Counterclockwise rotation of the western Alps since the Oligocene: New insights from paleomagnetic data

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[1] A paleomagnetic study of Penninic units in the southern part of the Alpine arc has been carried out. More than 200 samples (23 sites) were collected in Briançonnais Ammonitico rosso limestones of the high Ubaye valley and the Ligurian Alps. A characteristic component of magnetization of reverse polarity was isolated on most of the sites. This component does not pass the fold test and is interpreted as a Tertiary overprint related to Alpine metamorphism. Mean directions in geographic coordinates are D = 121°, I = −52°, α_{95} = 11°, and D = 72°, I = −48°, α_{95} = 15° for the Ubaye and the Liguria localities, respectively, indicating large counterclockwise rotations about vertical axis of 68° and 117° relative to stable Europe. These rotations, in agreement with a previous study conducted in the Briançon area, together with other paleomagnetic data from the western Alps, show that the internal Alps suffered a large but nonhomogeneous counterclockwise rotation since the Oligocene. The rotations are in agreement with the combination of earlier separately proposed processes: the rotation of the Adriatic plate accounts for about 25° of rotation, remaining rotation and southward gradient would be related to left-lateral shear accommodating the displacement between Adria and Europe at the southern border of the western Alps. Furthermore, the southward extrusion of the western Alps south of the Simplon fault zone may account for up to 10° of rotation. Rotations appear therefore as a major process accommodating deformation in the western Alps since the Oligocene. *INDEX TERMS:* 1525 Geomagnetism and Paleomagnetism: Paleomagnetism applied to tectonics (regional, global); 1533 Geomagnetism and Paleomagnetism: Remagnetization; 8110 Tectonophysics: Continental tectonics—general (0905); 8102 Tectonophysics: Continental contractional orogenic belts; *KEYWORDS:* Western Alps, rotation, paleomagnetism, alpine kinematics

1. Introduction

[2] The arc of the western Alps results from the convergence and collision between the Adriatic plate and the European margin of the Tethys since the Late Cretaceous. The present-day structure and geometry of the western Alps have been traditionally attributed to several successive phases of shortening, involving translations of tectonic units [*Tapponnier*, 1977; *Tricart*, 1980; *Ricou*, 1984; *Laubscher*, 1988; *Choukroune et al.*, 1986; *Platt et al.*, 1989]. Crustal-scale rotation mechanisms accommodating deformation have received little attention, mainly due to the lack of direct structural evidence. However, some authors have inferred large-scale rotations as a key mechanism in the western Alps, either as a result of the curvature of the structures [*Ménard*, 1988; *Laubscher*, 1996; *Stampfli and Marchant*, 1997], or conversely, to explain the arcuate shape of the Alpine arc [*Goguel*, 1963; *Gidon*, 1974; *Vialon et al.*, 1989; *Schmid and Kissling*, 2000]. In the internal western Alps (i.e., east of the Frontal Penninic Thrust (FPT)) where the largest rotations are expected, few paleomagnetic data allowing a quantification of the rotation pattern are available (Figure 1). This is mainly due to limited outcrops of Tertiary rocks and/or weak magnetization of Alpine metamorphosed rocks. However, a paleomagnetic study conducted in the Briançonnais zone around Briançon city [*Thomas et al.*, 1999] (Figure 1) revealed a stable Tertiary magnetic overprint related to Alpine metamorphism. Here, a large counterclockwise rotation relative to stable Europe since the Oligocene was indicated. This result incited us to extend our sampling to a larger portion of the Alpine arc. In the present study, new paleomagnetic data from the southern part of the Alpine arc are presented. We focus on the high Ubaye valley and the Ligurian Alps (L and U, Figure 1). With this study, we attempt to answer the following questions: What is the scale of rotations in the western Alps? When did they occur? What are the boundary conditions and mechanisms controlling the rotations?

2. Geological Setting and Paleomagnetic Sampling

[3] The studied areas are located in the Briançonnais zone in the southern part of the western Alpine Arc. The Briançonnais zone is one of the main internal (Penninic)

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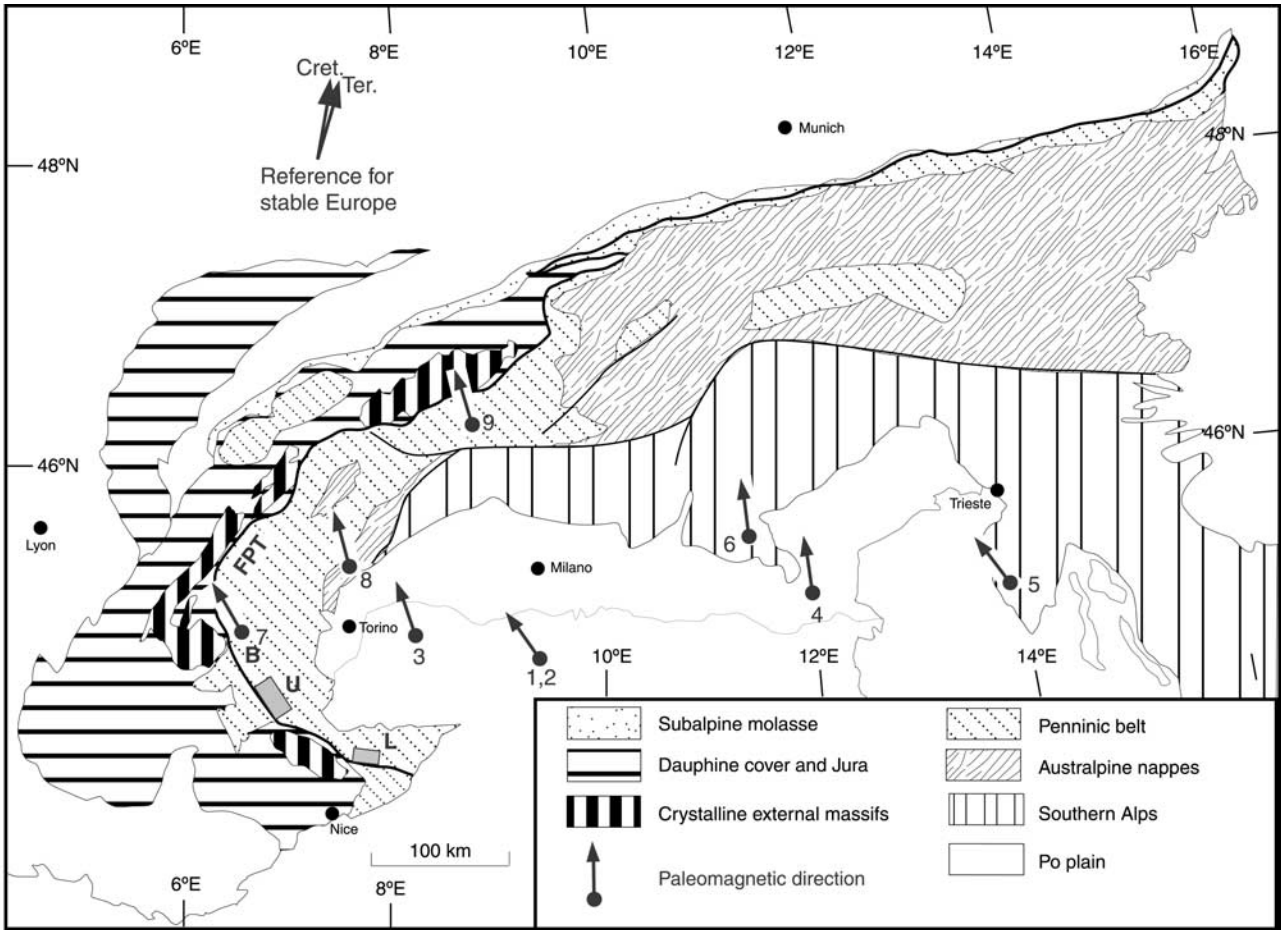

Figure 1. Main tectonic units of the Alps with selected paleomagnetic data (minimum quality factor Q of 4 [*Van der Voo*, 1993]) of the internal Alps and northern Adriatic plate (see also Table 4). Gray boxes indicate the studied areas: U = Ubaye, L = Liguria. The frontal Penninic thrust (FPT, thick line) is referred as the boundary between the external and internal Alps. Numbers refer to data in Table 4. B = area studied by *Thomas et al.* [1999].

alpine zones, thrusted on the main external alpine zone (the Dauphiné zone) along the Penninic thrust (FPT). It consists of a stack of nappes, essentially made up of Meso-Cenozoic sediments, affected by high pressure-low temperature metamorphism during Paleogene time. From the Miocene onwards, this area underwent regional-scale brittle extension [*Sue*, 1998; *Sue and Tricart*, 1999; *Tricart et al.*, 1996].

[4] The discussion on the paleomagnetic results from the following parts will refer to a relative tectonic chronology, based on indirect datations. Actually, available metamorphic rocks of the Briançonnais zone do not allow to access an accurate thermal chronology and very few reliable radiometric datations are available. Many schists, calcschists, and limestones can nevertheless be found in this area. As successive deformation phases are properly recorded in these rocks under superimposed schistosites, it is possible in each place to locate the main structures within a relative chronology.

[5] The rock facies sampled for paleomagnetic study in both studied areas is the Upper Jurassic Ammonitico Rosso limestone made of white carbonaceous nodules in a pale red clay matrix.

2.1. Ubaye Valley

[6] The studied area is located in the upper Ubaye valley, near Saint-Paul-sur-Ubaye, between the Font Sancte massif to the northwest and the Aiguille de Chambeyron massif to the southeast (Figures 1 and 2). The Briançonnais zone consists here of two main superimposed nappes in contact with the Helminthoid flysch along the FPT.

[7] Geological structures crossing the Ubaye valley extend directly to the north in the Briançon-Guillestre area where the regional tectonic chronology has been defined. Tertiary tectonics can be summarized in four main deformation phases (Table 1).

[8] The first phase (D1) corresponds to the emplacement of the Briançonnais nappes. The associated schistosity was formed under high pressure-greenschist facies conditions (lawsonite-bearing greenschist grading into blueschist facies from west to east). These overthrusts achieved the clastic

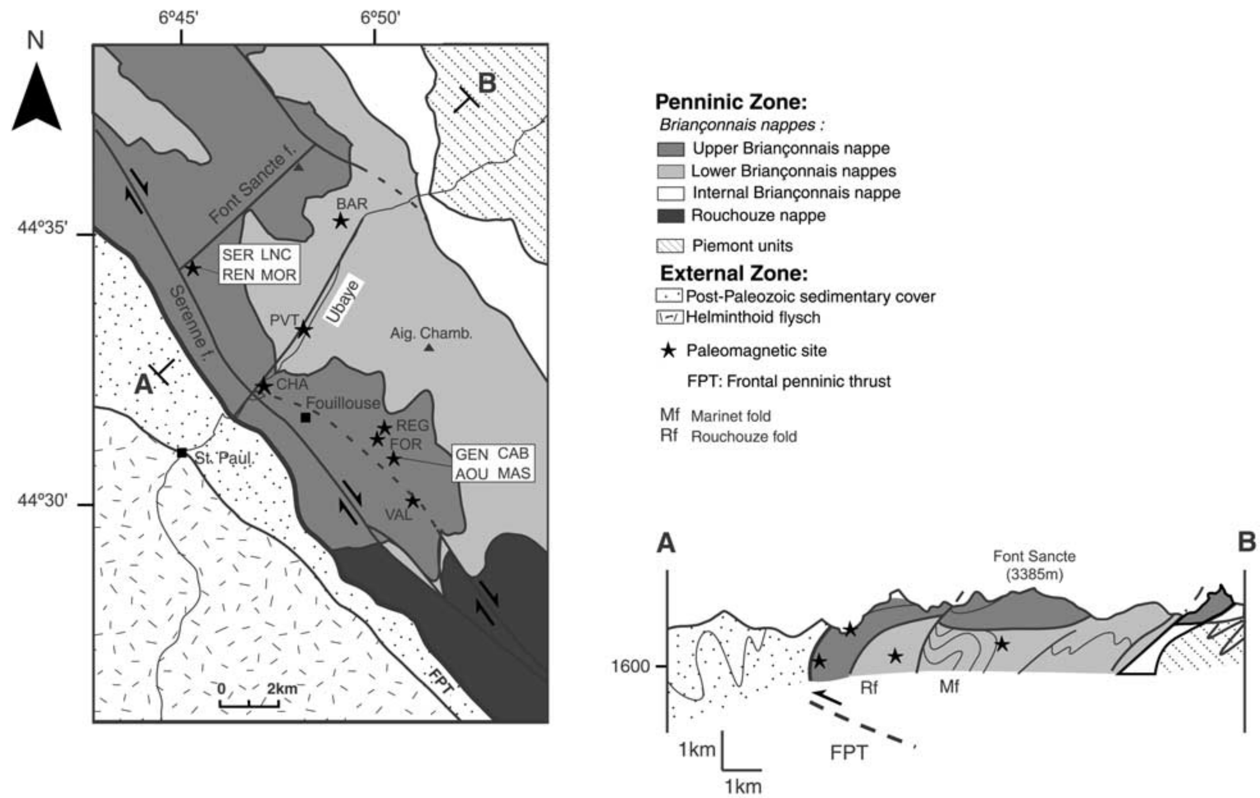

Figure 2. Structural map and simplified cross section of the Ubaye area (adapted from *Gidon et al.* [1994]). The paleomagnetic sites are projected on the cross sections.

sedimentation (Flysch Noir) locally dated between 35 My and 50 My. This D1 phase can therefore be attributed to the late Eocene.

[9] During the second phase (D2), the stack of nappes was sliced, folded and thrusted over the external zone (FPT). The associated temperature are equivalent to the D1 conditions but pressure is lower (prehnite-pumpellyite facies). The only way to date this event is to consider the age of the youngest rocks (external flysch) pinched under the FPT: to the south, the Annot Sandstones contain microfauna which belongs to the early Oligocene and to the north, the Champsaur sandstones hold volcanites with a radiometric age close to 32 My [*Boyet et al.*, 2001]. The D2 phase can thus reasonably be considered of Oligocene age [*Tricart et al.*, 2001].

[10] The D3 phase consists in an east verging folding and scaling event with greenschist metamorphism. This phase is not precisely dated, but it is followed by a rapid uplift and cooling of the area. Indeed, fission tracks in apatite indicate that the 100°C isotherm was crossed around 24 My [*Tricart et al.*, 2001]. D3 is thus probably Oligocene.

[11] During the D4 phase, normal and strike-slip faults widely affect the internal zones, and particularly the Briançonnais zone [*Sue*, 1998; *Sue and Tricart*, 2002]. To the south of Briançon it is accompanied by extensive movements on the FPT [*Sue and Tricart*, 1999]. Apatite fission

Table 1. Simplified Tertiary Deformation Phases in the Briançonnais Zone[a]

Phase	Structures	Metamorphism	Stratigraphic Datation	Radiometric Datation	Proposed Age
D1	Briançonnais thrusting	high-pressure greenschist	post Flysch Noir sedimentation		late Eocene
D2	Frontal Penninic Thrust (FPT)	greenschist	post external flysch deposition (5)		Oligocene
D3	back-thrusting	weak metamorphism, and rapid cooling (4)		>fission tracks age in apatite (24 My.) (4)	late Oligocene
D4	normal/strike-slip faults (1,2,3)	brittle conditions (1,2,3)			Miocene to Actual (2,4)

[a] Sources are as follows: 1, *Sue* [1998]; 2, *Sue and Tricart* [1999]; 3, *Sue and Tricart* [2002]; 4, *Tricart et al.* [2001]; 5, *Boyet et al.* [2001].

Table 2. Geographic and Structural Information of the Paleomagnetic Sites[a]

Site	Latitude °N	Longitude °E	S_0, dd/dip	S_1, dd/dip
		Ubaye		
PVT	44.55	6.81	fold	S1//S0
BAR	44.58	6.82	fold	S1//S0
CHA	44.54	6.78	210/40	55/80
SER	44.54	6.75	225/36	
REN	44.57	6.76	256/32	
MOR	44.57	6.76	208/25	
LNC	44.57	6.76	249/28	
VAL	44.5	6.85	316/72	
MAS	44.51	6.84	253/90	23/57
AOU	44.51	6.84	230/60	25/65
CAB	44.51	6.84	205/15	191/90
GEN	44.51	6.84	202/35	25/42
FOR	44.52	6.83	228/40	
REG	44.52	6.84	178/13	100/10
		Liguria		
SIG	44.17	7.67	240/20	220/23
BER	44.17	7.65	240/20	120/20
POU	44.17	7.64	125/27	
BOA	44.16	7.6		
DBA	44.16	7.67	214/52	
GOR	44.17	7.62	310/10	
TAN	44.13	7.73	190/65	
FAS	44.16	7.8	185/50	
NAV	44.11	7.87	186/39	

[a] Definitions are as follows: S_0/S_1, bedding/foliation; dd, dip direction.

tracks data differ in each side of this front and suggest activity during all the Miocene [*Tricart et al.*, 2001]. This brittle extension is still active today [*Sue and Tricart*, 1999].

[12] The Rouchouze and Marinet folds oriented N120 to N130 have been formed during D2 and have been probably accentuated during D3. Main faults oriented N160 and N40 to N70 respectively (e.g., the Serenne and Font Sancte faults; Figure 2) are related to D4.

[13] About 130 samples were collected from 14 sites within the Rouchouze and Marinet folds. Three sites were sampled in the Ubaye valley (PVT, BAR, CHA), four sites to the north close to the Serenne pass (SER, LNC, REN, MOR) and seven sites to the south in the Fouillouse valley (FOR, REG, GEN, CAB, AOU, MAS, VAL) (Figure 2 and Table 2).

2.2. Liguria

[14] The second area is located in the Monte Marguareis-Mongioie massif, east of the Tende pass, where the most external units of the Ligurian Briançonnais zone crop out: the Upega-Nava–Carnino unit to the south and the Marguareis-Mongioie-saline unit to the north (Figure 3). The tectonometamorphic evolution of the area essentially occurred during the late Eocene–early Oligocene as for the Ubaye area [*Vanossi and Gosso*, 1983].

[15] Three sites have been sampled on a pluri-kilometric fold N100 oriented of the Upega-Nava-Carnino unit (FAS, TAN, NAV). The other sites are located in the Marguareis-Mongioie unit (Figure 3 and Table 2).

3. Paleomagnetic Study

[16] Cores were collected with a portable gasoline-powered equipment and oriented with a magnetic compass. Natural remanent magnetization (NRM) was measured with a two-axis cryogenic magnetometer (LETI) in the Laboratory of Geosciences Rennes. Schonstedt TSD1 and Pyrox furnaces were used for thermal demagnetizations. The susceptibility was measured using MS2 Bartington after each heating step. In general, magnetic and paleomagnetic data are homogeneous between localities and close to that

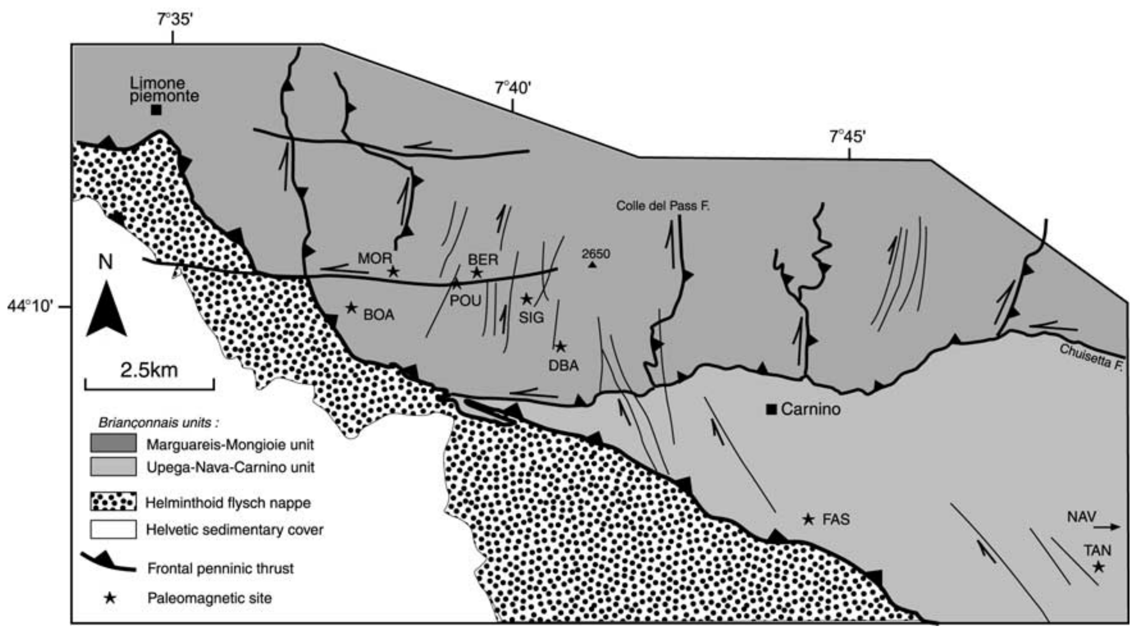

Figure 3. Structural map of the Liguria area with paleomagnetic sites (adapted from *Lanteaume et al.* [1991]). (The site NAV is situated 4 km to the east of TAN.)

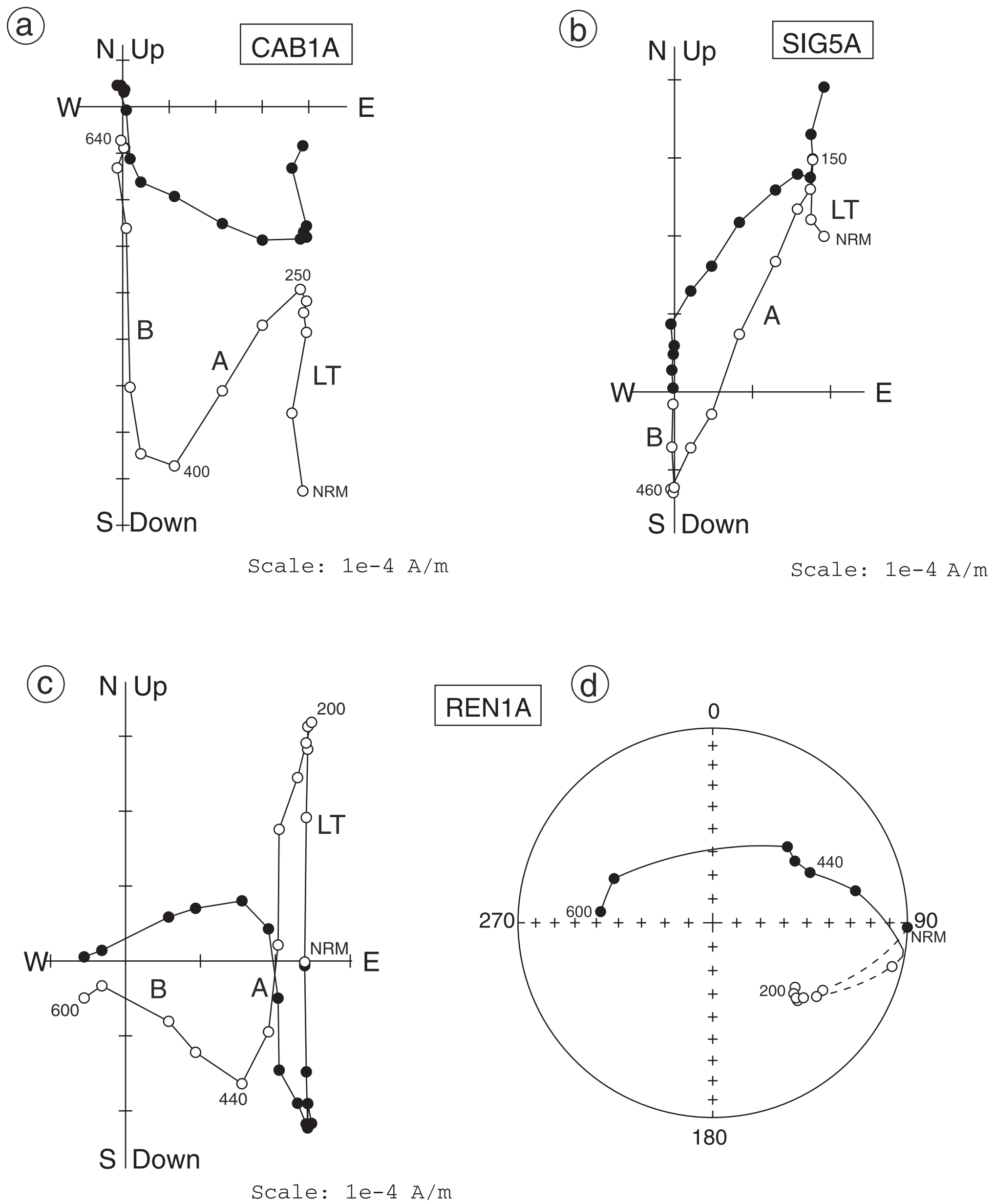

Figure 4. Representative thermal demagnetizations in geographic coordinates. (a–c) Orthogonal plots; circle, vertical component dot, horizontal component. (d) Stereographic projection; dot, normal polarity; circle, reverse polarity. Numbers indicate temperature steps. LT, A, B: low temperature, A, and B components, respectively.

observed on similar facies in the Briançon area [*Thomas et al.*, 1999].

3.1. Magnetic Behavior During Demagnetization

[17] Most of the samples show low NRM intensities of about 4×10^{-4} A/m. At the Ubaye locality, two sites, LNC and VAL, and some cores of sites REG and FOR however reveal much higher NRM intensities (1×10^{-2} A/m) carried by low-coercivity magnetic minerals. This probably corresponds to a natural isothermal remanent magnetization due to lightning. These data will not be considered in the following discussion.

[18] Three components of magnetization are usually observed during thermal demagnetization (Figure 4): a first low-temperature component, with maximum unblocking temperature around 200°C to 250°C and close to the present day magnetic field in the sampling area; a second component (A) with maximum unblocking temperatures around 450°C, well defined in all the sites and exclusively of reverse polarity; a third component (B) observed above 450°C. Unfortunately, very few sites reveal a clear B component

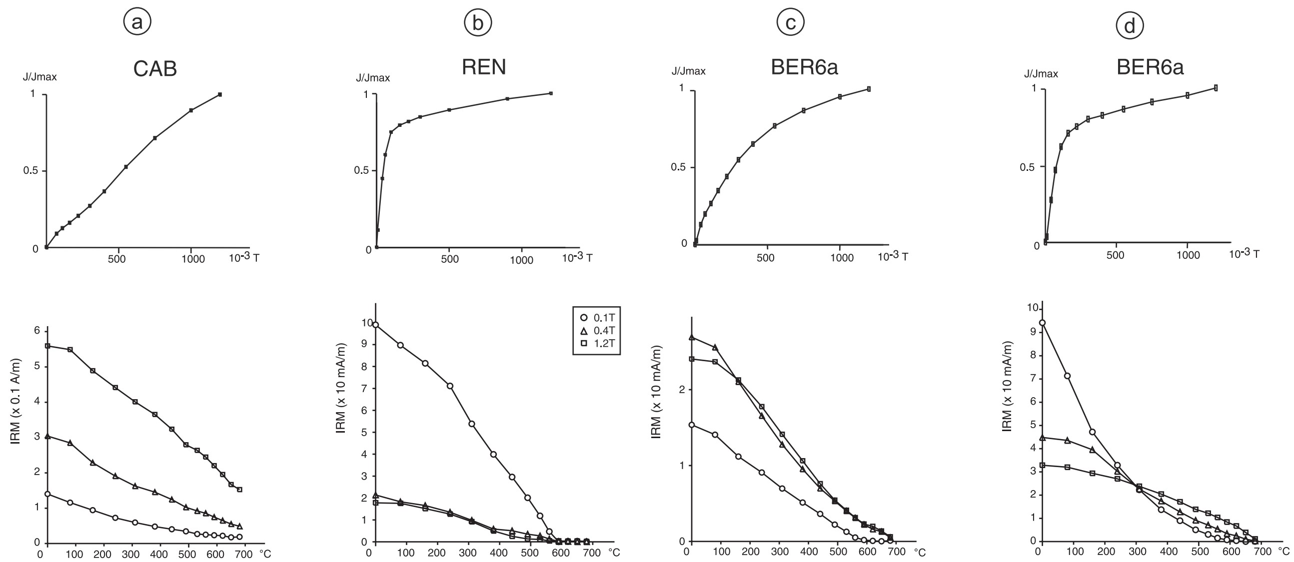

Figure 5. Isothermal remanent magnetization curves (IRM) and associated thermal demagnetization of three-axis IRM for representative samples. After the first IRM acquisition and demagnetization of sample BER6a (c) the same procedure was repeated a second time (d).

(Figure 4c). In most cases this component does not show stable end points during the demagnetization (Figures 4a, 4c, and 4d) and is difficult to isolate. This is probably due to a simultaneously strong increase of a viscous magnetization and of the bulk susceptibility above 450°C (see below).

3.2. Magnetic Mineralogy

[19] Representative samples were analyzed by progressive acquisition of isothermal remanent magnetization (IRM) followed by thermal demagnetization of three mutually isothermal remanence components acquired at a field of 1.2, 0.4 and 0.1T, respectively [*Lowrie*, 1990]. Analysis indicates variable amounts of coercivity phases between sites. None of the samples studied reaches saturation at 1.2T (Figures 5a–5c) which indicates the presence of high-coercivity minerals. The high coercivity phase is removed above 670°C during three axis thermal demagnetization of IRM, and probably corresponds to hematite, responsible for the red pigment of the Ammonitico rosso facies. In most cases, a low coercivity magnetic phase (Figures 5b and 5c) removed below 580°C also occurs and probably corresponds to magnetite. After the first cleaning, we performed for each sample a second IRM acquisition and thermal demagnetization of three IRM components (Figure 5d). In all cases, a new magnetic low coercivity phase is observed with unblocking temperature of 580°C. Growth of magnetite during heating is therefore likely, causing the increase of susceptibility and viscosity observed during thermal demagnetizations. This emphasizes the special care needed for the interpretation of the B component.

3.3. Paleomagnetic Directions

[20] In folded areas, the analysis and dating of paleomagnetic directions with respect to tectonic event is firstly based on the fold test. The respective effect of each deformation phase on local bedding may be estimated only if a specific detailed structural analysis has been carried out. In the Ubaye and Liguria areas, effects of the late tertiary extension has not been precisely quantified. We will therefore only discuss fold tests relative to the Eocene-Oligocene folding phases.

3.3.1. Low-Temperature and B Components

[21] The low-temperature component exhibits a very stable direction close to the present-day magnetic field and is most probably a recent viscous overprint.

[22] The B component was usually unstable and difficult to isolate. We attempt to isolate it for four sites from Ubaye (AOU, CAB, REN, MAS) and three sites from Liguria (DBA, SIG, BER) using principal component and great circle analyses. However, a high scattering of mean site directions is observed (Figure 6) and does not allow statistical interpretation. This component therefore will not be discussed further.

3.3.2. A Component

[23] In the Ubaye area, all mean sites directions point to the SSE in geographic coordinates and the mean direction is D = 121°; I = −52°; k = 17; α_{95} = 11° [*Fisher*, 1953] (Figure 7a and Table 3). After tilt correction we observe a significant increase in scattering and a mean direction in stratigraphic coordinates of D = 98°; I = −33°; α_{95} = 22°. The fold test is negative at the 99% confidence level [*McFadden and Jones*, 1981]. Additional local fold tests were performed on smaller scales: several sites sampled on a section of the Rouchouze fold (sites FOR and REG), Southeast of Fouillouse (Figure 3) also reveal a negative fold test at the 99% confidence level and the same holds at the sample level, for the BAR and PVT sites sampled on

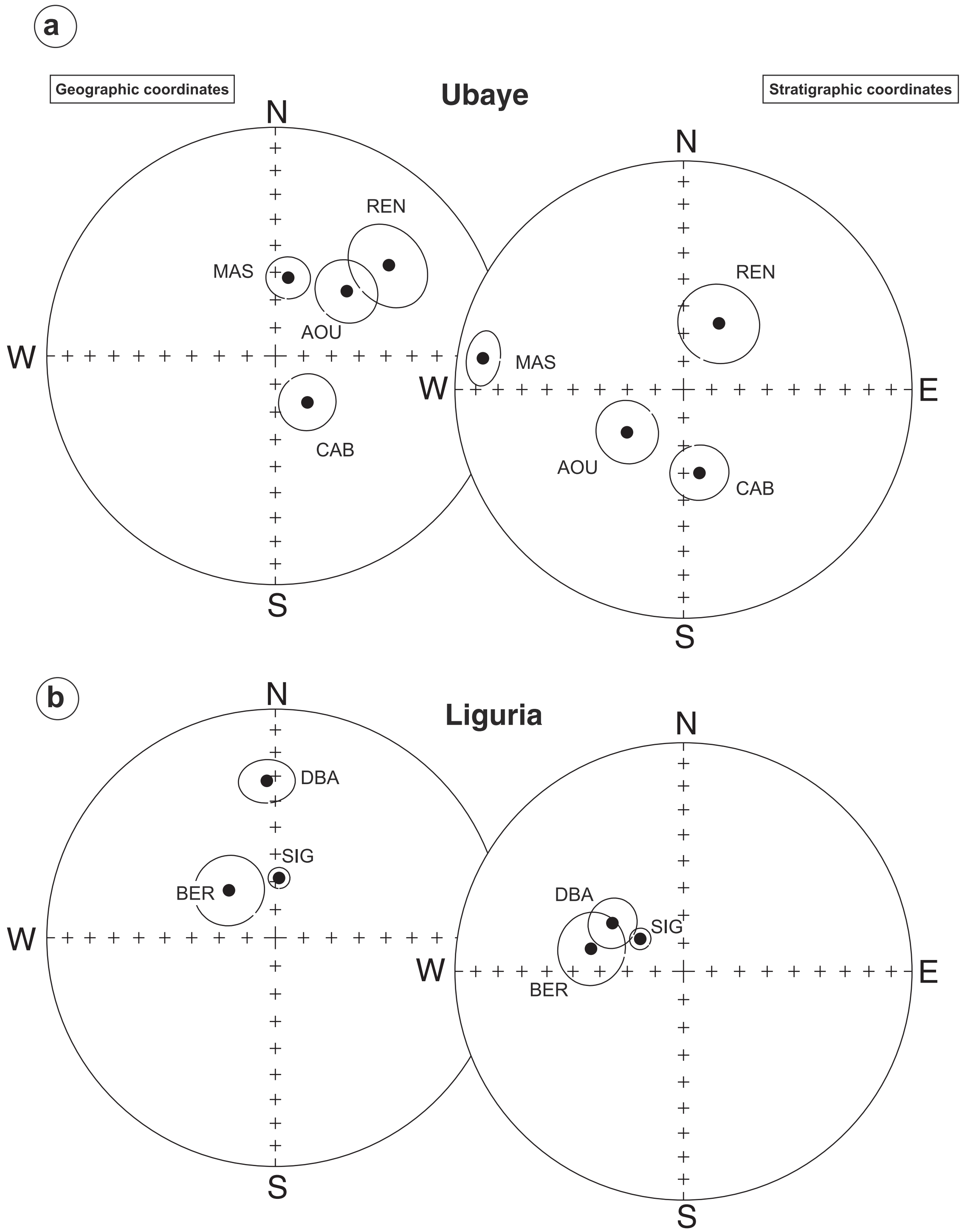

Figure 6. Stereographic projection of the mean site directions of the B component with associated confidence circles for the Ubaye (a) and Liguria (b) localities. All data are of normal polarity.

D3 folds of metric scale (Table 2). Moreover, for both BAR and PVT sites, an incremental unfolding indicates a maximum k value for 0% of unfolding. This component is therefore clearly post-folding (post D3).

[24] In the Liguria area, one site (BOA) sampled in strongly fractured rocks showed very unstable NRM during demagnetization and no reliable characteristic component was isolated. Two other sites (DBA and POU) revealed strongly deviated mean directions relative to other sites (Table 3) and were not therefore used to calculate a regional mean direction for the Ligurian locality. Concerning the site POU, we afterwards realized that it was sampled very close

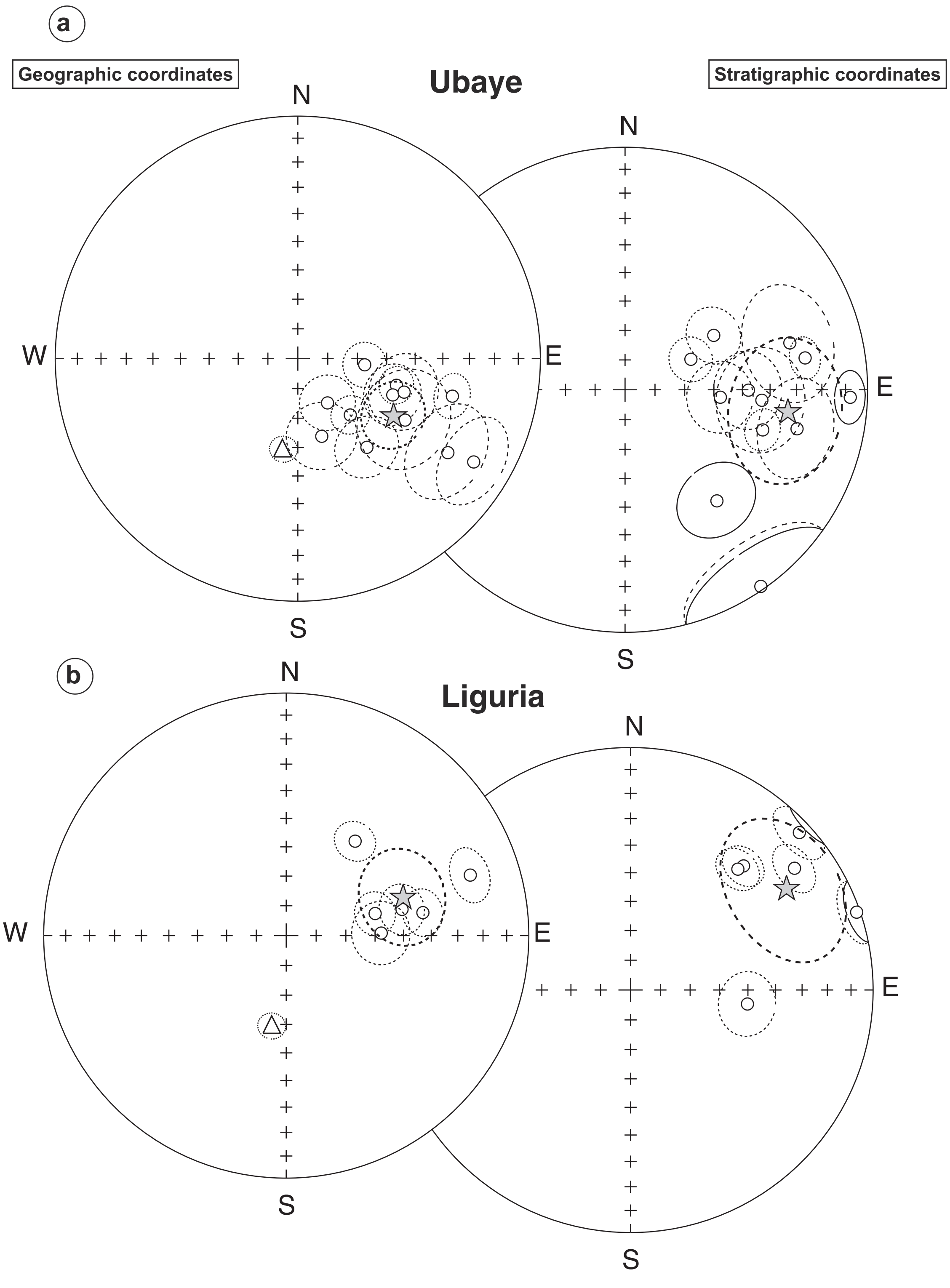

Figure 7. Stereographic projection of the mean site directions of the A component with associated confidence circles for the Ubaye (a) and Liguria (b) localities. Triangle is the reference direction for stable Europe at 30 Ma [*Besse and Courtillot*, 1991]. All data are of reverse polarity.

to a major fault plane, which may explain this anomalous direction.

[25] For the six remaining sites, we obtain in geographic coordinates a mean direction of reverse polarity D = 72°; I = −48°; k = 20; α_{95} = 15° (Figure 7b and Table 3). In stratigraphic coordinates we observe a significant increase in scatter with a negative fold test at the 99% level and a mean direction D = 57°; I = −24°; k = 10; α_{95} = 22°.

Table 3. Paleomagnetic Data for the A Component[a]

Site	n/N	Geographic Coordinates D	I	k	α_{95}	Stratigraphic Coordinates D	I	k	α_{95}
				Ubaye					
PVT	10/10	111	−56	28	10	74	−30	10	17
BAR	7/10	142	−52	34	10	145	−2	10	20
CHA	5/6	146	−72	68	9	59	−55	68	9
SER	6/7	163	−63	35	12	94	−58	35	12
REN	9/9	137	−64	65	6	106	−41	65	6
MOR	6/6	120	−48	18	16	94	−43	18	16
LNC[b]									
VAL[b]									
MAS	5/8	120	−17	37	13	140	40	37	13
AOU	7/8	104	−35	81	7	92	8	81	7
CAB	7/8	108	−52	25	12	90	−48	25	12
GEN	3/6	122	−28	71	15	103	−28	71	15
FOR	5/12	105	−55	161	6	80	−26	161	6
REG	5/13	95	−67	108	7	65	−66	108	7
FOR[c] +REG	10/25	101	−62	72	6	75	−46	13	14
MEAN	12/14	121	−52	17	11	98	−33	5	22
				Liguria					
SIG	10/10	36	−50	52	7	42	−31	52	7
BER	9/10	72	−21	44	8	71	−2	44	8
POU[c]	9/10	301	10	15	14	299	35	13	15
BOA[b]	3/10								
DBA[c]c	9/9	354	−72	404	3	21	−23	404	3
GOR	8/8	89	−58	31	10	96	−51	32	10
TAN	6/7	77	−49	71	8	47	−5	71	8
FAS	8/8	81	−42	58	7	53	−17	58	7
NAV	8/10	76	−59	62	7	42	−33	62	7
MEAN	6/8	72	−48	20	15	57	−24	10	22

[a] Definitions are as follows: n, number of samples (or sites) used for statistics; N, total number of studied samples (or sites); mean, mean global directions; D, declination; I, inclination; k, dispersion parameter; α_{95}, confidence circle at 95% confidence level.

[b] Sites for which it was not possible to isolate stable components of magnetization.

[c] Sites for which stable component was isolated but not used for calculation of mean direction.

[26] In both areas, statistics at site or locality levels indicate consistent negative fold tests and therefore suggests that the A component is an overprint acquired after the last regional-scale folding. This is in agreement with the data obtained to the north in the Briançon area [*Thomas et al.*, 1999] where the regional fold test is clearly negative. In this area, data show also a very good clustering after the correction from late alpine tilting (D4, accurately documented in this area), indicating clearly an overprint between D3 and D4. Taking into account the close similarity between tectonic contexts of the Ubaye, Liguria, and Briancon-Guillestre areas, we infer that the A component in the Ubaye and Liguria was acquired after the main folding phase (D3) and prior to the late Alpine tilting (D4). Age constrains on the metamorphic and folding phases allow us to propose that the overprint occurred after the early Oligocene and probably during the late Oligocene.

[27] A striking result is the systematic reverse polarity of the A component, in the Liguria and Ubaye areas and also to the north in the Briançon area [*Thomas et al.*, 1999]. Occurrence of fluids expelled from buried continental units and associated with the alpine metamorphism could explain a global chemical remagnetization but no evidence of such large-scale flows have yet been evidenced in the field [*Henry et al.*, 1996] and no trace of fluids can be observed in thin sections. If remagnetization is of thermal origin, a very fast post-metamorphic cooling should be excepted as the longer reverse-polarity chron in the Oligocene (chron called 12r) [*Cande and Kent*, 1995] lasted 2.1 My. Petrographic [*Goffé and Velde*, 1984] data however indicate that the maximum temperature reached during metamorphism is 320° and that cooling down to 100°C occurred over several Myr. Alternatively, if remagnetization is carried by single-domain grains and if more than half of the magnetic grains reached their blocking volume during one reversal, global observed magnetization can be of reverse polarity. With data in our possession, we cannot discriminate between various possible mechanisms and deeper studies, especially on magnetic mineralogy, are required.

4. Interpretation of Paleomagnetic Directions

4.1. Scattering of Site Mean Directions

[28] Despite a negative fold test, a significant scatter of sites directions remains in geographic coordinates, especially in inclinations which ranges for instance between −17° and −72° at the Ubaye locality (Figure 7a). This is likely related to extensional tilting after the acquisition of the remanence. In the Briançon area [*Thomas et al.*, 1999], a better clustering of mean sites directions in geographic coordinates was obtained when correcting tilts up to 35° related to late Tertiary extension (D4) [*Sue*, 1998]. At the Ubaye locality, a few tens of kilometers south of the Briançonnais locality, rotations of 10° to 35° about a horizontal axis oriented N40 could satisfactorily correct the sites with low inclinations or high inclination (MAS, GEN, AOU, CHA). Indeed, although, tilts are not yet quantified, two sets of conjugated normal faults of hundred meter to kilometer scale oriented respectively N160 and N40 to N70 [*Sue*, 1998] have been recognized and could have accommodated tilting of order. Moreover, tilting on faults oriented N160 could also partly explain the remaining scatter in declination (e.g., site SER). Similarly, at the Liguria locality, late Alpine normal faults roughly oriented NS and EW have been recognized [*Lecanu and Villey*, 1974]. Tilting along NS faults could explain data with low inclinations (e.g., site BER).

4.2. Comparison With Stable Europe

[29] As reference for stable Europe, we use the apparent polar wander path for Eurasia which does not show substantial variations during the Oligocene. Taking into account the uncertainty on the age of the overprint, we choose the reference at 30 My (D = 189°; I = −59°; α_{95} = 3°) [*Besse and Courtillot*, 1991]. Compared to this reference, the Ubaye and Liguria mean directions show significant and large deviations of 68° ± 15° and 117° ± 19°, respectively

Table 4. Selected Tertiary and Cretaceous Paleomagnetic Poles for the Northern Adriatic Plate and the Alpine Range[a]

Site	Age	Latitude °N	Longitude °E	**N**/n	Paleopole Lat	Paleopole Lon	α_{95}, dp/dm	Rotation	Q	Reference
Apennine foreland and Pô plain										
1, Voltri, Liguria	Late Eoc/early Olig.	43	9.1	33	65	255	5.2/7.8	36°±8°	6	*Vanden*Berg [1979]
2, Ramero-Garbagna	Late Olig/early Mioc.	43	9.1	**10**	49	261	4.9/8.3	51°±8°	5	*Hong* Kie [1988]
3, Turin mountains	Mid. Early Mioc.	45.1	7.8	51	67	236	7.5/11.6	29°±11°	5	*Bormioli and Lanza* [1994]
4, Colle Euganei	Late Eoc (?)Early-Middle Olig.	45.3	11.7	**21**	74	217	8.9/13.4	18°±14°	4	*Soffel* [1974]; *Channel et al.* [1978]
Istria										
5, Kvarner, N. Istria, Triestre	Cretaceous	45.5	14.0	**25**	65	245	4.9/7.7	22°±8°	6	*Marton et al.* [1990]
Southern Alps										
6, Monti Lessini	Eocene	45.5	11.5	**25**	64	206	6.7/11.5	36°±8°	4	*Soffel* [1975]; *Channel et al.* [1978]
Western and central Alps										
7, Briançonnais	Oligocene	44.6	6.6	**9**	61	276	8.5/11.6	47°±13°	5	*Thomas et al.* [1999]
7, Ubaye	Oligocene	44.5	6.8	**12**	43	283	10.3/15.0	68°±15°	5	This study
7, Liguria	Oligocene	44.1	7.6	**6**	8.3	310	12.8/19.6	117°±19°	5	This study
8, Sezia Lanzo zone	Late Oligocene	45.6	7.9	**28**	33	239	3.1/6.1	≈25°	4	*Lanza* [1977, 1979, 1984]
9, Lepontine dome	Late Olig.-Early Mio	46.3	8.8	**9**	69	271	7.8/10.4	27°±11°	5	*Heller* [1980]

[a] Definitions are as follows: **N**/n, number of sites/number of samples; rotation, positive counterclockwise; Q, quality factor according to *Van der Voo* [1993] criterion.

(Figure 7 and Table 4). Several hypotheses may be invoked to explain this discrepancy.

[30] First, one should consider a possible deviation of the remanence during its acquisition due to rock anisotropy. When possible, we measured the tectonic foliation at the sampling sites (Figure 8). On most cases, site mean directions are significantly away from the foliation, and can even be orthogonal (site PVT). Furthermore, differences in strain between sites are not correlated with differences in directions. Similar observations were made in the Briançon area [*Thomas et al.*, 1999], suggesting at most only a weak effect of rock strain on remanence

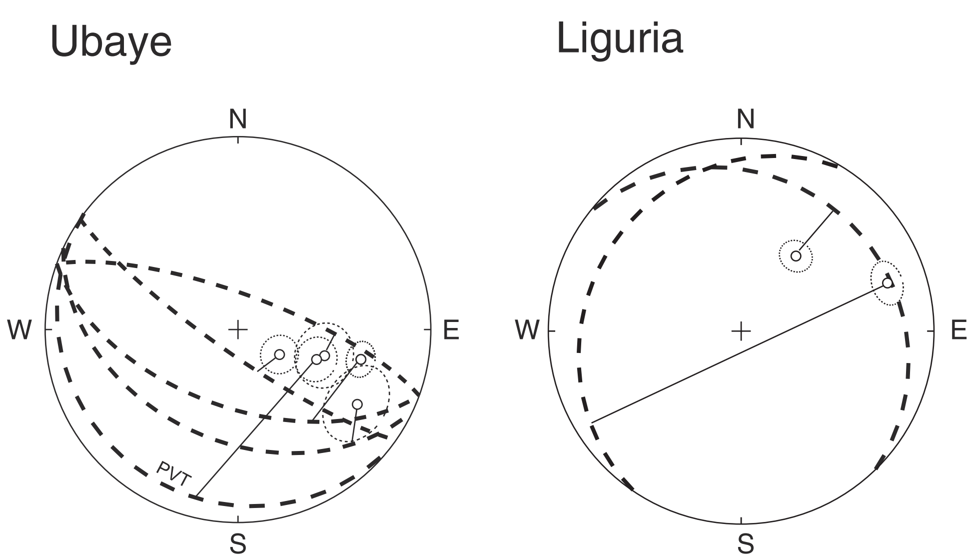

Figure 8. Tectonic foliation (great circles) and mean paleomagnetic directions (connected by lines) for the Ubaye and Liguria localities.

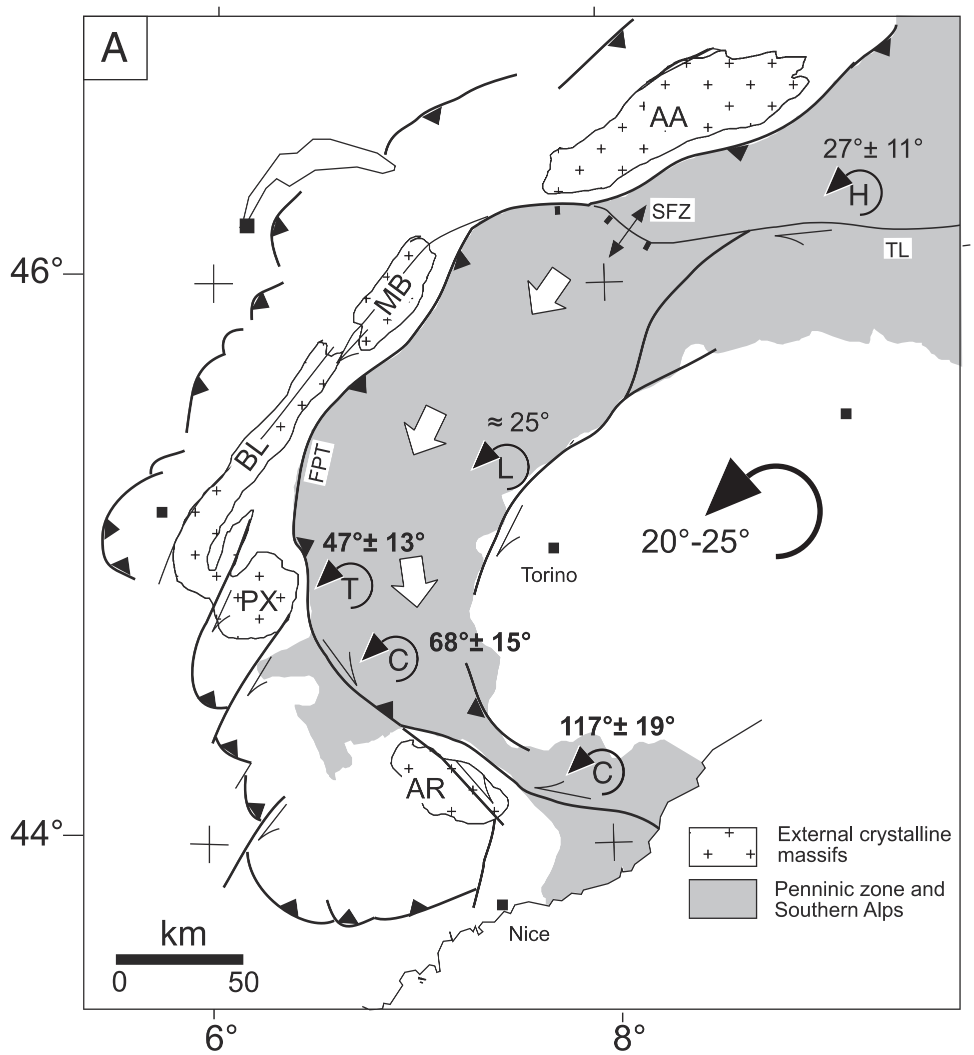

Figure 9. Simplified tectonic map of the western Alps outlying the Neogene kinematics. Vertical axis rotations are those deduced from the paleomagnetism (see also Figure 1 and Table 4): H, L, T, C, data respectively from *Heller* [1980], *Lanza* [1977, 1979, 1984], *Thomas et al.* [1999], and this study. The white arrows indicate the southward displacement of the internal Alps related to the extension at the Simplon fault zone. AA: Aar; AR: Argentera; BL: Belledonne; MB: Mont Blanc; PX: Pelvoux; FPT: Frontal Penninic Thrust; SFZ: Simplon fault zone; TL: Tonale Line.

acquisition. Additionally, measurements of the anisotropy of magnetic susceptibility on representative sites indicate a very weak anisotropy ratio P (kmax/kmin, with k susceptibility factor), always lower than 3% and no clear relation between magnetic susceptibility axes and remanence directions can be found.

[31] Second, regional tilting about horizontal axis could also be invoked as late Tertiary tilting (D4) is known in the studied areas. This is however unlikely for the following reasons. First, in the Ubaye area for instance, observed deviation would require a regional eastward tilting of at least 45° along a N160 oriented fault, while observed normal faults occurs at much smaller scale and involve essentially westward tilting. Second, in the Liguria area, deviation would require a huge unrealistic regional tilting of 65°, and along faults oriented N145 while normal faults in the area are either NS or EW.

[32] Therefore the most likely hypothesis is that the southern Penninic Alps suffered counterclockwise rotations about vertical axis relative to stable Europe.

5. Discussion

[33] Paleomagnetic data on the Briançonnais zone indicate large and systematic counterclockwise rotations. The amount of rotation increases significantly from North to South, with 47° ± 13° rotation in the Briançon area [*Thomas et al.*, 1999], 68° ± 15° in the Ubaye and up to 117° ± 19° in the Liguria (this study) (Figure 9). To the north, Tertiary paleomagnetic data are available in the internal Alps on

Oligo-Miocene intrusives of the Traversella massif [*Lanza*, 1984], on volcanics of the Sezia zone [*Lanza*, 1977, 1979] and on gneisses of the Lepontine dome remagnetized during late Oligocene-Miocene metamorphism [*Heller*, 1980] (Figures 1 and 9; Table 4). Fold tests were not possible in any of these studies and low inclinations indicate probable tilt about horizontal axis. However, all data also suggest a minimum counterclockwise rotation of 25° (25° for the Traversella massif, 25°–30° for the Sezia zone and 27° ± 13° for the Lepontine dome). In contrast, little or localized rotations are observed to the west in the Dauphiné zone [*Crouzet et al.*, 1996; *Aubourg and Chabert-Pelline*, 1999]. Hence the consistency of the sense of rotation within different tectonic units along the Alpine arc strongly suggests that, east of the Frontal Penninic Thrust (FPT) (Figure 9), the western Alps suffered a regional counterclockwise rotation. However, the complicate pattern of rotations along the Alpine arc, e.g., their increasing amounts toward the south and, in some cases, their very large amount may reflect interaction between several processes.

[34] Several issues should be discussed in the light of the kinematic models for the Alps: (1) What are the boundary conditions controlling rotations, (2), what are the processes involved, and (3), how can the different amount of rotations be explained?

5.1. Rotation Mechanisms

[35] In this section, we examine several rotation mechanisms for the western Alps, to see what rotation pattern they predict and how they fit with the tectonic and paleomagnetic record.

5.1.1. Rotation of the Adriatic Plate

[36] On the basis of post-Eocene kinematic indicators, which indicate dominant right-lateral slip along longitudinal faults (i.e., on the FPT) and counterclockwise rotation of transport directions along the western Alpine arc, it has been postulated that the western Alps have suffered a regional counterclockwise rotation [*Gidon*, 1974; *Vialon et al.*, 1989]. This would be related to a coupling between the internal Alps and the Adriatic plate with attached Ivrea body [*Stampfli and Marchant*, 1997] which rotated counterclockwise during the Tertiary indentation (Figure 10a). Adriatic indenter is considered to have rotated approximately 20° since the Oligocene (18° for *Schmid and Kissling* [2000] and 22° for *Vialon et al.* [1989]). This hypothesis implies (1) a maximum and homogeneous rotation of about 20° of the internal Alps, and (2), that right-lateral faulting should occur everywhere on faults parallel to the arc, in order to accommodate this large-scale counterclockwise movement.

[37] The rotation of the Adriatic plate is a matter of debate because of the lack of Tertiary paleomagnetic data out of the Apennines, and due to the suspicion that Adria did not behave as a rigid block during the Tertiary [*Lowrie*, 1986; *Van der Voo*, 1993]. Several reliable paleomagnetic data are, however, available to the north of the Adriatic plate, in the Padan basin and in Istria (Figure 1 and Table 4) and declinations all consistently indicate significant counterclockwise rotations. In the Padan basin, a counterclockwise rotation of 25° is observed in Miocene sediments of the external Apenninic units (Torino hills) [*Bormioli and Lanza*, 1995] and 35° to 45° rotation in Eocene to Miocene sediments of Garbagna [*Vandenberg*, 1979; *Hong Kie*, 1988]. The volcanics of the Colli Euganei to the northeast, although not well constrained in age (late Eocene to middle Oligocene) and with scattered mean sites directions [*Soffel*, 1974, 1975; *Channel*, 1978], do indicate a rotation of about 20°. Finally, Late Cretaceous data of the Istria peninsula also show a rotation of about 40° [*Marton et al.*, 1990]. Preliminary data on Tertiary rocks confirm the rotation [*Marton et al.*, 1998]. Local tectonic effects may explain the different amount of rotations between domains of northern Adria, but a rotation of about 20°–25° is likely. This is substantiated by structural data in the Southern Alps [*Schönborn*, 1992]. Indeed, south of the Tonale line, the amount of shortening decreases from east to west which implies a 15° counterclockwise rotation of the Adriatic plate relative to Europe. Furthermore, rotation could be still active, according to the first permanent GPS data on the Alpine domain [*Caporali and Martin*, 2000].

[38] The rotation of the Adriatic plate is, therefore, an important boundary condition for rotations in the Alps, as suggested by some kinematic models. It does not, however, explain the large rotations (>45°) and their varying amounts.

5.1.2. Southward Extrusion of the Penninic Alps Along Curved Faults

[39] In this model, the western and central Penninic Alps are extruded toward the south since the Oligocene in response to the collision. Penninic units move southward along the curved frontal Penninic thrust, and thus suffer counterclockwise rotation [*Ménard*, 1988] (Figure 10c). Indeed, curvature of the Alpine arc was probably already present, at least partly, in the Oligocene. Two main predictions are associated with this model: (1) similarly to the Adriatic rotation plate model, right-lateral displacement occurs along faults parallel to the Arc, and (2) the amount of rotation depends upon (a) the total displacement of the extruded units and (b) the shape of the arc. Lateral extrusion caused by indentation of the Adriatic plate into Europe has been independently proposed for the Alpine orogen [*Goguel*, 1963; *Tapponnier*, 1977; *Ratschbacher et al.*, 1991; *Mancktelow*, 1992]. According to *Mancktelow* [1992], NNW-SSE shortening in the central Alps is accommodated since the early Miocene by extension parallel to the orogen on the Simplon fault zone (Figure 9) and affected structural levels up to 25 km deep. The total horizontal displacement on the Simplon fault is around 15 km [*Hubbard and Mancktelow*, 1992], probably close to the total displacement related to orogen parallel extension in the western Alps as no other such crustal fault zone is known. By fitting the FPT to a circle (Figure 10c) we obtain an associated counterclockwise rotation of units of about 5°. Up to 10° rotation may be reached in the southern part of the Alpine arc where the curvature is accentuated (Figures 9 and 10c). Hence the contribution of this mechanism on rotations measured in the western and central Alps, although

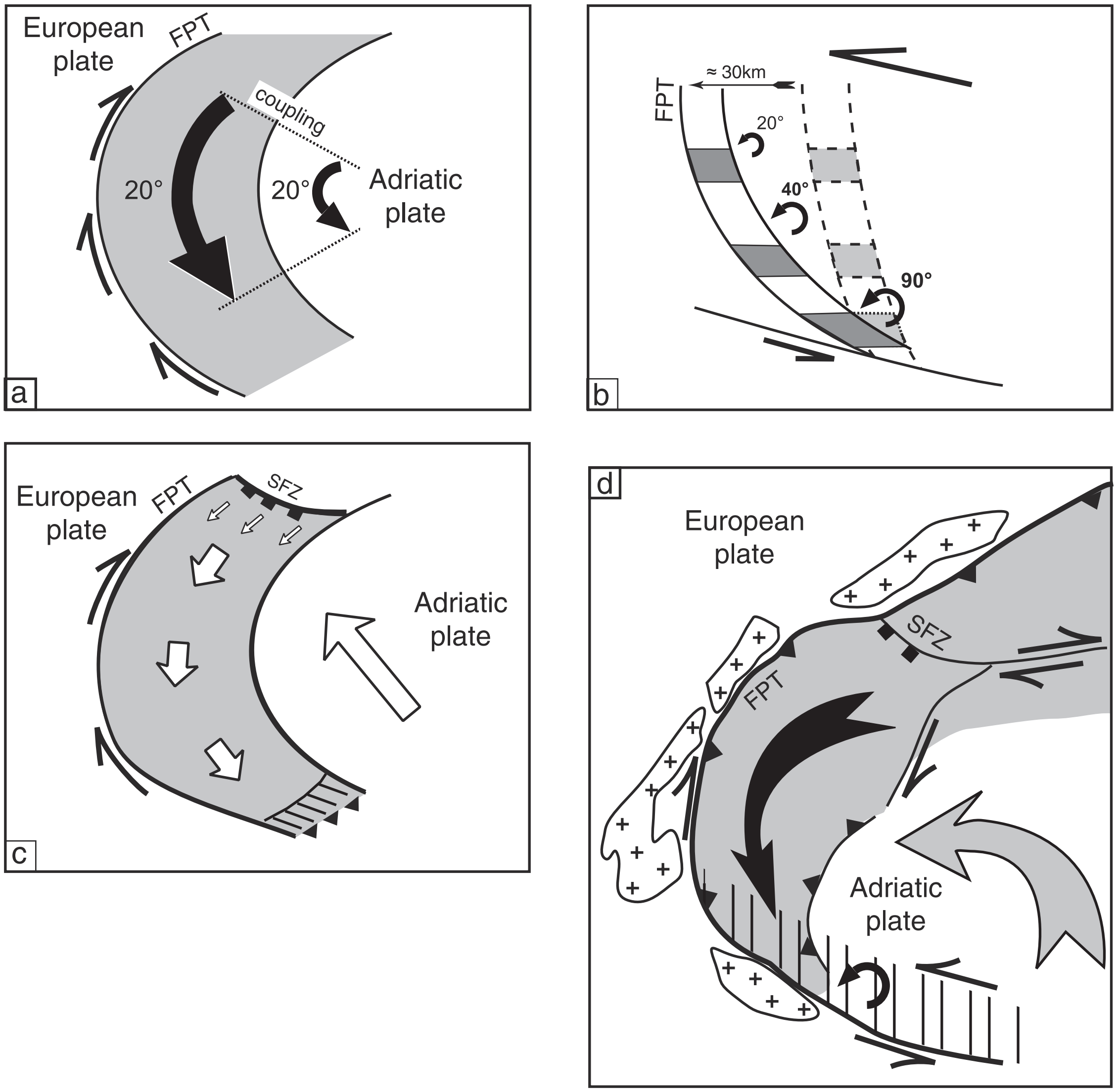

Figure 10. Various mechanisms inferred to explain rotations in the western Alps. (a) Rotation of the Adriatic plate and attached Ivrea body induce rotation of the internal Alps of about the same amount. Right-lateral faulting is expected on faults parallel to the arc; gray: internal Alps. (b) Left-lateral shear in the southern part of the Alpine arc accommodates the relative displacement between the Adriatic and European plates. Associated rotations increases to the south toward the velocity boundary. Amounts of rotation imply an about 30 km westward displacement of the internal units since the Oligocene. (c) Southward extrusion of the internal Alps south of the Simplon fault zone (SFZ) occurs in response to the indentation of the Adriatic plate into Europe. Extrusion along curved FPT induces counterclockwise rotations. Amount of rotation depends upon the quantity of horizontal displacement of units and the curvature of the arc; gray: internal Alps. (d) Composite rotation model for the western Alps. The domain in gray suffered rotations related to the rotation of the Adriatic plate and to southward extrusion south of SFZ. To the south (hatch) the western Alps suffered rotation related to left-lateral shear accommodating relative motion between the Adriatic and European plates. Crosses: external crystalline massifs.

significant, remains probably minor relative to other processes described in the following paragraph.

5.1.3. Oroclinal Bending by Simple Shear at the Southern Margin of the Alpine Arc

[40] Several authors consider that part or most of the arcuate shape of the Alpine arc was acquired before 35 Myr ago, on the convex European-Adriatic plate boundary [*Laubscher*, 1988; *Stampfli and Marchant*, 1997; *Schmid and Kissling*, 2000]. However, after 35 Myr ago (i.e., the lower age bound for the paleomagnetic rotation), the arcuate shape was probably accentuated [*Schmid and Kissling*, 2000]. Left-lateral simple shear at the southern border of the Alpine arc is a mechanism that

could be responsible for both curvature and gradual rotations of deformed areas (Figure 10b). Indeed, left-lateral faulting, which accommodates the northwestward motion of the Adriatic plate relative to the European plate, occurs on orogen-parallel faults back of the Argentera massif and in Liguria (Figures 3 and 9) during late alpine times [*Ricou*, 1981; *Lanteaume*, 1991]. A global simple shear model (Figure 10b) [*Ramsay*, 1983], satisfactorily explains 20° and 40° of rotation for the Briançonnais and Ubaye areas and up to 90° for the Liguria. The restoration, with help of our measured rotations, of the Briançonnais zone before the left-lateral simple shear, leads to structures oriented N30° which fall in line with similar restored structures in Corsica [*Ricou*, 1994; *Gattacceca*, 2001]. This model also implies a Northwestward displacement of the internal units of about 30 km, in rough agreement with recent estimates deduced from crustal sections [*Schmid and Kissling*, 2000]. This displacement would be accommodated by thrusting of the Subalpine chains [*Gratier et al.*, 1989] and on the Penninic thrust.

5.2. A Composite Rotation Model for the Alps

[41] None of the models alone presented above are sufficient to explain the rotation pattern in the western Alps. Obviously, several mechanisms operate simultaneously (Figure 10d). We infer at least two major mechanisms that occurred since the Oligocene in the arc: (1) the rotation of the Adriatic plate and the attached Ivrea body [*Stampfli and Marchant*, 1997] induces a global rotation of the internal western Alps of about 25°. This mechanism may be still active, according to permanent GPS data [*Caporali and Martin*, 2000]; and (2) left-lateral simple shear at the southern border of the Alpine arc may account for most of the remaining rotation and especially the important southward increase of rotation. The southward extrusion of the Alps along the curved FPT is probably a significant third mechanism inducing rotations but do not account for more than 10°.

[42] In this model, the southern termination of the extruded domain and the transition with the left lateral shear zone is located in a strip north of the Argentera Massif (Figures 9 and 10d). It is noticeable that, in this domain, intense eastward and northeastward back thrusting is observed in the Penninic units and the Ivrea body [*Eva and Solarino*, 1998].

6. Conclusion

[43] New paleomagnetic data presented here on the southern part of the Alps indicate large counterclockwise rotations, up to 117° of the Penninic Alps relative to stable Europe since the Oligocene. The consistency in sense of rotation with published data further to the north strongly suggests that the internal Alps suffered a global significant counterclockwise rotation relative to stable Europe. Several mechanisms seem necessary to explain the varying degree of rotation along the Arc. We propose that the rotation of the Adriatic plate and the left-lateral shear at the southern margin of the Alpine arc are the two main boundary conditions controlling rotations. Southward extrusion of the internal Alps along the curved Penninic thrust may also be a significant process but minor relative to the others.

[44] Hence, after the Eocene, crustal scale rotations in the western Alps are a major process that accommodates deformation and convergence between Adria and Europe. Rotations are consistent with the extrusion models; they also emphasize the rotation of the Adriatic plate as a major boundary condition controlling deformation in the western Alps, since the Oligocene, and eventually for the active tectonics if GPS data are confirmed. Studies based on regional restored cross sections, strain trajectories, and paleogeographic reconstructions should take this evidence into account.

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