31,2
219 S35	Laggin Biwak	8,0452	46,1654	156228	65,93	72	74	200	10	292	12	21	0,136	9,9	2	46,1
220 S36	Hübschhorn S	8,0547	46,2256	162039	67,16	67	73	332	2	242	17	34	0,192	8,559	1	5,2
221 S37	Breithorn	8,0781	46,2345	162233	67,88	83	73	335	5	243	16	27	0,325	5,667	1	4,9
222 S38	Chesselhorn	8,0818	46,221	160737	67,77	150	64	6	21	270	14	15	0,388	8,9	2	22,2
223 S39	Casermetta	8,1149	46,1962	157221	68,24	12	87	137	2	227	3	17	0,482	7,2	2	21,2
224 S40	Waira	8,1328	46,153	152248	68,03	257	71	350	1	81	19	34	0,266	12,72	2	13,0
225 S41	Stalden	7,8937	46,2785	172630	64,16	56	76	325	1	235	14	15	0,24	12,73	2	9,2
226 S42	Furgghalte	8,0214	46,2055	161052	66,00	166	76	316	12	47	7	24	0,501	9,9	1	19,0
227 S43	Schilthorn	8,0127	46,2105	161836	65,87	242	73	334	1	65	17	15	0,138	6,8	2	0,9
228 S44	Wyssbode	8,0179	46,2121	161824	66,02	284	70	24	4	116	20	12	0,361	9,5	3	50,0
229 S45	Obre Stosbode	8,0181	46,2022	160819	65,87	238	85	341	1	71	5	9	0,28	9,556	3	5,1
230 S46	Holiecht	8,0535	46,2067	160153	66,83	174	85	322	5	52	3	26	0,396	8,3	1	14,8
231 S47	Gärtjini	8,046	46,1487	154525	65,67	148	76	332	14	242	1	27	0,311	11,2	2	3,7
232 S48	Weissmies	8,0408	46,1416	153976	65,40	180	80	344	9	74	2	19	0,253	7,6	1	8,6
233 S49	Schafnuwald	8,1245	46,1629	153514	67,97	337	74	147	15	237	3	21	0,241	9,1	1	11,0
234 S50	Tannuwald	8,1082	46,154	153095	67,39	190	77	26	12	295	3	10	0,589	7,2	3	47,6
235 S51	Sera	8,1219	46,171	154425	68,02	5	80	160	10	250	4	9	0,529	8	3	2,0

Table 1 (continued)

236	S52	Ramsema	8,1292	46,2007	157259	68,68	30	76	134	4	224	14	19	0,423	7,47	2	24,7
237	S53	Altes Hospiz	8,0162	46,2337	164063	66,33	121	73	322	16	230	6	27	0,166	9,963	1	16,3
238	S54	Nidristi Alp	7,9548	46,2578	168490	65,24	130	75	325	15	235	4	21	0,785	7,9	1	10,2
239	S55	Gampisch	8,0055	46,2333	164365	66,06	9	75	140	0	232	11	11	0,162	6,6	3	14,1
240	S56	Zwischbergen	8,0544	46,1174	151100	65,33	165	56	340	34	71	3	10	0,227	12,2	3	5,7
241	S57	Galaberr	8,0778	46,151	153737	66,53	24	72	203	18	293	1	19	0,253	7,9	2	46,5
242	S58	Glis	7,963	46,2983	172294	66,08	356	69	91	2	181	21	11	0,337	8,9	3	65,1
243	S59	Mäderhitza	7,9583	46,2838	170985	65,74	12	75	281	1	191	15	18	0,114	11,3	2	54,7
244	S60	Mäderhitza	7,9568	46,2763	170277	65,59	114	86	248	3	338	3	26	0,292	13,04	2	87,6
245	S61	Griewald	7,959	46,2868	171268	65,81	1	87	227	2	137	2	13	0,163	15,77	3	71,2
246	SD	Staldhorn	8,0227	46,2645	166983	66,97	145	4	357	85	235	2	11	0,737	9,7	3	12,0
247	1	BDTNO	6,5208	44,7313	186998	-4,29	142	77	349	18	258	6	30	0,6	4,7	1	82,3
248	2	BDTSU	6,529	44,7147	186555	-4,88	108	83	356	3	265	6	25	0,4	4,8	1	89,9
249	3	RUBUR	6,9732	44,3968	160292	-18,99	2	3	260	76	93	13	12	0,8	17,8	2	68,0
250	4	BOUCH	6,9492	44,6902	153907	-7,28	64	69	236	21	327	3	30	0,2	7,5	1	25,7
251	5	CERVI	6,7505	44,8862	167829	0,91	208	76	313	4	44	14	18	0,3	9,7	2	43,1
252	6	CHABE	6,759	44,973	167323	4,22	193	83	58	5	327	5	21	0,4	9,5	1	37,2
253	7	CHAMB	6,8347	44,5413	166085	-12,45	32	67	214	23	124	1	23	0,3	11,4	2	43,5
254	8	CHENO	6,753	44,9253	167637	2,40	111	76	317	13	226	6	10	0,4	14	3	43,6
255	9	CHESU	6,7527	44,9123	167646	1,91	261	73	97	17	5	4	10	0,3	11	3	3,1
256	10	MALAM	6,6433	44,7118	177599	-5,32	287	81	34	3	125	8	36	0,2	9,2	1	49,7
257	11	COLRI	6,5333	44,9342	184994	2,64	234	71	89	16	356	1	19	0,3	7,2	2	6,6
258	12	PEYGU	6,7403	44,8252	168851	-1,38	66	78	182	5	273	11	13	0,2	14,6	2	85,6
259	13	LONGE	6,9487	44,65	154686	-8,92	81	70	296	17	202	11	16	0,2	12,9	2	30,9
260	14	COLSN	6,841	44,4888	167107	-14,44	202	3	354	57	104	13	15	0,6	8,6	2	61,6
261	15	CPEYR	6,6245	44,7763	178355	-2,97	84	82	247	7	337	3	30	0,2	11,7	1	20,0
262	16	CROUS	6,6552	44,7238	176505	-4,92	62	67	294	15	199	17	8	0,4	15	3	23,9
263	17	CROUS	6,6552	44,7238	176505	-4,92	15	16	157	7	282	11	10	0,5	16,5	3	73,1
264	18	CRXSA	6,5508	44,8363	183762	-0,75	143	82	327	8	237	1	19	0,4	10,3	2	57,8
265	19	CRXSA	6,5508	44,8363	183762	-0,75	169	32	353	58	260	2	20	0,5	7,3	2	80,8
266	20	FOUIL	6,8003	44,5537	168416	-11,77	130	82	4	5	274	6	11	0,4	10,4	3	74,2
267	21	GROOU	6,6755	44,6593	175878	-7,30	218	68	48	22	317	4	27	0,2	11	1	35,7
268	22	GROOU	6,6755	44,6593	175878	-7,30	219	39	37	5	128	1	27	0,8	11,3	3	44,7
269	23	JANES	6,7385	44,9338	168797	2,71	236	70	53	19	143	1	11	0,5	5	3	39,7
270	24	JANES	6,7385	44,9338	168797	2,71	172	4	43	83	262	5	8	0,7	14,5	3	79,3
271	25	JANOU	6,7535	44,9382	167624	2,89	343	81	250	0	160	9	13	0,4	9,8		22,9
272	26	LCORD	6,7688	44,841	166517	-0,82	204	84	77	4	347	5	13	0,4	10,5	2	12,2
273	27	NEUFC	6,7725	44,5713	170132	-10,96	281	70	150	13	57	15	20	0,3	10,6	2	68,0
274	28	NEUFC	6,7725	44,5713	170132	-10,96	16	20	208	70	108	4	12	0,6	11,4	3	61,0
275	29	LAUSE	6,6652	44,8558	174642	-0,17	55	84	172	3	262	5	17	0,3	8,8	2	82,2
276	30	LAVAL	6,8773	44,935	157846	2,84	175	75	84	0	354	15	22	0,4	11,7	2	8,8
277	31	MROYN	6,7297	44,6923	171090	-6,31	32	18	204	72	301	2	10	0,8	9,4	3	52,7
278	32	ORECE	6,5042	44,8017	187647	-1,87	200	2	310	83	111	7	17	0,8	8,5	3	67,1
279	33	ORCEA	6,5047	44,8017	187608	-1,88	195	77	3	15	93	4	23	0,3	12	1	85,1
280	34	ORCEB	6,5043	44,8017	187639	-1,88	199	75	2	14	93	4	16	0,1	11,4	1	85,1
281	35	OREES	6,5112	44,7963	187134	-2,07	15	77	178	13	269	4	10	0,2	12,6	1	88,9
282	36	OREES	6,5112	44,7963	187134	-2,07	203	5	96	73	295	16	10	0,2	17,8	2	62,9
283	37	OREOU	6,5115	44,7967	187107	-2,06	192	15	18	75	283	1	26	0,5	13,5	3	74,9
284	38	OROUA	6,5215	44,7952	186329	-2,12	122	8	343	7	252	6	31	0,3	9,5	1	74,1
285	39	OROUA	6,5213	44,7952	186345	-2,12	144	75	0	12	268	8	32	0,2	11,2	1	89,9
286	40	PARPA	6,6775	44,4968	179417	-13,02	176	74	337	15	69	5	13	0,2	14	2	82,0
287	41	PTPUY	6,6457	44,8325	176283	-0,99	298	85	47	1	137	4	15	0,4	9	1	42,0
288	42	BEAUD	6,689	44,8187	172941	-1,55	142	80	41	2	310	1	26	0,3	15,5	1	48,4
289	43	HOUER	6,7825	44,5877	168969	-10,42	207	29	62	56	304	18	16	0,7	14,8	2	45,6
290	44	MLZOU	6,6318	44,8422	177335	-0,63	91	52	232	32	331	14	30	0,2	8,6	2	28,4
291	45	MLZSU	6,6363	44,8327	177025	-0,97	97	62	258	28	349	28	12	0,1	9	2	10,0
292	46	PSTRL	6,7918	44,5793	168443	-10,78	218	71	76	15	343	11	14	0,2	8,5	2	6,2
293	47	PCHAT	6,7878	44,54	169738	-12,20	210	69	64	18	330	11	29	0,1	14,3	1	17,8
294	48	PCHAT	6,7878	44,54	169738	-12,20	187	2	13	69	278	2	15	0,4	7,5	2	69,8
295	49	PRORE	6,5642	44,9053	182531	1,64	154	70	315	19	47	6	20	0,2	9	2	45,4
296	50	RMOES	6,6122	44,8347	178919	-0,87	252	72	102	16	10	8	19	0,2	7,7	1	10,9
297	51	RMOOU	6,6175	44,84	178474	-0,69	245	75	93	14	1	6	26	0,3	8,7	1	1,7
298	52	ROBAR	6,5698	44,808	182424	-1,76	15	86	159	3	249	2	20	0,4	10	1	70,8
299	53	RBLER	6,5543	44,9083	183313	1,74	101	72	247	15	340	9	45	0,5	9,3	1	21,7
300	54	RBLOU	6,5423	44,9083	184260	1,75	312	71	50	3	141	18	22	0,4	9,7	1	40,7
301	55	TURGE	6,7807	44,8288	165640	-1,30	181	76	82	2	351	14	25	0,5	8,8	2	7,7
302	56	ESCPE	6,677	44,6393	176119	-8,02	16	10	118	60	277	27	25	0,2	7,6	1	75,0
303	57	ESCRI	6,6898	44,6428	175053	-7,95	205	38	10	52	110	7	34	0,9	6	1	62,0
304	58	ESCNO	6,7003	44,635	174379	-8,28	19	1	276	83	108	7	30	0,4	9	1	63,7
305	59	ESCSU	6,7163	44,6295	173235	-8,55	15	2	111	73	284	17	29	0,4	7,3	1	67,4
306	60	FREIS	6,5357	44,7608	185505	-3,32	213	83	329	3	59	7	15	0,3	15,8	2	62,3
307	61	FOURN	6,5443	44,7962	184521	-2,13	290	80	33	0	113	10	25	0,4	11,7	2	64,9
308	62	BARAI	6,8263	44,5552	166367	-11,88	256	83	33	5	123	5	15	0,4	14,4	2	45,1
309	63	BARAI	6,8263	44,5552	166367	-11,88	21	33	188	57	287	6	21	0,7	15,7	2	61,1
310	64	VMARY	6,8625	44,5702	163187	-11,55	50	73	206	16	298	7	17	0,4	10,5	2	50,5
311	65	VHOUÉ	6,8242	44,5788	165942	-10,99	24	40	203	50	293	1	17	0,8	9,8	2	56,0
312	66	VLAUG	6,7508	44,5945	171279	-9,99	325	79	89	6	180	9	6	0,4	10,3	3	10,0

QUATRIEME PARTIE

Evolution tectonique néogène à actuelle de l'arc alpin; discussion et interprétations

*La nature a une perfection à elle, surprenante, et qui résulte d'une addition de limites.
La nature est parfaite parce qu'elle n'est pas infinie.
Si on comprend les limites, on comprend comment le mécanisme fonctionne.*

A. Barricco

*Le monde est infini non seulement dans toutes les directions de l'espace,
mais aussi dans ses vérités*

R. Barjavel

Cette thèse a été menée conjointement à celle de Bastien Delacou concernant la tectonique active de l'arc alpin. Notre collaboration a permis d'établir des modèles prenant en compte différents contextes géodynamiques, que nous proposons dans cette partie. Préalablement, je présenterai une synthèse des travaux de Bastien Delacou sur la déformation actuelle de la chaîne, ainsi que ses interprétations géodynamiques. Deux articles utilisés dans cette discussion [Delacou et al., 2004a; in press] se trouvent en annexe.

Nous proposons ensuite une évolution géodynamique qui explique le passage du régime tectonique néogène au régime tectonique actuel.

Même si la convergence entre l'Afrique et l'Europe est bien établie [e.g. Nocquet, 2002], les études géodésiques récentes n'ont montré aucune convergence dans les Alpes occidentales [Calais et al., 2002]; de plus, le mouvement de la partie Nord du promontoire Apulien par rapport à l'Europe semble très faible [Oldow et al., 2002]. La convergence continentale est donc probablement accommodée dans d'autres orogènes péri-méditerranéens. D'une manière générale, les études géodésiques sont en accord avec les résultats sismotectoniques, mais, la plus grande partie (plus de 80-90%) de la déformation des Alpes occidentales semble être accommodée « asismiquement », par du creeping, de la déformation ductile ou une mise en charge élastique [Sue et al., submitted].

L'extension sismogène est très bien développée dans l'arc des zones internes. Comme cela a été démontré par Bastien Delacou (annexe 2), cette extension est localisée au niveau de la croûte épaissie. De plus, les directions d'extension sont orientées perpendiculairement aux structures alpines. Les rares séismes compressifs sont localisés au pied du fort gradient de topographie. Une réponse gravitaire à l'absence de convergence est proposée, et différentes modélisations numériques [Delacou et al., in press] confirment ces résultats (voir annexe 3). Une partie des tenseurs de paléocontraintes, associés à des failles normales tardives sont orientés perpendiculairement à la chaîne, et pourraient être l'expression d'un régime tectonique comparable au régime actuel.

Comme nous l'avons vu, la tectonique cassante, tardive, de l'arc des Alpes occidentales internes est principalement extensive. Une part non-négligeable de la déformation est décrochante, et représente 20 à 25% du nombre de failles mesurées. Les directions d'extension sont principalement parallèles aux structures alpines, mais certains axes σ_3 sont orientés perpendiculairement ou obliquement à la chaîne. Il convient donc de proposer un modèle géodynamique qui rende compte de ces observations. Le problème a été abordé par Sue [1998], qui examinait les différents mécanismes d'extension en contexte syn- et post-orogénique, et proposait différents modèles possibles pour les Alpes occidentales. Ce travail et celui de Bastien Delacou a permis d'accroître la taille de la zone d'étude, et surtout de reconnaître deux mécanismes d'extension distincts, pour le Néogène et l'Actuel.

Le passage d'un régime tectonique guidé par la convergence (extension liée à l'extrusion et / ou à des soulèvements relatifs) à un régime tectonique guidé par l'absence de convergence (rééquilibrage isostatique et étalement gravitaire) montre l'importance des forces aux limites. Cependant, les forces de volume deviennent prépondérantes si la collision ralenti ou s'arrête et si des modifications de l'équilibre isostatique interviennent.

I. Tectonique active et géodynamique actuelle de l'arc Alpin

Je présente ici les résultats de la thèse de Bastien Delacou [Delacou, 2005], qui a analysé le régime tectonique actif de la chaîne alpine, ainsi que ses interprétations géodynamiques pour les Alpes centrales et occidentales. Ce chapitre a été écrit par Bastien Delacou, et repris pour être intégré ici.

1) Tectonique active

Dans une chaîne où la déformation est particulièrement lente (1-2 mm.an⁻¹, [e.g. Calais *et al.*, 2002]) et la couverture végétale abondante en dessous de 2000-2500 m, il est difficile d'observer des indices néotectoniques. En effet, si l'évolution tectonique associée à la formation des nappes de charriage en Interne (à l'Eocène-Oligocène), et à la propagation du front de déformation vers l'Externe (au Miocène-Pliocène) sont bien caractérisées [e.g. Tricart, 1980; Choukroune *et al.*, 1986; Fry, 1989; Gratier *et al.*, 1989; Burkhard, 1990; Laubscher, 1991; Pognante, 1991; Ford, 1996; Spalla *et al.*, 1996; Burkhard et Sommaruga, 1998; Schmid et Kissling, 2000], les observations de terrain concernant la déformation active sont rares et souvent controversées, ne permettant pas d'aboutir à une image homogène de la déformation active. Dans ce contexte, l'analyse de la sismicité fournit des informations capitales sur le régime tectonique actuel de la chaîne.

Avec l'installation des premiers sismographes dans les années 1940, cette analyse a consisté à établir des catalogues qualitatifs de la sismicité, dans lesquels la localisation des séismes permettait uniquement une image de la répartition de la sismicité [e.g. Rothé, 1941; Pavoni, 1961; Ahorner *et al.*, 1972]. Le mode de déformation associé à cette sismicité n'était alors pas identifié et les interprétations tectoniques consistaient à appliquer les concepts de la formation d'une chaîne de collision à la répartition de la sismicité.

Dans les années 1970, avec le développement de réseaux sismologiques plus denses, la construction de mécanismes au foyer a été rendue possible, permettant de définir le régime (compressif/extensif/décrochant) ainsi que les directions (axes P: pression ; axes T: tension) de la déformation associée à la sismicité. La synthèse des mécanismes au foyer disponibles aujourd'hui, réalisée par Bastien Delacou (voir annexe 2), permet d'aboutir à une base de données comportant 389 mécanismes au foyer, répartis dans l'ensemble de la chaîne et de son avant-pays [Delacou *et al.*, 2004a]. L'analyse de cette base de données, autorisée par une méthode originale de régionalisation de la déformation (figure IV.1), permet l'obtention d'une image fiable et homogène du régime de déformation actuel, complétée de l'état de contraintes des régions considérées. La caractéristique principale de ce champ de déformation/contraintes obtenu est l'occurrence d'un régime extensif, déjà reconnu régionalement dans les travaux de [Maurer *et al.*, 1997; Eva *et al.*, 1998; Sue *et al.*, 1999; Baroux *et al.*, 2001; Kastrup *et al.*, 2004]. Ce régime est généralisé à l'ensemble des zones internes des Alpes centrales/occidentales depuis le Sud Valais jusqu'à l'arrière du massif de l'Argentera. Caractérisant les zones 'hautes' de la chaîne, cette extension présente des directions radiales à l'arc alpin. Au niveau de la zone externe, le régime de déformation sismogène est dominé par des décrochements, avec localement de l'extension (bassin molassique suisse, Nord Valais) ou de la compression (Nord-Est des chaînons Helvétique, front de Belledonne, front de la nappe de Digne, bordure de la plaine du Pô). Ce régime de déformation contrasté présente toutefois une stabilité des axes de déformation, avec des directions de compression en zone externe s'organisant de manière radiale, perpendiculairement à l'axe de la chaîne. Cet éventail, centré sur la plaine du Pô, avait déjà reconnu Fréchet [1978] et Pavoni [1986], avec beaucoup moins de séismes.

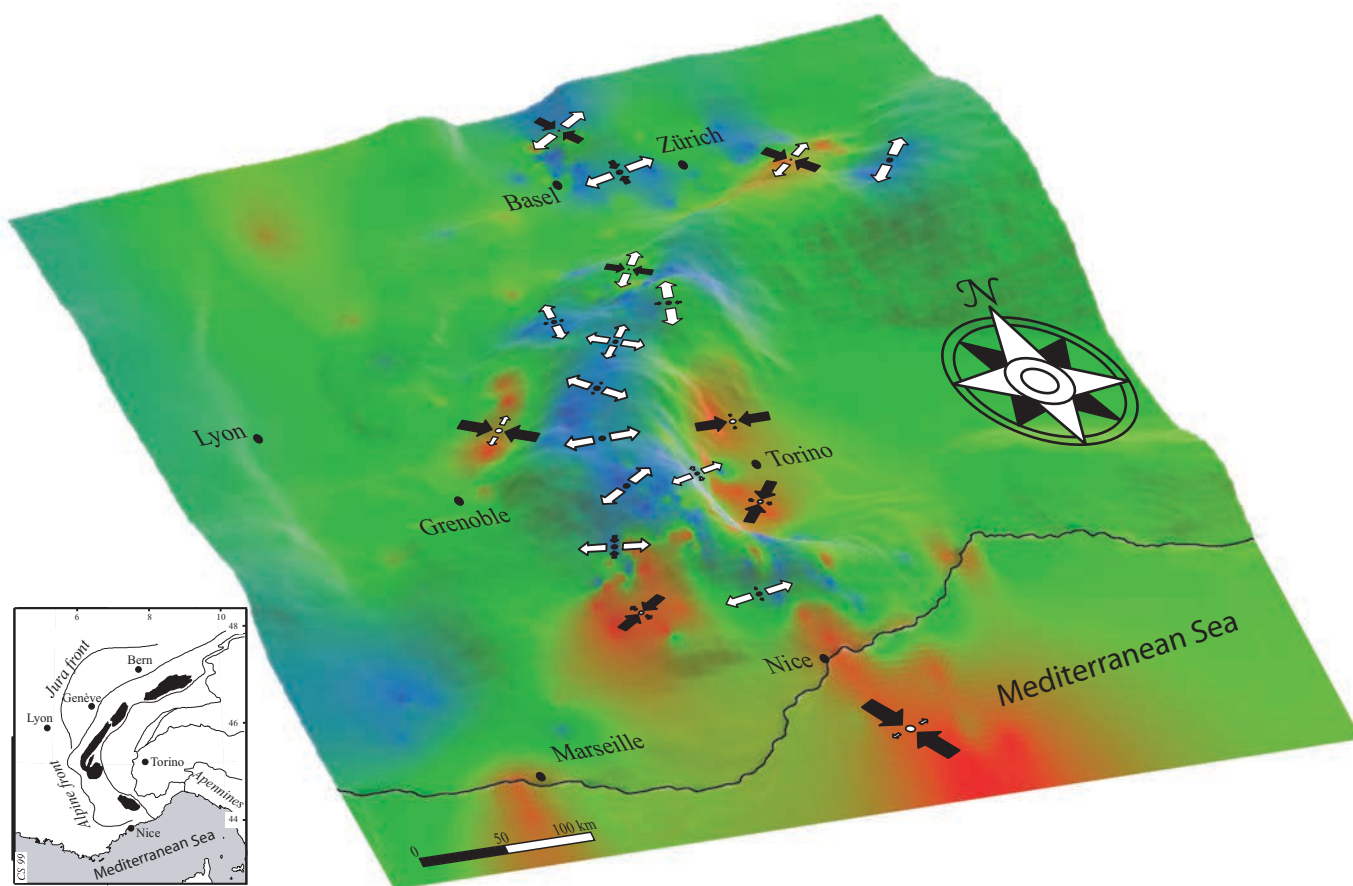


Figure IV.1: Vue tridimensionnelle des Alpes centrales et occidentales utilisant un MNT des altitudes moyennes sur un diamètre de 50 km. La couleur correspond au régime tectonique : les zones extensives (en bleu) sont continues dans la haute chaîne, du massif de l'Argentera au Valais, et plus à l'Est, dans les Grisons (Suisse orientale). Ce régime extensif suit la courbure de l'arc, corrélée avec la croûte épaissie. Le régime compressif (en rouge) est limité à quelques zones au pied du fort relief moyen. Le régime décrochant (en vert) se retrouve dans toutes les Alpes. Les flèches correspondent au champs de contraintes actuel, calculé par inversion de populations de mécanismes au foyer (σ_1 en noir, σ_3 en blanc). Voir l'annexe 2 pour plus de détails.

Malgré les informations capitales fournies par ce catalogue sismotectonique, l'analyse des mécanismes au foyer seule ne permet pas l'identification univoque de failles associées aux séismes 'mécanisés' à cause de l'ambiguïté entre les deux plans nodaux. Afin de pouvoir définir le champ de fracturation active (figure IV.2), différentes méthodes, plus ou moins fiables, peuvent être utilisées. La plus précise d'entre elles consiste à analyser des crises de sismicité par relocalisations relatives. Cette technique est basée sur la corrélation (en temps ou en fréquence) de séismes présentant des formes d'ondes similaires (dû à un trajet similaire des fronts d'onde). Elle aboutit à une localisation des événements les uns par rapport aux autres avec une précision de l'ordre d'une dizaine de mètres [e.g. Deichmann et Garcia-Fernandez, 1992; Maurer et Deichmann, 1995]. Il est alors possible de définir le plan de faille associé à la crise sismique qui s'aligne avec le (ou les) mécanisme(s) au foyer d'un (ou des) séisme(s) de la séquence. L'ensemble des données de localisation relative [Deichmann et Garcia-Fernandez, 1992; Augliera *et al.*, 1995; Maurer et Deichmann, 1995; Deichmann *et al.*, 2002; Kastrup *et al.*, 2004; Delacou *et al.*, submitted] a été compilée (en rouge) sur la carte de déformation active de la figure IV.2.

Une deuxième technique permettant d'analyser la fracturation active consiste à analyser les alignements locaux/régionaux de séismes qui définissent une 'zone de fracturation' (et

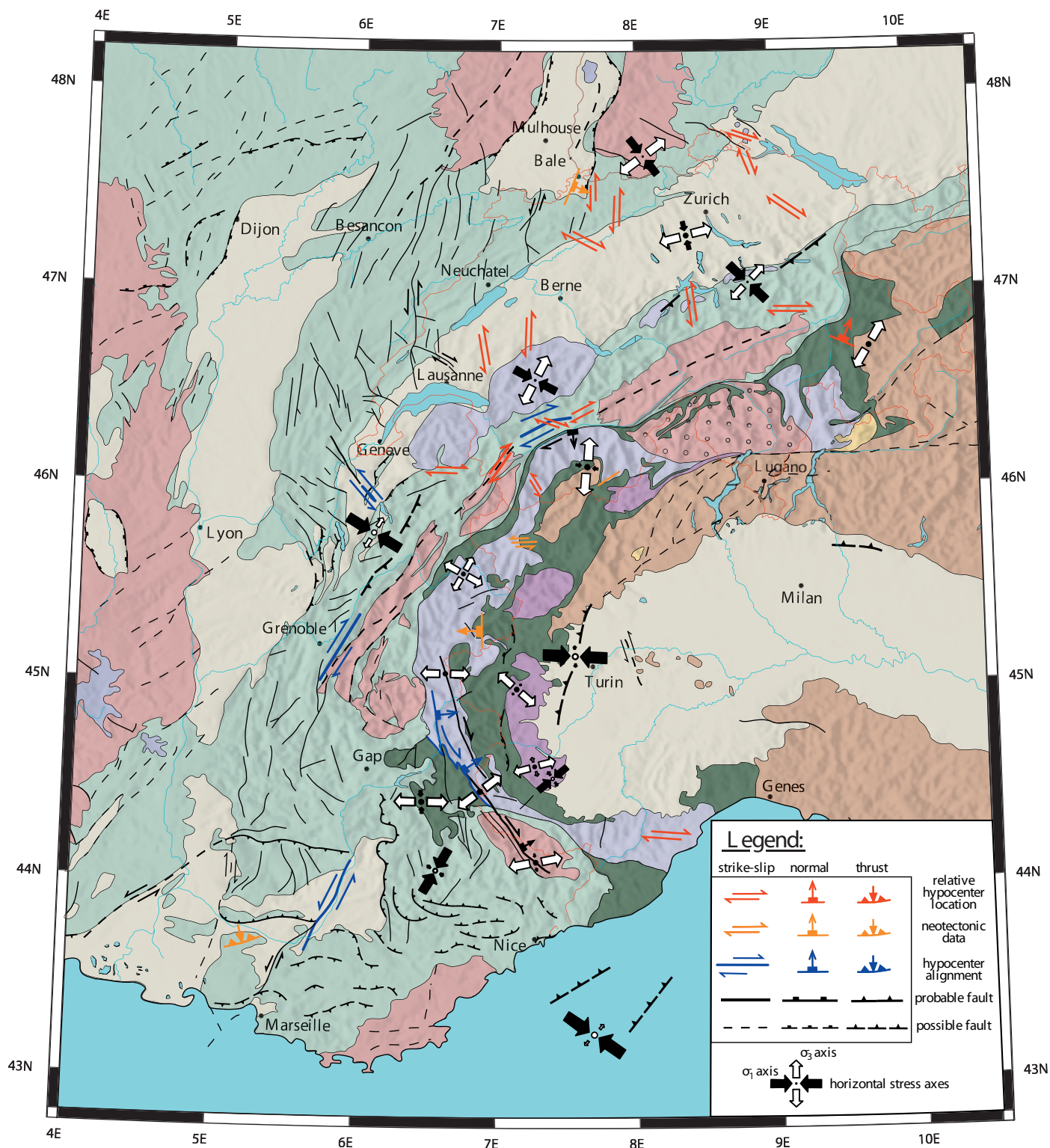


Figure IV.2: Carte synthétique des structures tectoniques actives de l'arc des Alpes centrales/occidentales, d'après Deichmann & Garcia-Fernandez [1992] ; Augliera *et al.* [1995] ; Maurer & Deichmann [1995] ; Deichmann *et al.* [2002] ; Kastrup *et al.* [2004] ; Maurer [1993] ; Eva *et al.* [1998] ; Sue [1998] ; Thouvenot *et al.* [1998] ; Thouvenot *et al.* [2003] ; Ferry *et al.* [2001] ; Lacassin *et al.* [2001] ; Carraro *et al.* [1994] ; Meghraoui [2001] ; Meghraoui *et al.* [2001] ; Dutour *et al.* [2002] ; Champagnac *et al.* [submitted-a]. Voir le texte pour plus de détails.

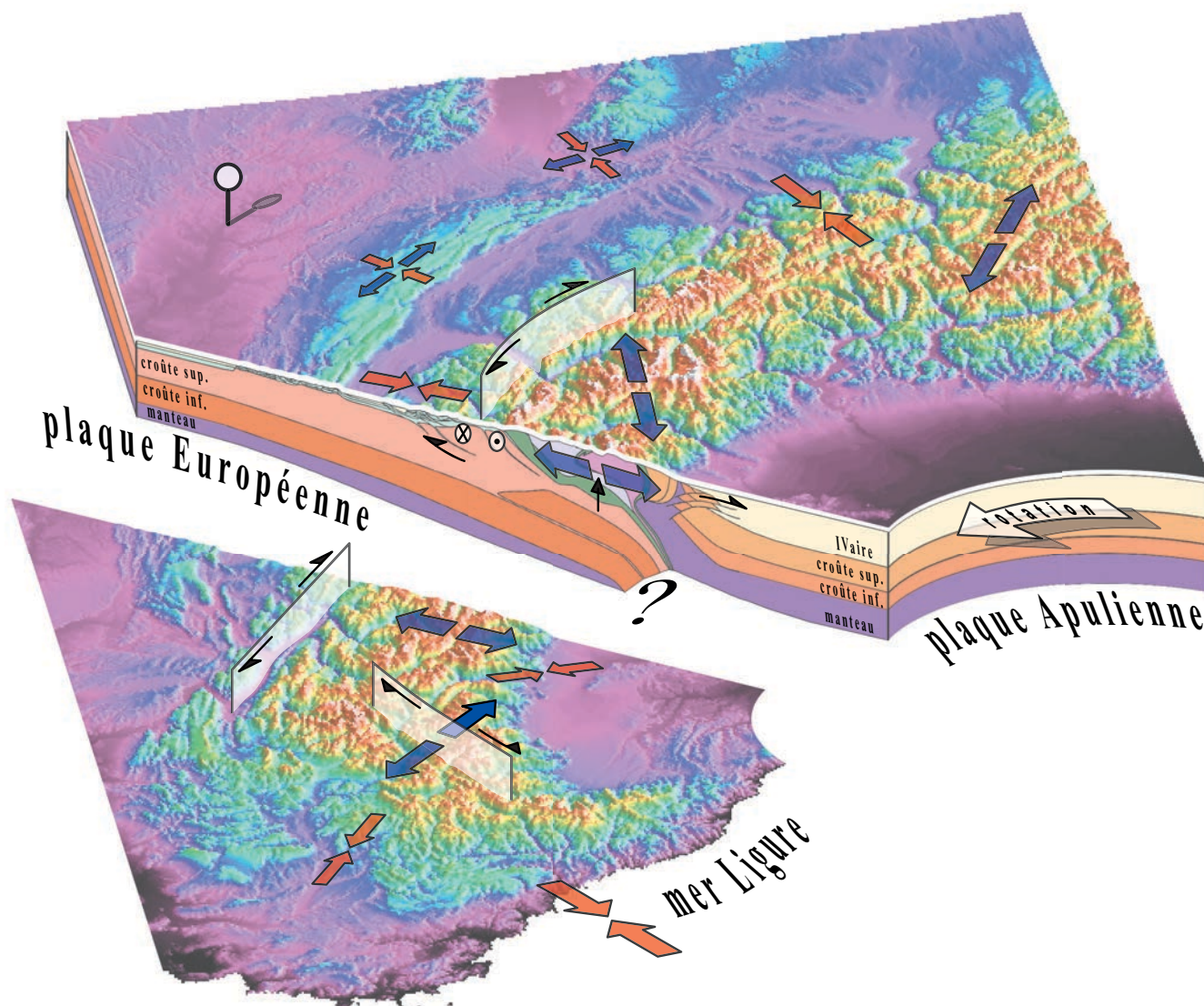


Figure IV.3: Bloc 3D synthétique représentant la tectonique active et le régime géodynamique actuel de l'arc alpin. Le régime tectonique, dominé par l'extension perpendiculaire à la chaîne dans les zones 'hautes' contraste avec le régime décrochant à compressif caractérisant les flancs de l'orogène. Les conditions aux limites sont indiqués par une plaque Apulienne soumise à une rotation anti-horaire par rapport à une plaque Européenne fixe (représenté par une punaise au nord-ouest du modèle).

non un plan de faille unique), plus ou moins continue suivant les cas. La zone de failles du Wildhorn, dans le Nord Valais (figure IV.2), constitue un bon exemple de ce type d'alignement de séismes [Maurer et Deichmann, 1995], définissant un système dextre parallèle à la vallée du Rhône. Cependant, les études de localisation relatives de séquences sismiques ayant eu lieu dans cette zone montrent que les failles ainsi définies présentent une configuration oblique, interprétée comme des structures de type 'Riedel' qui aboutissent à l'alignement observé par une répartition en échelon. Une synthèse des alignements sismiques [Maurer, 1993; Eva *et al.*, 1998; Sue, 1998; Thouvenot *et al.*, 1998; Thouvenot *et al.*, 2003] est présentée (en bleu) sur la carte tectonique synthétique de la figure IV.2.

Malgré les difficultés rencontrées sur le terrain dans l'étude des structures tectoniques actives des Alpes centrales/occidentales, quelques études (souvent controversées), ont permis l'identification de structures néotectoniques, présentées en orange sur la figure IV.2 [Carraro

et al., 1994; Sue, 1998; Ferry *et al.*, 2001; Lacassin *et al.*, 2001; Meghraoui, 2001; Meghraoui *et al.*, 2001; Dutour *et al.*, 2002; Champagnac *et al.*, in prep.]. Ces études sont basées sur des travaux de tranchées (faille de Bâle-Reinach supposée avoir causée le séisme destructeur de Bâle en 1356, [Ferry *et al.*, 2001; Meghraoui *et al.*, 2001]) ou sur des déformations affectant le Quaternaire ([Carraro *et al.*, 1994 ; Champagnac *et al.*, in prep.], voir le chapitre II.3). Elles peuvent être ensuite comparées à la sismicité régionale afin d'analyser la cohérence des indices de déformation. En règle générale, la difficulté réside dans la différenciation entre une origine tectonique ou gravitaire (glissement de versant, surcharge des glaciers) de ces structures cassantes. Des indices tels que la continuité sur plusieurs versants de la zone de fracturation, la compatibilité avec le champ régional de fracturation ou la présence de 'coins' de colluvions le long d'un plan de faille permettent d'attribuer à ces structures une origine tectonique. Les taux de déformation actuels étant faibles, les indices néotectoniques considérés fiables sont rares, et une liste exhaustive des failles actives n'est pas réalisable à l'heure actuelle.

L'ensemble de ces données sismotectoniques et néotectoniques a été complété par le tracé de failles reconnues sur le terrain, mais dont l'activité n'est pas attestée. Deux classes de fiabilité ont été introduites (possible et probable), en considérant l'orientation de ces failles dans le contexte tectonique régional définie par le champ de déformation/contraintes déduit de l'analyse géodésique et sismotectonique [Delacou *et al.*, 2004a; Delacou, 2005]. Si les failles ainsi définies s'intègrent dans le régime tectonique local, elles sont qualifiées de 'probables', tandis que si elles représentent des structures régionales importantes, sans que le régime tectonique associé soit bien défini par notre étude (dans des régions de changement de régime tectonique ou de sismicité contrastée), elles sont alors qualifiées de 'possibles'. L'interprétation des ces structures doit rester prudente ; elles ne représentent qu'une proposition, réalisées dans le but d'obtenir une image homogène de la tectonique active.

L'analyse de la figure IV.2 montre que le régime tectonique actuel est caractérisé par :

- une extension perpendiculaire à la chaîne généralisée au niveau des zones internes, qui provoque localement l'inversion de la discontinuité majeure que représente le Front Pennique, bien documentée dans le Briançonnais [Sue *et al.*, 1999; Sue et Tricart, 2003]. Cette inversion est postulée en arrière du Mont-Blanc [Seward et Mancktelow, 1994] et dans le Valais (Rahn, pers. comm.) sur la base d'études de traces de fissions. Il est d'ailleurs intéressant de noter que l'activité sismogène de cette zone extensive est plus abondante dans les zones placées en arrière des ensembles majeurs des Massifs Cristallins Externes (sud Valais entre Aar et Mont-Blanc et Briançonnais entre Pelvoux et Argentera). Ces massifs (Cristallins Externes), pourraient alors être considérés comme des môles rigides 'soutenant' les zones internes, bornant le régime extensif dans les zones internes. Entre ces ensembles l'extension pourrait se propager vers l'externe (sous les chaînons helvétiques du Nord-Valais et les nappes de flyschs de l'Embrunnais).

- la présence d'un système de décrochements dextres généralisé à l'ensemble de la bordure externe occidentale de la chaîne, depuis l'alignement du Wildhorn dans le nord-Valais [Maurer et Deichmann, 1995; Maurer *et al.*, 1997] jusqu'à la Haute-Durance/Argentera [Sue, 1998; Sue *et al.*, 1999; Sue et Tricart, 2003] en passant par le décrochement des Aiguilles Rouges [Deichmann *et al.*, 2002] et le front de Belledonne [Thouvenot *et al.*, 2003]. Ce système décrochant, suivant la courbure de l'arc, s'intègre bien dans un modèle de rotation anti-horaire de la plaque Apulienne [e.g. Gidon, 1974; Anderson et Jackson, 1987; Ménard, 1988; Calais *et al.*, 2002; Collombet *et al.*, 2002],

- un système de fracturation diffus, caractérisant l'ensemble des zones externes, avec la présence de décrochements conjugués associés à des axes de compression radiaux perpendiculaires à l'orogène (bien exprimé par exemple sur le bassin molassique Suisse et le Jura, avec des décrochements sénestres N-S et dextres WNW-ESE), dérivant localement soit vers un régime extensif (région de Zürich, Sud du graben du Rhin), soit vers un régime

compressif (front de Belledonne, front de la nappe de Digne, chaînons helvétiques). Ce système est interprété comme résultant d'un régime de contraintes proche d'un état sphérique (σ_1 , σ_2 et σ_3 du même ordre de grandeur), permettant aux sources de contraintes locales de second ordre de s'exprimer.

En conclusion, la tectonique active de l'arc des Alpes centrales/occidentales est caractérisée par des déformations lentes (de l'ordre de 3 à 6e-08 an⁻¹, avec des vitesses de surface de l'ordre de 1 à 2 mm.an⁻¹ au maximum, [Calais *et al.*, 2002; Nocquet et Calais, 2004; Sue *et al.*, submitted] et un régime tectonique contrasté, caractérisé par la présence de tous les types de régimes de déformation (extensif, compressif et décrochant). Malgré cette apparente complexité, l'étude de Bastien Delacou montre une bonne cohérence dans la régionalisation de la déformation, avec un régime extensif caractérisant l'ensemble des zones 'hautes' internes, associé à des zones compressives restreintes au pied du relief alpin. Les décrochements, sont particulièrement abondants en externe (mais également présents dans les zones internes), et sont compatibles avec les orientation d'axes de contraintes.

2) Géodynamique :

D'un point de vue qualitatif, la corrélation entre régime de déformation et épaisseurs crustales (topographie et anomalie de Bouguer) établie à partir de la synthèse sismotectonique de Bastien Delacou (annexe 2) amène à proposer un régime tectonique contrôlé par des forces de volume (figure IV.3). Dans cette hypothèse, l'extension observée en interne au niveau des zones de croûte épaissies serait induite par le rééquilibrage des épaisseurs crustales vis-à-vis de l'avant-pays occidental et de la plaine du Pô, caractérisées par des épaisseurs crustales 'normales' (environ 30 km). Ces zones externes seraient alors soumises, en réaction à l'extension des zones internes, à un régime compressif localisé au pied du relief alpin. Ce régime résulte de l'équilibrage des potentiels gravitationnels entre zones internes et externes. Les conditions aux limites en rotation compliquent ce modèle et provoquent un régime décrochant dextre parcourant l'ensemble de la chaîne (figure IV.3).

Afin de préciser la contribution des mécanismes de rééquilibrage gravitaire sur la tectonique actuelle de la chaîne, des études de modélisation numérique ont été conduites par Bastien Delacou, d'une part en 3D dans un modèle de déformation visco-plastique (code SHELLS [Kong et Bird, 1995; Bird, 1999], voir l'annexe 3), d'autre part en coupe dans un modèle de déformation élasto-visco-plastique (code ADELI, [Hassani, 1994; Hassani et al., 1997]). Ces études montrent qu'en l'absence de conditions aux limites mobiles, le réajustement en volume de la chaîne aboutit à un régime tectonique très proche de celui observé grâce à l'étude sismotectonique : l'extension est radiale à la chaîne dans les zones internes et la compression (également perpendiculaire à l'arc), caractérise la zone externe (figure IV.4). Les taux de déformation calculés montrent une bonne correspondance avec les calculs de déformation géodésiques, du même ordre de grandeur (3 à 6e-08 an⁻¹). De plus, les modélisations réalisées en coupe (profil ECORS) montrent qu'en présence de conditions aux limites mobiles, l'état de déformation s'écarte rapidement de celui observé, avec un système totalement compressif (respectivement extensif) dès qu'on atteint des taux de convergence (respectivement divergence) de 1 mm.an⁻¹. Le régime actuel de l'arc des Alpes centrales/occidentales apparaît donc comme résultant d'un équilibre interne entre extension et compression, généré par le rééquilibrage gravitaire des épaisseurs crustales en l'absence de convergence/divergence aux limites. Le rôle de la rotation reste difficile à quantifier, mais permettrait d'expliquer la réorientation des axes d'extension en interne, ainsi que l'occurrence de décrochements dextre généralisée au niveau de la zone externe.

Nous proposons donc que le régime géodynamique actuel de l'arc alpin résulte de l'arrêt

ISOSTATIC MODEL; FIXED BOUNDARIES (Delacou et al., in press)

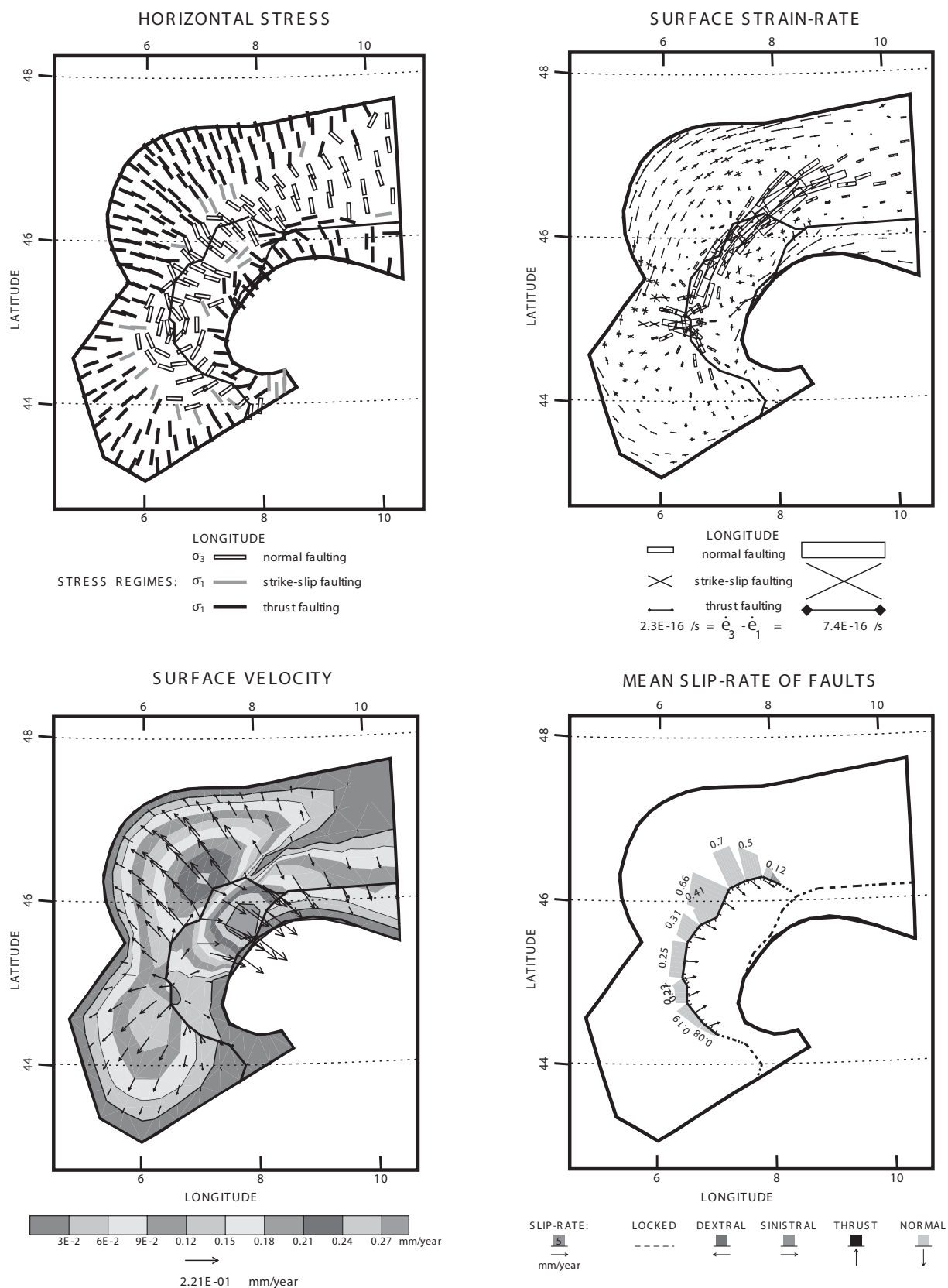


Figure IV.4: Exemple de résultats des modélisations numériques calculées par Bastien Delacou. Ce modèle utilise une géométrie crustale réaliste et des conditions aux limites fixes. Il représente une réponse tectonique à une anomalie de potentiel gravitaire des Alpes occidentales et centrales. La contrainte horizontale (en haut à gauche), les taux de déformation (en haut à droite), la vitesse de surface (en bas à gauche) et les mouvements sur les failles sont calculés et représentés (voir l'annexe 3 pour plus de détails).

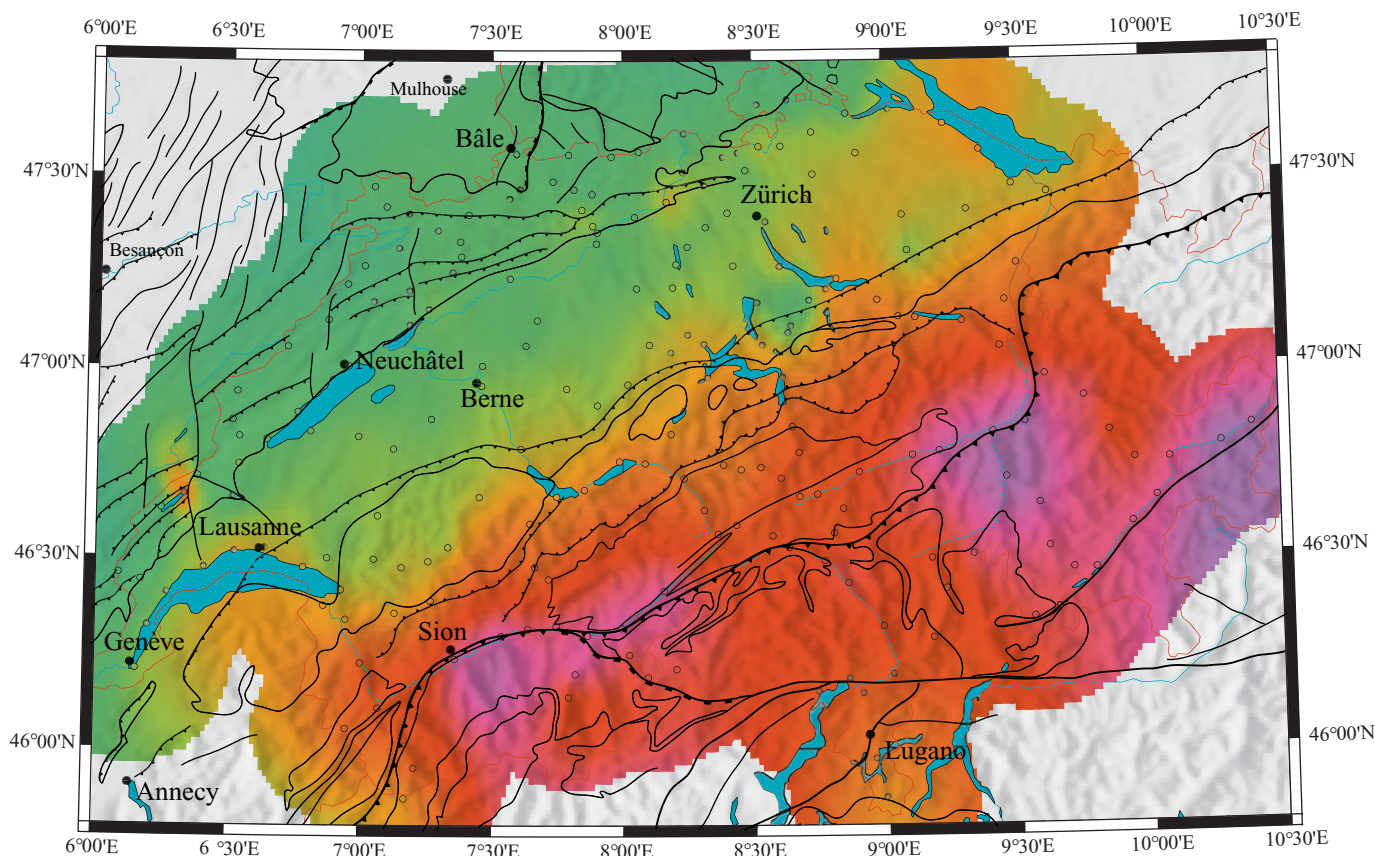
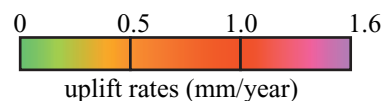


Figure IV.5: Carte de taux de soulèvement relatif par rapport à un point fixe situé à Aarberg (Nord de la Suisse centrale), d'après Gubler *et al.* [1981].



de la convergence Apulie/Europe, avec une probable contribution de conditions aux limites en rotation, définissant ainsi un régime tectonique post-collisionnel (figure IV.3). Cependant, d'autres contributions (dont l'importance reste à définir), pourraient avoir un rôle important dans le régime tectonique de la chaîne. En particulier, il apparaît que le soulèvement des zones internes (par rapport aux zones externes), quelle que soit son origine, pourrait aboutir, par flexure de la lithosphère, à un régime tectonique proche de celui observé dans la synthèse sismotectonique de Bastien Delacou (extension en interne et transpression/compression en externe). Des études de nivellement, réalisées sur le territoire Suisse [Gubler *et al.*, 1981; Kahle *et al.*, 1997], montrent de tels soulèvements relatifs (figure IV.5), atteignant 1.5 mm/an au niveau des zones 'hautes' comparativement à un point fixe situé dans le Nord-Est du bassin molassique suisse. Ce soulèvement, dans notre modèle de rééquilibrage gravitaire post-collisionnel, serait induit par la réaction isostatique consécutive à l'extension observée dans les zones internes. Cependant, d'autres types de réaction isostatique (rôle de l'érosion et/ou d'un rebond post-glaciaire) pourraient jouer un rôle important.

Un autre type de réajustement, d'origine plus profonde, pourrait aussi avoir un rôle majeur, mais particulièrement difficile à quantifier. En effet, la structure lithosphérique de la chaîne, étudiée par tomographie sismique, montre une configuration complexe de la géométrie du (des) slab(s) lithosphérique(s) en profondeur (figure IV.6), interprétée de manières différentes suivant les auteurs et les techniques de calcul [Lippitsch *et al.*, 2003; Spakman et Wortel, 2004]. Au niveau des Alpes occidentales, un slab à pendage Est à Sud Est semble être correctement identifié jusqu'à 100-150 km, même si sa continuité en profondeur reste sujette à

discussion. Ce slab, lié à l'histoire de la subduction océanique (et/ou continentale) de la Téthys alpine (et/ou de ses marges continentales) pourrait, par des mécanismes tels que la rupture de slab (slab break-off) ou le recul de la subduction (slab roll-back) impliquer des conséquences majeures sur la dynamique crustale des Alpes. Sa rupture, postulée par Stampfli *et al.* [2002] à l'Oligocène ou par Lippitsch [2002] à l'actuel sous les Alpes occidentales, pourrait induire un remplacement du matériel subduit par l'asthénosphère avoisinante, ce qui entraînerait une réponse isostatique positive des zones internes sus-jacentes, ainsi qu'une flexure de l'ensemble de la lithosphère. Les effets de ce type de dynamique sur l'état de déformation/contraintes sont difficiles à appréhender et des études plus poussées (modélisation) sont nécessaires pour tenter de quantifier ces mécanismes. De la même manière, le corps d'Ivrée, identifié par les anomalies gravimétriques positives qu'il engendre, est interprété comme une remontée de matériel mantellique jusqu'en sub-surface. Sa position est particulièrement instable dans l'édifice alpin (d'un point de vue isostatique), et ses conséquences sur la dynamique actuelle de la chaîne

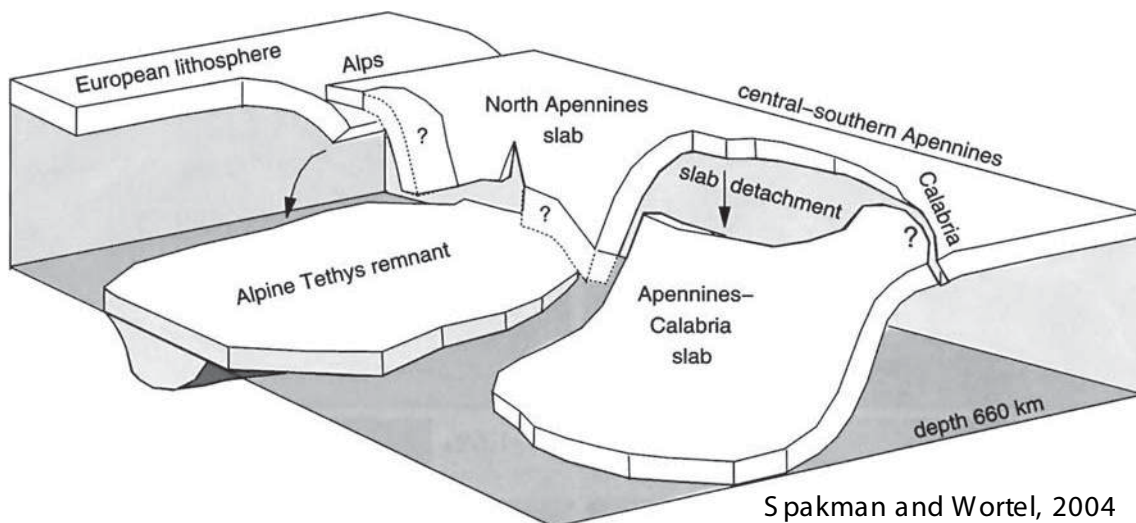
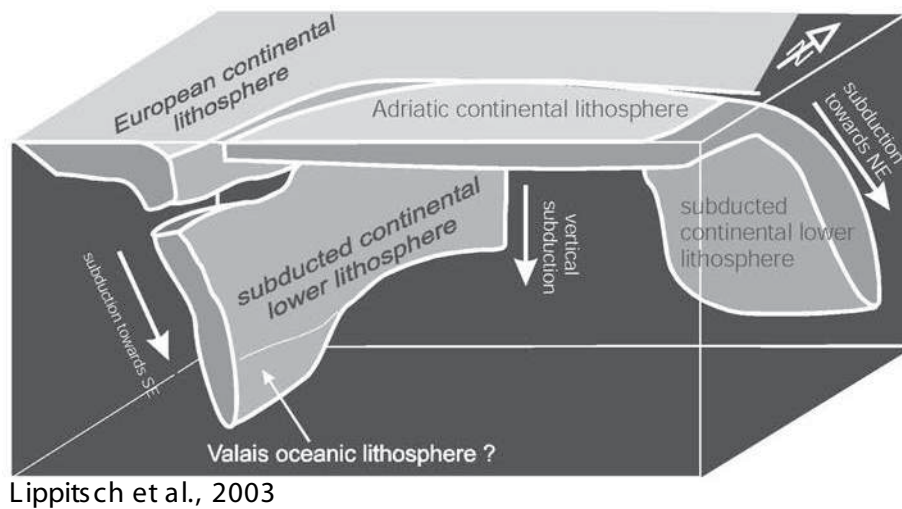


Figure IV.6: Blocs 3D lithosphériques interprétatifs basé sur les modèles de tomographie établis par Lippitsch *et al.* [2003], en haut ; et Spakman et Wortel [2004], en bas.

restent mal contraintes.

Malgré ces inconnues, le travail de Bastien Delacou a montré le rôle prépondérant du rééquilibrage gravitaire post-collisionnel dû aux hétérogénéités crustales de la chaîne, qui aboutit au régime tectonique analysé grâce aux outils de la sismotectonique. Ce travail se concentrant sur la dynamique actuelle de la chaîne, la question de l'âge de mise en place de ce régime post-collisionnel, et les raisons géodynamiques d'un arrêt de la convergence restent ouvertes. Les comparaisons avec les résultats du présent volume, nous aideront à proposer (chapitre IV.3) un modèle d'évolution Mio-Pliocène à Quaternaire de la dynamique tectonique alpine.

II Géodynamique néogène de l'arc Alpin

Les phénomènes extensifs dans les chaînes de montagnes sont bien connus, et ont été étudiés en particulier dans les Andes [e.g. Dalmayrac et Molnar, 1981; Sébrier *et al.*, 1985; Deverchère, 1988], l'Himalaya [Molnar et Tapponnier, 1978; Armijo *et al.*, 1986; England et Houseman, 1989; Harrison *et al.*, 1992; Molnar, 1992], le Basin and Range [Malavieille, 1987; Lister et Davis, 1989; Jones *et al.*, 1992; Thatcher *et al.*, 1999] et la chaîne hercynienne [Ménard et Molnar, 1988; Echtler et Malavieille, 1990; Doblas, 1991]. D'autre part, les chaînes péri-méditerranéennes (cordillères Bétiques, Alpes occidentales, Apennins, Dinarides, Héliénides, Maghrébides) ont toutes subi une extension liée aux ouvertures océaniques néogènes [Platt et Vissers, 1989; Tricart *et al.*, 1994; Doglioni *et al.*, 1997; Jolivet *et al.*, 1998; Durand *et al.*, 1999; Jolivet et Faccenna, 2000; Rosenbaum *et al.*, 2002]. Différents modèles géodynamiques ont été proposés pour expliquer ces extensions, qui mettent en jeu des forces de volume (intrinsèques) et des forces aux limites (extrinsèques) qui s'équilibrent subtilement, changent au cours du temps et donnent à l'orogène la géométrie et la cinématique observées.

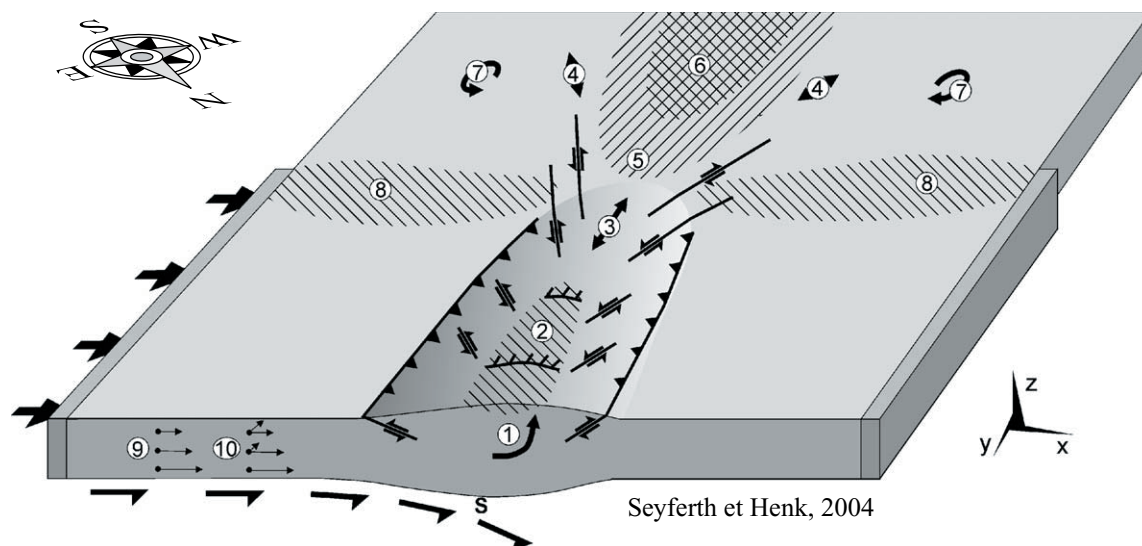
La plus grande partie de l'extension documentée par ce travail d'analyse de la fracturation est orientée parallèlement aux structures alpines, et suit la direction générale de l'arc. Cette tectonique extensive bien que difficilement datable (voir chapitre II.4) est contemporaine (pour sa plus grande partie) d'une tectonique compressive en externe. La coexistence dans un même orogène d'extension et de compression permet d'abandonner les modèles géodynamiques liés à des contextes post-orogéniques (effondrement provoqué par l'arrêt de la convergence [Lister et Davis, 1989; Thatcher *et al.*, 1999]). Les autres modèles géodynamiques possibles en contexte de convergence (collapse syn-orogénique, slab break-off, slab rollback) impliquent une direction d'extension parallèle à la direction de raccourcissement [Fleitout et Froidevaux, 1982; Molnar et Lyon-Caen, 1988; England et Houseman, 1989; Molnar et Lyon-Caen, 1989; Blanckenburg von et Davies, 1995; Jolivet *et al.*, 1998; Lippitsch *et al.*, 2003] et ne peuvent donc pas être appliqués à la tectonique néogène des Alpes.

D'autres modèles, comme l'extension sur l'extrados d'un pli de rampe crustal [Wilschko et Eastman, 1983; Burg *et al.*, 2002], le poinçonnement vertical d'un coin mantellique [Schwartz, 2002] ou une zone transtensive [Mancktelow, 1985; Hubbard et Mancktelow, 1992; Steck et Hunziker, 1994] peuvent être considérés localement, mais ne peuvent probablement pas expliquer un régime extensif aussi durable et étendu avec la direction d'extension que nous observons. Ces modèles ont déjà été commentés dans le cas des Alpes occidentales [Sue et Tricart, 2002], je ne les détaillerai donc pas ici.

Un modèle géodynamique basé sur les observations de terrain doit expliquer une extension parallèle à la chaîne en contexte de convergence. L'extrusion latérale, c'est à dire l'échappement d'un bloc vers une bordure libre sous l'effet d'un serrage, est une solution pour produire un contexte extensif à grande échelle, orienté perpendiculairement à la direction de raccourcissement. Comme cela a été montré par des modèles numériques [Seyferth et Henk, 2004], l'extrusion latérale est commune dans l'évolution tardive des orogènes, même dans le

cas d'un faible épaissement crustal, et même en l'absence de bordure libre. Quel que soit le contexte, la quantité d'extension accommodée par ce mécanisme varie proportionnellement de 10% à 70% de la quantité de raccourcissement, en fonction des conditions géodynamiques (figure IV.7). On retrouve ce mode de déformation au Tibet [Molnar et Tapponnier, 1975; Molnar *et al.*, 1987; Jolivet, 1995; Tapponnier *et al.*, 2001], dans les Alpes orientales [Tapponnier, 1977; Ratschbacher *et al.*, 1989; Seyferth et Henk, 2004], en Turquie [Dewey *et al.*, 1986; Le Pichon *et al.*, 1994].

Nous avons proposé ce modèle pour les Alpes occidentales [Champagnac *et al.*, 2004;

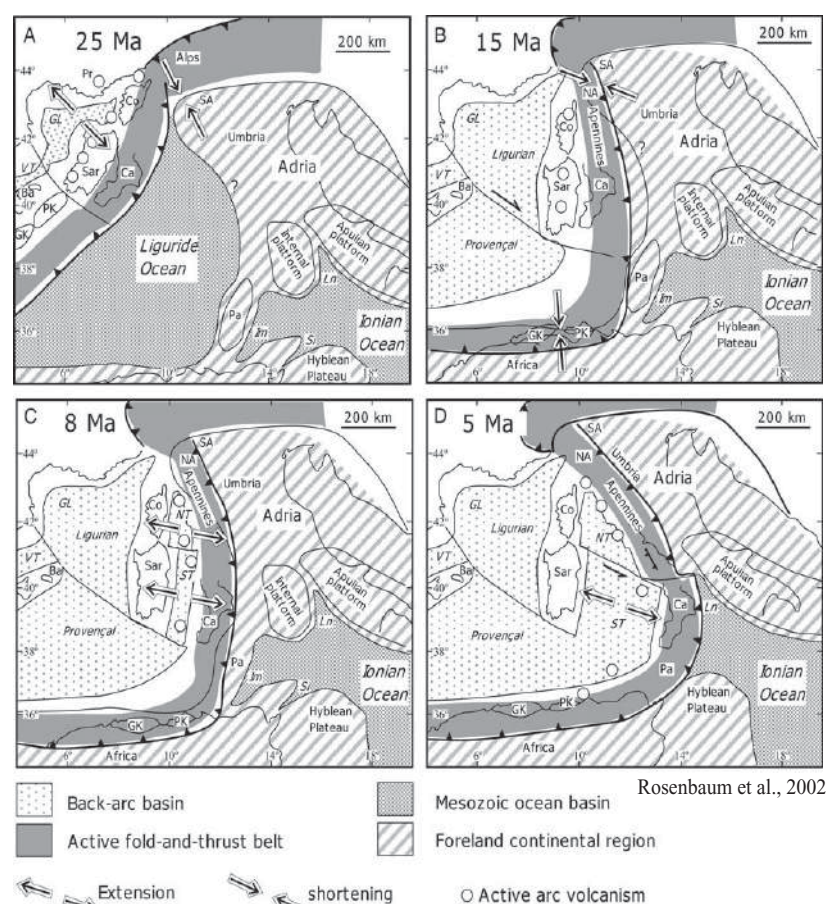


Schematic overview of prominent structures and processes observed in the numerical models:

- (1) maximum uplift of rocks; (2) zone of superficial crustal thinning, possible occurrence of normal faults;
- (3) and (4) areas of maximum orogen-parallel extension; (5) maximum amounts of lateral extrusion;
- (6) zone of extension in convergence-parallel direction; (7) rotation of foreland flanks;
- (8) zone of diffuse crustal thickening; (9) successive mechanical decoupling along the vertical crustal profile;
- (10) additional decoupling by partitioning of the convergence vector.

Figure IV.7: Modèle conceptuel d'extrusion latérale, basé sur des modélisations numériques [Seyferth et Henk, 2004]. L'orientation est indiquée pour comparaison avec les Alpes occidentales.

Champagnac *et al.*, submitted-b], lié et favorisé par l'ouverture puis la présence de la mer Ligure jouant le rôle de bordure libre. La rigidité du bloc considéré (qu'il reste d'ailleurs à définir) peut être discutée, mais la présence d'extension sur plusieurs centaines de km implique une rigidité probablement assez faible. Deux arguments ont été avancés par Sue [Sue, 1998; Sue et Tricart, 2002] pour repousser ce modèle de l'explication du régime extensif dans les Alpes sud-occidentales : la courbure importante de l'arc au Sud et à l'est de l'Argentera, et l'absence de décrochements sénestres conjugués aux grandes failles dextres. Comme nous l'avons écrit dans l'article pour *Tectonics* (voir la troisième partie), ces arguments peuvent être écartés : la forme très courbe de la partie la plus au Sud de l'arc (entre Nice et Gênes) semble être liée, pour partie, au processus de retrait du slab Apennin, au cours du Miocène Supérieur et du Pliocène [Gueguen *et al.*, 1998; Rosenbaum et Lister, 2004a; b], figure IV.8. Des études de traces de fission sur apatites donnent des âges maximums de 11 Ma, avec une accélération du soulèvement vers 5 Ma de l'Argentera et des Alpes Ligures [Bigot-Cormier *et al.*, 2000; Bogdanoff *et al.*, 2000; Foeken *et al.*, 2003]. Cet âge (11 Ma) correspond au transfert de l'extension de la mer Ligure vers le bassin Tyrrhénien [Kastens et Mascles, 1990; Faccenna *et al.*, 1996; Carminati, 2001; Rollet *et al.*, 2002; Rosenbaum *et al.*, 2002]. La géométrie alpine au cours du Miocène autorise donc une bordure libre directement en contact avec les unités internes. La faible importance



Schematic reconstruction of the tectonic evolution of the Apennine-Maghrebide belt. A. early Miocene (25 Ma); B. middle Miocene (15 Ma); C. late Miocene (8 Ma); D. Pliocene (5 Ma). Note that the Internal Platform is accreted to the overriding plate between C and D. Ba—Balearic Islands; Ca—Calabria; Co—Corsica; GK—Grand Kabylie; GL—Gulf of Lion; Im—Imerese; Ln—Lagonegro; NA—Northern Apennines; NT—Northern Tyrrhenian; Pa—Panormide platform; PK—Petite Kabylie; Pr—Provence; SA—Southern Alps; Sar—Sardinia; Si—Sicanian; ST—Southern Tyrrhenian; VT—Valencia Trough.

Figure IV.8: Evolution néogène des bassins Ligure et Tyrrhénien, en relation avec les Apennins et les Maghrébides.

des failles sénestres à l'Est de la chaîne alpine semble interdire un modèle d'extrusion entre deux décrochement conjugués. Néanmoins, l'importance de la rotation anti-horaire de la plaque Apulienne [Gidon, 1974; Anderson et Jackson, 1987; Vialon *et al.*, 1989; Collombet, 2001; Collombet *et al.*, 2002] explique cette lacune, en accommodant le mouvement relatif attendu le long d'un décrochement rotatif.

Hubbard et Mancktelow [1992] avaient proposé un modèle comparable, mais en transférant le mouvement des unités internes (Valais et Val d'Aoste en particulier) vers les nappes de flyschs et la nappe de Dignes (figure IV.9). Nos données montrent

que la direction d'extension suit la chaîne, vers le Sud et le Sud-Est, là où ces auteurs proposaient une translation vers le Sud-Ouest. Néanmoins, une géométrie pour ce bloc extrudé était proposée, limité au Nord-Ouest par la faille du Simplon, au Nord et à l'Ouest par les failles du Rhône et le décrochement de Belledonne. Un modèle comparable a également été proposé [Bistacchi *et al.*, 2001], en limitant le bloc à l'Est par une faille sénestre (faille d'Ospizio-Sottile) et en reprenant les limites de Hubbard et Mancktelow [1992] au Nord et à l'Ouest (figure IV.10).

Ces résultats permettent de proposer un bloc semi-rigide, limité au Nord-Est par la faille du Simplon, au Nord par la faille du Rhône, puis par le décrochement de Belledonne à l'Ouest. Cette limite semble avoir accommodé une déformation importante. Les décrochements équivalents, plus au Sud (failles dextres de Haute Durance-Serrenne-Berzeio) seraient la limite Sud-Ouest de ce bloc. La relation cinématique entre ces deux systèmes dextres (Rhône-Belledonne et Haute Durance-Serrenne-Berzeio) ne semble pas directe, et reste ouverte. La limite orientale du bloc proposé reste imprécise, et est moins franche que sa limite occidentale.

Comme nous l'avons vu, une partie des directions d'extension est perpendiculaire ou oblique à la direction alpine. Ces directions avaient déjà été observées localement, et cette étude confirme la présence de cette extension dans tout l'arc, et plus particulièrement dans la partie Sud, entre la Vanoise et l'Argentera. Cette extension a été reconnue en déformation ductile à ductile-cassante [e.g. Rolland *et al.*, 2000; Ganne *et al.*, 2004; Schwartz *et al.*, 2004] et interprétée comme

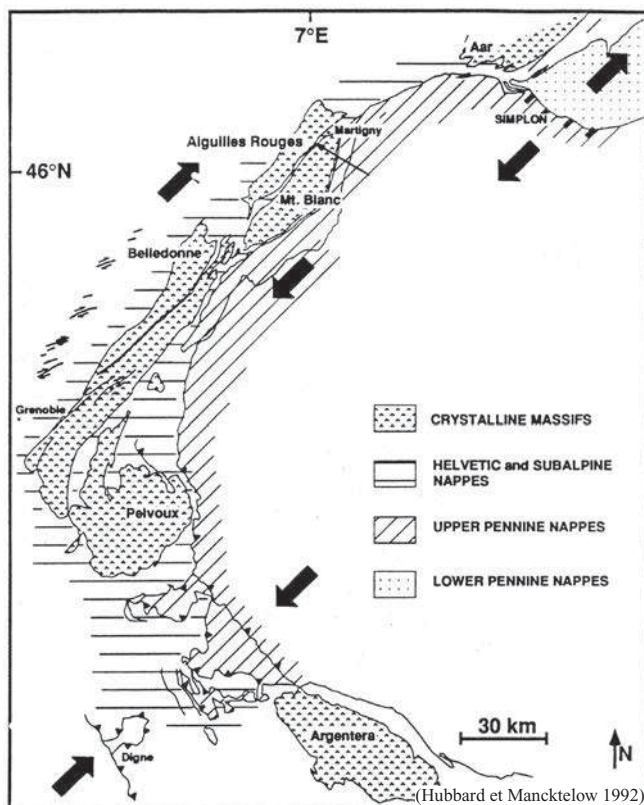


Figure IV.9: Modèle d'extrusion latérale proposé par Hubbard et Mancktelow [1992]. Les quantités de mouvements et les âges de la déformation sont comparable entre la région du Simplon (extension) et les nappes de charriage du Sud-Ouest de l'arc Alpin.

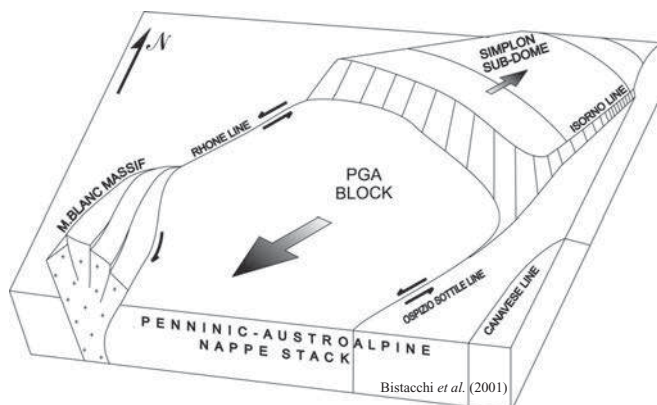


Figure IV.10: Modèle d'extrusion proposé par Bistacchi *et al.* [2001] entre le Mont Blanc et le dôme Lépointin.

une conséquence du soulèvement relatif des Massifs Cristallins Internes. Elle a également été reconnue en déformation fragile [Sue, 1998; Rolland *et al.*, 2000; Sue et Tricart, 2002; Champagnac *et al.*, 2004], en particulier en arrière du Front Pennique, et a été interprétée comme une conséquence du soulèvement relatif des Massifs Cristallins Externes [Seward et Mancktelow, 1994; Aillères *et al.*, 1995; Cannic *et al.*, 1999]. Enfin, cette direction correspond au régime tectonique actuel, documenté par la sismotectonique (voir chapitre IV.1). Ces origines différentes (soulèvements relatifs et rééquilibrage gravitaire) ne sont pas identifiables de manière certaine sur le terrain, et ont probablement interagis en se succédant dans le temps. Une partie en tout cas des déformations cassantes observées provient de niveau structuraux superficiels (voir chapitre II.4). Par analogie, ces déformations sont assimilables au régime tectonique actuel. Des indices néotectoniques, même s'ils sont discutables, montrent également une telle direction d'extension, plus récente que 15000 ans (voir chapitre II.3).

Ces différents moteurs de l'extension selon différentes directions ne sont pas exclusifs les uns des autres, et ont probablement interagis pour donner des structures complexes (extension multidirectionnelle, formation de dômes et bassins, reprise de structures compressives en extension). A ces différents moteurs, liés à un contexte général compressif, il faut ajouter la rotation de la microplaque Apulienne, [Gidon, 1974; Anderson and Jackson, 1987; Ménard, 1988; Laubscher, 1991; Collombet, 2001]. Ce mouvement

complexe de translation-rotation du bloc Apulien semble pouvoir expliquer une grande partie des déformations observées dans les Alpes. En fonction de la position du pôle de rotation, la partie septentrionale de cette plaque a pu provoquer une partie des mouvements compressifs, indépendamment du poinçonnement général. De la même manière, alors que le poinçonnement devenait moins actif, cette rotation a pu diminuer l'importance des forces aux limites dans les Alpes occidentales et laisser s'exprimer les forces de volume.

III Changement de régime tectonique et implications géodynamiques

La comparaison entre les résultats de Bastien Delacou (analyse du régime sismotectonique) et les miens (analyse de la fracturation) montre qu'il a existé deux régimes tectoniques différents dans l'ensemble de la chaîne des Alpes centrales/occidentales. Les modalités et l'âge de passage d'un régime à l'autre sont discutés dans ce chapitre, écrit en commun.

Au **Néogène**, le régime tectonique est caractérisé par une extension parallèle à l'axe d'allongement de la chaîne au niveau de l'ensemble des zones internes ([Champagnac *et al.*, submitted-b] voir la troisième partie) alors que la collision s'exprime simultanément en domaine externe par la propagation du front compressif (soulèvement des Massifs Cristallins Externes et plissement de la couverture). Ce régime tectonique est interprété comme résultant de l'**extrusion latérale** des zones internes en réponse au poinçonnement de la plaque Apulienne. Un des problèmes de cette analyse de tectonique tardi-alpine concerne le **manque de contraintes temporelles** des structures cassantes observées sur le terrain. De manière qualitative, la fracturation des zones internes est clairement postérieure aux structures ductiles, ce qui nous permet de proposer un âge de mise en place Néogène (voir le chapitre II.4).

En comparaison, le régime tectonique **actuel** est caractérisé par une extension perpendiculaire à l'orogène dans la haute chaîne, tandis que les zones externes sont soumises à

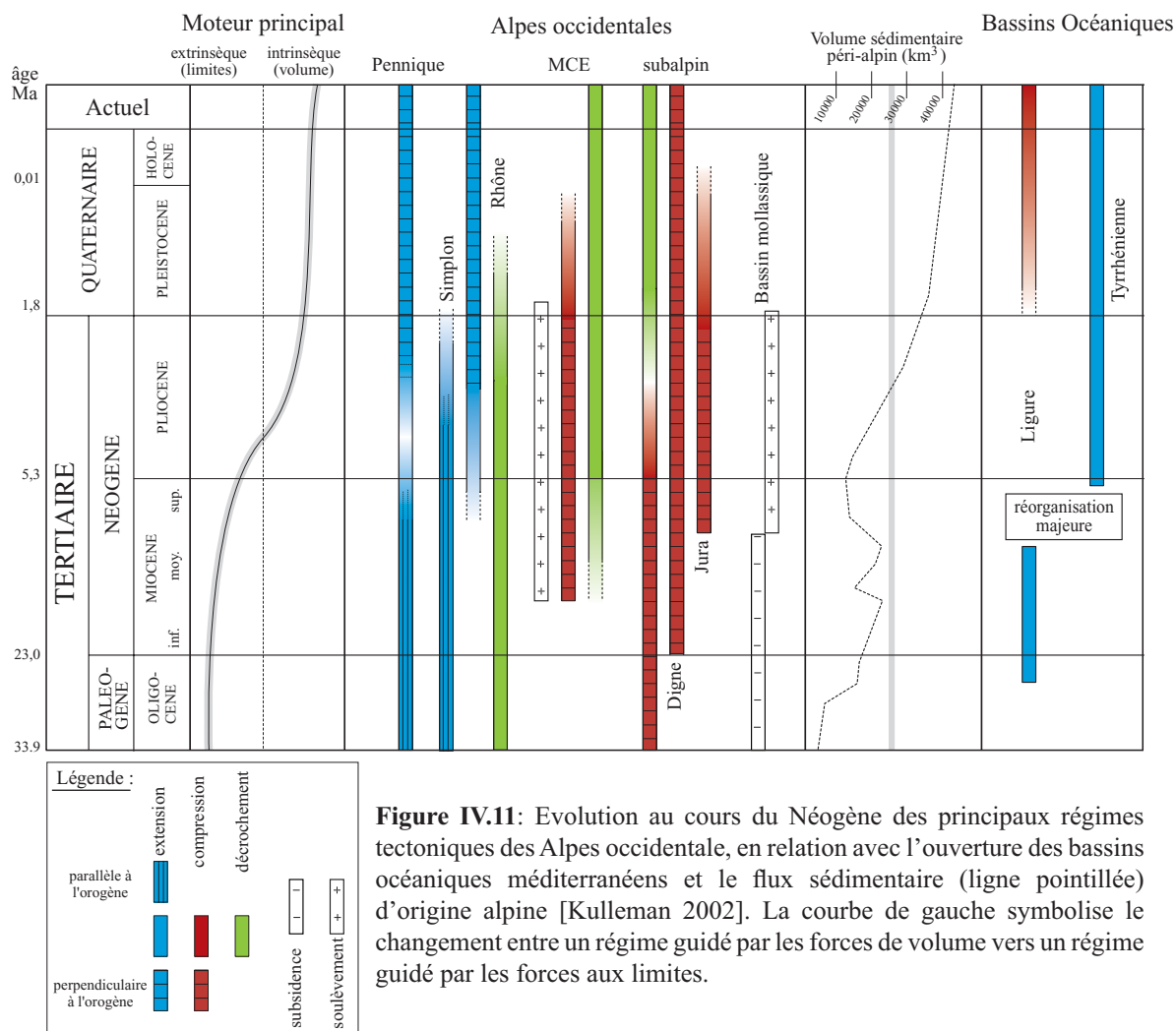


Figure IV.11: Evolution au cours du Néogène des principaux régimes tectoniques des Alpes occidentale, en relation avec l'ouverture des bassins océaniques méditerranéens et le flux sédimentaire (ligne pointillée) d'origine alpine [Kulleman 2002]. La courbe de gauche symbolise le changement entre un régime guidé par les forces de volume vers un régime guidé par les forces aux limites.

un régime majoritairement décrochant, avec des zones locales compressives au pied de la chaîne. Ce régime est interprété dans un contexte post-collisionnel dans lequel l'arrêt de la convergence aux limites permet aux forces de volume gravitaires de s'exprimer, en provoquant l'extension des zones de croûte épaissies (**rééquilibrage gravitaire**) et, en réponse, la compression observée localement en bordure de la chaîne. De plus, des conditions aux limites en rotation anti-horaire permettraient d'expliquer la présence des décrochements dextres parcourant l'ensemble de la bordure occidentale de la chaîne, en suivant sa géométrie arquée.

Ces deux régimes tectoniques, fondamentalement différents, résultent de l'interaction dans le temps et l'espace de différents processus géodynamiques (Fig IV.11. et fig IV 12) guidés par les mouvements aux limites de la chaîne, la dynamique profonde, mal connue et certains processus de surface:

1) Mouvements aux limites :

- *convergence/collision* : la convergence des plaques Apulienne et Européenne joue un rôle majeur dans l'édification de la chaîne, aboutissant à l'essentiel des structures observables à l'heure actuelle. Elle se met en place dès l'épisode de subduction au Crétacé sup./Eocène, aboutissant à un raccourcissement estimé à 120 km depuis l'Oligocène [Schmid et Kissling, 2000]. Les derniers témoins de cette convergence sont exprimés par la tectonique compressive de l'arc du Jura, qui se met en place à partir du Miocène Supérieur. Actuellement, les mesures GPS acquises depuis une dizaine d'années, montrent des déplacements faibles (de l'ordre de 1 à 2 mm.a⁻¹), sans qu'aucune convergence aux limites ne soit établie. La chaîne alpine a donc subi une diminution des taux de convergence entre le Miocène Supérieur et l'actuel, probablement durant le Pliocène.

- *rotation* : la rotation anti-horaire de la plaque Apulienne, documentée depuis l'Oligocène Supérieur [Vialon *et al.*, 1989; Schmid et Kissling, 2000], est interprétée comme un facteur majeur dans l'édification de l'arc alpin [e.g. Gidon, 1974; Ménard, 1988; Laubscher, 1991; Collombet *et al.*, 2002]. En particulier, son expression pourrait être retrouvée dans les décrochements dextres parcourant l'ensemble de la chaîne (ligne péri-adriatique, décrochements Rhône-Mont Blanc-Belledonne, décrochements Haute Durance-Argentera). Ces décrochements, de par leurs géométries, pourraient induire le développement de zones transpressives (Argentera, [Tricart, in press]) ou transtensives (Simplon, [e.g. Mancktelow, 1990]. A l'heure actuelle, la rotation de la plaque Apulienne est établie, avec de faibles vitesses anti-horaire autour d'un pôle situé à proximité de Milan [Anderson et Jackson, 1987; Calais *et al.*, 2002]. Cette rotation semble donc perdurer tout au long de l'histoire tectonique alpine Tertiaire à actuelle.

- *mise en place de la mer Ligure* : en s'ouvrant à partir du Miocène inférieur, la mer Ligure découpe l'architecture alpine précoce (en déplaçant le bloc Corso-Sarde) et aboutit à l'océanisation au cours du Miocène moyen [Carminati *et al.*, 1998; Gueguen *et al.*, 1998; Rollet *et al.*, 2002; Rosenbaum et Lister, 2004b]. L'amincissement lithosphérique se transfère au cours du Miocène supérieur vers le bassin Tyrrhénien, dans un contexte d'ouverture arrière-arc associé au recul de la subduction apenninique/ionienne [Rosenbaum *et al.*, 2002]. Aujourd'hui, la marge de la mer Ligure (côte d'Azur) est caractérisée par un régime compressif [Béthoux *et al.*, 1992], inversant les structures extensives miocènes au moins depuis le début du Quaternaire [Mauffret *et al.*, 1980].

2) Dynamique profonde :

- *slab break-off* : la rupture du slab lithosphérique (ou d'une partie uniquement de ce slab) de la Téthys Alpine semble être à l'origine des évènements extensifs et thermiques dans la chaîne alpine au cours de l'Oligocène [von Blanckenburg et Davies, 1995; Marchant et Stampfli, 1997; Stampfli *et al.*, 1998]. Les études de tomographie télé-sismiques montrent une configuration actuelle complexe des slabs lithosphériques sous les Alpes [Lippitsch *et al.*, 2003; Spakman et Wortel, 2004]. Cette configuration est interprétée par certains auteurs comme résultant d'un slab break-off en cours sous les Alpes occidentales [Lippitsch *et al.*, 2003]. Néanmoins, ces interprétations doivent être considérées avec prudence, et l'évolution de la structure profonde de la chaîne reste à discuter.

- *poinçonnement vertical* : ce phénomène, lié au mouvement vertical d'un poinçon d'origine profonde en contexte compressif, a été proposé pour expliquer le régime extensif observé dans une partie des zones internes de la chaîne [Rolland *et al.*, 2000; Wawrzyniec *et al.*, 2001; Schwartz, 2002; Ganne *et al.*, 2004]. A l'heure actuelle, un tel modèle impliquerait un découplage important des parties profondes en compression par rapport aux parties superficielles pour lesquelles les mesures GPS ne fournissent aucune évidence de cinématique convergente. Un tel découplage apparaît peu probable et semble ne pouvoir jouer un rôle que pendant l'histoire compressive de l'orogène.

3) Processus de surface :

- *augmentation des taux d'érosion* : une augmentation des taux d'érosion, analysée par des quantifications de flux sédimentaires de provenance alpine (bassins péri-alpins et deltas des fleuves principaux), est établie par [Kuhlemann *et al.*, 2002; Kuhlemann et Kempf, 2002] au cours du Pliocène. Cette augmentation serait reliée dans les Alpes à une modification générale du climat européen [Cederbom *et al.*, 2004] devenant plus humide en conséquence des changements de courants océaniques (lié à la fermeture de l'isthme de Panama à 4.6 Ma). Cette augmentation pourrait également être liée, de manière plus ou moins directe (voir ci-dessous), à des processus géodynamiques.

- *rebond post-glaciaire* : Le rebond isostatique consécutif à la fonte des glaciers würmiens il y a 19000 ans [Ivy-Ochs *et al.*, 2004] a fait l'objet de nombreuses discussions [Schaer et Jeanrichard, 1974; Gudmundsson, 1994; Persaud et Pfiffner, 2004], sans qu'aucune quantification ne soit clairement établie. La fonte rapide de cette calotte pourrait avoir provoqué un soulèvement généralisé, comme cela a été observé en Scandinavie [Klemann et Wolf, 1998; Wu *et al.*, 1999]. Cependant, les études cherchant à quantifier cette réponse se sont toutes heurtées à diverses inconnues, en particulier la méconnaissance des paramètres rhéologiques profonds qui guide les temps caractéristiques de rééquilibrage isostatique de l'accumulation, puis de la fonte des glaces. Ces études concluent toutes à une *possible* réponse isostatique actuelle, sans pouvoir en préciser les vitesses et les modalités. Un tel rebond, s'il était encore actif, devrait induire le soulèvement des zones correspondant aux grandes masses glaciaires [e.g. Kelly *et al.*, 2004]. Cependant, les taux de soulèvements calculés par nivellement sur le territoire suisse [Gubler *et al.*, 1981; Kahle *et al.*, 1997] ne montrent pas une telle corrélation, et sont plutôt liés au relief général et aux épaisseurs crustales de la chaîne. Il semble donc que le rebond post-glaciaire, s'il a lieu, soit intégré dans un soulèvement isostatique général d'une autre origine.

4) Interprétations

L'interaction entre ces différents processus conduit aux régimes tectoniques observés (figure IV.11 et IV.12) dans un équilibre subtil entre dynamique intrinsèque (isostasie et étalement gravitaire) et dynamique extrinsèque (cinématique aux limites et processus de surface).

En particulier, l'importance de la cinématique aux limites paraît prépondérante. Tout d'abord, c'est la **convergence** des plaques Apulienne et Européenne qui, en premier ordre, provoque l'extrusion latérale des zones internes, à l'origine de l'extension parallèle à l'orogène au Néogène, ainsi que la propagation simultanée du front compressif vers les zones externes. De plus, c'est l'**absence de convergence** qui, à l'heure actuelle, laisse les processus de rééquilibrage gravitaire s'exprimer et provoque l'extension perpendiculaire à l'orogène dans la haute chaîne, associée au régime localement compressif observé en bordure de l'orogène. La diminution de la vitesse de convergence entre le Miocène supérieur et l'actuel suggère donc une importance de plus en plus grande des phénomènes gravitaires.

La présence d'une **rotation anti-horaire** de la plaque Apulienne complique ce système compressif en modulant dans l'espace la quantité de raccourcissement. Au cours du Néogène, cette rotation pourrait favoriser l'extrusion des zones internes, en accommodant les mouvements vers le sud de cette partie de l'arc tout en expliquant le manque de décrochements sénestres sur la bordure orientale du bloc extrudé.

A l'actuel, selon certains auteurs [Calais et al., 2002], le régime tectonique résulterait d'un contexte uniquement rotatif, provoquant l'extension observée dans les Alpes occidentales et la compression exprimée dans les Alpes orientales (Frioul). Cependant, les études de modélisation numériques réalisées par Bastien Delacou (figure IV.4 et annexe 2) montrent le rôle majeur du rééquilibrage gravitaire sur le régime tectonique actuel. Le rééquilibrage gravitaire semble donc modulé par la rotation, dans un équilibre délicat restant à quantifier.

L'ouverture de la **mer Ligure**, en créant une bordure libre méridionale, a pu favoriser les phénomènes d'extrusion proposés pour le régime tectonique alpin Néogène. A partir du Miocène supérieur, le transfert de cette extension vers le bassin Tyrrhénien a pu rendre cette bordure 'moins libre' et favoriser le soulèvement de la branche sud de l'arc (Argentera et Alpes Ligures, [Bigot-Cormier et al., 2000; Bogdanoff et al., 2000; Foeken et al., 2003], aboutissant à la structure particulièrement arquée de la branche méridionale de la chaîne, réorientant les directions d'extension.

La possible **rupture** récente du **slab** alpin a pu affecter l'équilibre isostatique des Alpes occidentales [von Blanckenburg et Davies, 1995; Sue, 1998]. Cette rupture, si elle a eu lieu, a pu provoquer un réajustement de la géométrie et de la répartition des densités en profondeur, induisant le soulèvement des parties sus-jacentes [van der Meulen et al., 1999]. Ce soulèvement, par flexure, pourrait permettre le développement d'un régime extensif crustal. Cependant, malgré l'interprétation avancée par certains auteurs d'une rupture actuelle sous les Alpes occidentales [Lippitsch, 2002], le manque de précision sur la géométrie et la cinématique lithosphérique ne nous permet pas de préciser les conséquences du slab break-off sur les régimes tectoniques observés.

L'érosion, en transférant de la matière des parties hautes de la chaîne à la périphérie modifie la répartition des masses de l'orogène. Le taux d'érosion est fonction de différents paramètres, en particulier la vitesse de soulèvement de la chaîne et le régime climatique. Une **hausse des taux d'érosion** a été observée dans les bassins péri-alpins au cours du Pliocène [Kuhlemann et al., 2002]. Cette variation importante (figure IV.11) est probablement liée à une augmentation des vitesses verticales de la chaîne. Elle a pu être la cause de cette augmentation de soulèvement (l'augmentation d'érosion entraînant un réajustement isostatique et un soulèvement) ou la conséquence (le soulèvement d'origine tectonique entraînant une augmentation d'érosion).

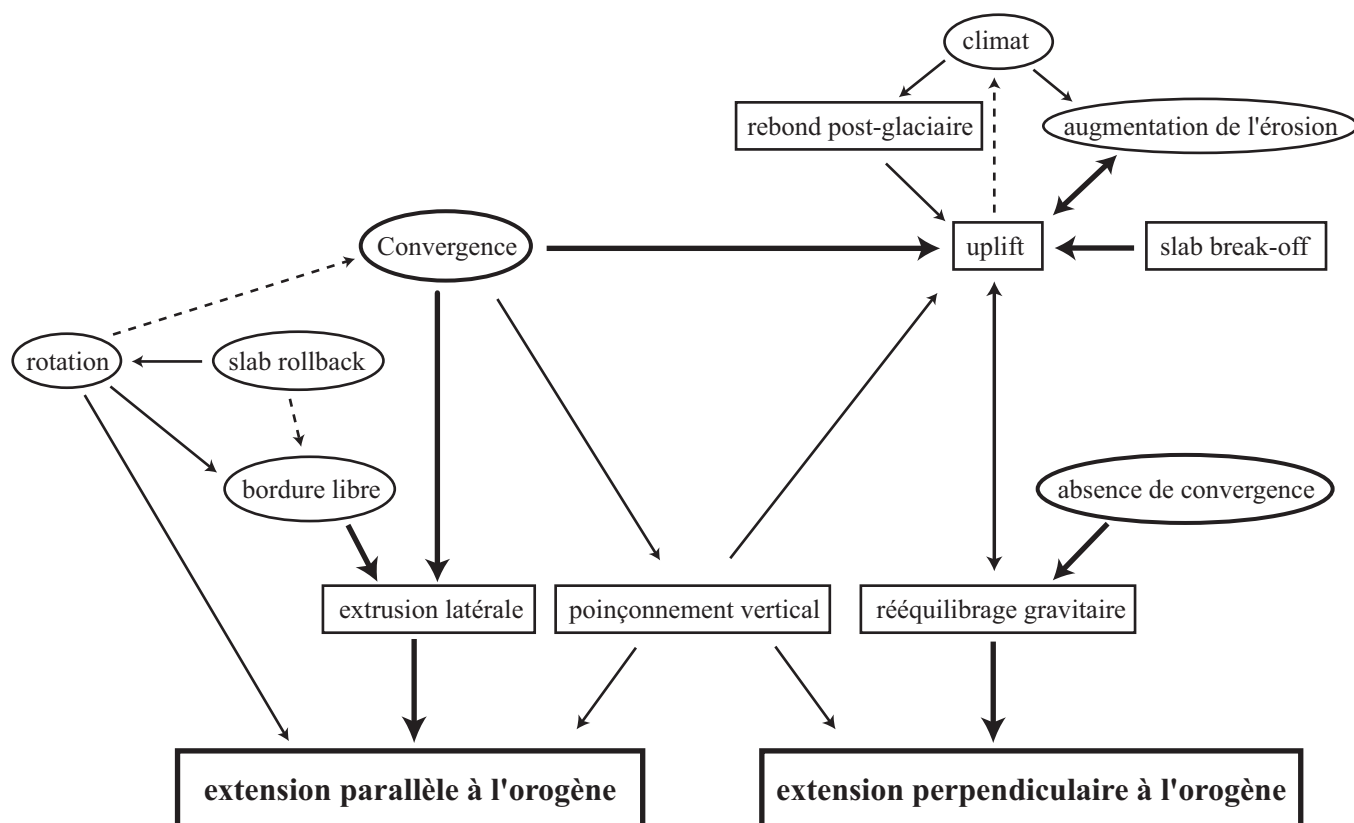


Figure IV.12: Organigramme conceptuel des différents mécanismes ayant pu avoir des conséquences sur les régimes tectoniques observés. Les rectangles symbolisent les forces de volume, les ellipses les forces aux limites. Les flèches en pointillé symbolisent une action possible d'un élément sur un autre ; les flèches fines représentent un lien probable entre un élément et le suivant ; les flèches épaisses correspondent aux liens qui nous semblent fondamentaux dans l'évolution néogène à actuelle de la chaîne alpine.

Quoiqu'il en soit, cette augmentation d'érosion marque un changement géodynamique majeur, qui pourrait se corrélérer à la transition entre les régimes tectoniques Néogène et actuel. L'augmentation de l'érosion au cours du Pliocène à une échelle mondiale [Molnar, 2004] suggère que l'augmentation de l'érosion dans les Alpes occidentales ait pu provoquer une modification gravitaire entraînant une réponse isostatique, et le régime tectonique observé actuellement.

Une synthèse des observations tectoniques Néogènes à actuelles ainsi que les liens avec les différents moteurs géodynamiques décrits ci-dessus sont présentés sur la figure IV.11. En particulier, trois changements majeurs semblent avoir des conséquences sur le régime tectonique de l'arc alpin, permettant de proposer une évolution temporelle. Tout d'abord, l'arrêt de l'ouverture de la mer Ligure, daté du Miocène supérieur, pourrait impliquer une diminution de l'extrusion vers le Sud, et entraîner une diminution de l'extension parallèle à l'orogène. Ensuite, l'augmentation des taux d'érosion, d'une origine tectonique ou climatique ('chicken or egg' [e.g. Molnar et England, 1990]), signe une modification géodynamique Pliocène. Cette modification a pu être déterminante dans la modification tectonique observée. Finalement, une diminution progressive des mouvements aux limites, en particulier des taux de convergence, apparaît prépondérante dans le changement de régime géodynamique. En effet, l'extrusion implique inévitablement une convergence aux limites qui, en diminuant, laisse aux forces de volume la possibilité de provoquer un étalement gravitaire. Cependant cette diminution de convergence est difficile à quantifier, mais agit probablement de manière progressive depuis la fin du Miocène.

En conclusion, nous proposons que le passage d'un régime tectonique guidé par l'extrusion en contexte de collision à un régime gouverné par le rééquilibrage gravitaire post-collisionnel soit lié à un changement dans l'équilibre entre force aux limites et forces de volume. Cette transition a probablement eu lieu durant le Pliocène, en relation avec la diminution du taux de convergence et une forte augmentation de l'érosion.

Références

La terre nous en apprend plus long sur nous que tous les livres. Parce qu'elle nous résiste. L'homme se découvre quand il se mesure avec l'obstacle

A. de Saint-Exupéry

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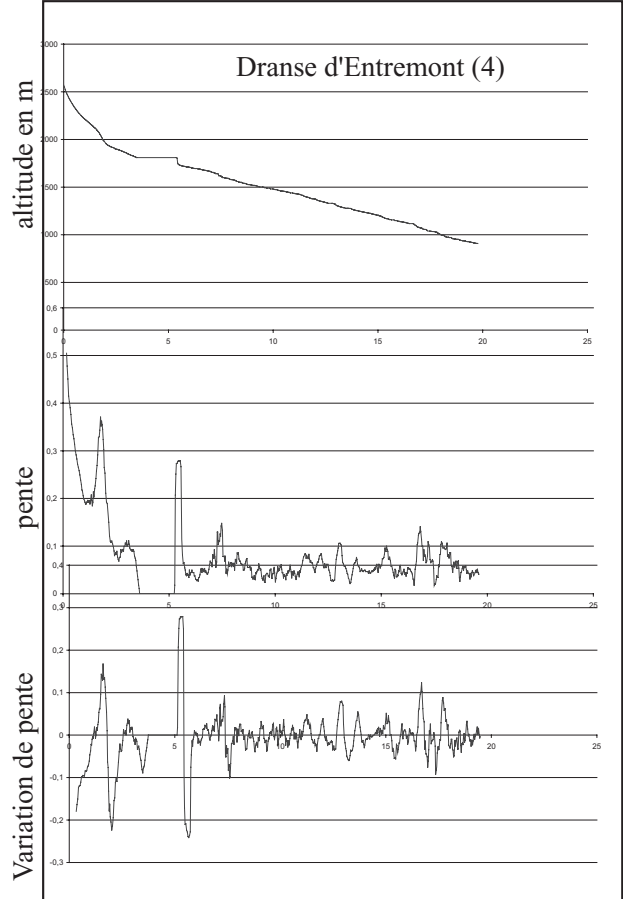
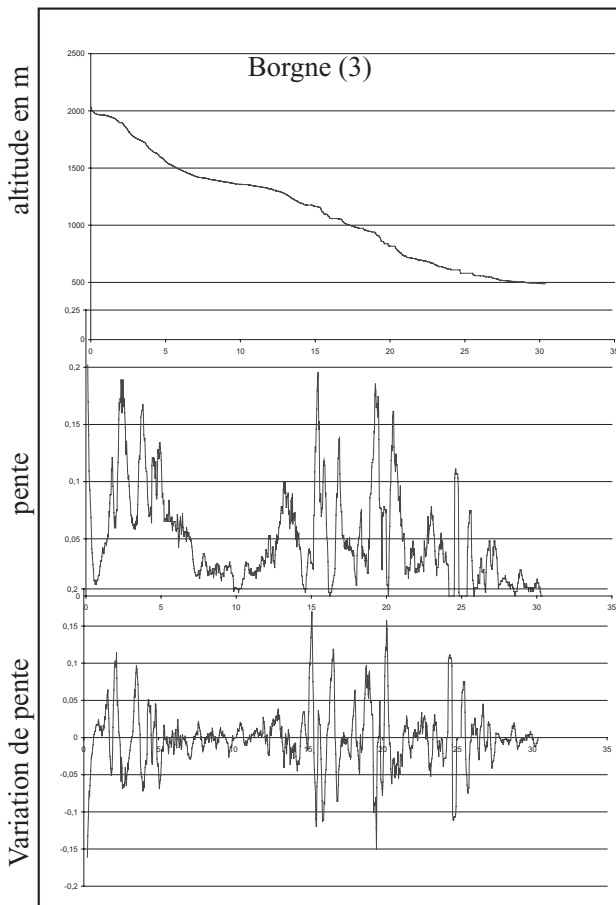
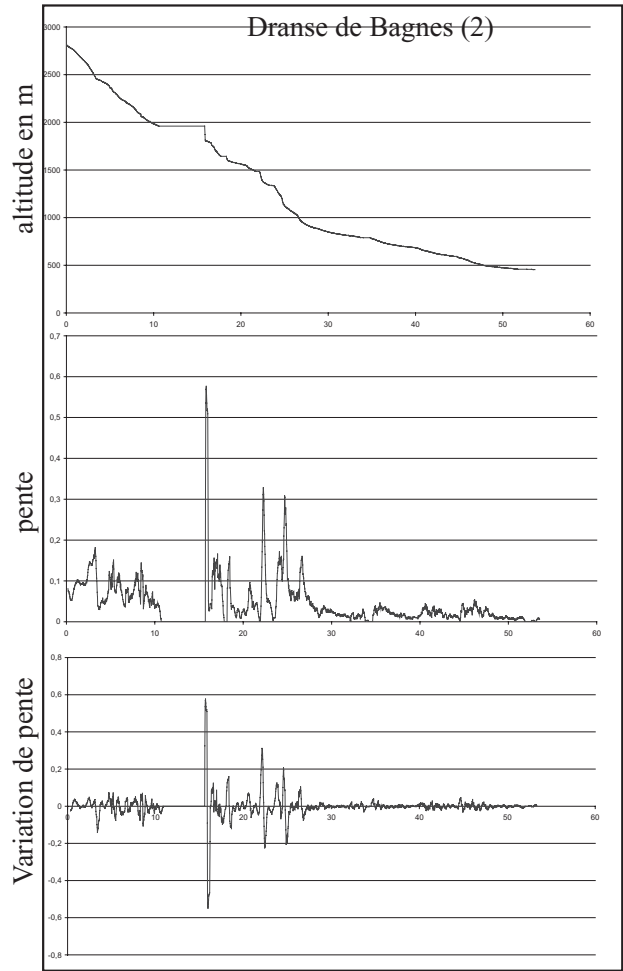
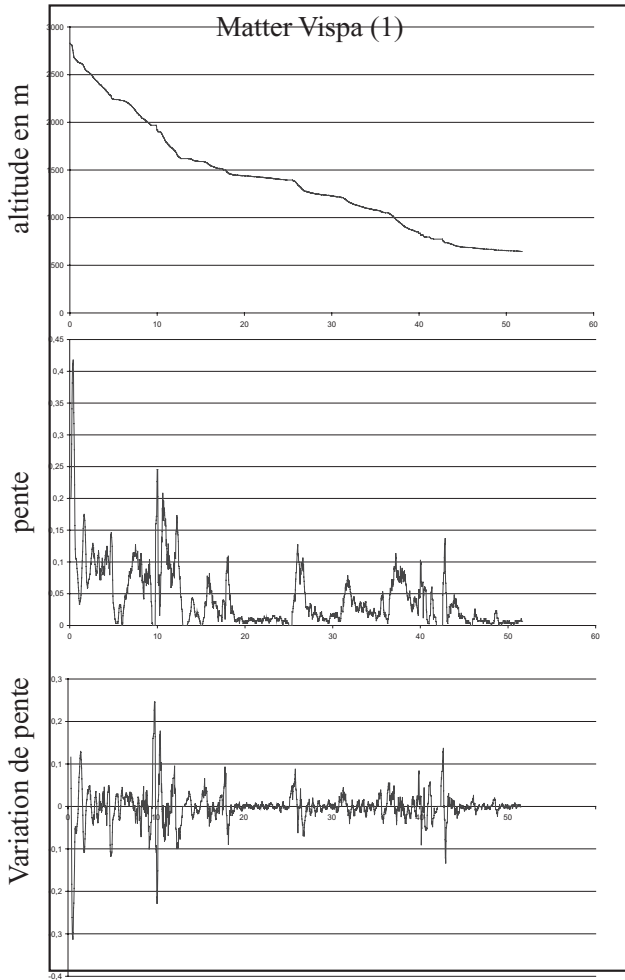
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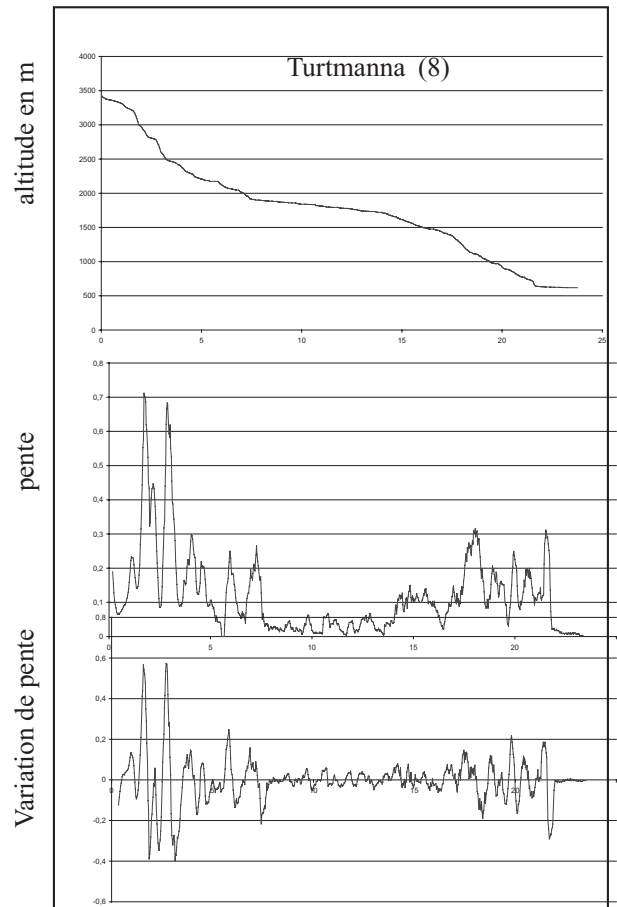
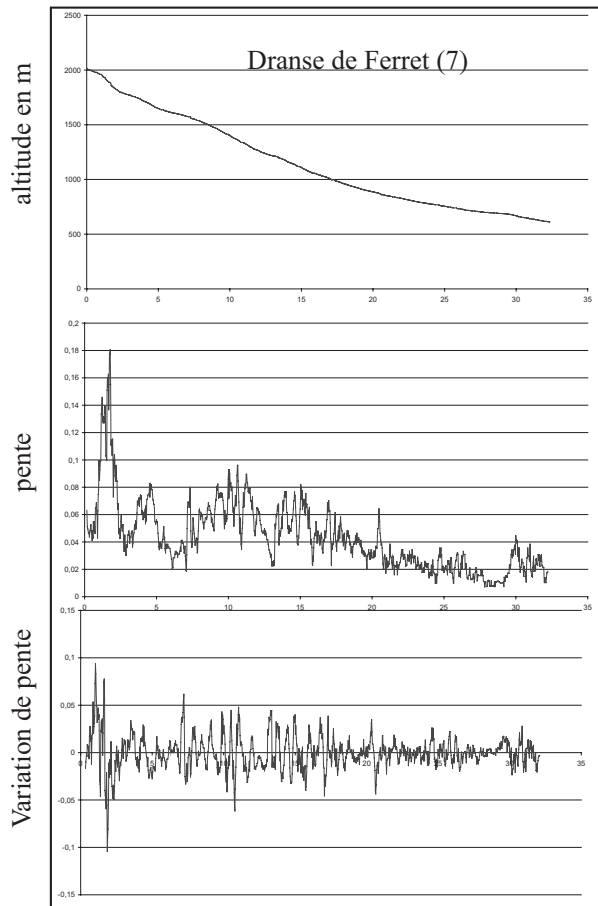
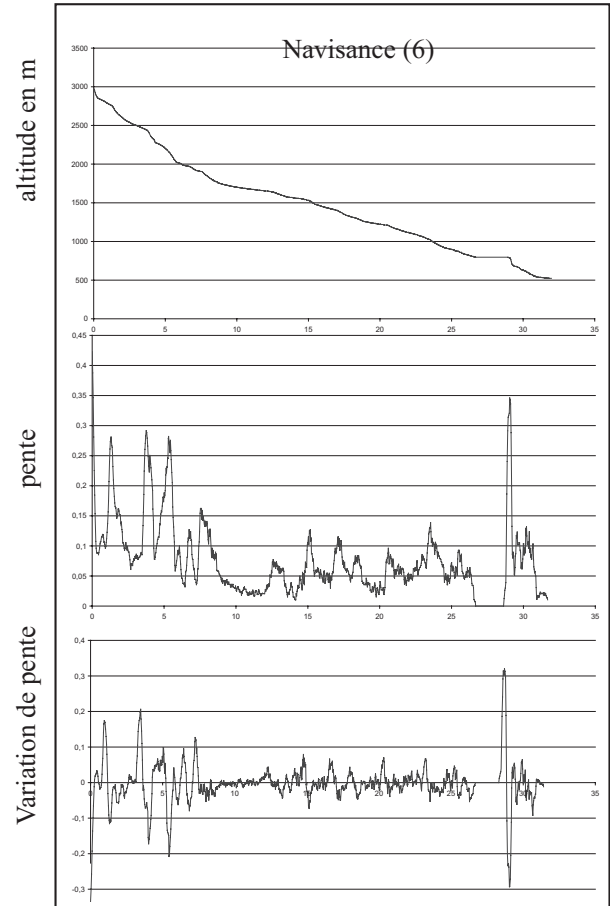
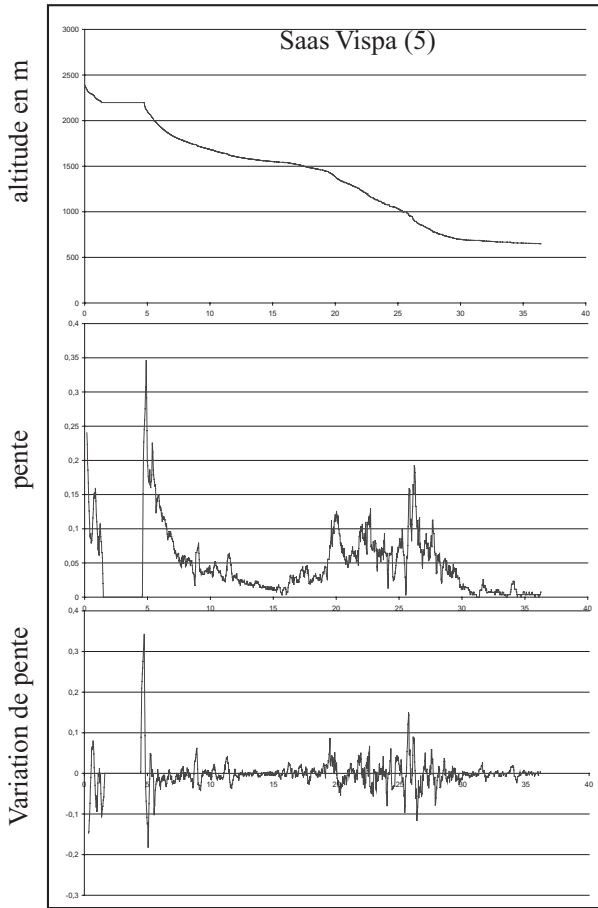
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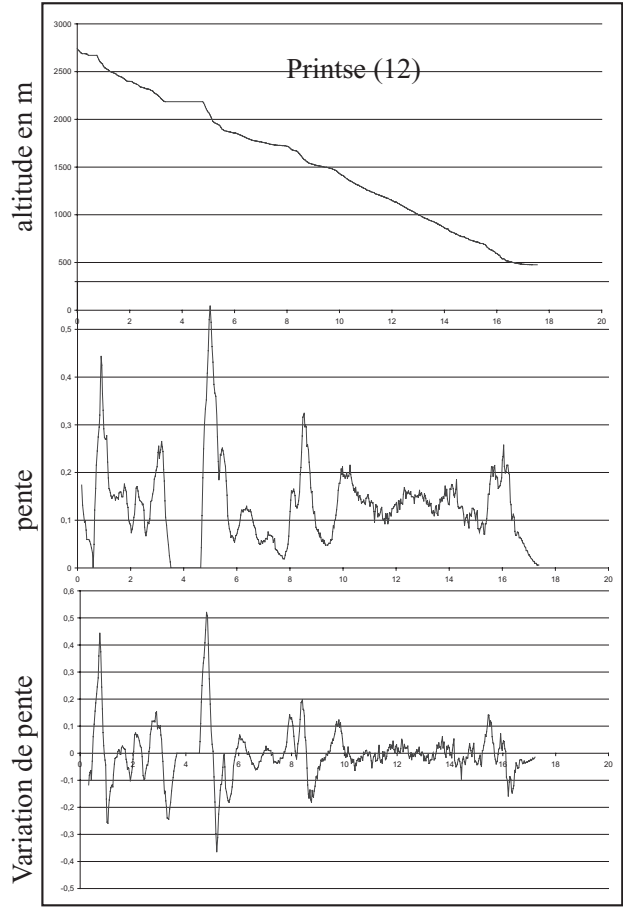
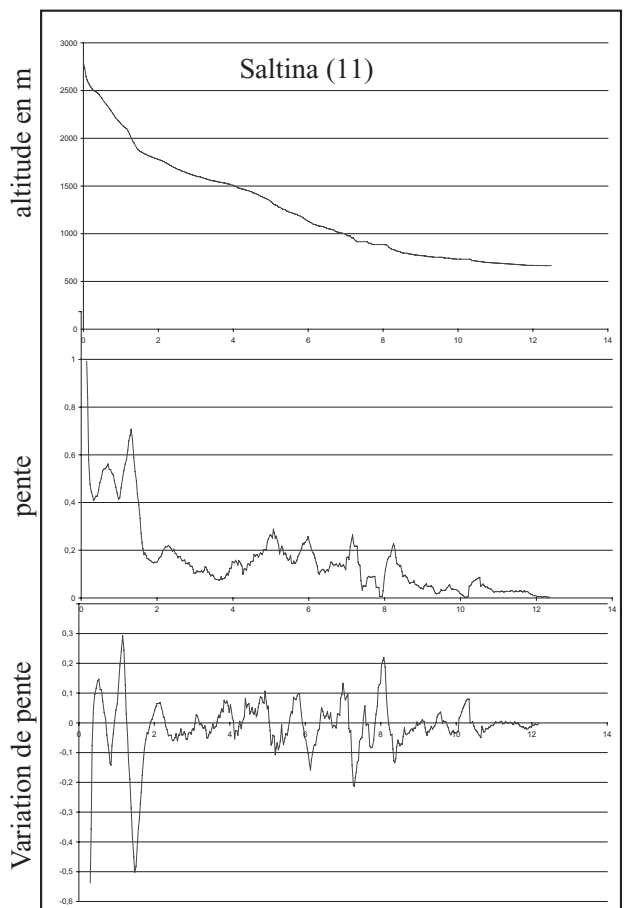
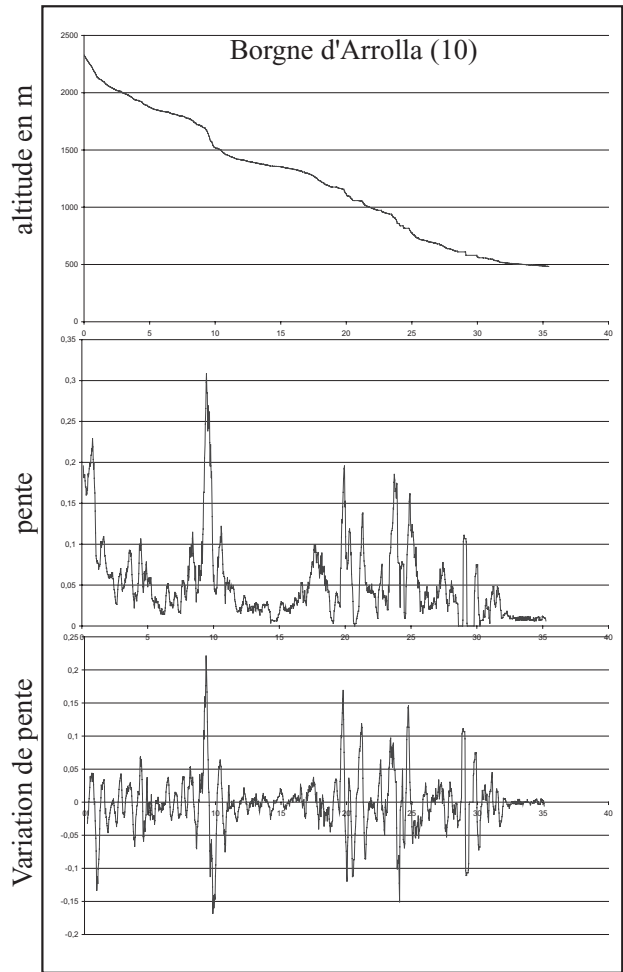
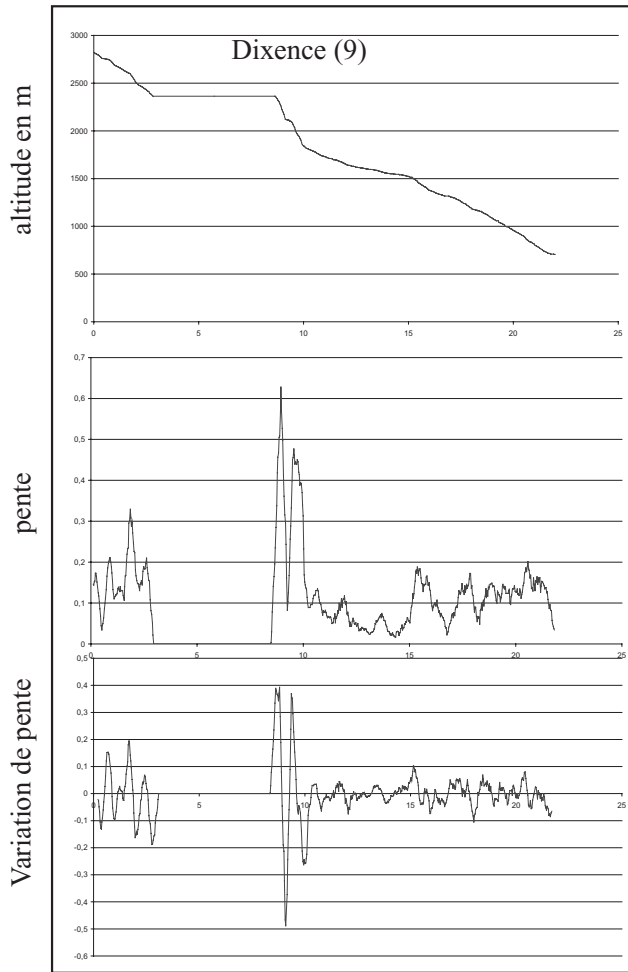
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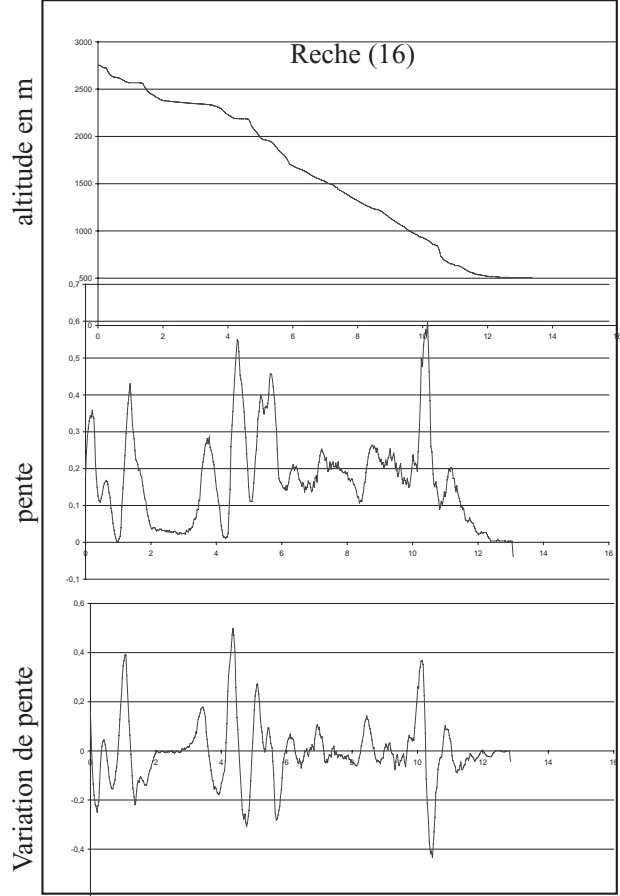
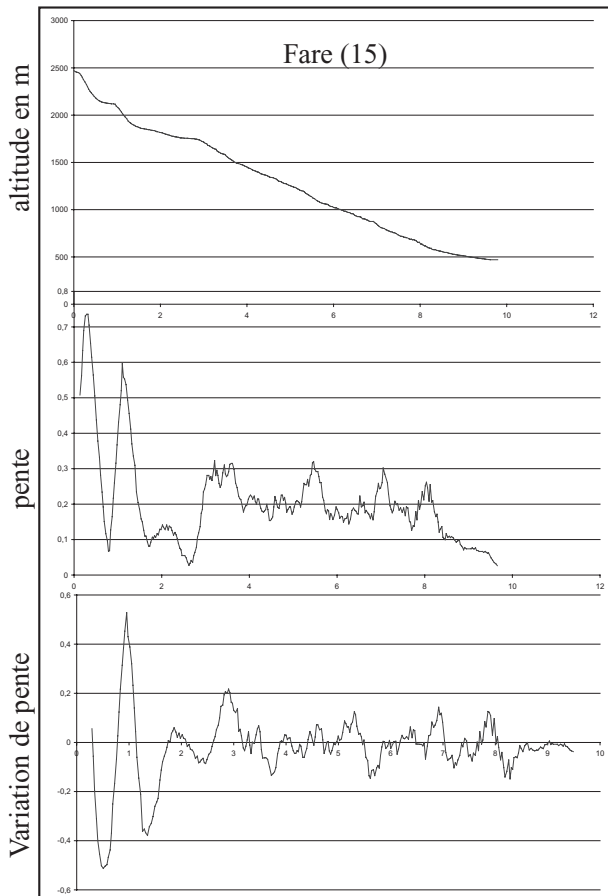
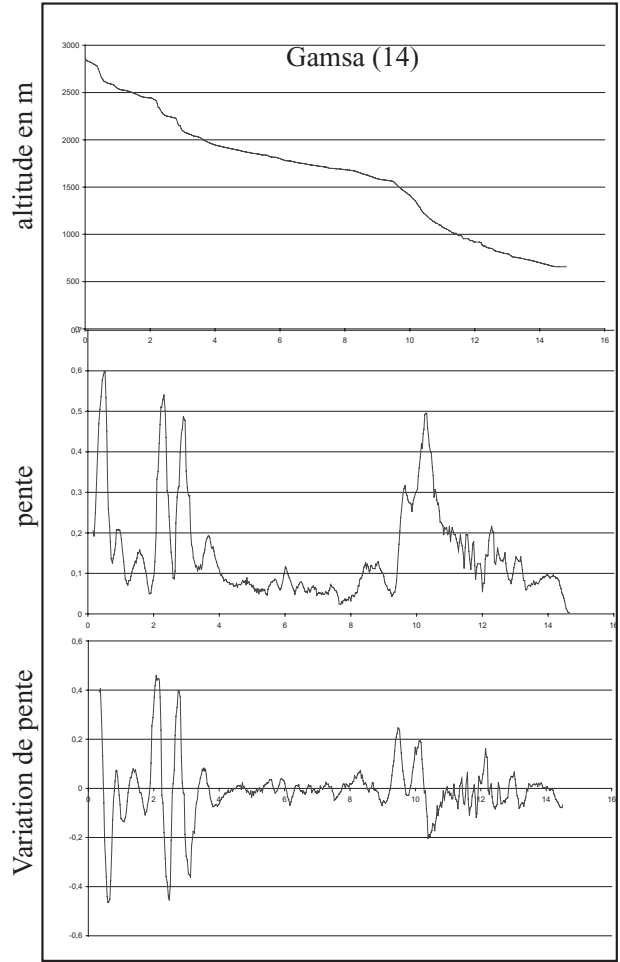
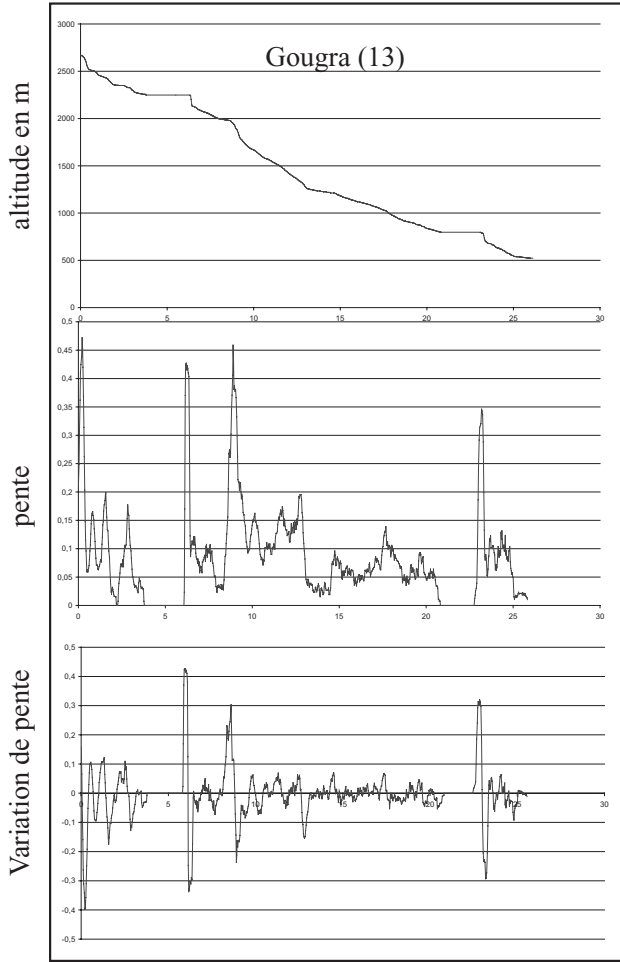
Annexe 1

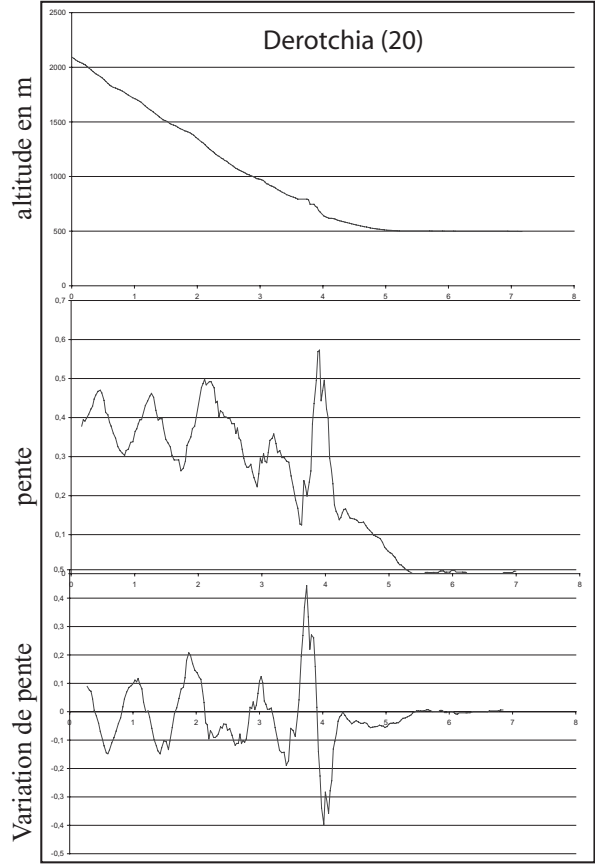
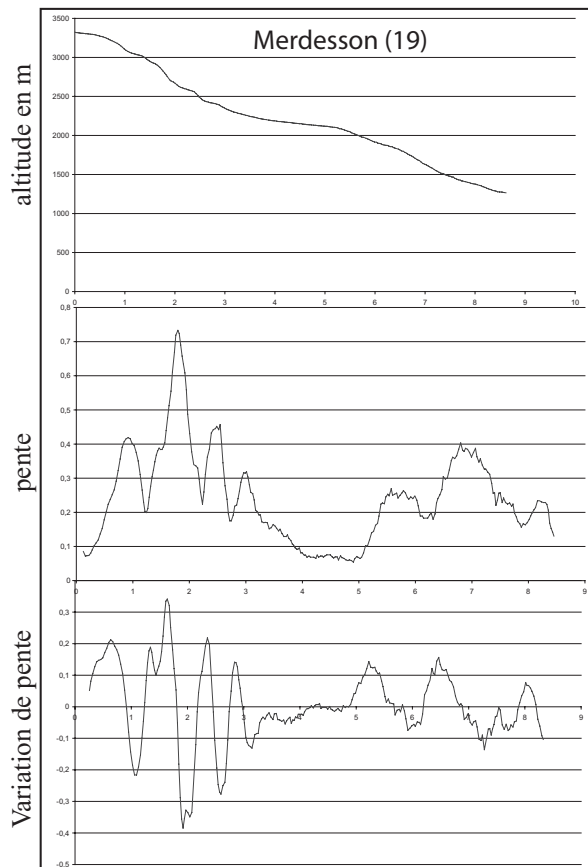
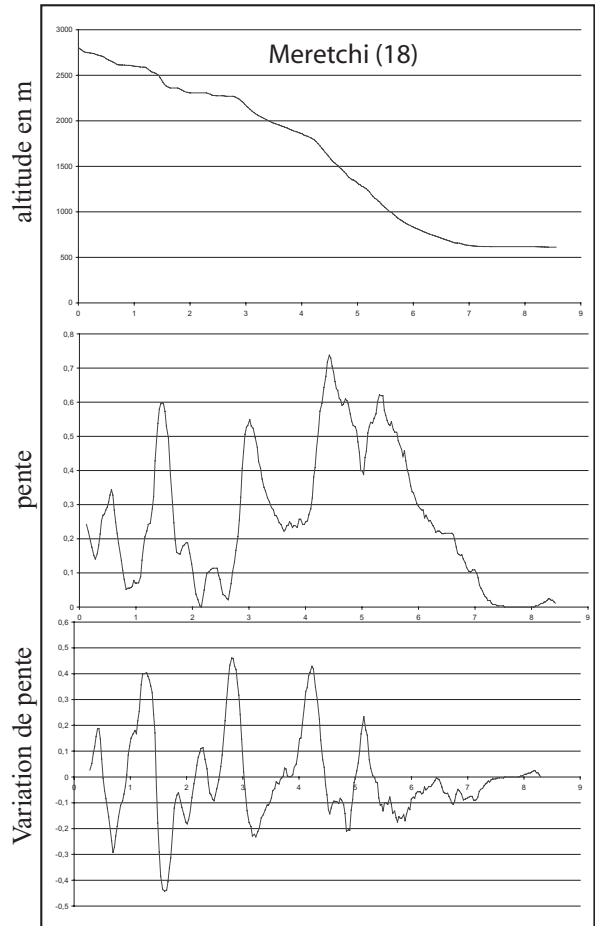
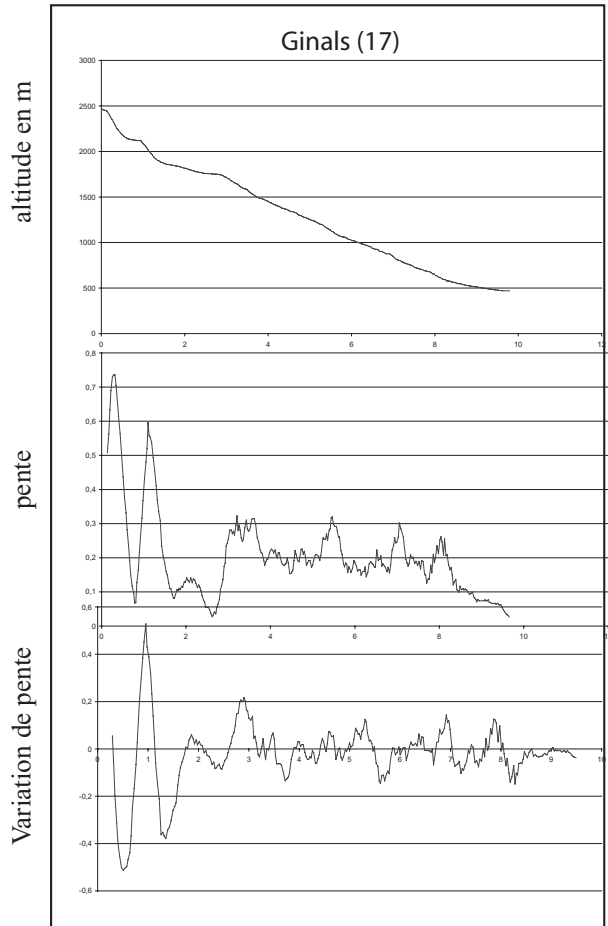
Profils de rivières du sud Valais











ANNEXE 2

« Present-day geodynamics in the bend of the western and central Alps
as constrained by earthquake analysis »
Delacou et al., *Geophys. J. Int.*, 2004

Present-day geodynamics in the bend of the western and central Alps as constrained by earthquake analysis

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SUMMARY

The contrasted tectonics of the western/central Alps is examined using a synthesis of 389 reliable focal mechanisms. The present-day strain regime is mapped and interpolated for the entire Alpine belt based on a newly developed method of regionalization. The most striking feature is a continuous area of extension which closely follows the large-scale topographic crest line of the Alpine arc. Thrusting is observed locally, limited to areas near the border of the Alpine chain. A majority of earthquakes within the Alps and its forelands are in strike-slip mode. Stress inversion methods have been applied to homogenous subsets of focal plane mechanisms in order to map regional variations in stress orientation. The stress state is confirmed to be orogen-perpendicular both for σ_3 in the inner extensional zones and σ_1 in the outer transcurrent/transpressional zones. Extensional areas are well correlated with the part of the belt which presents the thickest crust, as shown by the comparison with the Bouguer anomaly and the average topography of the belt. In the northwestern Swiss Alps, extension is also correlated with currently uplifting zones. These observations and our strain/stress analyses support a geodynamic model for the western Alps in which the current activity is mostly a result of gravitational ‘body’ forces. Earthquakes do not provide any direct evidence for ongoing convergence in the Alpine system, but a relationship with ongoing activity of complex block rotations of the Apulian microplate cannot be ruled out.

Key words: active tectonics, buoyancy forces, earthquake focal mechanisms, orogen-perpendicular extension, stress inversion, western/central Alps.

1 INTRODUCTION AND TECTONIC SETTING

The Alpine belt resulted from the Tertiary convergence between the European and African plates. The Apulian microplate was caught in between the two, leading to the closure of the mid-Jurassic Ligurian Tethys ocean during Upper Cretaceous–Eocene times and to subsequent continent–continent collision during the Tertiary (Coward & Dietrich 1989; Dewey *et al.* 1989; Laubscher 1991; Stampfli *et al.* 1998; Schmid & Kissling 2000). Thus, the Apulian plate acted as an indenter with respect to the European plate (Tapponnier 1977). The complex collision history is characterized by the propagation of the compressive front towards external zones. This collision started in Palaeogene times with syn-metamorphic structuring of the internal (Penninic) zones, which consists of a stack of high-temperature (HT) to high-pressure (HP) metamorphic nappes (Dal Piaz *et al.* 1972; Ernst 1973;

Goffé & Chopin 1986; Droop *et al.* 1990; Pognante 1991; Spalla *et al.* 1996; Duchêne *et al.* 1997). The metamorphic internal zones overthrust the external zones along the Penninic frontal thrust during Oligocene times (Butler *et al.* 1986; Choukroune *et al.* 1986; Mugnier & Ménard 1986; Fry 1989; Gratier *et al.* 1989; Butler 1992). The most recent manifestations of collision tectonics are seen in the thin-skinned external fold and thrust belts (Isler 1985; Laubscher 1987; Burkhard 1990; Burkhard & Sommaruga 1998; Schönborn 1999; Becker 2000) which developed in Oligocene (Helvetic chain) to Late Miocene times (Jura, sub-Alpine massifs, southern Alps). At the scale of the western/central Alps, the compressive structures present a fan-shaped pattern, resulting in a near 180° arcuate Alpine chain of 200 to 400 km in width and approximately 1000 km long from eastern Switzerland to the Ligurian margin. The mountain belt is surrounded by peripheral foreland troughs such as the Molasse and Pô basins north and south of the Alps respectively, by Oligo-Miocene rifts such as the Rhine, Bresse and Rhône graben system to the northwest; as well as the Oligocene Ligurian ocean to the southwest. In addition to the dominant and well-studied compressional structures such as nappes, thrusts and folds, extensional structures are now widely recognized to have played an important role in Alpine

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tectonics since at least Miocene times (Mancktelow 1992; Selverstone *et al.* 1995; Fügenschuh *et al.* 1999; Bistacchi & Massironi 2000; Sue *et al.* 2002; Champagnac *et al.* 2003; Sue & Tricart 2003; Champagnac *et al.* 2004).

While the Alpine structural setting is well constrained, the current tectonic regime and associated geodynamics remain a matter of debate. Instrumental earthquake monitoring began in the Alpine chain in the 1920s (e.g. Rothé 1941; Pavoni 1961; Ahorner *et al.* 1972; Fréchet 1978). The monitoring progressively improved with increasingly more dense seismic networks, so that today more than 74 stations (regrouping French and Swiss networks) are monitoring earthquakes in the central/western Alps (e.g. Pavoni 1980, 1986; Béthoux *et al.* 1988; Ménard 1988; Deichmann & Rybach 1989; Thouvenot *et al.* 1990). The seismicity is considered to be only low to moderate for most parts of the belt (typical magnitude range $3 < M_L < 5$), while a relatively high level of seismicity is found in the southern Valais, the Briançonnais and Piemontais arcs and the southern Rhine graben. Modern seismotectonic studies document the complexity of the present-day tectonic regime. In terms of stress field an orogen-perpendicular orientation of the maximum horizontal compression axis is established along the western periphery of the Alpine chain (Fréchet 1978; Pavoni 1986). In the inner Alpine arc, however, recent surveys have led to the unexpected discovery of an extensional regime (e.g. Maurer *et al.* 1997; Eva *et al.* 1998; Sue *et al.* 1999; Baroux *et al.* 2001; Kastrup *et al.* 2004).

These studies remained rather localized, and no Alpine synthesis has yet been achieved. In this paper we present a seismotectonic synthesis of the entire western/central Alps, leading to a new and comprehensive image of the overall stress state of the belt. The coexistence of extensional, compressional and transcurrent regimes in various areas of the Alps and surroundings still poses unsolved issues. Our synthesis provides a starting point for a discussion of the current geodynamic situation of the Alpine belt. Different scenarios will be discussed in the light of data from neighbouring fields such as geology, geodesy, gravimetry and neotectonics.

2 SEISMOTECTONIC DATA

This study is based on an extensive collection of previously published focal mechanism data, covering the entire arc of the western/central Alps from eastern Switzerland to the Mediterranean sea (Ligurian margin). Our compilation (tabulated in Appendix A) includes all available regional syntheses and local studies for this zone (Ménard 1988; Thouvenot 1996; Eva & Solarino 1998; Sue *et al.* 1999; Baroux *et al.* 2001; Kastrup *et al.* 2004). This database now contains 389 reliable focal mechanisms. The local magnitudes (M_L) range from 0.7 to 6.0 for earthquakes recorded between 1969 and 2000 (Fig. 1, see Appendix A). Focal mechanisms have systematically been controlled for their first-arrival polarity and the coherence of their nodal planes (low azimuthal gap and high number of stations) by both previous and present studies (nearly 4 per cent of focal mechanisms were discarded). They can thus be considered as good to very good quality focal solutions.

The complete database has been used to plot the epicentral locations shown in Figs 1 and 2. Cross-sections have been taken from (Schmid & Kissling 2000) and (Calais *et al.* 2000) and earthquakes have been projected vertically onto these sections from a horizontal distance of 25 to 40 km (depending on the density of earthquakes). Note that our catalogue is not a complete catalogue of the seismic activity recorded in the western central Alps, but only presents events for which reliable focal mechanisms are available. Nevertheless, the distribution of the available focal mechanisms provides a fair image

of the overall seismic activity of the belt. In comparison with more complete seismic maps of the belt (Thouvenot 1996; Pavoni *et al.* 1997; Béthoux *et al.* 1998; Sue *et al.* 1999; Baer *et al.* 2001), different seismic zones can be distinguished by their relative activity level (Fig. 1): concentrated seismicity occurs in localized zones such as the Basel region, the Valais area and the Piemontais and Briançonnais arcs (defined in Rothé 1941; Thouvenot 1996; Sue *et al.* 1999); more diffuse seismicity characterizes large zones such as the Swiss Molasse basin, the foreland northwest of the Belledonne massif or the Provence area. Large areas, such as the Vercors or the Lepontin areas, appear as almost aseismic.

Alpine earthquakes occur mainly within the upper crust (the first 15 km), as illustrated by the map and the cross-sections (Fig. 2). However, a few areas with relatively deep seismicity do exist: the Swiss Molasse basin (down to 30 km), the Pô plain (down to 25 km) and the Ligurian margin (down to 20 km). The deep seismicity of the Molasse basin has been interpreted as an indicator of high fluid pressure (Deichmann 1992). In contrast, the seismicity in more internal zones of the belt is restricted to the upper 15 km. It is important to note that informations about present-day stress orientations from focal plane solutions are restricted to this uppermost brittle part of the crust. Any inferences about deeper processes are necessarily indirect and rely on models regarding the coupling between the upper and deeper parts of the orogen.

3 SEISMIC DEFORMATION ANALYSIS

We have used our new database to map regional trends and principal stress orientations as well as to distinguish areas with contrasting stress regimes. In order to constrain the strain state associated with the seismicity, two key parameters have been analysed: the type of deformation (strike-slip, extension, compression) and the directions of P (compressional) and T (extensional) axes of deformation.

3.1 Type of deformation

In order to better visualize the type of deformation derived from focal mechanisms, we used an original approach based on the plunge of P and T axes. Extension is characterized by near vertical P axes, whereas compressional deformation is characterized by near vertical T axes. This qualitative assessment has been used for the calculation of a scalar parameter (see Appendix A), fully sufficient to define the type of deformation, based on assigning negative values of T -axes dips for extensional to transtensional mechanisms and positive values of P -axes dips for compressional to transpressional ones. This ' r ' parameter thus ranges linearly from -90 for pure extension to 0 for pure strike-slip and to $+90$ for pure compression. Negative intermediate values indicate a transtensional tectonic regime ($-90 < r < 0$), and positive intermediate values indicate a transpressional tectonic regime ($0 < r < +90$). This approach allows us to interpolate the scalar field of the parameter r , and the corresponding tectonic regime, over the entire area of interest. Such an interpolation (GMT continuous curvature splines in tension, Smith & Wessel 1990) remains open to criticism, as it 'creates' data, as for all interpolation procedures. This is why we also provide the coloured dots on the maps and cross-sections, which correspond to focal mechanisms, with calculated r parameters (see Appendix A). Areas with several dots of the same colour are well constrained by data, while areas in between, especially those with colour gradients and no data points, are filled in purely by interpolation. Different tests have been made in the smoothing procedure (with only minor changes in the resulting maps),

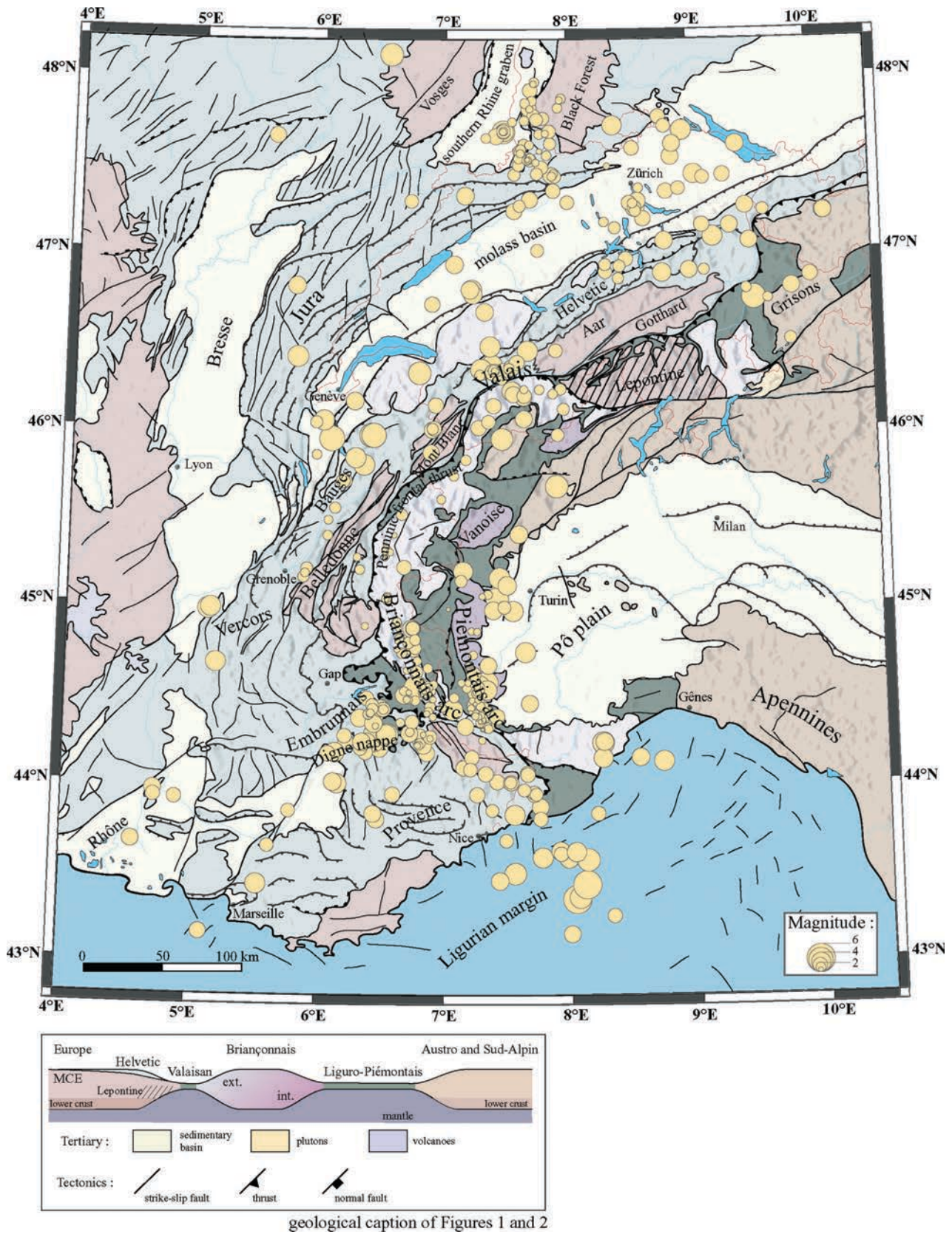


Figure 1. Seismicity map of the western/central Alps showing only the database used in this paper, namely the earthquakes for which a reliable focal mechanism is available. This synthetic database of 389 events recorded between 1969 and 2000 presents the overall features of the classical seismic maps for the Alpine belt: near-aseismic areas (e.g. the Lepontin dome, Vercors), areas of diffuse activity (e.g. Provence, the front of the Belledonne massif, eastern Switzerland) and concentrated active zones (e.g. the so-called Briançonnais and Piémontais arcs, Valais, and the Basel area). The size of the symbols is related to the local magnitude. The geological colour caption is given in the schematic paleogeographical cross-section.

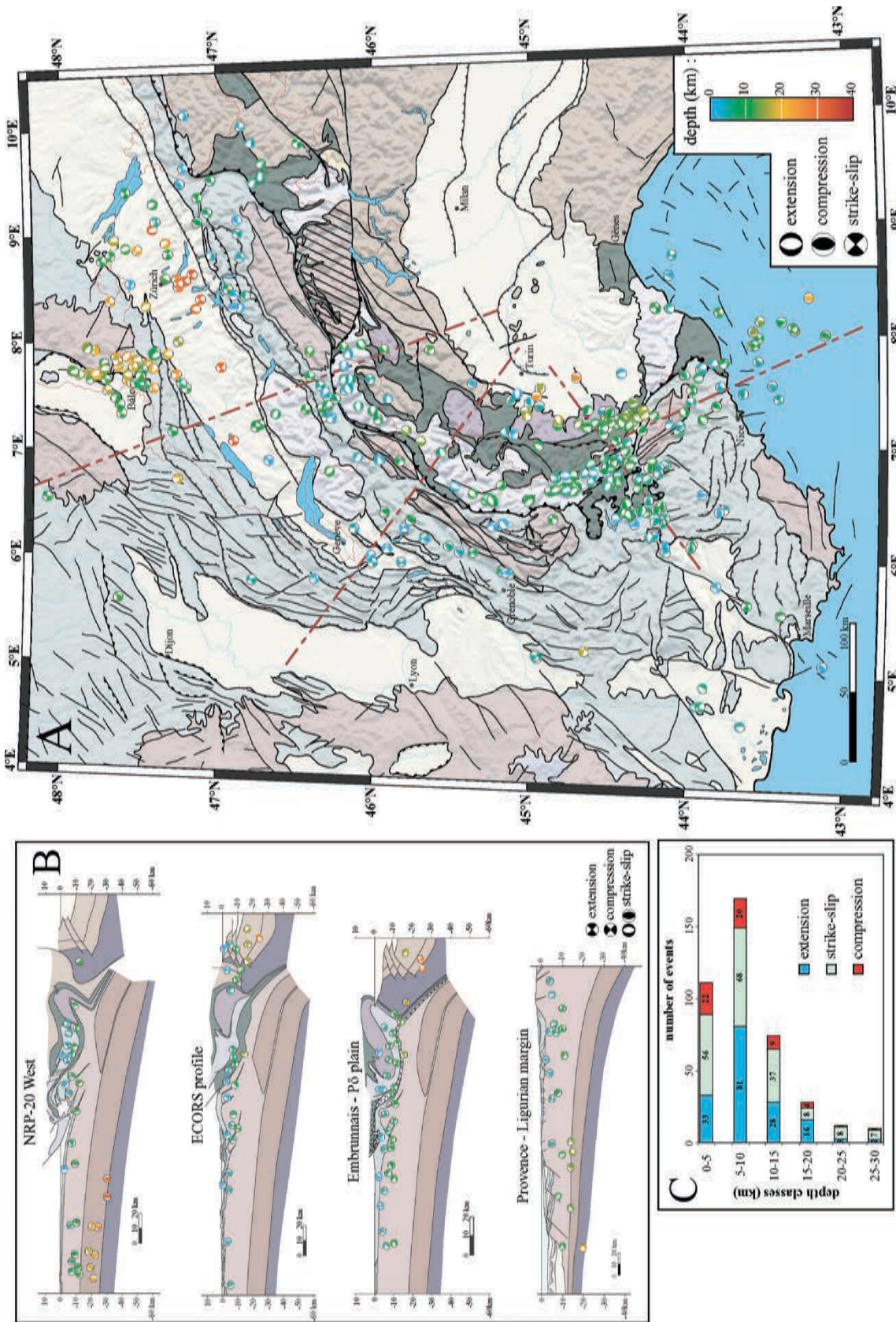


Figure 2. Seismotectonic map of the western Alps (A) showing the whole database used in this study. The colour code of the focal mechanisms corresponds to their depth, and ranges from blue for the shallower ones to red for the deeper ones (up to 35 km beneath the Swiss Molasse basin). The cross-sections (B) are drawn from the recent crustal reinterpretations of the ECORS-CROP and NRP20-West profiles by Schmid & Kissling (2000), and Calais *et al.* (2000) for the Ligurian margin. These key sections illustrate the upper-crustal seismicity in the belt (within the first 15–20 km), and the locally deep seismicity under the forelands. Strike-slip mechanisms are found throughout the whole belt. Reverse faulting is limited to its periphery, whereas extension characterizes the tectonics of the internal zones. The histogram (C) shows the depth distribution related to the deformation type for the whole database. See Fig. 1 for the geological caption.

and the parameters have been fixed to reflect the regional patterns and the structural setting of the different areas of interest. Taking into account the limitations inherent in all interpolation methods, our approach allows an accurate assessment of the regional variations of the tectonic regime over the entire western/central Alps (Fig. 3). This approach has its limitations, however, since strike-slip types of deformation (with low r values, corresponding to the green colour code) are obtained not only for the true strike-slip zones (where green dots for strike-slip events are present) but also as an artefact of interpolation between areas of pure extension and pure compression. Nevertheless, this artefact does not hinder compressive and extensive zones to clearly emerge from our interpolation. In summary, our large-scale regionalization approach allows the recognition of large zones with a homogeneous state of deformation and their spatial relationship with regions of contrasting strain regime all along the Alpine arc and the surrounding areas.

The most important feature revealed by the strain regime (Fig. 3) is the emergence of a continuous zone of extension prevalent in the internal zone of the chain, all along the belt from the southern Valais in Switzerland to the north of the Argentera external crystalline massif in southern France. Extension is also found in eastern Switzerland (Grisons area), but without any documented continuity with the western extensional areas. This discontinuity might be an artefact due to a lack of seismicity in the Lepontine dome that separates the extensional domains of Valais and Grisons. Extension has been recognized previously in various regional studies (Fréchet 1978; Roth *et al.* 1992; Maurer *et al.* 1997; Eva *et al.* 1998; Sue 1998; Sue *et al.* 1999; Kastrup *et al.* 2004); here we document a lateral continuity between these areas all along the internal zones of the western central Alps.

Another main feature is the presence of discontinuous transpressive zones localized along the borders of the Alpine belt (Fig. 3). Compression is observed in the eastern Helvetic domain, at the front of the Belledonne massif, in front of the Digne nappe and in the western Pô plain. These zones present only a few compressive focal mechanisms, always associated with strike-slip ones, defining a global transpressive mode of deformation. These compressional/transpressional areas remain very localized in the outer portions of the Alpine realm.

At the margins of the Alpine belt, peripheral systems are interfering with the Alpine system. This is the case for the southern Rhine graben, characterized by a transtensional type of deformation, extending continuously southward to the eastern Swiss Molasse basin in the Zurich region. This is also the case for the Ligurian margin, presenting a clear compressive tectonic regime, extending into the southern Provence area.

3.2 Directional data

Directional informations contained in focal plane mechanisms are visualized through projections of the P - and T -axes orientations on to the horizontal plane (Figs 4 and 5). This directional information is spatially interpolated (Fig. 4) using GMT continuous curvature splines in tension (Smith & Wessel 1990). The resulting maps for P - and T -axes trajectories are shown in Fig. 5. In this representation, P -axis trajectories are shown in transpressional to compressional areas whereas T -axis trajectories are displayed in transtensional to extensional areas (compare Fig. 3).

P -axis trajectories around the bend of the western Alps describe a large-scale fan pattern, convergent towards the Pô Plain, confirming earlier work based on far fewer data (Fréchet 1978; Pavoni 1986). P -axis trajectories are systematically oriented in an orogen-

perpendicular fashion, nearly perpendicular to the structural trend of the Alps. The P -axis fan swings of 120° from a NNW direction in eastern Switzerland to northwest in front of Belledonne massif, and southwest in front of the Digne nappe. The Ligurian margin, at the southernmost tip of the belt, is also characterized by horizontal P axis, directed northwest.

T -axis trajectories in internal zones define a radial orogen-perpendicular pattern very similar to the P -axis pattern of the outer Alpine border zones. T -axis trajectories are oriented at a high angle to the bend of the western/central Alpine relief, striking north-south in the Valais to east-west behind the Pelvoux massif area and southwest-northeast behind the Argentera massif. The eastern Swiss Alps (Grisons area) are characterized by T axis striking in a northeast-southwest direction. Thus, the seismic strain documented by these T axis within the internal zone of the Alps is indicating an orogen-perpendicular extensional tectonic regime.

4 STRESS INVERSION

To further characterize the present-day stress state of the western Alps, we applied stress inversion methods to subsets of the focal mechanism database using the software TENSOR (Delvaux 1993). Stress inversion methods assume a uniform state of stress within the study area. Furthermore, in contrast to the inversion of fault-striae data, standard inversion of earthquake data (e.g. Michael 1987; Gephart 1990; Delvaux 1993) does not *a priori* discriminate between the active and the virtual nodal plane. Despite such restrictions, stress inversion has been shown to provide a powerful tool for analysing focal plane mechanism data sets (Larroque *et al.* 1987; Rebaï *et al.* 1992; Delouis *et al.* 1993; Madeddu *et al.* 1996; Maurer *et al.* 1997; Plenefisch & Bonjer 1997; Eva *et al.* 1998; Montone *et al.* 1999; Sue *et al.* 1999; Baroux *et al.* 2001; Kastrup *et al.* 2004). The aim of the inversion of focal plane data is the determination of a regional stress tensor that satisfies most, if not all, observed individual earthquakes in a given area. In contrast to the simple interpolation of isolated, projected P - and T -axes directions (Figs 4 and 5), inversion methods take the entire 3-D orientation of focal plane mechanisms into account and search for a common stress tensor. Our inversion is based on an objective, visual selection of large homogeneous zones, which are characterized by an apparently uniform type of deformation. This selection of zones was based on both Fig. 3, following our regionalization of the r parameter, and Fig. 5, considering the orientation of P and T axes.

Stress inversion was performed for 21 zones (Table 1, Appendix A and B), with 6 to 34 focal mechanisms per zone (18 on average). This very finely divided data set (a high number of stress zones) is required by the extreme curvature of the Alpine arc. As a standard test of the coherence and quality of an inversion procedure, the misfit between the predicted and observed slip direction is calculated for each nodal plane. Average misfit values range from 11° to 27° , with a mean value of 18.8° . These are rather high values, which can be explained by the frequent occurrence of mixed types of focal mechanism (compressional, extensional and/or transcurrent) observed at the local scale. The coexistence of strike-slip focal planes with either extension (internal Alps) or compression (Alpine border) is the rule rather than the exception. Despite this pattern, stress inversion results appear to be fairly robust and reproducible on the regional scale. Our results are very similar to those presented in previous regional studies which used different inversion methods (Michael 1987; Gephart 1990; Delvaux 1993) and different subsets of focal

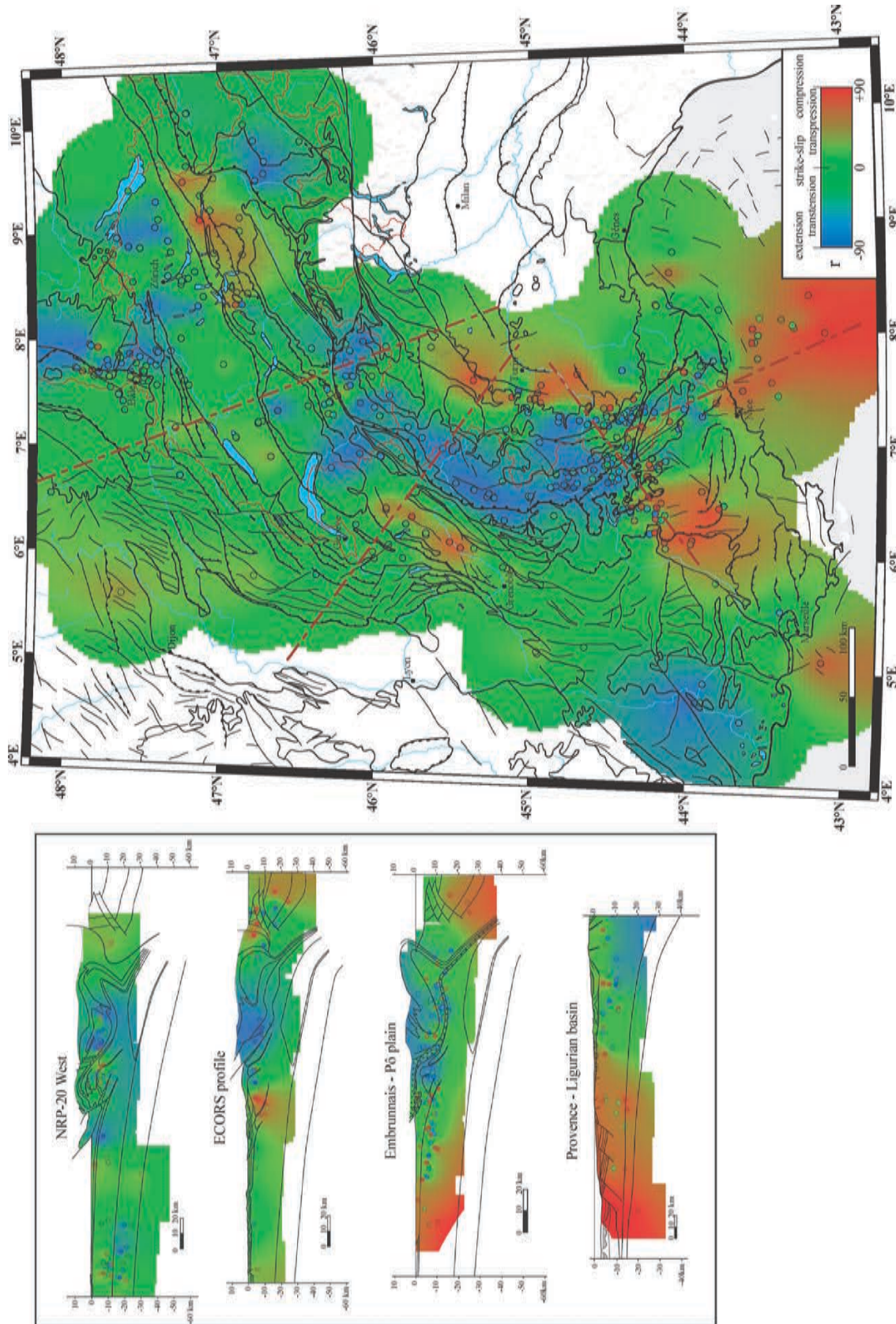


Figure 3. Regionalization of the deformation in the Alpine realm (r parameter, based on the P/T -axes dips, see text) in map and cross-sections. The colour code corresponds to the type of deformation (shortening in red, extension in blue, strike-slip in green). Small circles are observed focal mechanism drawn with their own colour code. The background colour comes from the interpolation of the type of deformation known where focal mechanisms are available. A mask (areas with no colour) is put on areas placed at a distance greater than 55 km from the nearest earthquake. This interpolation shows that extension prevails in the core of the belt, whereas shortening areas remains pretty local and limited to the border of the belt.

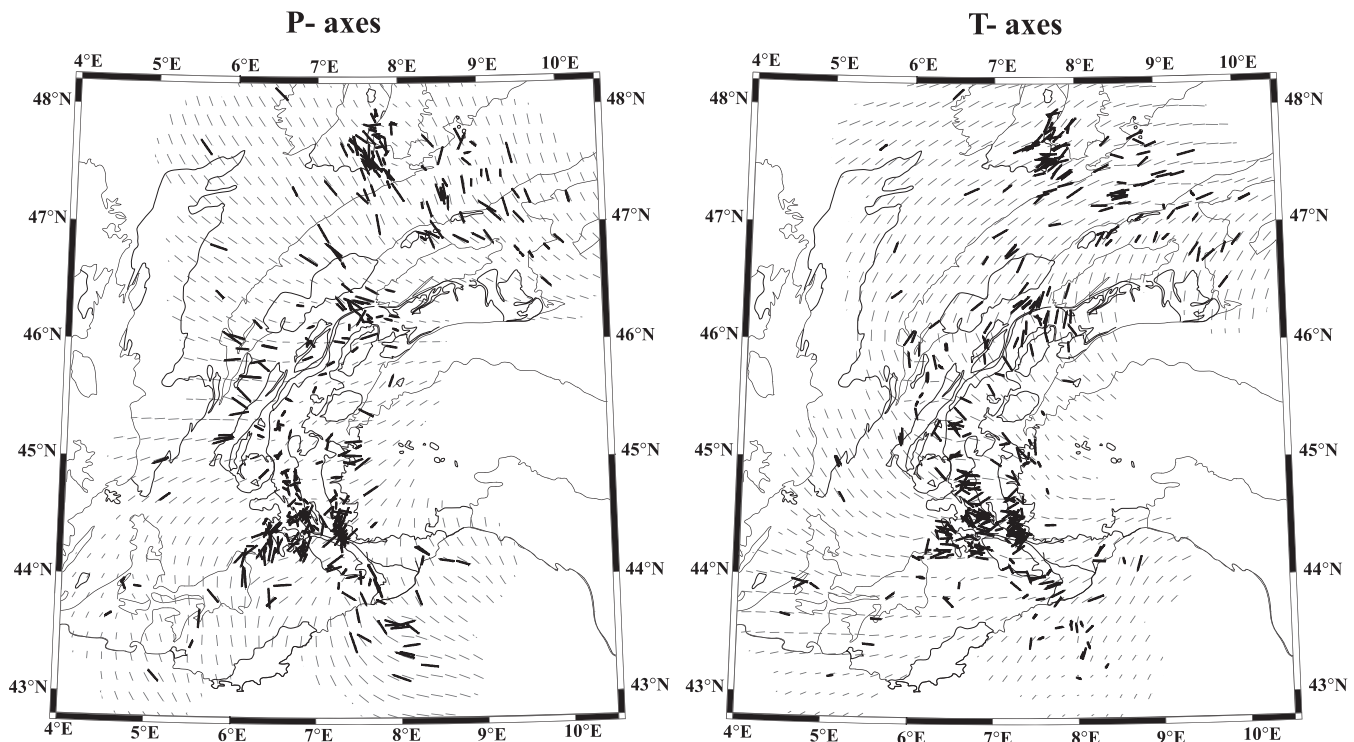


Figure 4. *P*- and *T*-axes fields. Thick lines represent observed *P* (left map) and *T* axes (right map) at the location of focal mechanisms. Thin lines represent interpolated axes. The lengths of axes are inversely proportional to their dips (as projected on the horizontal plane). Note the regionally stable orientation of axes.

plane solutions, such as Maurer *et al.* (1997) for the Valais region, Sue *et al.* (1999) in the southwestern Alps, (Kastrup *et al.* 2004) for all of Switzerland and Baroux *et al.* (2001) in the Provence and Ligurian areas.

Stress inversion results are shown in Fig. 5, together with the interpolated *P*/*T*-axes directions. Stress ellipsoids are further characterized by the shape parameter ($\Phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$), listed in Table 1.

4.1 Internal zones

Orogen-perpendicular extensional stress directions are confirmed and shown to be continuous all along the internal zones, systematically at a high angle to the Penninic frontal thrust (almost perpendicular). The direction of σ_3 varies from N6° in a pure extensive stress state in southern Valais (vss, $\Phi = 0.72$), N119° near radial extension in northern Briançonnais (b1, $\Phi = 0.08$), N91° pure extension in central Briançonnais (b2, $\Phi = 0.50$), N101° transtension in southwestern Briançonnais (b3N, $\Phi = 0.86$) and N53° pure extension in southeastern Briançonnais (b3S, $\Phi = 0.48$). For the Piemontais seismic arc, we also find orogen-perpendicular σ_3 directions with a N131° direction in the north (pieN) and N74° in the south (pieS), both with a nearly pure extensive stress state ($\Phi = 0.56$ and 0.36 respectively). An exception to this overall internal extension is revealed by a few compressive focal mechanisms mixed with extensive ones that have occurred in the southern Piemontais area (Fig. 2). A precise relocation of seismic events recorded in this zone with a dense temporary network (Béthoux *et al.* 2004) show a possible decoupling of the stress state in front of the Ivrea zone, with extension at shallow levels, and compression at depth. This decoupling is not resolved in our large-scale analysis. This is a very complex area with uncertainties in the geometry of the Ivrea body and associated high-pressure tectonic units, as well as in

the regional kinematics. Nevertheless, the two types of deformation are analysed independently, following the results of Béthoux *et al.* (2004). We therefore define an independent compressive stress state ($\Phi = 0.22$) in the southern Piemontais zone (pieScomp), with σ_1 oriented N50°.

4.2 External zones

External zones are characterized by contrasted states of stress, with the occurrence of all three possible tectonic modes: strike-slip, extension and compression, according to the zone of investigation (Figs 3 and 4). Generally speaking, strike-slip focal mechanisms dominate in external zones, and lateral variations of tectonic mode to extension (transtension) or compression (transpression) are only locally important. The extensional tectonic mode ranges from pure extensive stress state in northern Provence (pro, $\Phi = 0.63$), eastern Embrunais (diE, $\Phi = 0.76$) and Chamonix areas (cham, $\Phi = 0.43$) to transtensive ones in northeastern Switzerland (zu, $\Phi = 0.92$) and the northern Basel area (baN, $\Phi = 0.92$). Pure strike-slip stress state prevails in northern Valais (vsn, $\Phi = 0.62$). The compressional tectonic mode ranges from pure compressive stress states in the western Pô Plain area (po, $\Phi = 0.4$), the western Embrunais (diW, $\Phi = 0.35$) and the northern Ligurian zone (lig, $\Phi = 0.3$) to transpressive states in front of the Belledonne massif (bel, $\Phi = 0.1$) and eastern Helvetic zones (hel, $\Phi = 0.31$). The front of the Digne nappe (Embrunais) is characterized by a diffuse zone of mixed type of focal mechanisms (compressive, transcurrent and extensive) at the transition between an internal extensive zone and an external compressive one (see Fig. 3). In order to obtain a homogeneous database for the stress inversion, the two types of focal mechanisms (extensive and compressive) have been regrouped independently, resulting in two different stress states (diW and diE zones).

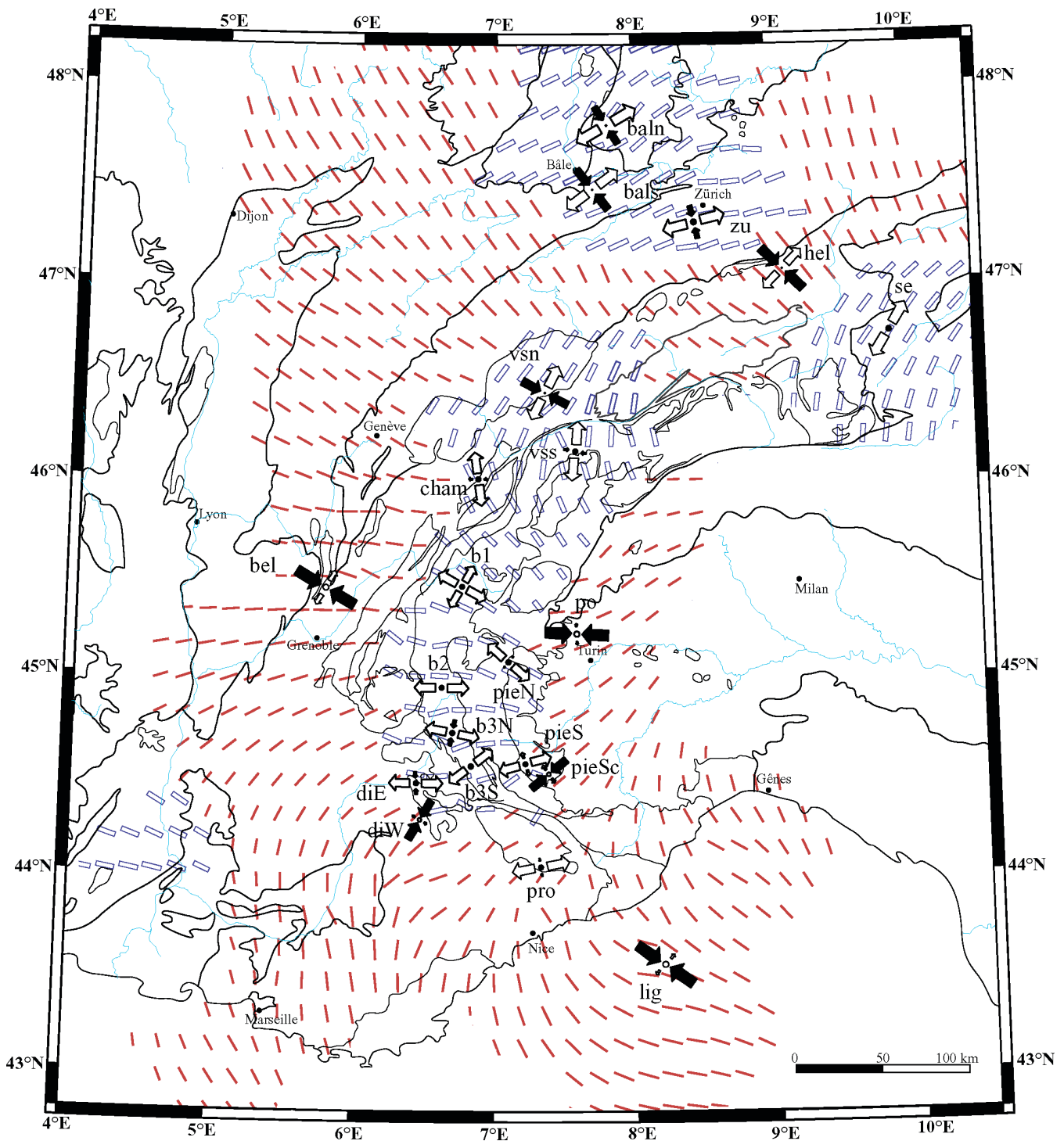


Figure 5. Map of the Alpine strain/stress states. The stress tensors have been inverted in homogeneous areas of deformation determined using the regionalization drawn Fig. 3. Each tensor is presented with the code of the area of inversion (see Table 1 and Appendix B), a black arrow for horizontal σ_1 , and an open arrow for horizontal σ_3 . The thin red lines correspond to the interpolation of the P axes for transpressive to compressive areas, and the large blue lines correspond to the interpolation of the T axes for transtensive to extensive areas (see Fig. 4).

Despite the complex pattern of stress state at the local/regional scale, large-scale principal stress directions remain coherent all along the external zones, rotating progressively and defining a large-scale radial orogen-perpendicular pattern of σ_1 perpendicular to the belt, from a NNW–SSE direction in northern Switzerland to northwest–southeast in front of Belledonne and southwest–northeast in front of the Digne nappé system.

4.3 Foreland areas

The southern Rhine graben (northern Basel zone, balN) shows a transtensive stress state that continuously extends southeastwards beyond the eastern Jura (balS) and into northern Switzerland (Molass basin, zu), with almost the same σ_1 direction (N140°/160°). The slight differences in the extensive versus transtensive state of

Table 1. Stress tensor parameters. For each stress inversion, the name of the area and the corresponding code (see Fig. 5) are given, with the trend and dip of the principal stress axes $\sigma_1, \sigma_2, \sigma_3$ (strike, dip). Φ is the shape parameter of the ellipsoid shape, N is the number of focal mechanisms used for the inversion and M is the misfit parameter (average of the differential angles).

Zone	Code	N	σ_1		σ_2		σ_3		Φ	M
			Strike	Dip	Strike	Dip	Strike	Dip		
Northern Valais	vsn	20	118	10	264	78	27	6	0.62	16.81
Grisons	se	6	288	66	122	23	30	5	0.52	11.04
Eastern Helvetic	hel	18	133	1	228	78	43	12	0.31	20.64
Southern Valais	vss	15	253	63	101	24	6	11	0.72	21.71
Chamonix	cham	6	230	55	93	27	352	20	0.43	13.6
Belledonne Front	bel	17	301	1	211	3	50	87	0.1	11.84
Zürich	zu	25	158	59	346	31	254	3	0.92	17.08
Northern Briançonnais	b1	13	340	82	210	5	119	6	0.08	17.27
Western Briançonnais	b2	19	52	85	180	3	271	4	0.5	15.89
Southwestern Briançonnais	b3N	22	194	71	11	19	101	1	0.86	15.94
Southern Briançonnais	b3S	14	335	59	139	30	233	7	0.48	21.86
Eastern Embrunnais	diE	19	12	54	176	35	271	8	0.76	12.16
Western Embrunnais	diW	24	31	3	301	0	206	86	0.35	22.22
Ligure	lig	25	124	13	222	29	13	58	0.3	21.96
Northern Provence	pro	14	160	69	352	21	260	4	0.63	27.31
Basel north	ba1N	28	147	39	336	50	240	4	0.92	24.39
Basel south	ba1S	31	142	12	355	76	233	8	0.69	18.23
Northern Piemontais	pieN	13	29	87	221	3	131	1	0.56	21.85
Southern Piemontais (ext.)	pieS	34	205	77	343	10	74	8	0.36	23.45
Southern Piemontais (comp.)	pieSc	11	230	7	326	37	130	52	0.22	24.77
Pô Plain	po	9	93	17	356	21	218	63	0.4	15.76

stress can be explained by permutations between the two principal stress axes σ_1 and σ_2 , as evidenced by the high Φ ratios computed in these zones (respectively 0.92, 0.69 and 0.92). In contrast, the Ligurian margin is characterized by a pure compressive stress state (lig, $\Phi = 0.3$), with σ_1 oriented N124° perpendicularly to the extensive structures of the Oligocene Ligurian opening. It thus appears that the Ligurian sea is currently reactivated in a compressional tectonic regime (Béthoux *et al.* 1992; Baroux *et al.* 2001).

In summary, the stress field around the arc of the western central Alps is defined as follows: generalized and continuous extension in the core of the belt, with orogen-perpendicular σ_3 axes, contrasting with localized zones of transpression at the outer limits of the belt, in external zones, with σ_1 also perpendicular to the structural trend of the Alpine arc.

5 DISCUSSION

The west European intraplate stresses are characterized by a near spherical ellipsoid of stresses and a consistent N145° ± 26° σ_1 /Shmax direction (Zoback *et al.* 1989; Muller *et al.* 1992; Zoback 1992; Golke & Coblenz 1996; Muller *et al.* 1997). This stable σ_1 direction is thought to derive from the Atlantic ridge push, perturbed in a complex fashion in the proximity of the Alps (i.e. within some 300 km around this mountain chain). Numerical modelling by Golke & Coblenz (1996) suggests that the dominant factor responsible for the West European stress field is ridge push, with little or no influence from the Europe/Africa convergence in the Alpine belt. In that case, the West European stress field does not necessarily have to be interpreted in terms of collision processes. However, the near spherical stress ellipsoid allows minor sources of stress to exert a strong influence on the regional to local scale. Thus, the Alpine stress field, with its strong correlation between topography and orogen-perpendicular stress axis trajectories, appears to be largely independent of the far-field European stress fields.

In the following, we will compare the results of our seismotectonic analysis with other geophysical parameters related to the strain/stress states of the Alpine belt.

5.1 Geodesy

On the scale of the western Alps, GPS monitoring puts tight constraints on the permissible present-day displacement vectors between plates and microplates involved in the Europe–Africa collision belt (Calais *et al.* 2002; Nocquet 2002; Oldow *et al.* 2002). While an overall convergence between Africa and Europe is ongoing at rates of 3 to 8 mm yr⁻¹ in a general north to northwest direction (Argus *et al.* 1989; Demets *et al.* 1990, 1994; Albarello *et al.* 1995; Crétaux *et al.* 1998; Kreemer & Holt 2001; Nocquet 2002) no clear signal of any relative displacements between northern Italy, eastern France and southern Germany has been detected so far. Given the accuracy of GPS and a limited time span of observation of less than 10 yr, overall Alpine convergence, divergence and/or strike slip movements, if any, have to be less than about 2 mm yr⁻¹.

Within the western Alps, however, 6 yr of continuous GPS monitoring, does indicate some significant displacements (Calais *et al.* 2002; Nocquet 2002). Notably, extension is documented along the Lyon–Turin profile across the western Alps. Along this profile, southeast-directed velocities with increasing strain rates from northwest to southeast, from 0.5 ± 0.9 mm yr⁻¹ at La Feclaz (Bauges massif) to 1.7 ± 0.4 mm yr⁻¹ at Modane (Vanoise massif), are observed. This results in a lengthening of the Lyon–Modane baseline (along the ECORS–CROP profile) at a rate of 1.4 ± 0.4 mm yr⁻¹. This lengthening correlates very well with the extensional regime documented in our seismotectonic analysis. In the outermost zones of the belt, GPS shows localized zones of convergence, e.g. at the western Pô plain with 1.0 ± 0.5 mm yr⁻¹ of east–west to northwest–southeast convergence between Modane and Turin and in the Provence area with 1.4 ± 0.5 mm yr⁻¹ of north–south to northwest–southeast shortening between Grasse and Turin. In

summary, GPS results confirm and strengthen the results obtained from seismotectonic investigations, notably the extensional nature of the present-day core of the Alps, apparently compensated by localized compression near the Alpine border.

Additional geodetic information is provided by repeated precise levelling investigations, spanning about 100 yr, available for Switzerland from the Swiss Federal Topographic Office (Gubler *et al.* 1981) and France (see Fourniguet 1977). The Swiss survey has the advantage of covering a large portion of the central Alps including a north–south section across the Gotthard traverse. Furthermore, in contrast to France, where levelling data remain isolated within individual levelling profiles, the entire Swiss levelling data set has been processed so as to provide a coherent picture of the present-day velocity field of vertical movements, with a reference point at Aarberg in central northern Switzerland. With respect to this ‘stable’ foreland, the entire body of the Alps is rising at a rate of between 1.2 and 1.6 mm yr⁻¹. Maximum velocities are observed in two broad elliptical zones centred in the Valais near Brig-Sion (1.6 mm yr⁻¹) and in the Grisons area (1.4 mm yr⁻¹). In between these two maxima, the Gotthard region appears as a saddle with ‘only’ about 1.2 mm yr⁻¹. Vertical velocities decrease smoothly northwards and southwards, with isolines running parallel to the general strike of the Alpine chain. Not a single one of the numerous late Alpine faults (post-Miocene) and lineaments which have been crossed by levelling lines shows any indication of tectonic activity within the last 100 yr. This is in stark contrast to the French survey of (Fourniguet 1977), who identified a series of local discontinuities of similar magnitude but barely any regional, large-scale trend when approaching the Alps.

5.2 Deformation versus crustal thickness

5.2.1 Topography

In order to qualitatively examine the relationship between the state of strain/stress and topography we used the GTOPO30 Digital Elevation Model (DEM) database (US Geological Survey EROS Data Center, <http://edcdaac.usgs.gov/gtopo30/gtopo30.html>). High-frequency topographic features were removed using a smoothing algorithm, calculating at each point the average altitude within a radius of 25 km. This smoothing process provides a proxy for the topographic load, relevant on the scale of the lithosphere, where high average topography is associated (to first order in the western/central Alps) with thickened crust. By smoothing the DEM, we discard high-frequency signals, such as lineaments, or faults. Our purpose was not to correlate the Alpine seismicity with the complex Alpine structures but to study the large-scale relationship between average topography and stress state. Maxima in average topography exist in eastern Switzerland, in the Valais and in the Vanoise areas, whereas more localized and isolated high mountain ranges in external zones, such as the Mont Blanc massif, almost disappeared in our smoothing process. We tested a series of different filters before subjectively choosing the 25 km smoothing radius. Actually, when draping the map of the regionalized deformation (Fig. 3) over the average smoothed Alpine topography (Fig. 6), the high internal areas (the convex crest line of the Alps) appear to very closely match the areas undergoing extensional deformation (eastern Switzerland, southern Valais, Briançonnais and Piemontais arcs). Moreover, transpression very nicely coincides with the negative (concave) curvature at the transition between the Alps and its flat foreland (eastern Helvetic chains, front of the Belledonne massif, western Pô plain, front of the Digne nappe).

5.2.2 Gravimetry

High-resolution gravimetric map have been published recently for the entire western Alpine arc (Masson *et al.* 1999). Internal zones are characterized by strong negative Bouguer anomalies (–160 to –220 mGal), directly related to the thickened Alpine crustal root resulting from the stacking of low-density materials during the Alpine orogenesis. The Bouguer anomaly is closely related to the topography (in the Alpine chain, high topography is generally related to thickened crust), with the exception of the area surrounding the Ivrea body, characterized by a remarkable positive anomaly which is not reflected in topography. This anomaly is classically interpreted as a slab of dense mantle and/or lower crust (Berkhemer 1968; Kissling 1993; Paul *et al.* 2001). Except for the Ivrea body, negative Bouguer anomalies (e.g. zones of high crustal thickness) are closely correlated with internal extensional deformation (Fig. 3) continuously from the Valais to the edge of the Mont Blanc massif, the Vanoise zone and all along the Briançonnais arc (up to the Argentera massif).

In summary, in the western/central Alps as a whole there exists a very close correlation between the generalized Alpine extensional tectonic regime and the zones of high crustal thicknesses (characterized by high large-scale topography and strong negative Bouguer anomalies). This correlation is a strong argument for proposing a geodynamic model in which the current Alpine tectonism is controlled, at least partly, by internal gravitational body forces. In this model, external zones will undergo compression/transpression in response to the balance of gravitational potential energy.

6 MODELS

Several different non-unique geodynamic models can be envisaged in the light of our large-scale seismotectonic analysis and the comparisons previously mentioned.

6.1 Gravitational body forces

Recent studies in the eastern Alps and the adjacent Pannonian basin (Bada *et al.* 2001) using numerical modelling, show that a topography of 1000 to 3000 m can induce 6 to 22 MPa of extensive stress in high zones (eastern Alps relief) and 3 to 12 MPa of compressive stress in the bordering Pannonian basin, contradicting the idea that the relief of the Alps is not high enough to induce significant topographic stresses (Sue *et al.* 1999). Topographically induced stresses would be expected at a high angle to the strike of the belt, as observed in the western Alpine arc (with orogen-perpendicular stresses).

Assuming that large-scale convergent tectonics are negligible in the western Alps (as supported by GPS monitoring, Nocquet 2002), gravitational body forces will tend to equilibrate the mountain belt by balancing the gravitational potential energy between the core of the belt characterized by high crustal thicknesses and its margins. In this case, extensional tectonics are expected within the inner parts of the belt and compressional stresses at the borders. As an isostatic response to this equilibration, uplift is expected in the core of the belt, correlated with negative Bouguer anomalies, as observed in Switzerland (e.g. the Valais and Grisons areas). In terms of isostasy, further complications arise from perturbations induced by Quaternary glaciations, which may have an effect on the rates of vertical uplift and the stress state observed within the upper crust. Simple models of glacial rebound depend strongly on the unknown elastic thickness of the Alpine lithosphere as well as assumed viscosities of the underlying asthenosphere (Gudmundsson 1994). In any case, isostatic rebound effects are expected to correlate with the well-known maximum thickness of glaciers. In Switzerland, two

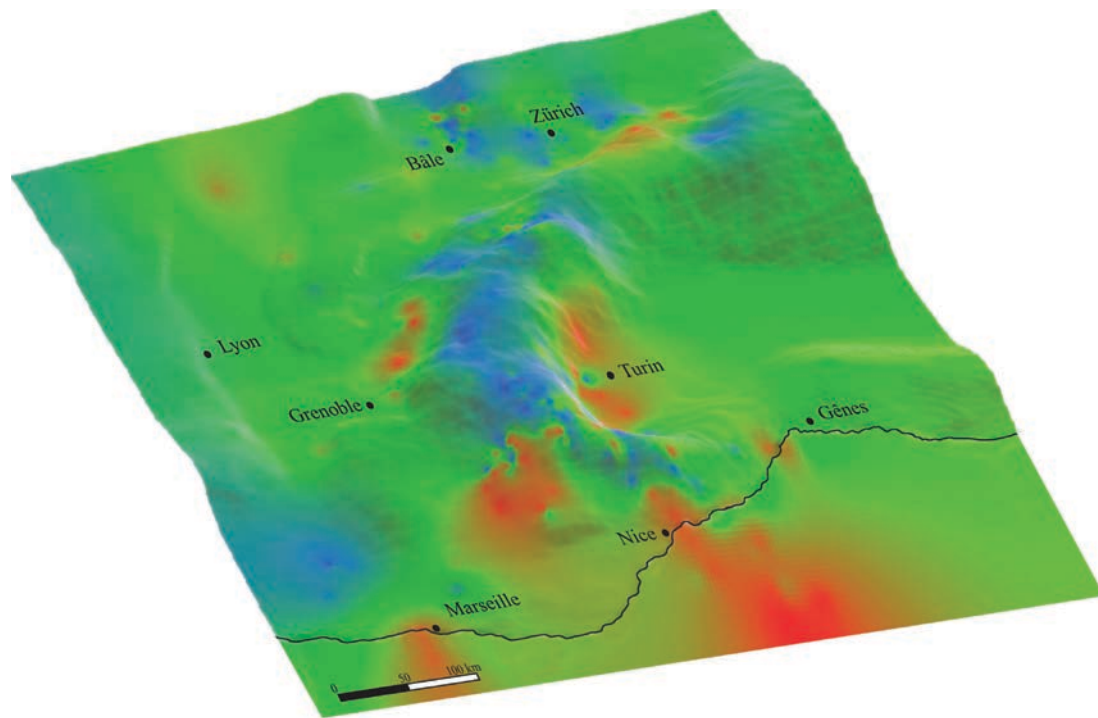


Figure 6. 3-D view of the regionalization of the Alpine deformation. The map of deformation is draped on a smooth digital elevation model (average topography within a radius of 25 km). The continuous extensive zone perfectly correlates with high average topography. Localized external compressive/transpressive zones are located at the bottom of high topographic gradients.

most important ice masses were present in the areas of lakes Geneva and Constance (Jäckli 1962, 1970; Florineth & Schlüchter 1998). Maps of present-day uplift do not exactly reflect this pattern, however, and if present, we think that the effect of glacial rebound on present-day uplift is hidden in the much stronger signal of crustal-scale uplift.

6.2 Rotational models

Geologists have long speculated about the possibility of block rotations between Apulia (African promontory) and Europe as an important factor in the building of the western Alpine arc (Gidon 1974; Anderson & Jackson 1987; Ménard 1988; Vialon *et al.* 1989; Thomas *et al.* 1999; Calais *et al.* 2002). Simple analogue rotation models using sand-box experiments (Collombet 2001; Collombet *et al.* 2002) show great similarities with the Alpine structure: external oblique strike-slip zones, local external thrusting, multiscale arcuate tectonic features. Therefore, rotation models could allow us to explain the large-scale strike-slip mode of deformation, in an overall dextral style, that is observed in external zones (e.g. northern Valais, Mont Blanc/Aiguilles Rouges, front of Belledonne, Briançonnais arc), and that cannot be driven by gravitational body forces. Apulian rotation is further supported by large-scale GPS monitoring regrouping French, Swiss and Italian stations resulting in a microplate anticlockwise rotation of $0.52^\circ \text{ Myr}^{-1}$ around a pole located at $45.36^\circ \text{ N}/9.10^\circ \text{ S}$, near Milan (Calais *et al.* 2002). However, rotation models cannot explain by themselves the overall orogen-perpendicular extension observed on the highest zones of the Alpine belt that is likely to be induced by body forces.

6.3 Proposed model

A combination between gravitational body forces and rotational tectonics could explain most of the current features observed in the

western/central Alps. This association, which remains to be quantified, succeeds in explaining the current strain/stress states analysed in this study using seismotectonic tools, namely the generalized orogen-perpendicular extension we characterized in the highest areas of the chain correlated to crustal uplift, the contrasted tectonics between the highest core of the belt and its outer limits in transpression, and the transcurrent part of the Alpine tectonism.

However, the limitations of this analysis (especially in depth) do not permit us to identify the deep deformation processes that could interact in this model. In particular the role of the Ivrea body (moving bloc, passive indenter, etc.) remains unclear. Our impression is that focal mechanism data imply rather consistent deformation with depth. However, improvements in our knowledge of the deep geometry of the Alpine chain would allow us to better define deep tectonic processes.

7 CONCLUSIONS

The compilation of 389 focal mechanisms, all along the Alpine arc and its foreland, allowed us to provide a synthetic and innovative view of the strain/stress states of the western/central Alpine realm as a whole (Fig. 7). The main features of this state of strain/stress are: continuous orogen-perpendicular extension in the inner areas of the belt, and localized zones of compression/transpression at the outer boundaries of the belt, associated with strike-slip areas in external zones, and defining a large-scale fan pattern with orogen-perpendicular σ_1/P axes. Correlations are established between extensional areas and high crustal thicknesses as well as between localized compressive/transpressive areas in external zones and the bottom of high topographic gradients. Moreover, internal extensive zones correlate in its northern part (Switzerland) with areas of maximum crustal uplift (of about 1.6 mm yr^{-1}). In a context of slow horizontal motions (GPS extensional velocities of less than 2 mm

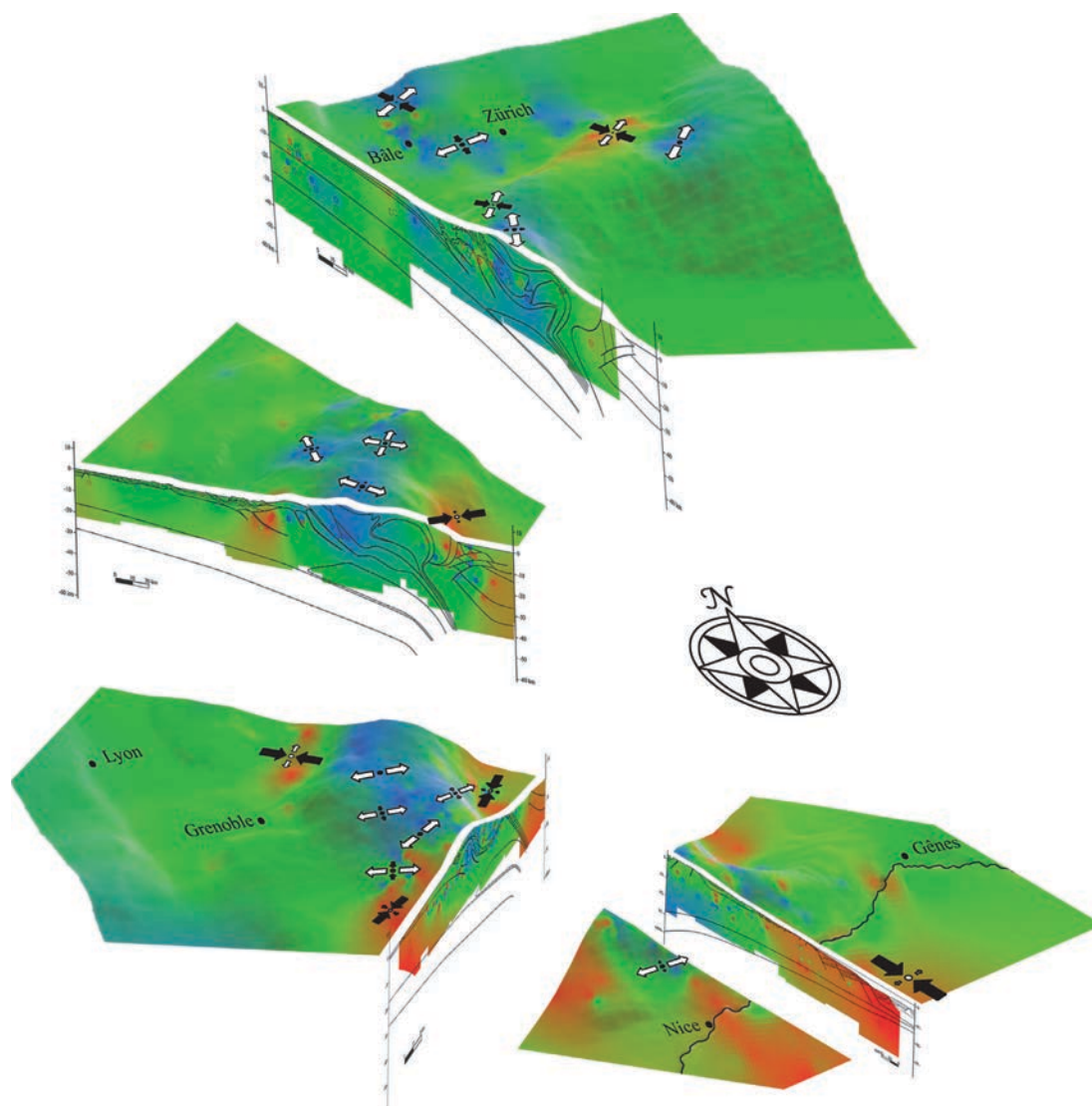


Figure 7. Synthetic 3-D split block of the western Alps showing both the state of stress (inversion) and the deformation state inside the whole belt. The contrasted tectonics between inner and outer areas of the chain and the role of topography and deep structures of the belt are underlined.

yr^{-1} across the whole belt, Calais *et al.* 2002), we propose a model to explain such a strain/stress field combining the following factors: gravitational body forces tending to equilibrate the contrasted gravitational potential energies between the zones of high and low crustal thickness, and large-scale rotational tectonics at the limits of the chain.

Our study addresses the importance of current collisional processes in the realm of the western/central Alps, and more generally the problem of the convergence accommodation between the European and African plates, which should range from 3 to 8 mm yr^{-1} in a north to northwest direction at the longitude of the Alps (Argus *et al.* 1989; Demets *et al.* 1990, 1994; Albarello *et al.* 1995; Crétaux *et al.* 1998; Kreemer & Holt 2001; Nocquet 2002). This convergence could be consumed in different geodynamic areas located between 'stable' Europe and 'stable' Africa such as the Maghrebic belts, the Calabrian subduction, the Apennines, the Dinarides or the eastern Alps. However, in the light of our large-scale seismotectonic study, no direct effect of Europe/Africa convergence can be identified in the western Alpine belt, since the stress field appears to be mostly controlled by internal body forces.

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APPENDIX A: FOCAL MECHANISMS COMPILED IN THE SYNTHETIC DATABASE

Table A1. List and characteristics of focal mechanisms compiled in the synthetic database.

Yr	Mo	Dy	Hr	Mn	Long.	Lat.	Depth	Mag.	Az	Dip	Rake	AzP	DipP	AzT	DipT	r	Zone	Ref.
1968	6	18	05	27.583	7.9000	45.6700	12.0	4.7	240	56	0	200	24	100	25	25	none	M
1970	12	30	02	20.000	8.2530	44.1380	5.0	4.0	224	52	-25	193	42	93	11	-42	none	E
1971	6	21	07	25.000	5.8000	46.4000	3.0	4.4	99	57	-166	315	32	54	14	-32	none	K
1975	1	8	09	12.000	5.7800	46.8000	5.0	3.7	242	70	169	108	7	200	22	22	none	K
1979	4	16	12	27.183	5.1900	44.6700	17.0	4.3	012	60	180	233	22	330	20	-22	none	M
1984	2	19	21	14.628	5.5400	43.4200	8.0	4.3	226	44	-27	204	47	095	17	-47	none	B
1984	4	17	08	53.662	5.1200	44.9700	5.0	4.4	025	90	164	072	14	338	14	14	none	N
1984	4	19	20	41.312	5.1400	44.9800	5.0	4.2	018	84	152	068	15	331	24	24	none	N
1984	12	29	11	2.602	6.5400	48.1100	10.0	4.8	00	89	11	135	07	226	08	08	none	N
1985	11	5	21	35.593	5.6000	47.6500	12.0	3.4	013	63	21	324	05	231	33	33	none	N
1986	2	25	17	10.665	4.7200	43.9500	5.0	3.6	203	43	-78	212	82	105	03	-82	none	B
1987	2	5	9	59.630	4.5600	43.6600	5.0	3.5	356	72	-113	236	57	104	24	-57	none	B
1988	8	5	22	1.554	6.4690	43.7877	5.0	3.6	270	70	-9	228	20	135	08	-20	none	B
1989	4	30	03	38.000	6.7150	47.2820	19.0	2.9	115	61	-156	332	36	66	5	-36	none	K
1992	1	28	21	35.090	5.1043	43.1460	0.5	3.4	250	36	122	137	13	260	67	67	none	B
1996	3	25	4	27.544	4.7263	43.9135	6.0	3.1	190	57	-29	157	42	062	05	-42	none	B
1996	9	26	11	5.672	6.3683	44.8775	6.7	1.5	5	70	-170	227	21	320	7	-21	none	S
1996	10	7	12	26.465	5.7845	43.8335	3.0	2.9	094	67	169	319	09	053	23	23	none	B
1996	11	24	0	27.135	7.6783	44.4450	3.0	3.5	212	27	-45	226	59	089	23	-59	none	B
1997	2	8	19	18.713	5.6228	43.6370	9.0	2.9	050	73	11	004	05	273	19	19	none	B
1998	2	9	14	16.939	4.8913	43.9055	6.0	3.1	024	73	-102	277	60	123	27	-60	none	B
1993	7	21	01	59.272	6.6577	45.5092	3.8	2.4	25	30	-90	115	75	295	15	-75	b1	S
1993	11	22	03	28.905	6.9702	45.5955	6.6	1.8	40	35	-120	205	69	331	13	-69	b1	S
1994	8	1	21	39.438	6.3238	45.1963	1.1	2.1	45	65	-100	295	68	142	19	-68	b1	S
1995	4	21	18	19.517	7.0707	45.7275	13.7	2.1	45	20	-50	75	58	284	29	-58	b1	S
1996	3	31	05	43.134	6.5952	45.3927	8.1	1.2	60	50	-70	35	74	136	3	-74	b1	S
1996	8	1	00	13.047	6.2992	45.2673	2.4	1.7	80	65	-150	299	38	208	1	-38	b1	S
1996	10	25	08	37.133	6.5337	45.3083	7.6	2.0	335	50	-100	192	81	72	5	-81	b1	S
1996	10	28	07	35.518	6.5400	45.2713	8.0	0.8	70	65	-90	340	70	160	20	-70	b1	S
1996	11	5	03	32.343	6.5250	45.2627	8.0	1.2	60	45	-80	56	83	323	0	-83	b1	S
1997	2	19	05	12.897	6.5640	45.2970	6.9	1.5	15	55	-90	285	80	105	10	-80	b1	S
1997	5	15	00	24.064	6.6755	45.2127	9.4	3.1	35	30	-10	15	42	248	33	-42	b1	S
1997	7	14	02	57.936	7.1692	45.8192	14.1	2.2	90	55	-40	60	51	327	2	-51	b1	S
1989	12	13	08	8.227	6.7153	44.7882	9.8	2.3	5	30	-80	69	74	268	15	-74	b2	S
1991	2	11	15	43.713	6.7383	44.8648	6.0	3.8	45	65	-10	5	24	270	11	-24	b2	S
1991	2	13	15	49.650	6.7500	44.8683	3.9	3.0	45	75	-30	1	32	97	9	-32	b2	S
1991	2	13	12	54.704	6.7500	44.8683	5.6	2.8	135	45	-160	341	42	90	19	-42	b2	S
1991	8	12	22	56.152	6.7662	44.8027	2.7	2.2	0	35	-90	90	80	270	10	-80	b2	S
1993	7	10	20	3.983	6.6205	44.8940	2.8	2.2	65	35	-40	61	57	300	19	-57	b2	S
1993	10	30	05	45.205	6.6297	44.7973	5.6	1.2	170	55	-70	131	72	246	8	-72	b2	S
1993	11	10	19	13.288	6.6237	44.7517	8.5	1.4	140	45	-90	301	90	50	0	-90	b2	S
1993	12	14	03	7.120	6.5423	45.0383	7.1	1.9	10	25	-70	61	67	265	21	-67	b2	S
1994	6	18	04	59.971	6.6363	44.8657	9.2	1.2	160	45	-80	156	83	63	0	-83	b2	S
1994	9	17	11	46.998	6.5268	45.0343	8.7	1.5	135	35	-100	262	78	52	10	-78	b2	S
1995	11	22	11	12.878	6.5442	45.0430	8.4	2.1	40	30	-30	36	52	267	26	-52	b2	S
1996	2	18	04	16.551	6.7555	44.7540	9.6	3.3	0	40	-100	147	82	277	5	-82	b2	S
1997	2	21	20	1.752	6.6488	44.8143	9.9	1.9	125	50	-80	88	81	208	5	-81	b2	S
1997	2	21	19	51.549	6.6405	44.8085	8.1	1.8	25	20	-80	98	65	287	25	-65	b2	S
1997	7	19	01	25.708	6.5427	45.0278	9.8	2.0	10	35	-60	25	69	259	13	-69	b2	S
1997	8	3	10	26.424	6.6223	44.9027	7.5	1.8	45	20	-40	64	55	276	31	-55	b2	S
1997	8	30	06	56.607	6.6638	44.7303	8.8	2.2	45	70	-70	344	60	120	22	-60	b2	S
1997	9	13	17	59.648	6.7688	44.7572	8.8	2.6	305	40	-150	142	50	255	18	-50	b2	S

Table A1. (Continued.)

Yr	Mo	Dy	Hr	Mn	Long.	Lat.	Depth	Mag.	Az	Dip	Rake	AzP	DipP	AzT	DipT	r	Zone	Ref.
1959	4	5	10	48.000	6.7800	44.5300	0.0	5.3	170	72	-142	34	39	295	11	-39	b3N	E
1977	9	16	18	27.000	6.7848	44.6242	3.1	2.5	6	29	-90	96	74	276	16	-74	b3N	E
1988	3	26	12	17.172	6.6862	44.4912	7.0	3.7	008	56	-123	222	63	121	06	-63	b3N	B
1991	2	7	00	46.907	6.8902	44.4245	9.7	2.3	345	70	-140	208	42	108	11	-42	b3N	S
1991	4	23	05	52.637	6.7173	44.4677	9.8	1.7	95	45	-30	73	49	326	14	-49	b3N	S
1991	11	27	12	18.425	6.8618	44.5240	9.1	1.6	355	50	-110	200	74	99	3	-74	b3N	S
1992	4	11	06	56.862	6.7043	44.4658	9.4	1.6	60	50	-50	37	60	303	2	-60	b3N	S
1993	10	21	15	30.287	6.8777	44.4002	10.6	1.9	60	55	-20	26	37	287	12	-37	b3N	S
1994	2	11	11	35.378	6.9125	44.3682	6.8	1.5	355	45	-110	182	76	279	2	-76	b3N	S
1994	6	22	23	8.599	6.9138	44.5498	11.2	1.8	70	85	-10	25	11	116	3	-11	b3N	S
1994	9	16	17	58.180	6.8715	44.6440	6.1	2.1	160	50	-70	135	74	236	3	-74	b3N	S
1994	9	24	04	18.298	6.8770	44.5363	3.6	2.5	5	70	-110	246	60	110	22	-60	b3N	S
1995	9	11	22	55.888	6.7847	44.6850	5.0	1.9	180	60	-40	145	48	237	2	-48	b3N	S
1995	10	8	06	7.783	6.8955	44.5137	4.8	2.1	10	75	-90	280	60	100	30	-60	b3N	S
1995	10	13	22	7.705	6.8488	44.5113	6.1	2.9	340	70	-140	203	42	103	11	-42	b3N	S
1995	11	17	00	48.739	6.6838	44.5148	8.3	1.8	95	40	-70	108	76	351	7	-76	b3N	S
1995	12	29	02	20.878	6.7205	44.5083	7.9	1.2	95	65	-40	55	45	152	6	-45	b3N	S
1996	6	10	09	2.932	6.8770	44.5338	5.4	1.8	155	65	-90	65	70	245	20	-70	b3N	S
1996	9	9	08	13.402	6.8858	44.4990	10.2	1.0	335	75	-150	199	32	103	9	-32	b3N	S
1996	9	12	08	46.391	6.8262	44.5532	8.8	1.6	345	65	-130	207	52	103	11	-52	b3N	S
1996	12	15	03	56.178	6.8357	44.5383	8.1	1.2	260	80	0	215	7	125	7	7	b3N	S
1996	12	30	11	22.634	6.7030	44.6308	5.4	1.6	80	55	-20	46	37	307	12	-37	b3N	S
1977	9	23	02	41.000	6.8660	44.5327	2.0	2.5	0	22	-57	36	61	245	26	-61	b3S	E
1978	9	30	09	41.000	6.8577	44.5108	7.7	2.5	167	70	-117	293	57	57	20	-57	b3S	E
1980	10	10	21	42.868	7.0700	44.4100	5.0	4.2	128	80	52	9	25	254	42	42	b3S	E
1993	3	22	04	27.046	6.9057	44.4692	8.5	1.6	95	65	150	147	1	56	38	38	b3S	S
1993	6	15	15	0.363	6.8567	44.5213	7.4	1.6	155	70	-90	65	65	245	25	-65	b3S	S
1995	10	18	02	13.158	6.8883	44.5092	4.3	2.1	135	55	-110	354	72	239	8	-72	b3S	S
1996	1	22	16	41.756	6.7720	44.4610	5.4	2.0	5	45	-40	347	55	242	10	-55	b3S	S
1996	8	22	16	14.833	6.9133	44.4677	4.7	1.3	30	70	20	342	1	251	28	28	b3S	S
1996	9	3	01	40.645	6.6710	44.5333	5.4		115	40	-90	205	85	25	5	-85	b3S	S
1996	9	8	17	46.488	6.8625	44.3875	7.8	1.4	150	30	-110	287	71	75	16	-71	b3S	S
1996	10	25	06	13.180	6.8427	44.5120	8.1	1.1	155	35	-60	170	69	44	13	-69	b3S	S
1997	3	1	11	23.335	6.9903	44.4217	10.2	1.7	115	45	-130	309	62	52	7	-62	b3S	S
1997	5	14	17	23.018	7.0803	44.4775	9.1	2.0	200	85	30	330	17	68	24	24	b3S	S
1980	7	15	12	54.000	7.4850	47.6740	10.0	3.7	117	46	-132	314	60	55	6	-60	balN	K
1980	7	15	12	17.000	7.4750	47.6730	12.0	4.7	125	80	174	350	3	81	11	11	balN	K
1980	7	16	15	0.000	7.4810	47.6710	13.0	3.8	201	42	64	129	6	21	72	72	balN	K
1982	10	4	04	6.000	7.8520	47.6740	23.0	2.9	36	74	-6	353	15	261	7	-15	balN	K
1984	6	16	06	43.000	7.8000	47.7500	9.0	2.7	295	41	-118	113	70	225	8	-70	balN	K
1985	2	28	21	33.000	7.4130	47.6500	10.0	3.4	292	49	-169	145	34	250	21	-34	balN	K
1985	9	15	18	18.000	7.7330	47.9540	14.0	2.0	180	44	-33	160	51	52	14	-51	balN	K
1986	1	20	03	48.000	7.7260	47.9450	12.0	1.4	200	40	-48	193	62	81	12	-62	balN	K
1986	10	7	22	23.000	7.9540	47.8600	18.0	2.1	297	42	-114	116	74	224	5	-74	balN	K
1987	7	18	08	59.000	7.4760	47.6730	12.0	2.8	299	80	177	164	5	255	9	9	balN	K
1987	11	21	14	1.000	7.4760	47.6790	12.0	2.8	209	38	64	138	9	18	72	72	balN	K
1988	3	23	21	11.000	7.4740	47.6750	11.0	1.6	7	30	-13	350	44	222	33	-44	balN	K
1988	8	26	00	30.000	7.6880	47.8040	19.0	3.3	307	30	-118	97	67	237	18	-67	balN	K
1988	8	28	20	45.000	7.6940	47.8030	20.0	1.5	296	33	-134	111	61	237	19	-61	balN	K
1988	10	18	11	19.000	7.6480	47.7380	12.0	2.0	272	73	170	138	5	229	19	19	balN	K
1988	11	20	20	43.000	7.5480	47.7300	17.0	1.9	263	68	-177	125	17	220	13	-17	balN	K
1989	3	18	14	26.000	7.6980	47.9090	14.0	3.0	184	27	7	154	36	23	42	42	balN	K
1989	8	12	14	19.000	7.7260	47.7670	19.0	2.7	275	35	-120	80	69	206	13	-69	balN	K
1990	5	11	06	29.000	7.9240	47.8080	20.0	2.0	58	14	56	356	33	193	56	56	balN	K
1990	6	20	10	59.000	7.7130	47.8480	17.0	2.0	31	35	145	263	20	24	54	54	balN	K
1990	7	31	19	13.000	7.7700	47.6590	19.0	2.0	318	21	-109	80	64	243	25	-64	balN	K
1990	12	11	09	10.000	7.9410	47.8530	13.0	1.5	92	35	-132	269	62	32	16	-62	balN	K
1991	1	1	07	29.000	7.6540	47.8360	12.0	2.0	68	63	-176	288	21	25	16	-21	balN	K
1991	5	20	00	13.000	7.8230	47.6640	17.0	1.5	105	73	-170	328	19	59	5	-19	balN	K
1991	8	25	00	6.000	7.3300	47.6380	12.0	2.0	292	76	-172	155	16	247	4	-16	balN	K
1991	11	12	19	10.000	7.4750	47.6790	12.0	1.8	175	59	-22	139	36	44	8	-36	balN	K
1992	12	30	21	34.000	8.3800	47.7100	22.0	4.0	181	71	3	137	11	44	15	15	balN	K
1995	1	10	11	26.000	7.7480	47.7440	14.0	2.7	336	36	-108	126	75	259	10	-75	balN	K
1978	8	13	04	2.000	7.6900	47.2900	24.0	3.4	121	66	-168	341	25	75	8	-25	balS	K
1982	3	25	18	45.000	7.6010	47.4870	7.0	2.5	110	79	-172	334	13	64	2	-13	balS	K

Table A1. (Continued.)

Yr	Mo	Dy	Hr	Mn	Long.	Lat.	Depth	Mag.	Az	Dip	Rake	AzP	DipP	AzT	DipT	r	Zone	Ref.
1982	9	3	19	12.000	7.9000	47.4200	11.0	2.5	97	70	-175	319	18	53	10	-18	balS	K
1984	4	10	16	50.000	7.5650	47.4320	22.0	2.6	300	62	-176	160	22	257	17	-22	balS	K
1984	4	12	00	50.000	7.7480	47.4350	21.0	2.5	162	42	-30	143	49	32	17	-49	balS	K
1986	11	1	04	1.000	7.7700	47.5650	19.0	1.2	296	81	-174	160	11	251	2	-11	balS	K
1987	1	8	19	24.000	7.6050	47.2550	6.0	2.6	298	62	-174	158	23	255	16	-23	balS	K
1987	4	11	03	14.000	7.8700	47.4280	7.0	3.4	190	76	-11	146	18	56	2	-18	balS	K
1987	12	11	02	25.000	7.1610	47.3130	9.0	3.7	274	70	168	140	6	232	22	22	balS	K
1987	12	16	09	36.000	7.6750	47.5210	9.0	2.7	6	86	36	134	21	236	28	28	balS	K
1987	12	31	15	16.000	7.6760	47.5180	12.0	1.1	53	40	14	13	26	258	41	41	balS	K
1988	4	16	14	5.000	7.8890	47.4360	9.0	1.9	310	63	-108	187	67	53	16	-67	balS	K
1988	5	11	11	12.000	7.6770	47.5150	10.0	1.5	199	75	-16	156	22	66	0	-22	balS	K
1988	10	27	20	52.000	7.7410	47.5000	12.0	1.6	275	77	-177	139	11	230	7	-11	balS	K
1989	5	5	17	44.000	7.6090	47.5590	10.0	2.2	312	79	-170	176	15	266	1	-15	balS	K
1990	6	16	22	41.000	7.6190	47.5760	18.0	2.0	293	80	177	158	5	249	9	9	balS	K
1990	7	25	14	38.000	7.6720	47.5160	10.0	2.0	180	86	-32	131	25	231	19	-25	balS	K
1990	8	16	18	39.000	7.5990	47.5230	11.0	2.1	282	61	-167	140	29	237	12	-29	balS	K
1990	11	8	19	38.000	7.6980	47.5240	11.0	2.0	282	50	-141	127	53	225	6	-53	balS	K
1990	11	28	01	38.000	7.8300	47.5390	18.0	2.0	319	48	-130	159	61	256	4	-61	balS	K
1991	6	4	17	17.000	7.6140	47.5520	7.0	1.7	360	56	24	311	9	213	39	39	balS	K
1991	11	5	09	13.000	7.6920	47.5990	17.0	1.8	334	43	-122	160	68	266	7	-68	balS	K
1992	3	25	05	33.000	7.6330	47.5150	8.0	2.6	278	65	-160	137	31	230	5	-31	balS	K
1996	4	24	09	36.000	7.6070	47.5650	12.0	2.7	292	55	174	153	20	254	28	28	balS	K
1996	6	15	01	5.000	7.6420	47.6020	21.0	2.4	314	73	165	180	2	271	23	23	balS	K
1996	12	15	04	49.000	7.8860	47.3410	20.0	3.0	313	50	-141	158	53	256	6	-53	balS	K
1997	2	21	05	4.000	7.8750	47.4220	8.0	1.8	316	55	-114	171	69	63	7	-69	balS	K
1997	9	2	00	30.000	7.8610	47.6060	23.0	2.6	128	53	-90	38	82	218	8	-82	balS	K
1999	7	13	20	47.000	7.6960	47.5140	19.0	2.7	215	70	-5	173	17	79	11	-17	balS	K
2000	6	20	06	19.000	7.7870	47.4710	18.0	2.9	111	35	-118	273	70	41	13	-70	balS	K
2000	11	13	16	31.000	7.5600	47.2250	10.0	3.4	90	75	-178	313	12	45	9	-12	balS	K
1975	5	29	00	32.000	6.0200	46.0400	0.0	4.2	242	70	174	106	10	200	18	18	bel	K
1980	12	2	05	58.000	6.2800	45.8300	1.0	4.3	302	76	-4	258	13	167	7	-13	bel	K
1982	11	8	13	2.000	6.2700	46.1500	4.0	3.8	97	62	-167	316	28	52	12	-28	bel	K
1983	11	16	00	27.000	5.9600	46.0300	4.0	2.6	349	90	0	304	0	34	0	0	bel	K
1994	12	14	08	56.000	6.4250	45.9580	10.0	5.1	332	44	29	282	15	173	49	49	bel	K
1996	7	15	00	13.000	6.0880	45.9380	2.0	5.3	316	70	-11	274	22	181	7	-22	bel	K
1994	12	14	08	55.983	6.4090	45.9570	7.0	5.1	220	70	130	281	16	173	49	49	bel	T
1995	4	25	13	2.967	5.9660	45.8450	4.0	2.1	220	85	-169	264	11	354	4	-11	bel	T
1995	9	4	21	1.667	6.1820	45.7000	3.0	2.8	225	70	160	93	1	183	28	28	bel	T
1995	9	4	17	2.900	6.1990	45.7000	11.0	2.9	225	75	160	93	3	181	25	25	bel	T
1995	8	28	12	42.500	6.1190	45.5460	6.0	2.3	25	45	60	315	4	215	69	69	bel	T
1995	12	24	04	5.100	6.0670	45.4760	4.0	1.8	15	45	60	305	4	205	69	69	bel	T
1994	2	4	22	19.783	6.0630	45.3890	7.0	2.0	212	80	164	259	4	168	18	18	bel	T
1995	9	8	16	46.950	5.8990	45.2010	7.0	2.5	45	75	-156	268	18	359	4	-18	bel	T
1994	7	25	00	18.950	5.8850	45.1780	2.0	1.8	215	75	160	263	3	171	25	25	bel	T
1992	3	9	01	54.567	5.8720	45.1540	6.0	2.3	25	70	160	253	1	343	28	28	bel	T
1968	8	19	00	36.683	6.7900	46.3100	9.0	4.8	150	60	-71	098	70	231	09	-70	cham	M
1985	5	25	10	39.951	6.9130	45.9990	4.0	3.0	75	75	81	136	20	25	45	45	cham	E
1986	1	17	07	5.510	6.8952	45.9878	3.0	3.4	50	20	-40	211	55	359	31	-55	cham	E
1988	6	11	22	44.000	6.8860	45.8610	8.0	3.4	34	50	-174	249	31	354	23	-31	cham	K
1988	8	4	10	35.980	6.8978	45.9948	3.0	2.4	40	45	-130	234	62	337	7	-62	cham	E
1999	12	29	09	29.000	6.9230	46.1290	4.0	3.3	111	34	-105	249	76	32	11	-76	cham	K
1986	1	17	20	27.317	6.3960	44.2290	6.0	3.6	010	43	-73	013	78	268	03	-78	diE	B
1986	3	23	13	59.398	6.4400	44.2800	7.0	3.7	140	40	-155	339	47	093	20	-47	diE	B
1987	5	9	6	0.283	6.8650	44.1640	6.0	3.4	050	47	-28	025	47	280	14	-47	diE	B
1990	5	7	14	20.862	6.7480	44.3400	5.0	2.9	255	58	-9	217	28	118	16	-28	diE	B
1990	6	29	8	55.000	6.3420	44.1900	6.0	2.8	018	64	-22	340	33	247	04	-33	diE	B
1992	1	2	02	12.431	6.4352	44.4127	8.3	2.3	50	55	-30	18	44	282	7	-44	diE	S
1992	4	19	22	24.888	6.2155	44.2607	5.0	3.0	121	54	-62	089	67	192	05	-67	diE	B
1992	7	31	20	14.458	6.3883	44.4722	0.5	3.0	035	39	-51	033	64	278	12	-64	diE	B
1994	6	27	17	48.804	6.4328	44.4330	7.2	2.7	165	15	-40	190	53	34	34	-53	diE	S
1994	11	28	08	28.238	6.6562	44.3372	9.2	1.8	15	60	-40	340	48	72	2	-48	diE	S
1996	4	18	05	39.741	6.8903	44.2473	10.0	1.4	5	35	-60	20	69	254	13	-69	diE	S
1996	8	9	17	31.270	6.4180	44.3878	5.9	1.7	350	80	-170	214	14	304	0	-14	diE	S
1996	8	9	18	40.889	6.4025	44.3827	8.7	2.2	345	50	-130	188	60	282	2	-60	diE	S
1996	10	7	02	13.415	6.8093	44.2190	7.9	2.2	175	50	-110	20	74	279	3	-74	diE	S

Table A1. (Continued.)

Yr	Mo	Dy	Hr	Mn	Long.	Lat.	Depth	Mag.	Az	Dip	Rake	AzP	DipP	AzT	DipT	<i>r</i>	Zone	Ref.
1996	10	26	16	21.972	6.8013	44.2067	3.4	1.9	25	70	-60	333	55	93	19	-55	diE	S
1996	12	1	11	23.484	6.7923	44.2078	4.7	1.4	15	75	-20	332	25	63	3	-25	diE	S
1997	10	3	15	3.591	6.4440	44.3303	0.5	3.8	037	52	-27	007	43	267	11	-43	diE	B
1997	10	22	04	51.145	6.5215	44.4098	9.1	2.1	20	20	-140	181	55	329	31	-55	diE	S
1969	11	22	07	49.250	6.8060	44.2550	7.0	3.6	166	60	127	231	08	128	58	58	diW	B
1972	6	19	4	9.850	6.3330	44.3600	2.0	3.8	199	60	153	070	05	163	39	39	diW	B
1980	3	15	8	0.798	6.3528	44.2248	5.0	3.8	147	45	124	034	05	135	67	67	diW	B
1983	3	20	16	1.518	6.4500	44.3800	6.0	3.9	010	40	114	263	07	018	73	73	diW	B
1983	12	22	18	12.350	6.7280	44.2750	6.0	3.5	356	57	155	226	08	322	39	39	diW	B
1984	6	19	11	40.618	6.1600	43.9900	10.0	4.1	278	44	109	175	02	276	77	77	diW	B
1984	6	30	19	34.097	6.1300	44.0000	6.0	3.8	300	55	129	003	02	269	59	59	diW	B
1987	5	9	6	0.279	6.8377	44.2050	0.5	3.4	316	43	133	197	10	304	60	60	diW	B
1987	6	28	2	12.881	6.1410	44.1668	1.0	4.0	125	53	118	194	04	095	68	68	diW	B
1989	2	12	3	52.062	6.4930	44.1900	9.0	3.8	302	60	119	012	10	261	63	63	diW	B
1990	6	29	1	19.000	6.3840	44.1670	6.0	3.1	309	86	166	355	07	264	13	13	diW	B
1990	11	9	10	59.043	6.5980	43.9300	2.0	3.3	152	58	55	266	07	008	60	60	diW	B
1993	4	14	10	32.113	6.2272	44.2285	3.0	3.2	134	34	79	052	11	260	77	77	diW	B
1993	5	5	04	34.020	6.8372	44.2683	10.4	1.2	115	25	110	10	21	166	67	67	diW	S
1994	4	15	02	58.218	6.7310	44.2833	6.3	1.8	150	75	-70	85	34	224	63	63	diW	S
1994	11	13	00	36.083	6.4608	44.3180	7.1	1.4	100	70	100	182	24	26	64	64	diW	S
1994	11	24	21	17.590	6.4443	43.8198	1.5	3.5	077	49	77	176	03	285	80	80	diW	B
1996	4	18	05	31.680	6.8898	44.2552	9.7	2.8	65	90	0	20	0	110	0	0	diW	S
1997	10	31	04	23.711	6.5467	44.2710	5.4	4.0	60	60	50	177	7	277	55	55	diW	S
1997	11	6	12	39.799	6.5185	44.4105	8.6	3.1	95	75	30	223	9	319	32	32	diW	S
1998	5	6	12	2.437	6.0858	44.1605	4.0	3.2	166	80	142	221	18	118	34	34	diW	B
1985	9	29	23	36.000	8.3080	46.9220	1.0	2.5	39	26	122	285	22	70	64	64	hel	K
1985	12	21	17	19.000	8.3110	46.8800	2.0	2.9	320	46	-63	307	71	211	2	-71	hel	K
1987	7	26	10	56.000	9.1210	46.8900	1.0	2.4	90	72	144	145	10	47	38	38	hel	K
1987	10	28	23	49.000	9.1960	47.0780	7.0	4.2	178	70	13	132	5	40	23	23	hel	K
1987	11	1	10	16.000	9.6170	47.2250	1.0	2.6	295	78	-169	159	16	249	1	-16	hel	K
1989	4	2	06	58.000	9.1110	47.1440	8.0	3.2	31	43	87	303	2	168	87	87	hel	K
1989	11	19	21	20.000	8.4160	46.8450	6.0	2.4	196	45	8	157	25	47	35	35	hel	K
1990	11	22	15	51.000	8.9990	46.8900	5.0	3.6	341	60	6	298	17	200	24	24	hel	K
1994	8	28	06	4.000	8.7770	46.8750	4.0	3.9	68	56	156	297	9	34	39	39	hel	K
1995	11	16	05	57.000	8.7980	47.0570	4.0	3.8	16	45	0	341	30	231	30	30	hel	K
1996	12	7	05	34.000	8.4250	46.9130	2.0	2.5	172	74	36	297	11	36	37	37	hel	K
1998	4	21	02	30.000	9.3380	47.1400	10.0	3.6	209	78	6	164	4	73	13	13	hel	K
2000	2	23	04	7.000	9.4990	47.0520	7.0	3.6	183	56	18	137	12	38	35	35	hel	K
2000	3	4	15	43.000	9.4700	47.2500	3.0	3.6	235	20	90	145	25	325	65	65	hel	K
2000	6	3	15	14.000	10.1150	47.2140	3.0	3.8	23	57	-12	347	31	247	15	-31	hel	K
2000	6	10	05	51.000	10.1160	47.2120	3.0	3.6	19	53	-13	345	33	243	18	-33	hel	K
2000	8	17	07	14.000	8.4800	46.9540	10.0	3.0	280	80	172	145	1	235	13	13	hel	K
1963	7	19	5	46.067	8.0390	43.3360	14.0	6.0	356	53	60	107	04	205	66	66	lig	B
1963	7	27	5	57.000	8.1300	43.5600	14.0	4.8	000	80	31	129	13	226	28	28	lig	B
1971	9	25	10	34.000	8.7300	44.1170	5.0	4.2	150	75	-11	107	18	016	04	-18	lig	B
1981	1	5	8	10.000	8.0000	43.1410	10.0	3.6	020	50	90	110	05	290	85	85	lig	B
1981	4	22	4	26.350	8.0650	43.3490	9.0	4.5	240	68	0	103	15	197	15	15	lig	B
1985	10	4	15	22.183	7.9160	43.6100	14.0	3.9	210	45	108	107	01	204	77	77	lig	B
1985	10	4	13	17.358	7.9800	43.5700	10.0	4.0	132	66	17	085	06	352	28	28	lig	B
1985	10	5	15	58.667	7.9160	43.5930	11.0	3.1	040	77	159	088	05	356	24	24	lig	B
1986	5	1	00	28.030	7.4400	43.4400	5.0	3.8	115	78	166	341	00	007	17	17	lig	B
1986	10	29	08	13.567	8.2100	43.8210	10.0	3.0	204	84	-9	159	11	250	02	-11	lig	B
1989	12	26	19	59.983	7.5610	43.4830	4.0	4.5	015	60	70	119	13	244	68	68	lig	B
1990	4	15	7	50.600	7.7740	43.5740	5.0	4.3	025	70	42	148	12	259	43	43	lig	B
1990	9	8	8	31.382	7.3800	43.8400	11.0	2.7	060	40	132	301	12	053	61	61	lig	B
1991	2	19	15	33.000	7.6580	44.0430	7.0	3.0	215	40	55	149	10	036	66	66	lig	B
1991	2	25	11	30.197	7.6600	44.0480	4.0	3.3	215	40	53	151	10	038	64	64	lig	B
1991	6	28	23	48.800	7.4900	43.6700	5.0	2.9	092	62	108	169	15	038	68	68	lig	B
1992	9	21	12	37.067	8.3278	43.2445	20.0	3.0	000	50	80	097	05	217	81	81	lig	B
1993	7	17	11	8.387	8.2623	44.2273	9.0	3.7	085	70	-171	307	21	040	07	-21	lig	B
1993	7	17	10	35.010	8.2525	44.2215	7.8	4.5	165	65	10	120	11	25	24	24	lig	E
1995	4	21	8	2.958	7.5563	43.8155	4.0	4.3	030	80	39	155	19	259	35	35	lig	B
1996	11	25	19	47.387	8.5465	44.1390	3.0	3.8	335	40	40	278	14	165	58	58	lig	B
1983	1	22	12	41.950	7.1500	45.1900	5.0	4.1	192	51	-154	041	43	142	12	-43	pieN	N
1984	1	12	08	24.773	7.3500	44.6600	10.0	3.6	5	20	166	215	37	358	46	46	pieN	E

Table A1. (Continued.)

Yr	Mo	Dy	Hr	Mn	Long.	Lat.	Depth	Mag.	Az	Dip	Rake	AzP	DipP	AzT	DipT	r	Zone	Ref.
1989	10	30	11	24.095	7.2332	44.6117	9.8	3.0	135	60	-110	4	68	239	13	-68	pieN	S
1989	12	2	08	56.516	7.2277	44.7180	13.6	1.8	120	55	-110	339	72	224	8	-72	pieN	S
1990	1	20	19	25.324	7.1308	45.1347	1.6	2.5	315	90	-140	188	27	82	27	27	pieN	S
1991	7	29	08	46.278	7.2153	44.8510	8.8	1.6	45	25	-60	81	64	293	22	-64	pieN	S
1994	2	9	08	33.383	7.3450	45.0583	15.2	1.8	90	50	-20	60	40	316	16	-40	pieN	S
1995	4	24	00	39.664	7.1958	44.6608	11.4	1.8	10	70	-110	251	60	115	22	-60	pieN	S
1996	10	22	03	39.881	7.0303	44.9755	9.0	0.8	20	60	-110	249	68	124	13	-68	pieN	S
1996	11	3	19	4.203	7.1930	44.6665	10.8	1.1	350	70	-120	222	55	102	19	-55	pieN	S
1996	11	23	10	49.445	7.1927	44.6645	9.4	1.5	170	30	-70	213	71	65	16	-71	pieN	S
1996	12	11	17	50.689	7.2620	44.8483	16.5	1.5	85	45	-60	74	69	334	4	-69	pieN	S
1996	12	16	05	22.622	7.3020	45.0470	16.2	1.4	40	50	-140	245	53	343	6	-53	pieN	S
1971	2	1	12	26.103	7.2600	44.4300	2.0	4.3	150	55	-133	120	56	211	1	-56	pieS	E
1981	1	4	04	9.000	7.3410	44.3280	5.0	3.5	135	70	-50	88	49	197	15	-49	pieS	E
1986	1	17	18	48.050	7.3390	44.3510	6.0	3.3	210	33	-50	219	63	092	17	-63	pieS	B
1986	3	11	07	46.630	7.3200	44.4000	5.0	3.6	247	79	-159	203	23	295	7	-23	pieS	E
1986	7	17	07	35.568	7.2600	44.5300	1.0	3.2	225	45	-140	207	55	102	10	-55	pieS	E
1987	6	15	21	27.302	7.3100	44.4100	10.0	3.3	222	35	-138	44	58	166	18	-58	pieS	E
1992	10	27	03	12.527	7.2428	44.5018	8.7	2.9	140	75	-70	205	56	66	27	-56	pieS	E
1992	11	11	00	59.882	7.2640	44.4847	7.6	2.1	170	45	-80	166	83	73	0	-83	pieS	S
1993	2	15	12	15.046	7.2993	44.3350	11.3	1.9	115	40	-100	262	82	32	5	-82	pieS	S
1993	3	15	23	43.491	7.3235	44.3642	12.3	3.4	110	55	-120	323	65	221	6	-65	pieS	S
1993	4	7	16	36.056	7.2132	44.4185	7.3	1.5	130	75	-100	26	59	228	29	-59	pieS	S
1993	4	10	17	54.425	7.2867	44.4310	14.6	1.8	245	60	-30	210	41	117	3	-41	pieS	S
1994	3	5	08	12.031	7.2238	44.4633	11.4	1.4	130	50	-90	40	85	220	5	-85	pieS	S
1994	9	28	12	43.587	7.3003	44.2363	8.3	1.5	130	55	-110	349	72	234	8	-72	pieS	S
1994	12	7	21	45.618	7.1787	44.5308	12.9	1.8	160	40	-70	173	76	56	7	-76	pieS	S
1995	10	7	19	15.023	7.2803	44.3738	12.5	2.1	10	30	-130	176	62	309	20	-62	pieS	S
1995	10	18	12	52.979	7.3502	44.3028	15.6	1.8	120	45	-100	304	83	37	0	-83	pieS	S
1995	11	24	05	50.275	7.2907	44.3800	15.2	1.6	165	30	-80	229	74	68	15	-74	pieS	S
1996	1	26	01	0.837	7.2583	44.5103	11.9	1.7	335	60	-120	196	62	86	10	-62	pieS	S
1996	1	26	02	19.767	7.2563	44.5043	14.3	2.0	120	35	-130	295	63	58	16	-63	pieS	S
1996	8	9	17	14.630	7.2697	44.4633	9.8	1.4	65	70	-10	23	21	290	7	-21	pieS	S
1996	8	11	08	25.196	7.1908	44.5620	6.9	1.4	325	70	-150	187	35	93	5	-35	pieS	S
1996	8	17	20	5.313	7.2677	44.3692	13.1	1.5	155	50	-100	12	81	252	5	-81	pieS	S
1996	8	23	05	54.655	7.2767	44.4560	11.1	2.0	10	75	-140	236	38	134	15	-38	pieS	S
1996	9	2	00	8.617	7.2533	44.3810	14.9	2.0	125	45	-140	323	55	68	10	-55	pieS	S
1996	9	2	00	17.566	7.2455	44.3753	14.3	1.5	185	30	-80	249	74	88	15	-74	pieS	S
1996	9	11	05	40.641	7.2972	44.3490	12.6	1.9	40	70	-40	357	42	97	11	-42	pieS	S
1996	9	20	22	5.383	7.2592	44.5423	12.2	1.4	345	60	-160	201	34	297	8	-34	pieS	S
1996	10	27	10	11.068	7.2833	44.3442	13.1	0.9	10	50	-110	215	74	114	3	-74	pieS	S
1996	11	3	20	1.406	7.2092	44.3953	11.3	0.8	145	60	-70	96	68	221	13	-68	pieS	S
1996	11	15	23	17.671	7.3070	44.2993	15.5	0.7	170	25	-60	206	64	58	22	-64	pieS	S
1996	11	15	23	35.246	7.3045	44.2990	15.0	1.1	125	50	-130	328	60	62	2	-60	pieS	S
1996	12	12	16	25.964	7.2453	44.4445	12.5	0.9	30	65	-120	257	59	141	15	-59	pieS	S
1996	12	26	19	33.821	7.3038	44.3527	14.9	2.5	335	70	-160	196	28	287	1	-28	pieS	S
1972	12	29	0	14.283	7.1690	44.3140	9.0	3.6	295	48	54	229	03	134	64	64	pieSc	B
1977	2	6	16	1.045	7.3400	44.5200	10.0	4.0	120	48	78	202	2	97	81	81	pieSc	E
1985	2	21	18	0.575	7.4200	44.3700	14.0	3.2	157	65	62	227	15	108	60	60	pieSc	E
1992	11	9	13	11.646	7.3448	44.3137	12.8	1.8	110	70	110	185	22	49	60	60	pieSc	S
1994	1	20	06	59.239	7.3380	44.5612	4.8	4.7	22	75	123	281	20	170	45	45	pieSc	E
1994	1	20	07	5.717	7.2803	44.5473	14.1	4.3	160	75	139	104	15	207	39	39	pieSc	E
1996	8	17	19	29.111	7.2982	44.3528	13.5	1.7	70	90	60	187	38	313	38	38	pieSc	S
1996	9	28	15	48.133	7.1367	44.5628	9.2	1.6	160	85	120	225	33	99	42	42	pieSc	S
1996	11	25	08	39.352	7.2460	44.5110	12.0		40	40	170	258	28	13	38	38	pieSc	S
1996	12	26	19	38.673	7.2908	44.3400	14.0	1.1	350	75	160	38	3	307	25	25	pieSc	S
1996	12	26	19	58.853	7.2830	44.3357	13.5	1.8	270	90	40	37	27	143	27	27	pieSc	S
1980	1	5	14	31.498	7.4190	45.0340	4.0	4.8	215	55	40	92	2	185	51	51	po	E
1981	2	8	04	30.175	7.4390	45.1520	5.0	4.4	155	40	120	266	9	153	69	69	po	E
1981	2	8	04	30.117	7.5000	45.1100	1.0	3.9	100	50	-74	060	78	177	03	-78	po	M
1983	9	6	22	43.307	7.3900	44.9700	5.0	3.8	000	72	75	101	26	249	60	60	po	N
1987	7	3	10	46.951	7.5955	45.3990	3.0	3.7	20	35	80	297	10	147	78	78	po	E
1990	2	11	07	7.797	7.4757	44.9872	24.0	2.7	0	65	120	69	15	313	59	59	po	E
1990	2	11	07	0.630	7.5473	44.9650	16.0	4.2	120	55	120	231	6	333	65	65	po	E
1995	3	4	01	58.230	7.6445	44.7342	25.1	4.3	160	40	60	56	9	162	69	69	po	E
1982	9	2	21	45.417	7.2630	43.9280	10.0	3.3	235	60	-71	185	69	311	13	-69	pro	B

Table A1. (Continued.)

Yr	Mo	Dy	Hr	Mn	Long.	Lat.	Depth	Mag.	Az	Dip	Rake	AzP	DipP	AzT	DipT	<i>r</i>	Zone	Ref.
1983	12	4	17	34.850	7.7590	43.8600	4.0	3.5	190	54	-32	160	46	063	07	-46	pro	B
1986	8	18	11	37.200	7.1550	44.0810	6.0	3.2	155	75	-95	065	60	245	30	-60	pro	B
1986	10	20	20	29.183	7.7090	43.9300	2.0	3.0	203	79	-10	159	15	069	01	-15	pro	B
1990	7	2	18	42.000	7.7250	43.9320	4.0	2.7	190	63	-43	152	49	249	06	-49	pro	B
1990	8	9	19	16.960	7.4200	44.0030	6.0	3.2	116	60	-12	078	29	341	13	-29	pro	B
1990	10	2	2	6.402	7.7100	43.9400	11.0	2.9	300	80	-153	165	26	070	11	-26	pro	B
1990	10	22	2	11.147	7.2200	44.1400	4.0	3.0	353	60	-46	053	05	317	52	52	pro	B
1991	2	5	9	6.172	7.7600	43.7900	8.0	3.0	339	75	-44	296	40	037	17	-40	pro	B
1991	7	14	20	47.842	7.2100	44.0700	5.0	2.9	020	81	151	071	13	334	27	27	pro	B
1996	9	26	21	37.612	7.6307	43.9562	7.0	2.7	187	40	-64	194	72	079	08	-72	pro	B
1996	10	17	15	21.646	7.5235	43.9990	11.5	2.5	40	75	-10	357	18	266	4	-18	pro	S
1987	4	29	20	41.000	9.8210	46.4930	8.0	2.6	353	67	-12	312	24	219	8	-24	se	K
1988	4	17	03	41.000	9.4670	46.7830	6.0	2.2	327	43	-59	321	69	216	6	-69	se	K
1988	5	23	21	56.000	9.6420	46.7260	7.0	2.1	345	47	-54	328	64	230	4	-64	se	K
1990	3	18	09	54.000	9.8370	46.7920	4.0	3.5	326	38	-38	317	56	201	17	-56	se	K
1991	11	20	01	54.000	9.5270	46.7310	6.0	5.0	294	37	-72	321	76	191	9	-76	se	K
2000	2	22	22	46.000	9.9940	46.8540	4.0	3.3	174	68	-10	133	22	39	9	-22	se	K
1965	10	24	12	15.937	7.3770	46.3560	10.0	4.4	165	75	-130	115	45	226	20	-45	vsn	E
1967	3	24	17	37.000	7.3630	46.4620	10.0	4.3	265	80	-160	130	21	37	7	-21	vsn	E
1970	8	18	04	25.528	7.6690	46.4370	10.0	4.2	160	60	2	119	19	20	22	22	vsn	E
1979	7	3	21	13.000	7.0720	46.9250	30.0	3.8	285	86	179	150	2	240	4	4	vsn	K
1981	9	26	13	54.768	7.2900	46.3300	5.0	4.4	189	83	23	321	11	55	21	21	vsn	E
1986	10	9	10	8.000	7.4720	46.3190	4.0	3.6	79	61	167	304	12	41	28	28	vsn	K
1987	9	20	11	53.000	7.2200	46.7560	9.0	3.9	7	81	0	323	6	232	6	6	vsn	K
1988	10	14	19	2.000	6.8890	46.6980	2.0	3.3	350	69	20	302	2	211	29	29	vsn	K
1989	1	7	02	29.000	7.5390	46.3420	4.0	3.4	57	68	170	282	9	16	22	22	vsn	K
1989	9	30	04	41.000	7.3940	46.3170	6.0	3.5	110	90	140	163	27	57	27	27	vsn	K
1990	4	28	22	24.000	7.5160	46.3370	3.0	2.2	266	46	-145	108	52	212	11	-52	vsn	K
1990	5	7	16	6.000	7.4040	46.3230	7.0	1.6	175	45	-31	153	49	46	14	-49	vsn	K
1990	6	3	19	23.000	7.2820	46.2980	3.0	2.2	100	60	-151	315	41	48	3	-41	vsn	K
1990	7	26	12	30.000	7.3950	46.3250	7.0	2.4	285	80	-140	154	35	50	19	-35	vsn	K
1990	8	31	10	57.000	7.4580	46.2710	7.0	2.0	181	53	25	132	11	32	42	42	vsn	K
1995	9	17	16	29.000	7.2000	46.7820	10.0	3.8	175	88	3	310	1	40	4	4	vsn	K
1996	2	21	18	57.000	7.5790	46.3680	5.0	3.3	242	87	-178	107	4	197	1	-4	vsn	K
1997	11	28	08	30.000	7.8980	46.4370	12.0	2.9	250	60	-150	105	41	198	3	-41	vsn	K
1999	2	14	05	58.000	7.2120	46.7820	10.0	4.3	354	88	9	129	5	219	8	8	vsn	K
1999	5	20	13	11.000	7.3200	46.6550	7.0	3.8	300	42	-82	326	84	204	3	-84	vsn	K
1968	7	8	05	45.582	7.5400	46.2100	5.0	4.0	79	58	156	30	8	294	38	38	vss	E
1985	1	4	16	57.000	7.2690	46.0020	10.0	3.2	329	82	-40	279	33	23	21	-33	vss	K
1986	1	19	06	54.000	7.6400	46.1830	6.0	3.0	110	40	-80	143	82	13	5	-82	vss	K
1986	2	15	01	43.000	7.6380	46.0510	5.0	3.6	27	70	170	252	7	345	21	21	vss	K
1986	2	26	13	7.000	7.3500	46.0340	7.0	2.9	249	51	-133	94	58	188	2	-58	vss	K
1986	6	9	17	58.649	7.9578	46.1063	10.0	2.6	60	35	-80	113	78	323	10	-78	vss	E
1987	3	22	01	36.000	7.8720	46.1920	4.0	2.1	311	51	-47	286	58	192	2	-58	vss	K
1987	5	30	19	45.000	7.9090	45.9610	9.0	2.7	135	50	-10	101	33	357	21	-33	vss	K
1990	5	11	08	16.000	7.7650	46.2180	1.0	2.0	263	40	-116	76	72	191	8	-72	vss	K
1990	9	25	05	19.000	7.6350	46.1730	5.0	3.6	70	50	-130	273	60	7	2	-60	vss	K
1990	12	17	23	34.000	7.6380	46.2190	5.0	1.7	319	42	-49	310	62	201	10	-62	vss	K
1991	9	7	18	9.000	7.9370	46.2190	8.0	2.4	135	55	-19	101	37	2	12	-37	vss	K
1996	3	31	06	8.000	7.4600	45.9380	4.0	4.6	44	38	-137	231	59	347	15	-59	vss	K
1998	5	7	17	16.000	7.3930	46.1260	6.0	3.3	92	55	-90	2	80	182	10	-80	vss	K
1998	12	9	22	8.000	7.5520	46.1910	4.0	3.4	256	28	-80	323	72	159	17	-72	vss	K
1976	3	2	08	27.000	9.4000	47.6000	10.0	3.7	31	90	0	346	0	76	0	0	zu	K
1977	11	21	19	27.000	8.5800	47.2800	25.0	3.5	33	80	-5	349	11	258	4	-11	zu	K
1978	8	28	14	44.000	8.9200	47.3500	22.0	2.8	9	40	-46	1	60	249	12	-60	zu	K
1979	11	30	00	44.000	8.5100	47.2700	27.0	3.1	296	84	-176	161	7	251	1	-7	zu	K
1983	9	4	21	51.000	8.8070	47.7030	8.0	2.8	159	74	175	24	8	116	15	15	zu	K
1984	1	11	14	11.000	8.8150	47.3350	11.0	3.2	36	76	5	351	6	259	13	13	zu	K
1984	9	5	05	16.000	8.5620	47.2470	15.0	4.0	8	44	-26	345	46	236	17	-46	zu	K
1984	9	14	22	30.000	8.5570	47.2430	24.0	2.9	315	67	-158	175	31	266	2	-31	zu	K
1985	1	7	09	52.000	8.3030	47.1620	27.0	2.1	336	46	-125	170	65	270	4	-65	zu	K
1985	7	7	00	8.000	7.7530	47.0030	30.0	2.7	124	80	169	170	1	80	15	15	zu	K
1986	2	27	12	7.000	8.9550	47.6800	17.0	4.2	304	38	-138	131	58	247	15	-58	zu	K
1986	10	8	03	12.000	8.5420	47.2670	28.0	2.0	315	66	-160	174	30	267	4	-30	zu	K
1987	1	29	00	7.000	9.2870	47.4260	8.0	3.2	10	45	-54	357	65	255	6	-65	zu	K

Table A1. (Continued.)

Yr	Mo	Dy	Hr	Mn	Long.	Lat.	Depth	Mag.	Az	Dip	Rake	AzP	DipP	AzT	DipT	<i>r</i>	Zone	Ref.
1987	5	5	20	29.000	8.5640	47.2250	29.0	2.3	304	75	-170	167	18	258	4	-18	zu	K
1988	9	11	23	1.000	8.3900	47.1300	29.0	2.5	298	74	180	162	11	254	11	11	zu	K
1989	2	21	23	36.000	8.8580	47.5310	22.0	3.5	273	62	-165	131	30	227	10	-30	zu	K
1989	6	9	01	30.000	8.3310	47.4780	18.0	1.3	142	42	-105	311	79	63	4	-79	zu	K
1989	10	24	12	3.000	8.5910	47.3530	12.0	2.1	314	30	-166	150	44	278	32	-44	zu	K
1990	1	5	04	21.000	9.1230	47.4120	5.0	2.9	126	78	-160	350	23	258	5	-23	zu	K
1990	8	11	05	31.000	8.0000	47.2740	15.0	2.8	11	90	0	326	0	236	0	0	zu	K
1995	6	25	18	53.000	8.8730	47.6040	12.0	3.5	167	58	-90	77	77	257	13	-77	zu	K
1996	6	28	03	43.000	8.7610	47.7590	9.0	3.1	289	78	-172	153	14	244	3	-14	zu	K
1996	8	24	02	38.000	9.0490	47.4320	29.0	4.0	184	42	-63	183	72	75	6	-72	zu	K
1997	10	23	12	7.000	8.6240	47.1810	30.0	3.2	221	65	-2	179	19	84	16	-19	zu	K
1999	9	12	13	25.000	8.5380	47.5800	2.0	3.1	151	80	175	16	3	107	11	11	zu	K

Yr, year; Mo, month; Dy, day; Hr, hours; Mn, minutes and seconds; Long., longitude; Lat., latitude; Mag., magnitude (M_L); Az, azimuth of fault plane; Dip, dip of fault plane; Rake, rake of fault plane solution; AzP(T), azimuth of P(T) axes; DipP(T), dip of P(T) axes; *r*, parameter defining the type of deformation (see Fig. 3; Zone, associated stress inversion zone; Ref., reference (B, Baroux *et al.* (2001); E, Eva & Solarino (1998); K, Kastrup *et al.* (2004); M, Ménard (1988); N, Nicolas *et al.* (1990); S, Sue *et al.* (1999); T, Thouvenot (1996)).

APPENDIX B:

Stereograms of inverted stress tensors and associated focal planes used for the inversion. Inside the stereograms: circles are σ_1 prin-

cipal stress axes; squares σ_2 axes; triangles σ_3 axes. Outside the stereograms: black arrows represent the horizontal direction of compression and open arrows the direction of extension. The size of the arrows is a function of the Φ ratio of the ellipsoid shape.

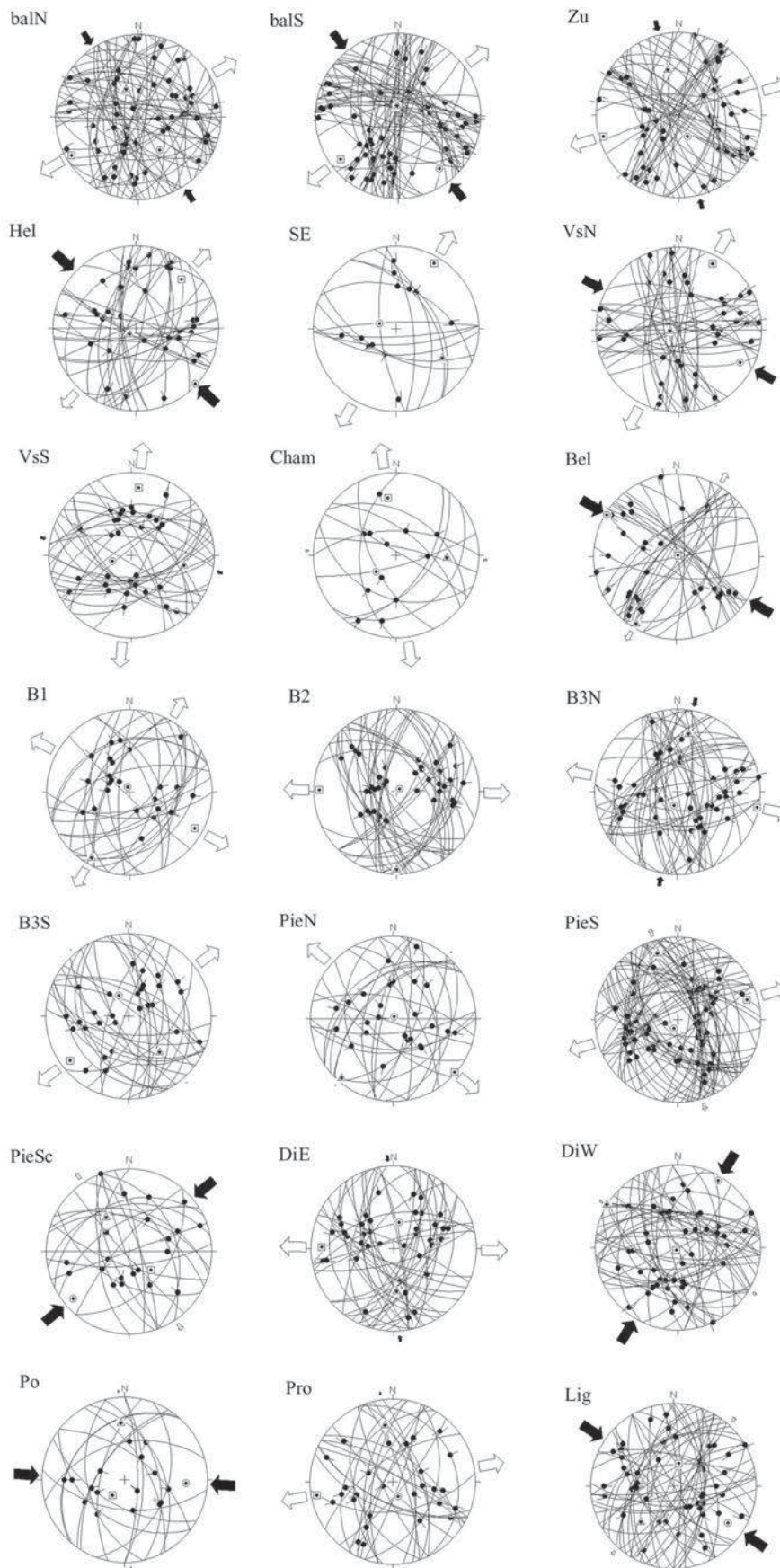


Figure B1.

ANNEXE 3

« Origin of the current stress field in the western/central Alps: role of gravitational re-equilibration constrained by numerical modelling»

Delacou et al., *J. Geol. Soc. London*, in press.

Origin of the current stress field in the western/central Alps: role of gravitational re-equilibration constrained by numerical modelling

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Abstract

We interpret the strain and stress fields of the western/central Alpine arc on the basis of 2.5D finite element modelling and a recent seismotectonic synthesis (Delacou *et al.*, 2004). Models have fixed boundary forces and different crustal geometries, so that they respond to buoyancy forces (variations in gravitational potential energies). The seismotectonic regime, characterized by orogen-perpendicular extension in the high topographic core of the belt and local orogen-perpendicular compressional/transpressional deformation in the external zones, appears to be very close to the modelled gravitational regime. Rotation of Apulia has a minor effect on the current strain or stress fields of the Alpine realm. Nevertheless, it could help to explain the orogen-parallel dextral faulting that is observed all along external zones, from the northern Valais to the Argentera external crystalline massif. Our results highlight the consequences for the Alpine realm of ongoing convergence between the African and European plates. Our interpretation is that collision is no longer ongoing and that buoyancy-driven stresses dominate the present-day geodynamics of the western/central Alps.

Key words: western/central Alps, finite element modelling, buoyancy forces, gravitational potential energy, stress field, geodynamics.

The Alpine belt has resulted from Tertiary collision between the Apulian micro-plate (considered as an African promontory) and the European plate, following Late Cretaceous to Eocene subduction of the Alpine Tethys (Coward & Dietrich, 1989; Dewey *et al.*, 1989; Laubscher, 1991; Stampfli *et al.*, 1998; Schmid & Kissling, 2000). Whereas compressional structures, such as nappes, metamorphic zones and phases of folding have been well documented (e.g. Choukroune *et al.*, 1986; Fry, 1989; Burkhard, 1990; Pognante, 1991; Butler, 1992; Spalla *et al.*, 1996; Duchêne *et al.*, 1997; Burkhard & Sommaruga, 1998; Becker, 2000) the current tectonic context remains debatable. Is collision still active or has the Alpine belt come to the end of its compressive history? The relatively recent discovery of extensional tectonics, through seismotectonic and structural analyses (Mancktelow, 1992; Maurer *et al.*, 1997; Eva *et al.*, 1998; Fügenschuh *et al.*, 1999; Sue *et al.*, 1999; Bistacchi *et al.*, 2000; Kastrup, 2002; Sue & Tricart, 2002; Champagnac *et al.*, 2003; Sue & Tricart, 2003; Champagnac *et al.*, in press) goes a long way toward answering the question. Extensional earthquakes have been known for a long time (Pavoni, 1961; Ahorner *et al.*, 1972; Fréchet, 1978). The large scale seismotectonic synthesis of (Delacou *et al.*, 2004) demonstrates that an extensional regime operates throughout all the internal zones of the belt. In addition, structural analyses of fault slip data indicate that extensional tectonics have been prevalent in these zones since at least Miocene times (Mancktelow, 1992; Bistacchi *et al.*, 2000; Tricart *et al.*, 2001; Sue & Tricart, 2003; Champagnac *et al.*, in press). Extension is therefore a major feature of the recent to present-day geodynamics of the Alpine arc. Various contradictory models have been put forward to explain such intra-orogenic extensional tectonics: (1) large scale buckling under compressive conditions combined with outer-arc extension (Burg *et al.*, 2002), (2) lateral extrusion in an active convergent belt (Ratschbacher *et al.*, 1991; Frisch *et al.*, 2000; Sachsenhofer *et al.*, 2000), (3) slab break-off re-equilibration (Davies & von Blanckenburg, 1995; Sue, 1998), (4) rotational tectonics (Calais *et al.*, 2002; Collombet *et al.*, 2002) and (5) gravitational re-equilibration of an over-thickened crust (Bada *et al.*, 2001). While overall convergence between the African and European plates is still ongoing at a rate of 3 to 8 mm/year (Argus *et al.*, 1989; Demets *et al.*, 1994; Albarello *et al.*, 1995; Crétaux *et al.*, 1998; Nocquet, 2002), the boundary conditions around the Alpine belt, as estimated by recent GPS results (Calais *et al.*, 2002; Nocquet, 2002; Vigny *et al.*, 2002; Nocquet & Calais, 2003; Nocquet & Calais, 2004), reveal no clear relative movements between the Apulian and European microplates. Velocities across the belt are between 1 and 2 mm/year and they provide no clear indication of convergence or divergence. At best, the GPS data indicate anticlockwise rotation of Apulia with respect to Europe at an angular velocity of $0.5^\circ/\text{Ma}$, about a pole near Milan (Calais *et al.*, 2002).

In this study we use numerical modelling and the large-scale seismotectonic analysis of (Delacou *et al.*, 2004), to test the effects of gravitational body forces, coupled with rotation, on the current stress and strain fields of the western/central Alps. Numerical modelling has proved to be a powerful tool for analysing the geodynamics of different areas, such as the Himalayas (Cattin & Avouac, 2000; Cattin *et al.*, 2001), New Zealand (Liu & Bird, 2002), southern Spain and northern Africa (Negredo *et al.*, 2002), the United States and Mexico (Bird, 2002), the Baikal rift zone (Lesne *et al.*, 1998), the Basin and Range province (Hassani & Chéry, 1996) and Central Europe (Grünthal & Stromeier, 1992; Golke & Coblentz, 1996). Here, we use a 3D-model of the Alps to study the origins of the current stress and strain fields of the western/central Alpine arc.

Seismotectonic data

We test our numerical models by comparing calculated strain and stress fields with those obtained from earthquake analysis (Delacou *et al.*, 2004). Our data base is a compilation of 389 reliable focal mechanisms (Ménard, 1988; Thouvenot, 1996; Eva & Solarino, 1998; Sue *et al.*, 1999; Baroux *et al.*, 2001; Kastrop, 2002), covering the entire arc of the western/central Alps, from eastern Switzerland to the Ligurian margin (Fig. 1). Local magnitudes (M_l) range from 0.7 to 6.0, for earthquakes recorded between 1969 and 2000. Foci are mainly in the upper crust (first 20 km), especially in the core of the belt where no deeper earthquakes have occurred. There are a few exceptions in external areas (30 km under the Swiss Molasse basin, 25 km under the western Po plain and 20 km under the Ligurian margin).

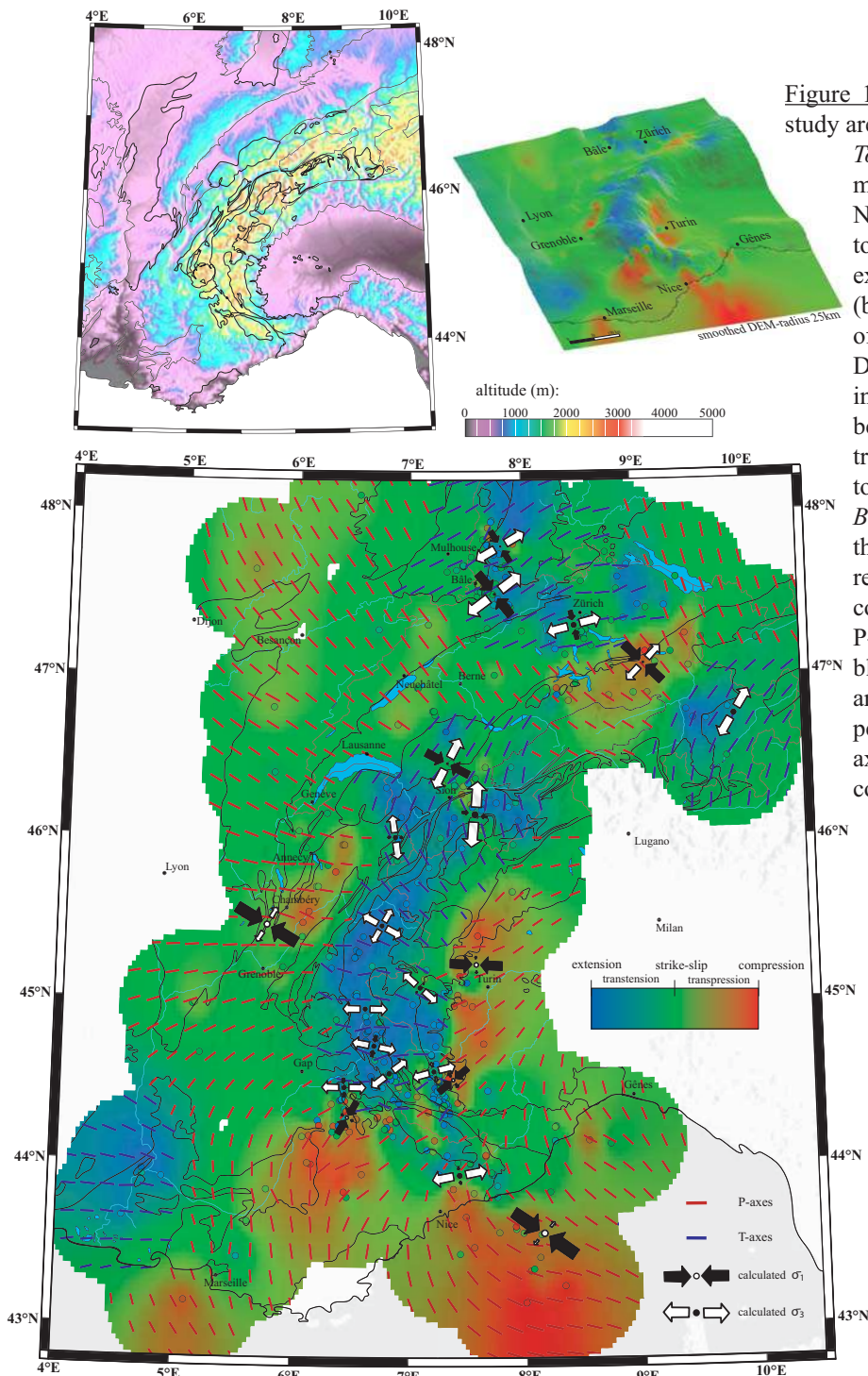


Figure 1: Seismotectonic overview of the study area (Delacou *et al.*, 2004).

Top: Left: Digital elevation model and geological contours. Note correspondence between topographically high areas and extensional zones of deformation (bottom map). Right: Regionalization of deformation draped on smooth DEM (radius 25km). Note extension in inner areas that follows crest of belt and localized compressive/transpressive areas at feet of topographic gradients.

Bottom: Strain and stress fields of the Alpine realm. Background colour represents type of deformation, small coloured lines represent earthquake P-axes (red) and T-axes (blue), black arrows are σ_1 axes and white arrows σ_3 axes. Note the orogen-perpendicular pattern of both tensile axes (in the core of the belt) and compressive axes (in external areas).

Seismotectonic strain and stress fields

The strain and stress states of the Alpine realm are defined via three parameters (Fig. 1): type of deformation (compressional, extensional or transcurrent), principal directions of deformation (P- and T- axes) and principal stress axes (σ_1 , σ_2 , σ_3) obtained from inversion of focal plane solutions.

We used the dips of P- and T-axes to calculate an r-parameter (P-axis dip - T-axis dip) that summarizes the type of deformation, *i.e.* compressional, extensional or transcurrent (Delacou *et al.*, 2004). In Figure 1 the r-parameter is shown by coloured dots at epicentres, whereas interpolation provides the background colour. This large-scale regionalization reveals large zones of homogeneous deformation. In the internal zones, a continuous zone of extension follows the crest line from the southern Valais to the Argentera massif. Extension is also found in eastern Switzerland, over topographic highs, but continuity with the main zone is not proven, because the Lepontine dome is almost seismically active. Other notable features are local zones of compressional/transpressive deformation along the edges of the Alpine belt, in the eastern Helvetic domain, the front of the Belledonne massif, the front of the Digne nappe and the western Po plain.

We made a map of P- and T-axis trajectories, by projecting the axes onto a horizontal plane and interpolating vectorially (Fig. 1). In internal zones, orogen-perpendicular extension prevails, T-axes striking N-S in the Valais, E-W behind the Pelvoux massif and SW-NE behind the Argentera massif. In external zones, P-axis trajectories define a large-scale fan, convergent toward the Po plain. Orogen-perpendicular compressive axes swing through 120° , from a NNW trend in eastern Switzerland, to NW in front of the Belledonne massif, and SW in front of the Digne nappe. This orogen-perpendicular configuration confirms earlier results, which were based on far fewer data (Fréchet, 1978; Pavoni, 1986).

Stress inversion methods have been applied to subsets of the focal mechanism data, to constrain the present day stress field of the Alpine arc. For details of the analysis and calculations, see (Delacou *et al.*, 2004). The results (Fig. 1) reveal a generalized extensional stress field in the core of the belt. Orogen-perpendicular σ_3 , contrasts with localized zones of transpression in external zones, where fan-shaped orogen-perpendicular σ_1 converges toward the Po plain. Strike-slip faulting occurs everywhere in the belt, but is especially abundant in external zones.

Correlations with crustal thickness

We have used a Digital Elevation Model (DEM), GTOPO30, to calculate average Alpine topography, where each point of the grid represents average altitude within a radius of 25 km (Fig. 1). This average topography provides a proxy for topographic loading at the scale of the lithosphere, high average altitude being associated with over-thickened crust. The resulting map closely matches gravimetric maps (*e.g.* Masson *et al.*, 1999), high average topography (higher than 2500 m) corresponding to strong negative Bouguer anomalies (-160 to -220 mgal). On draping the map of regionalized deformation over the average DEM (Fig. 1), internal areas of high topography appear to match closely with areas where the state of strain/stress is extensional. In contrast, transpressive external zones coincide with zones of concave-upward curvature, between high mountains and low foreland.

To explain the close correlation between areas of large crustal thickness (directly correlated with high average topography) and generalized Alpine extensional tectonics, we favour a geodynamic model, where the current Alpine regime is controlled, at least partly,

by internal gravitational body forces. In this model, gravitational potential anomalies (GPA), driven by crustal thickness heterogeneities between internal and external zones, will induce extension in high internal zones. In response to this extensional regime, external areas will undergo compression/transpression. This kind of model will induce orogen-perpendicular extensional stress axes in high internal zones and orogen-perpendicular compressional stress axes in low external zones. In what follows, we use numerical techniques to test this model of gravitational re-equilibration, alone or combined with rotation.

2.5D finite element modelling

A numerical code (2.5D thin-shell finite element code, SHELLS) has been used to model the stress and strain field of the western/central Alpine arc. Basically, this code solves for stress equilibrium and conservation of mass, given the rheology and density at each point (Bird, 1989; Kong & Bird, 1995; Bird, 1999). Models include three dimensional variations in topography and thickness of crust and lithosphere. Because the code solves a momentum equation in a vertically integrated form (2D approximation), it is referred to as a “2.5D finite element method”. The thin-shell approximation yields only horizontal components of the momentum equation (the vertical component being replaced by an isostatic approximation) and no vertical shear traction is considered on vertical planes (flexural strength is ignored). Material behaviour is assumed to be anelastic: thermally activated non-linear dislocation creep in the lower crust and mantle, and Mohr-Coulomb frictional plasticity in the shallow parts of crust and upper mantle (Table 1). Given values of initial surface heat flow and steady thermal conduction are used to compute a 3D temperature distribution with constant but distinct heat productivity and conductivity for crust and mantle (Table 1).

Parameter	values (crust / mantle)	units
Heat conductivity	2.7 / 3.2	$\text{J.m}^{-1}.\text{s}^{-1}.\text{K}^{-1}$
Heat productivity	7.27E-7 / 3.2E-8	$\text{J.m}^{-3}.\text{s}^{-1}$
mean densities (P=0 and T=0)	2816 / 3332	kg.m^{-3}
Mohr-Coulomb frictional parameters:		
Fault friction coef.	0.03	
Continuum friction coef.	0.85	
Biot coef. (efficiency of pore pressure)	1	
Dislocation-creep parameters:		
ACREEP (shear stress coef.)	2.3E9 / 9.5E4	$\text{Pa s}^{1/3}$
BCREEP (temperature coef.)	4000 / 18314	K
CCREEP/G/p (pressure coef.)	0 / 0.0171	K.Pa^{-1}
DCREEP (max. shear stress)	5.00E+08	Pa
ECREEP (exponent) =1/n	0.333333	

Table1: Thermal parameters, densities and rheological parameters of models. For detailed description of rheological parameters, see (Bird, 1989).

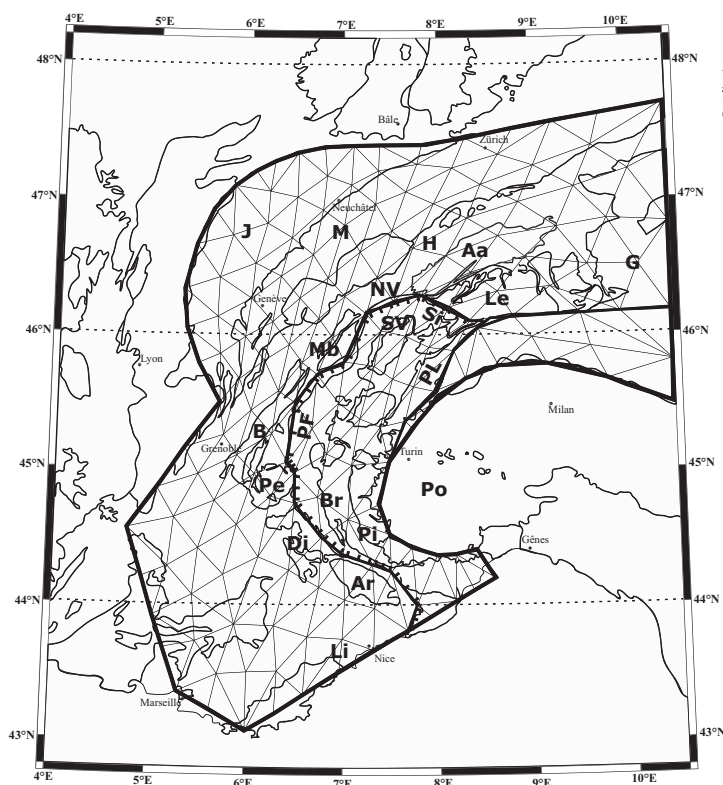


Figure 2: Grid and configuration in our finite element models.

Models have 295 elements, regularly spaced in the area of the western/central Alps. Bold lines inside models represent faults: Pennine Front (PF), Simplon fault (Si) and Periadriatic Line (PL). Aa: Aar external crystalline massif, Ar: Argentera external crystalline massif, B: Belledonne external crystalline massif, Br: Briançonnais area, Di: Digne nappe, G: Grisons, H: Helvetic zones J: Jura fold and thrust belt, Le: Lepontine dome, Li: Ligurian margin, M: Molasse basin, Mb: Mont-Blanc external crystalline massif, NV: Northern Valais, Pi: Piemontais area, Pe: Pelvoux external crystalline massif, Po: Po plain, SV: Southern Valais.

In summary, the assumptions and approximations of this method enable modelling of large-scale geodynamic systems over long time scales (given

the anelastic assumption, time scales smaller than a few thousand years are not adequately modelled). For orogenic systems like the one in this study, the thin-shell code can efficiently model the response to gravitational potential anomalies (GPA), but will not account for flexural strength (or isostatic rebound). However, even in processes such as post-glacial rebound or erosional denudation, where flexure is a significant component, the models would probably yield a stress pattern that is close to the one indicated by earthquakes (that is, extensional tectonics in internal uplifted areas). Another limitation of the 2.5D approximation is that decoupling of the stress field cannot occur at depth. Thus, it is not possible to model compression in the deep lithosphere and simultaneous extension at shallower depths. However, this limitation may not be serious, because no vertically decoupled tectonics of this kind have yet been identified at a large scale in the Alpine arc.

Given the assumptions, the models in this study are limited to the analysis of the stress or strain field generated by re-equilibration of gravitational potential anomalies (GPA) and its possible combination with rotational tectonics.

The boundaries of the models have been chosen to reflect the limits of the western/central Alps, as well as the limits of our seismotectonic study (Fig. 2). In the north, the boundary follows the outer edge of the Molasse Basin; in the northwest and west, the outer edges of the Jura and Subalpine chains; in the southwest, the lower Rhone valley; in the south, the Ligurian margin; and in the southeast, the Po plain. The eastern boundary of the model is an arbitrary north-south line, that is assumed to be frictionless and that limits our study area to the western/central Alps. The models in this study all have 295 cells, used in the finite element technique (Fig. 2).

Another feature of the code SHELLS is that it can take into account faults (Fig. 2, Table 1). In the western/central Alps, the problem has been to identify large faults that are potentially active. Indeed, recognized seismically active faults are scarce and of limited extents. Moreover, an exhaustive list of active faults is difficult to establish, as every new local seismic swarm defines a new active fault system. In our models, we have decided to take into account large-scale inherited structures that are supposed to play an important role in the current dynamics of the studied area, these being the Pennine front and the Insubric line (Fig. 2).

MODEL CONFIGURATIONS

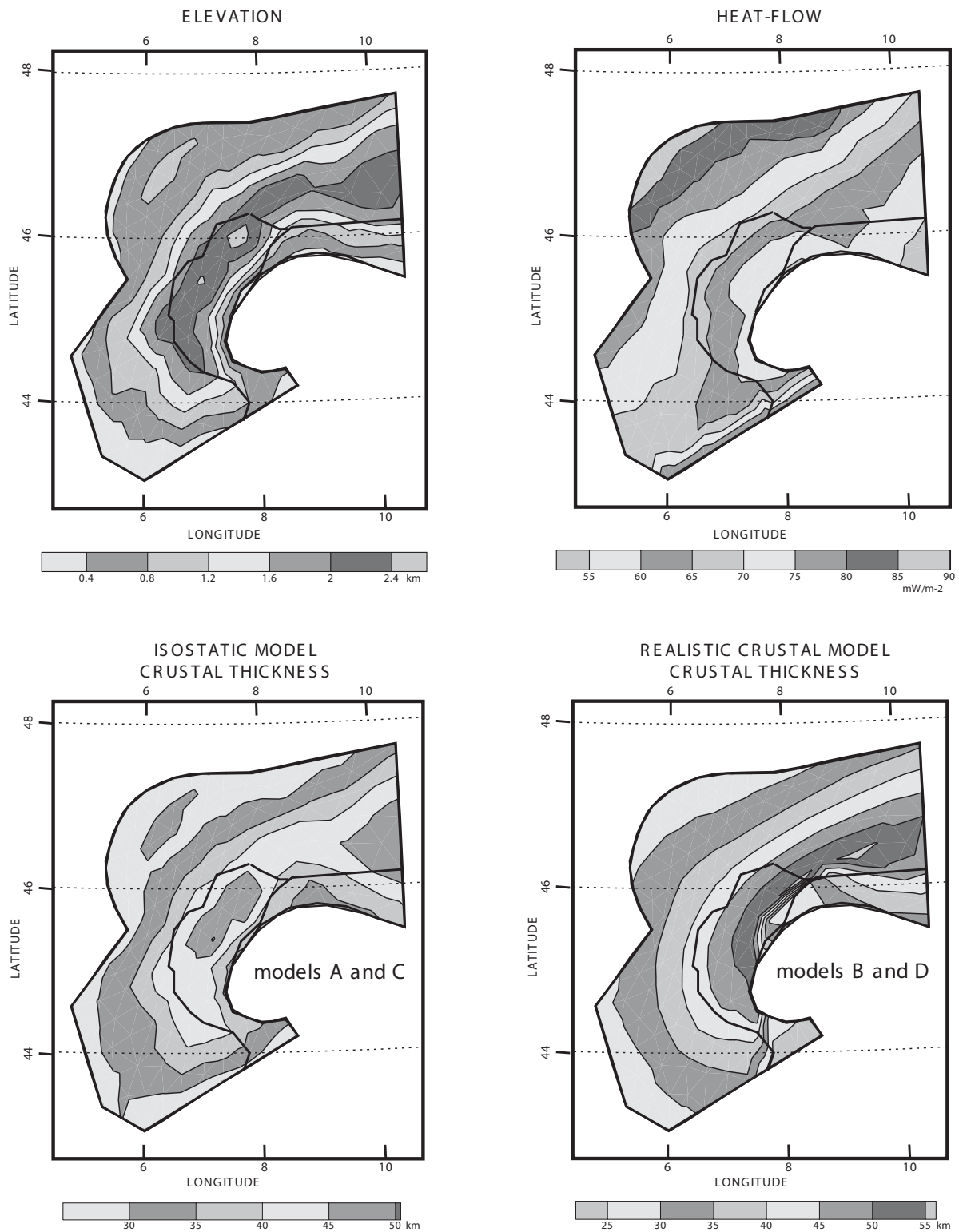


Figure 3: Model configuration.

Elevation and surface heat flow are common to all models. Note differences in crustal thicknesses between isostatic models (models A and C), where Moho depth is directly related to topography, and realistic models (models B and D), characterized by a Moho dipping toward the E/SE on the European side of the belt, and a complex geometry at eastern Po plain boundary. Moho geometry is taken from (Waldhauser *et al.*, 1998)

Models with fixed boundaries

In order to test the effects of buoyancy forces alone, models are assumed to have fixed boundaries. The strain/stress field is generated only by contrasting gravitational potential anomalies (GPA) between the inner areas of thickened crust and external “normal” ones.

Isostatic model (model A)

As a first step, a simple 3D model has been constructed under the assumption of isostatic equilibrium (Figs. 3 and 4). From the surface topography (taken from the GTOPO30 DEM data, smoothed at the mesh spacing size) and the surface heat flow (compiled from the European Geotraverse experiments (Blundell *et al.*, 1992)), SHELLS calculates routinely the 3D structure of the crust and the lithosphere that satisfies isostatic equilibrium (Fig. 3) and steady state thermal conduction, by taking into account the densities and thermal properties of crust and mantle (Table 1). We assume that all boundary nodes are stationary.

For model A, the calculated stress field is characterized by orogen-perpendicular extension in regions of high topography in the core of the belt and by orogen-perpendicular compression in external zones (Fig. 4). This pattern results from equilibration between regions of positive GPA in the inner areas, where high topography correlates with large crustal thickness (according to the assumption of isostatic equilibrium) and regions of “normal” GPA (near zero) in external zones, where altitudes are small and the Moho is close to its normal depth (around 30 km). This configuration results in an extensional stress state in the core of the belt, tending to reduce the over-thickened crust, and a compressional stress state in external regions.

In terms of strain rate (Fig. 4), a belt of horizontal stretching appears to follow the high topography, especially on its external side, from the Aar massif to the Argentera massif. Extensional strain rates are between 1 and $7 \times 10^{-16} \text{ s}^{-1}$. Compressional strain rates are about $2 \times 10^{-16} \text{ s}^{-1}$ in external zones. They seem to be guided by the fixed boundaries of the model, reaching a maximum in front of the Jura, the Po plain and the Rhone valley. This could be explained by GPA equilibration, whereby crustal thickness decreases over the whole system as far as the boundaries of the model, where it creates compression. In reality, external boundaries (that can be considered as fixed, far away from the Alps) are not as sharp as they are in our models, so that shortening should be more distributed.

The surface velocity field also follows the shape of the model, velocities reaching about 0.15 to 0.25 mm/year in directions (NW to SW) that are perpendicular to the belt. In internal zones, stretching leads to southeast-directed surface velocities, which reach 0.3 mm/year in the northern part (Valais).

Motion on faults is mainly manifest as extensional reactivation of the Pennine front. Slip perpendicular to this fault zone reaches 0.7 mm/year on its northern segment and decreases progressively toward the south. Near the Mediterranean, the fault appears to be locked. The Periadriatic line does not slip at all.

Realistic crustal model (model B)

For a more realistic 3D crustal structure, we have constructed a model (model B, Fig. 5), where the Moho geometry (Fig. 3) has been interpreted from wide-angle seismic

MODEL A
ISOSTATIC MODEL
FIXED BOUNDARIES

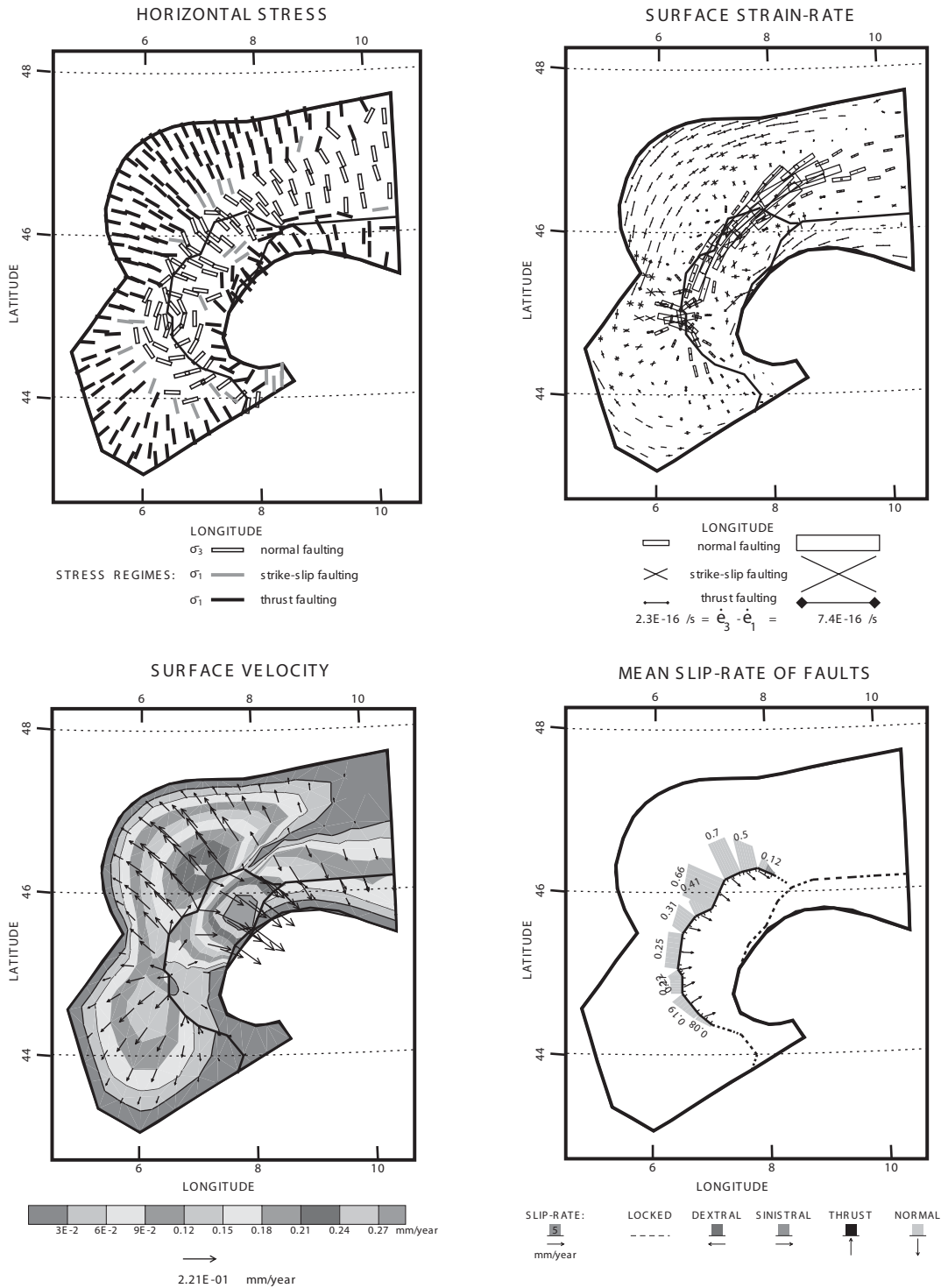


Figure 4: Model A.

Model with isostatic 3D crustal geometry (see Fig. 3) and fixed boundaries. This starting model represents tectonic response of Gravitational Potential Anomalies (GPA) in a simple model of the western/central Alps (see text for explanations).

MODEL B
 REALISTIC CRUSTAL MODEL
 FIXED BOUNDARIES

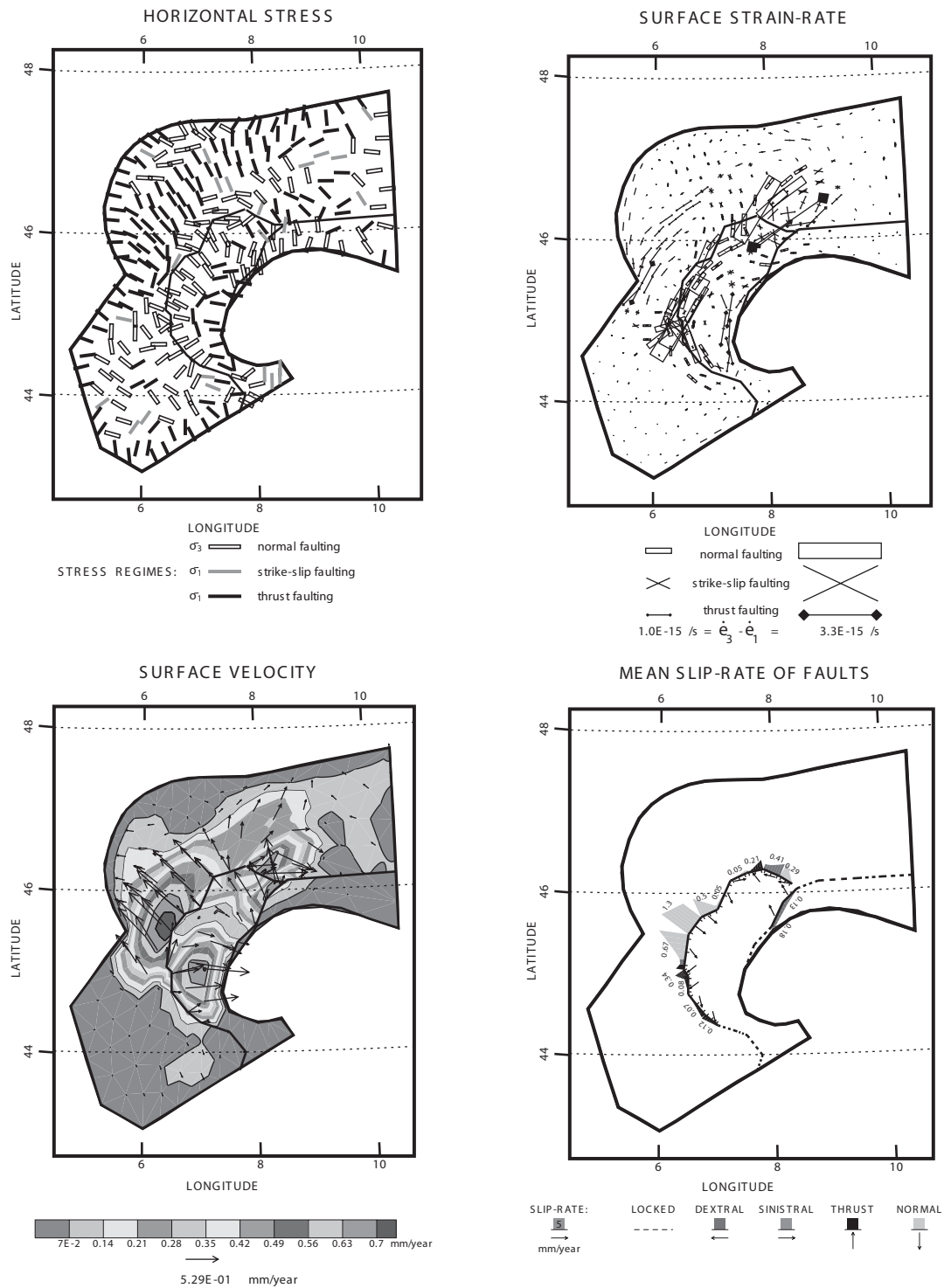


Figure 5: Model B.

Model with realistic 3D crustal geometry (see Fig. 3) and fixed boundaries. This model exhibits a more complex tectonic response than model A, as a result of complex crustal geometry (see text for explanation).

experiments (Waldhauser *et al.*, 1998). Given the topography, surface heat flow and realistic crustal geometry, lithosphere thickness is calculated, so as to respect the thermal properties of crust and mantle (assuming steady thermal conduction). This results in a complex 3D geometry (Fig. 3), where the highest altitudes do not directly overly the crustal root. The latter reaches a depth of about 50 - 55 km at a point that appears to be shifted toward the S/SE with respect to large-scale topography. A consequence of such a setting is that GPAs do not correlate in a simple manner with topography (as they do in model A), but depend on the whole 3D crustal structure. In regions of high topography and relatively shallow Moho depth, the GPA is positive and extension is expected in the anomalous lithosphere, whereas in regions of deep Moho and relatively moderate topography, the GPA is negative and compression is expected. Thus, the resulting stress field (Figure 5), appears to be more complex than in model A. A general trend, from inner extension to outer compression, is still present (as in model A), but with regional variations. This is so in the Jura, where extension now occurs in the northern inner part, in the southwestern external Alps, where there is a mix of compression and extension, and in the northwestern Po plain, where extension is observed. These can be considered as local effects of crustal thickness variations, which were not present in model A. In the southwestern Alps, where focal mechanisms are of mixed type (compressional, extensional and transcurrent), the model seems to fit the observations. In the northern part of the internal zone, the general orogen-perpendicular extension is cross-cut by an E-W band of N-S extension. This correlates with the northern edge of the Apulian crustal wedge (Figure 3), which may be correlate to the Val d'Aosta extensional fault zone (Bistacchi *et al.*, 2001).

Three bands of high strain rate (up to $3 \times 10^{-15} \text{ s}^{-1}$) can be recognized: a band of WNW-ESE shortening in the external zones beyond the Belledonne and Mont-Blanc massifs, a band of fan-shaped stretching that follows the topographic high (with two peaks in the Aar and Pelvoux regions), and E-W shortening in the western Po plain. These bands correlate fairly well with the seismotectonic setting and the concentrations of epicentres (see Figure 1).

There are three zones of high surface velocities: NW-directed velocities of up to 0.75 mm/year in external zones, E-directed velocities of up to 0.7 mm/year in the southern inner area, and a complex zone over the Aar massif.

The pattern of slip along faults is more complex than in model A. Extensional fault slip (up to 1.3 mm/year) occurs along the middle segment of the Pennine front, whereas the northern branch seems to accommodate complicated local movements, due to dextral transtension in the Simplon area and compression in the Valais. The southern branch of the Pennine front is now accommodating local thrusting (less than 0.3 mm/year), decreasing toward the south to reach a locked state near the Argentera massif. The Periadriatic line is almost inactive, except along its western segment, where dextral slip rates reach 0.15 mm/year.

Models with rotational boundaries

Rotation may have played an important role in the dynamics of the western/central Alps, since at least Oligo-Miocene times (Gidon, 1974; Anderson & Jackson, 1987; Ménard, 1988; Vialon *et al.*, 1989; Thomas *et al.*, 1999; Collombet *et al.*, 2002). On the strength of GPS monitoring, involving French, Swiss and Italian stations, (Calais *et al.*, 2002) claim that the Apulian promontory is rotating anticlockwise with respect to “stable” Europe at a rate of $0.52^\circ/\text{Ma}$, around a pole located at $45.36^\circ\text{N}/9.10^\circ\text{S}$ (near Milan).

In order to test the effects of such a rotation on the strain and stress field of the western/central Alpine arc, boundary nodes for the Po plain have been given appropriate velocities in

model C (same 3D crustal structure as model A) and model D (same 3D crustal structure as model B).

In terms of stress (Fig. 6 and Fig. 7), results for the rotation models appear to be quite similar to those for fixed models at a large scale. Orogen-perpendicular extensional stress is present in the internal zones, and orogen-perpendicular fan-like compression in the external zones (at least in the northwestern part). Only the regional/local pattern of stress axes is different from that of the fixed models. Thus rotation induces frontal compression at the eastern edge of the SW Alps and near the Po plain. This is especially true for model C, where compressional axes follow the rotational motion of boundary nodes). For model D, stress axes deviate less than for model C. This may be because GPAs are more variable in the non-isostatic model (model D), so that body forces are more dominant.

In terms of strain-rate, as well as stress, axes are almost the same as for fixed models and only small regional reorientations are observed. The main differences are at boundaries. For example, at the south Ligurian boundary, anticlockwise rotation induces large shortening. Surface velocities of up to 1.4 - 1.5 mm/year concentrate in internal zones and appear to be strongly linked to the rotational boundary. Velocity vectors follow this rotation, pointing more to the south than for fixed models. Rotation seems to have little effect on velocities of external zones.

Slip directions along faults are more south-directed than those of fixed models. For the Pennine front, this implies S-verging stretching of up to 1.7 mm/year in the northern segment (model C), dextral transtension in the middle segment (1.1 to 2 mm/year for model C, 2.1 mm/year for model D), and dextral transpression in the southern segment (1.4 mm/year for model C, 1.2 mm/year for model D). Another major difference with fixed models is the small dextral motion on the Periadriatic line (up to 0.22 mm/year for model C and 0.4 mm/year for model D).

Geodynamic implications

Numerical modelling and comparison with large-scale seismotectonic analysis have shown that body forces play a major role in determining the current stress field of the western Alpine arc. Balance of GPAs explains the orogen-perpendicular contrasted stress field in the western/central Alps (extensional in the core of the belt, locally compressional at the periphery). The role of rotational boundary forces is less obvious, as only local stress reorientations appear in our models. Nevertheless, rotation models seem suitable to explain dextral strike-slip faulting along the external zones (from the northern Valais to the Argentera massif). In addition, our results are consistent with GPS studies (*e.g.* Calais *et al.*, 2002) that give velocities of about 1 mm/year within the Alpine realm, compatible with velocities of 1 - 1.5 mm/year obtained in the models of this study. More precisely, GPS studies reveal extension in the core of the belt, including lengthening of the line Lyon-Turin (0.5 ± 0.9 mm/year to the SE at La Feclaz in the Subalpine chains and $1.4 \pm .4$ mm/year to the SE at Modane (in the internal Vanoise area). This geodetic stretching correlates well with the values obtained for the core of the belt by seismotectonic analysis and numerical modelling. Moreover, GPS results also indicate shortening in the western Po plain (1.0 ± 0.5 mm/year of E-W shortening between Modane and Turin) and in Provence (1.4 ± 0.5 mm/year of N-S shortening between Grasse and Turin). Despite this qualitative agreement with the results of our modelling and seismotectonic analysis, more detailed comparisons cannot be made, because the GPS data still have insufficient resolution.

This study addresses the consequences of ongoing convergence between Europe and

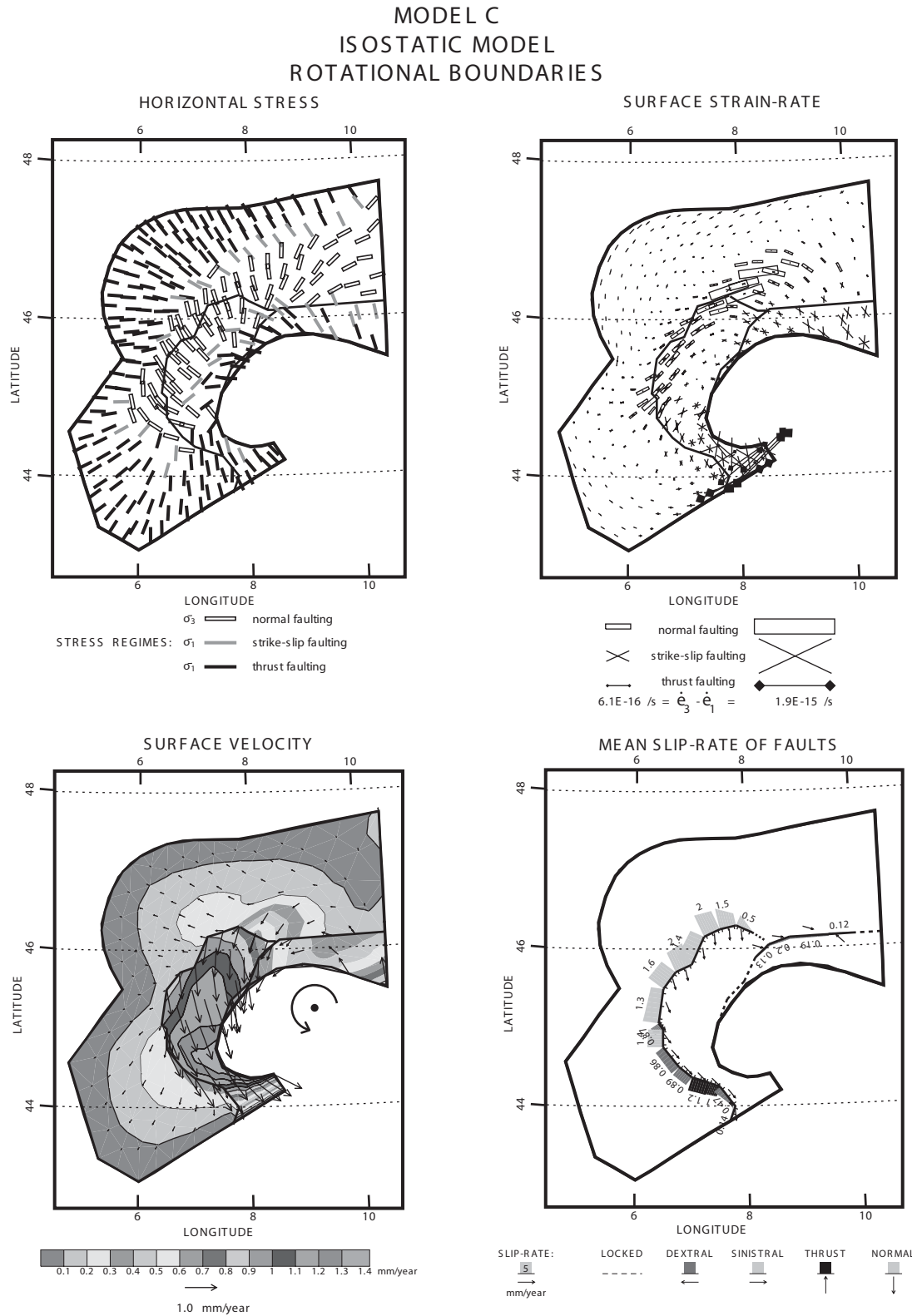


Figure 6: Model C.

Model with isostatic 3D crustal geometry and rotational Po plain boundary nodes. See Figure 4 for comparison. Differences between models A and C are only due to rotational Po plain boundary. Curved arrow on surface velocity map indicates rotation pole (see text for explanation).

MODEL D
REALISTIC CRUSTAL MODEL
ROTATIONAL BOUNDARIES

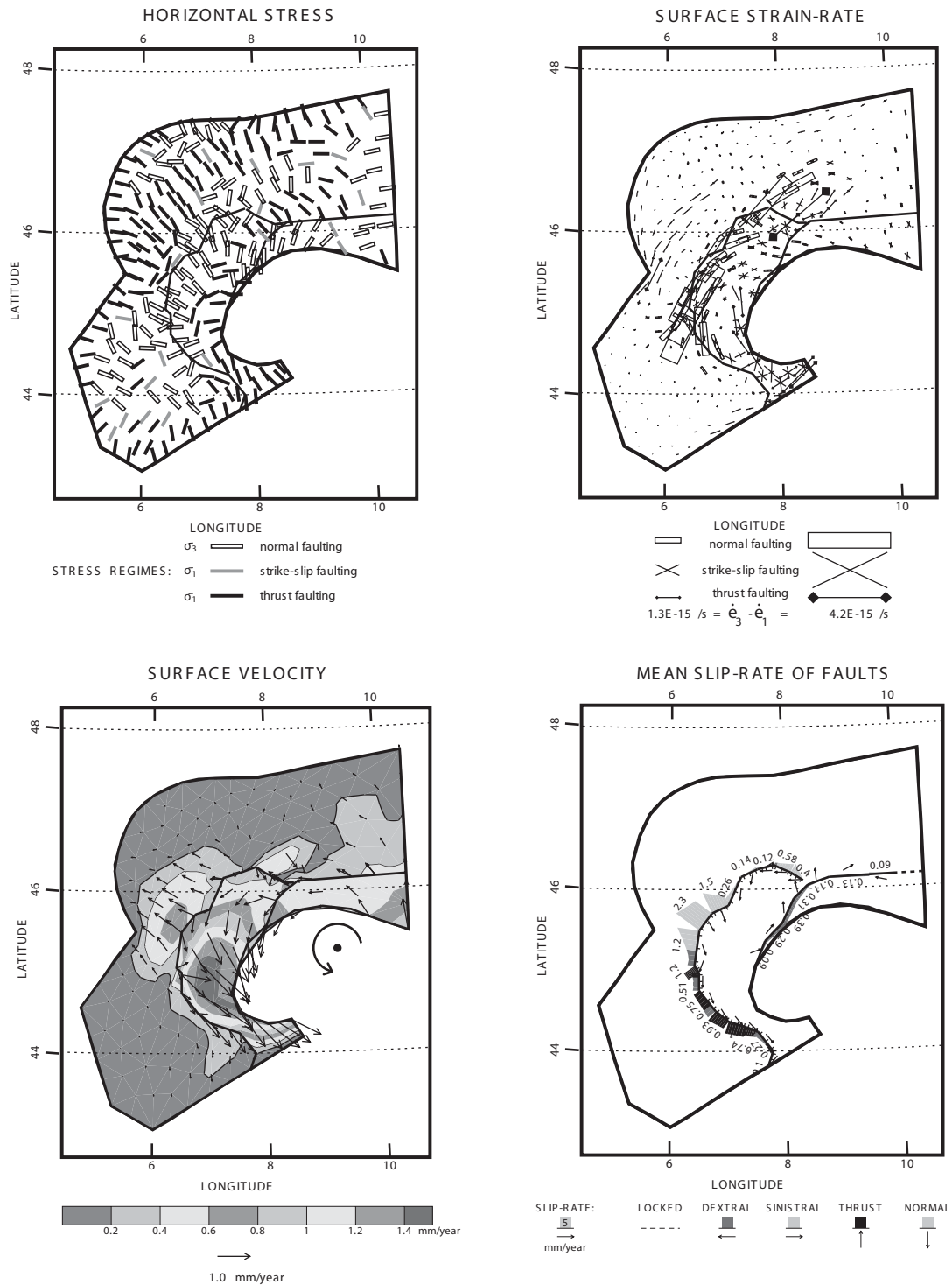


Figure 7: Model D.

Model with realistic 3D crustal geometry and rotational Po plain boundary nodes. See Figure 5 for comparisons. Differences between models B and D are only due to rotational Po plain boundary (see text for explanation).

Africa. The convergence velocity is estimated at 3 to 8 mm/year in a N to NW direction at the longitude of the Alps (Argus *et al.*, 1989; Demets *et al.*, 1990; Demets *et al.*, 1994; Albarello *et al.*, 1995; Crétaux *et al.*, 1998; Kreemer & Holt, 2001; Nocquet, 2002). It could be taken up in different areas between the European and African stable continents, such as Northern Africa, the Apennines, the Dinarides or the Calabrian subduction zone. In the vicinity of the western/central Alpine arc, the interaction between boundary forces and body forces is still a matter for debate. Studies, such as the one by (Thatcher *et al.*, 1999) in the Basin and Range province, show that gravitational extensional tectonics can interact with boundary conditions, leading to reorientation of extensional axes parallel to plate tectonic directions. However, in our study, direct effects of plate tectonics are less useful to explain the stress field of the western/central Alps, which appears to be controlled mostly by internal body forces. A more detailed analysis of the possible interactions between boundary forces and body forces in the Alpine belt would require a detailed 3D geometry of the models (accounting for lithospheric complexities), a fully 3D finite element code, as well as more constraints on boundary conditions between Apulian and European microplates. Recent tomographic studies (Lippitsch, 2002) have yielded a complex 3D geometry at great depth, which has been interpreted in terms of lithospheric slabs, possibly detached in the western Alps and sub-vertical under the central Alps. These lithospheric structures cannot be modelled by the techniques used in this study. Their consequences for the current stress field and recent tectonics of the Alpine arc remain to be analysed.

Conclusions

A seismotectonic investigation along the entire arc of the western/central Alps has revealed contrasting stress regimes. Within a zone of extension, that follows the arcuate crest line from the southern Valais to the Argentera massif, extensional axes are perpendicular to the orogen. Compression is limited to the external zones, where compressional axes are also perpendicular to the orogen. Strike-slip faulting occurs in both external and internal zones, but is particularly abundant in the latter, where it is right-lateral, all the way from the northern Valais to the Durance fault (northwest of the Argentera massif). This well-defined seismotectonic stress state, comparable to the ones computed with 2.5D numerical modelling, highlights the essential role of gravitational body forces, which are able to produce orogen-perpendicular extension in the topographic highs and resulting orogen-perpendicular compression at the periphery. The role of rotation, which has been tested in our models, is more ambiguous, but could explain the arcuate right-lateral faulting prevailing in the external zones.

In a context of ongoing far-field convergence between the European and African plates, no direct evidence of collision has been found in the Alpine realm, either by seismotectonic analyses, numerical modelling or GPS studies. This suggests that the current stress field in the western/central Alps is post-collisional.

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Tectonique cassante de l'arc interne des Alpes occidentales implications géodynamiques

Résumé

L'étude de la fracturation des zones internes de l'arc alpin occidental montre que la déformation extensive y est prédominante; environ 75% des failles mesurées présentent des mouvements normaux, et 25% des mouvements sont décrochants. Cette fracturation, globalement Néogène, est synchrone d'un régime compressif en externe (chaînons subalpins et Jura, par exemple). Des indices néotectoniques, comme la signature morphologique de certaines failles, des anomalies dans les profils de rivières ou la fracturation de dépôts quaternaires, montrent qu'une partie de cette fracturation est récente.

L'inversion par la méthode d'inversion directe [Angelier, 1990] de populations de plans striés mesurés systématiquement dans tout l'arc interne a permis l'obtention de 200 tenseurs de paléocontraintes répartis de façon homogène. Ces données, synthétisées avec des données comparables dans la région du col du Simplon [Grosjean et al., 2004] et dans la région de Briançon [Sue, 1998], donnent une image homogène et à grande échelle des champs de contraintes ayant provoqué cette fracturation. Les résultats principaux indiquent que:

- La majeure partie de l'extension est parallèle à la direction des structures alpines, c'est à dire ENE-WSW au Simplon et dans le Sud Valais, NNE-SSW dans le Val d'Aoste, N-S en Vanoise et WNW-ESE plus au Sud, dans la région de Briançon. Cette extension s'exprime sur des failles orientées radialement par rapport à l'arc alpin.
- Une partie des directions d'extension est perpendiculaire à la direction de la chaîne, et s'exprime sur des failles longitudinales. Cette extension augmente du Nord au Sud, et est particulièrement bien développée dans la région de Briançon.
- Un régime tectonique décrochant s'observe dans tout l'arc. Ces décrochements sont plus récents que l'extension dans la partie sud de l'arc, alors qu'il sont plus anciens dans le Sud Valais. Les direction d'axe de tension (σ_3) associés sont compatibles avec les directions générales de l'extension.

Nous interprétons ces observations comme la mise en évidence de deux régimes tectoniques différents dans les Alpes occidentales du Néogène à l'actuel. Différents moteurs géodynamiques sont proposés pour expliquer ces observations :

1) A l'échelle alpine, un phénomène d'extrusion des zones internes vers une bordure libre (la mer Ligure) pendant les derniers épisodes compressifs, en relation avec la rotation de la microplaque Apulienne, pourrait être responsable du signal tectonique majeur observé. Plus localement, le soulèvement relatif de massifs cristallins (MCE et MCI) aurait favorisé une extension radiale.

2) La collaboration avec Bastien Delacou, qui a travaillé sur le régime tectonique actuel de la chaîne, permet de proposer qu'une partie de cette extension radiale à l'arc soit également liée au régime tectonique actuel. Le régime tectonique actuel, documenté par la sismotectonique montre une orientation radiale à l'arc des axes d'extension. Ce régime se caractérise par une absence de convergence et est bien explicable par un étalement gravitaire, est fondamentalement différent du régime collisionnel néogène.

Le passage d'un régime à l'autre a probablement eu lieu durant le Pliocène, en relation avec le ralentissement de la convergence au niveau des Alpes occidentales et l'augmentation des taux d'érosion dans la chaîne.

