

Post-Eocene rotations in the Western Alpine realm: a review from sixty eight years of paleomagnetic investigations

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Abstract – A synthesis of more than 55 paleomagnetic studies yielding Tertiary primary or secondary magnetizations is used to evidence the rotations around a vertical axis since 40 Ma in the Western Alps and surrounding areas. In both external and internal zones of the orogenic prism, the rotations seem to be latitude dependent. In particular a widespread Eocene remagnetization of the Mesozoic European cover from Jura to Provence suggests possible effects of small local rotations of the External units of the belt. The most prominent feature is a consistent large (20–60 degrees) counterclockwise rotation observed in internal units and in the Northern Apennine areas. Also, the Corsica- North Sardinia block rotates similarly. Since the late Oligocene, apparent rotations around vertical axis are small North of the Po plain. It implies that the Torino-Monferrato North verging thrust plays a major role in accommodating the differential rotation. Therefore, domains separated from Europe by oceanic sutures (*i.e.* Liguria + Corsica – North Sardinia) can play as rigid bodies, while on the contrary, internal deformation deduced from paleomagnetic studies evidence that Apulia cannot be anymore regarded as a rigid body. In the Western Alps, the plate boundary, first localised at the ophiolite suture is then shifted along the Penninic Frontal Thrust. Tectonic models of the Alps that do not take into account the observed rotations have clearly to be reappraised.

Keywords: Western Alps / paleomagnetism / rotations

Résumé – **Rotations post-Eocène dans les Alpes occidentales : un examen de soixante-huit années de recherches paléomagnétiques.** Une synthèse de plus de 55 études paléomagnétiques basées sur des aimantations primaires ou secondaires d'âge Tertiaire est utilisée pour mettre en évidence les rotations autour d'un axe vertical depuis 40 Ma dans les Alpes occidentales et les régions environnantes. Dans les zones externes et internes du prisme orogénique, les rotations semblent dépendre de la latitude. En particulier, les directions issues d'une ré-aimantation générale à l'éocène de la couverture européenne mésozoïque, du Jura à la Provence, suggèrent des effets possibles de petites rotations locales des unités externes sont mises en évidence. La caractéristique majeure est une rotation anti-horaire importante (20–60 degrés) observée dans les unités internes et dans les zones de l'Apennin septentrional. Le bloc Corse – Nord Sardaigne subit également une rotation similaire. Depuis la fin de l'Oligocène, les rotations apparentes autour de l'axe vertical sont faibles au nord de la plaine du Pô. Cela implique que le chevauchement nord Torino-Monferrato joue un rôle majeur dans la prise en compte de la rotation différentielle. Par conséquent, les domaines séparés de l'Europe par des sutures océaniques (c'est-à-dire la Ligurie + la Corse-Sardaigne) peuvent jouer le rôle de corps rigides, alors qu'au contraire, la déformation interne déduite des études paléomagnétiques montre que l'Apulie ne peut plus être considérées comme un corps rigide. Dans les Alpes

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occidentales, la limite des plaques, d'abord localisée au niveau de la suture ophiolitique, est ensuite déplacée le long du Chevauchement Pennique Frontal. Les modèles tectoniques des Alpes qui ne prennent pas en compte les rotations observées doivent clairement être réévalués.

Mots-clés : Alpes occidentales / paléomagnétisme / rotations

1 Introduction

Since the precursory speculative view of [Gidon \(1974\)](#) who compared the shape of the western Alps to an atmospheric depression, it has been recognized that the kinematic history of the belt cannot be accounted for without significant rotations ([Vialon *et al.*, 1989](#); [Collombet *et al.*, 2002](#)). As shown by numerous studies ([Satolli *et al.*, 2005](#); [Weil *et al.*, 2010](#); [Pueyo *et al.*, 2016](#)) palaeomagnetism is a powerful tool to determine possible block rotations around vertical axis.

In the Alps, continental mobility has been evidenced since the end of the XIXth century ([Heim, 1878](#); [Argand, 1916](#)). The arcuate shape of the western Alps (*i.e.* between latitude and longitude of 43–47N and 4–10E respectively) is classically considered to be the consequence of oblique collision of the Apulian indenter associated with left lateral escape of the different units involved in the crustal collision process ([Goguel, 1963](#); [Tapponnier, 1978](#); [Rosenbaum and Lister, 2005](#)). The rotations may also affect the Apulian indenter as a whole and several geodynamic models have been proposed to take into account such rotations (see [Schmid and Kissling, 2000](#); [Ford *et al.*, 2006](#); [van Hinsbergen *et al.*, 2020](#)). In particular, the precursory study of [Ménard \(1988\)](#), based on a kinematic interpretation of the periadriatic lineament (that are composed from west to east by the Canavese, Insubrian, Judicaria and Gail lines) displaced with respect to its deep trace inducing, by flexure, the northern Po plain, proposed a two phases rotation scheme of the Austroalpine and Southern Alps basements dragging the underlying upper Penninic crust: 18 degrees during the Oligocene and 27 degrees in the Miocene. Such rotations can be tested using appropriate paleomagnetic data.

Many paleomagnetic works have been performed in the Western Alps since [Roche \(1957\)](#) and the review of the first thirty years of paleomagnetic investigations ([Heller *et al.*, 1989](#)). Published paleomagnetic data until now came up with contradictory conclusions. In fact, since [Heller *et al.* \(1989\)](#) no general review has been performed. A recent compilation is presented in [Brunsmann \(2023\)](#) without critical assessment on the data significance. Our aim is to offer a clear synthesis, adding data published since, or not used by [Heller *et al.* \(1989\)](#), and restraining the analysis to post middle Eocene (40 Ma) data. This work focuses only on the Western Alps and readers should refer to papers such as [Thöny *et al.* \(2006\)](#) for central and eastern Alps, [Maffione *et al.* \(2008\)](#) for North Apennine, [Siravo *et al.*, \(2023\)](#) for Corsica – Sardinia and [Cifelli and Mattei \(2010\)](#) for the Italian peninsula.

Sorting the data to only post middle Eocene has several essential advantages:

1) the debate on whether European or Africa referenced directions have to be used is pointless as suturing of both continental crusts have already begun between 50 and 35 Ma ([Schmid and Kissling, 2000](#); [Schmid and Kissling, 2000](#);

[Carrapa *et al.*, 2003](#)); therefore the kinematic analysis can be based only on relative movements with respect to stable Europe.

2) the apparent polar wander paths (APWP) of stable Europe and Africa are very similar since ca 40 Ma ([Torsvik *et al.* \(2012\)](#)). Moreover, the European APWP is much better defined than the African one, allowing to resolve rotations less than 10 degrees (see below).

3) the stability of reference declination and inclination from the Eocene to the Miocene, allows to use data poorly constrained in age like remagnetizations, left apart by [Heller *et al.* \(1989\)](#).

4) the observed post middle Eocene block rotations can be safely related to Alpine movements while older data may have recorded successive independent rotations linked to (1) the Liassic basin opening, (2) hypothetical pre-alpine phases of deformations (Cretaceous and Eocene phases, Pyrénéo-provençal phase, ...), or even (3) late Hercynian tectonic activity for the Permian data (*e.g.* [Henry, 1992](#)).

Regardless of the age of magnetization, the classical use of tilt correction (bedding correction) implies that the full kinematic of the folding is well known (geometry, fold axis ...). Since it is rarely the case, it can lead to inadequate tectonic corrections ([Cairanne *et al.*, 2002](#)). In mountains belts, several successive phases of deformation usually occurred, often combining unknown successive axis of rotation, which add another source of uncertainty. Therefore, primary paleomagnetic directions in fold and thrust belts should be used with caution ([Pueyo *et al.*, 2016](#)).

Overprinted secondary magnetization without paleohorizontal has always the problem of unknown tilt (*i.e.* rotation around horizontal axes), possibly yielding artefact rotation values. As a consequence, Tertiary post folding remagnetizations appear as a better tool to constrain late stages of Alpine tectonic deformations than pre-Tertiary primary magnetization. Nevertheless, in this work we will also consider Tertiary primary data.

2 Treatment process and data selection

The paleomagnetic database used here is provided in [Table 1](#). Each entry of the database is called by a number in square brackets that allow easy exchange between table, text and figures. This synthesis will be restricted to the Western Alps and its foreland (*i.e.* to the latitude and longitude rectangle 43–47N and 4–10E). The few data from Corsica-North Sardinia block are also used in order to strengthen the discussion. Data from Middle to Upper Eocene from South Sardinia ([Siravo *et al.*, 2023](#)) are not included in this discussion because they have suffered an extra ~ 30° CCW rotation prior to 21 Ma during the Liguro-provençal rifting. The limited size of the studied zone allows to base the discussion on directions rather than poles. [Table 2](#) gives the expected declinations and

Table 1. Paleomagnetic database used in the discussion. N: number of sites used, n: number of samples. D: declination, I: Inclination, $\alpha 95$: 95% confidence cone, K: precision parameter, R: predicted rotation, dR: error on the rotation (calculated after Demarest, 1983). The rotation and its error are calculated taking into account the age of magnetization and the corresponding Torsvik *et al.* (2012) synthetic APWP reference. (a): combination of data from Crouzet *et al.*, 1996; Dumont *et al.*, 2008; Ménéard *et al.*, 1992 and Lamarche *et al.*, 1988.

III. Primary directions with paleohorizontal													
Formation	Lat	Long	Age of magnetization (Ma)	N/n	D	I	alpha 95	K	Rotation	dR	Significant	Age - R	Reference
1	Swiss Molasse	46.5	6 \ 7	13-29	2412	16.4	46.7	3.3	82.9	12.4	Y	20	Kempf <i>et al.</i> , 1998
2	Savoie Molasse	46	5.9	26-23	2	352.2	53.8	6.3	11.4	-12.8	Y	25	Burbank <i>et al.</i> , 1992
3	Paleocene lacustrine	43.6	5.5	Paleocene	10/96	9.5	46.8	8.3	33.2	9.2	N	60	Westphal and Durand, 1989
4	Paleocene lacustrine	43.5	5.5	Paleocene	335	5.6	52.5	1.2	23	5.3	Y	60	Cojan <i>et al.</i> , 2000
5	Continental Oligocene	43.5	5.5	30-25	41	350.6	55.1	3.5	618	-16.5	Y	25	Kechra <i>et al.</i> , 2003
6	Arc de Nice Priabonian	43.8	7.41	35	2/26	229.1	-36.9	2.6	452	42.0	Y	35	Sonnette, 2012
7	Eo-Oligocene, Ultra helvetic nappes (Dérochoir)	46	6.8	Eo-Oligocene	16	312.3	58.5	11.4	9.5	-55.9	Y	40	Piquet <i>et al.</i> , 2000
8	Eo-Oligocene, Ultra helvetic nappes (Marais)	45.9	6.4	Eo-Oligocene	35	243.2	48.7	6.7	26.8	-125.1	Y	40	Piquet <i>et al.</i> , 2000
9	Torino and Monferrato Hills	45.1	8.1	Miocene	2/17	331.5	63.5	15.6	259.0	-31.6	Y	15	Bormioli and Lanza (1995)
10	Piemonte basin - Northwestern Apennine	44.8	9	Late Eocene-Early Oligocene	1/33	333.2	50.3	5.8	-	-32.8	Y	30	Vandenbergh (1979)
11	Oligocene Piemonte Basin	44.8	9	Oligocene	10	318.7	53.8	6.6	55.0	-46.3	Y	25	Thio, 1988
12	Tertiary Piemonte Basin	44.5	8.5	Oligocene-lower miocene	3/31	320.2	44.5	-	-	-43.8	Y	20	Carrapa <i>et al.</i> (2003)
13	Tertiary Piemonte Basin	44.5	8.5	Oligocene	23	310.6	45.6	13.7	19.7	-55.5	Y	30	Maffione <i>et al.</i> , 2008
14	Sardinia preopening volcanics (synthesis)	42	9	Late Oligocene-Aquitainian	59	329.2	44.7	4.9	15	-34.8	Y	20	Muttoni <i>et al.</i> , 1998
15	Sardinia sediments	39.6	8.8	Lower-Middle Miocene	1/24	340.6	39.3	3.9	58.6	-23.4	Y	20	Speranza <i>et al.</i> , 2002
16	Sardinia Volcanics	40.2	8.7	20-21	35	320.6	46.4	6.4	15	-43.4	Y	20	Gattaceca <i>et al.</i> , 2007
17	Corsica St Florent basin	42.7	9.3	Middle Miocene	4	342.6	47	9.3	99	-20.5	Y	15	Vigliotti and Kent, 1990
18	Corsica Balagne sediments	42.6	9	Middle Eocene	1/17	151	-47.2	4	80	-37.2	Y	40	Vigliotti and Kent, 1990
19	Corsica volcanics	41.4	9.2	~21	4	343	60	8.8	110	-21.0	Y	20	Ferrandini <i>et al.</i> , 2003
20	Corsica Oligocene Sediments	41.9	8.8	Chattian	1/8	140	-31	3.1	313	-45.0	Y	25	Ferrandini <i>et al.</i> , 2003
21	Epiligurian basins	44.4	10.8	Late Oligocene-Middle Miocene	7/62	303.5	48	11.2	30	-61.0	Y	25	Muttoni <i>et al.</i> , 1998
II. Secondary directions with paleohorizontal													
Formation	Lat	Long	Age (Ma)	N	D	I	alpha 95	K	Rotation	dR	Significant	Age - R	Reference
22	Metasediments Adamello	46	10.6	40-30	15	9.6	61.2	5.9	54.4	2.5	N	30	Kipfer and Heller, 1988
23	Chartreuse and Vercors	45.2	5.5	Tertiary	119	12.6	56	7	42	8.6	N	30	Aubourg and Rochette, 1992
24	Berrias normal	44.4	4.3	Tertiary ?	83	9	49.2	3.6	18.6	0.8	N	30	Galbrun, 1985
25	Berrias reverse	44.4	4.3	Berriasian	80	170.6	-43.6	4.6	11.4	-9.4	Y	*	Galbrun, 1985
26	Cevennes	44.2	4.1	Eocene	15/244	3.1	55.7	0.8	165	-5.1	Y	40	Henry <i>et al.</i> , 2001
27	Cevennes	44	3.8	40	11/88	10.4	63.9	7.3	39.9	2.2	N	40	Kechra <i>et al.</i> , 2003
28	Ventoux massif	44.2	5.8	40	10/80	355.5	55.1	7.6	41.4	-12.7	Y	40	Kechra <i>et al.</i> , 2003
29	Vocontian basin	44.4	5.6	40	15/227	357.7	54.8	6	42.1	-10.5	Y	40	Katz <i>et al.</i> , 1998, 2000
30	Dévoluy-Diois	44.6	5.7	Tertiary	89	338.6	53.5	10.6	17.8	-27.5	Y	30	Aubourg et Chabert-Polline, 1999
31	Barrot Dôme	44	6.8	30	4	300.9	58.0	9.9	52.1	-65.1	Y	30	Sonnette <i>et al.</i> , 2014
32	Esparon	44.32	6.15	<10	7/62	5.1	60.9	7	76.3	2.8	N	10	Cairanne, 2004
33	Gaubert	44.03	6.21	<10	3/28	14.8	58.4	5.7	475.7	12.5	Y	10	Cairanne, 2004
34	Bès	44.24	6.26	<23	4/31	347.3	60.2	9.7	91.3	-17.7	Y	25	Cairanne, 2004
35	Barême	43.96	6.41	<23	2/21	1.8	60.1	3.8	440.7	-3.2	Y	25	Cairanne, 2004
36	Arc de Castellane	43.92	6.8	<10	15	355.1	63.5	7	30.8	-7.2	N	10	Sonnette 2012
37	Arc de Nice	43.85	7.42	<10	3/30	349.2	62	7.1	303	-13.1	Y	10	Sonnette 2012
38	Jura	47.2	7.2	Miocene	16/192	359.1	63.8	5.7	43	-3.2	Y	15	Johnson <i>et al.</i> , 1984
39	Digne nappe	44	6.5	Tertiary	80	348.4	52.5	16.6	7.8	-17.6	N	30	Aubourg et Chabert-Polline, 1999
III. Primary directions without paleohorizontal													
Formation	Lat	Long	Age (Ma)	N	D	I	alpha 95	K	Rotation	dR	Significant	Age - R	Reference
39	Bergell massif	46	8	30-25	405	338.7	57.4	1.2	-	-26.3	Y	30	Heller, 1980
40	Sesia andesites dikes	45.5	8	33-30	68	337.2	37.3	9.7	-	-28.8	Y	30	Lanza, 1977

Table 1. (continued).

III. Primary directions with paleohorizontal													
	Lat	Long	Age (Ma)	N	D	I	alpha 95	K	Rotation	dR	Significant	Age - R	Reference
41	45.5	8	~30	152	135.9	-2.9	8.8	27.8	-50.1	7.1	Y	30	Lanza, 1979
42	45.5	7.8	~30	8/150	142.7	-6.3	6	-	-43.3	5.0	Y	30	Lanza, 1984
43	45.6	8.1	Tertiary	11	331	31	19	-	-35.0	17.7	Y	30	Bigoggero <i>et al.</i> , 1981
44	43.5	6.8	33	37	349.5	51	7.1	118	-17.6	9.6	Y	30	Zijderveld, 1975
IV. Secondary directions without paleohorizontal													
Formation	Lat	Long	Age (Ma)	N	D	I	alpha 95	K	Rotation	dR	Significant	Age - R	Reference
45	46.5	8.7	25-12.	2/27	186.7	-70.1	8.1	-	2.7	19.6	N	20	Heller, 1980
46	45.8	6.7	20-30	14	18.3	63.4	9.7	17.7	13.3	17.8	N	25	Crouzet Unpublished
47	45.3	6.3	20-30	43	358.9	63	4.7	22.6	-6.1	8.8	N	25	Ménard and Rochette, 1992
48	45	6.1	25-23	58	3.5	61.5	3.9	24.2	-1.5	7.3	N	25	(a)
49	44.7	6.6	30-25	76	142	-57	8	44	-44.0	11.8	Y	25	Thomas <i>et al.</i> , 1999
50	44.5	6.8	Lower Oligocene	85	121	-52	11	17	-64.0	14.6	Y	30	Collombet, 2001
51	44.1	7.6	Lower Oligocene	58	72	-48	15	20	-113.0	18.3	Y	30	Collombet, 2001
52	46.3	8.8	25-12.	8/102	331.7	59.5	7.8	51.9	-32.3	12.7	Y	20	Heller, 1980
53	45.5	7.8	post 30	2/34	338.7	55.7	25.4	98.6	-27.3	39.2	N	post 25	Lanza, 1984
54	45.8	8.9	Eocene	2/32	338.5	34.1	5.3	24.3	-27.5	5.3	Y	post 30	Dallanave and Muttoni, 2007
55	44.67	6.67	Eocene ?	8	147	-32	14	16.7	-39.0	13.2	Y	30	Roche and Westphal, 1969

The rotation is calculated after Demarest (1983) taking into account the age of magnetization and the corresponding Torsvik *et al.* (2012) synthetic APWP reference.

inclinations (D, I) with the associated confidence cone ($\alpha 95$), at the center of our zone (45N and 7E) from 50 to 0 Ma, calculated according to Besse and Courtillot (2002), Schettino and Scotese (2005) and Torsvik *et al.*, (2012). The difference in calculated expected declination is less than 5°. This value is usually below the confidence cone, therefore using either of the references is not limiting in view of the uncertainties. Using Torsvik *et al.*, (2012), the angular deviation of directions is about 3° since 50 Ma. Thus, the magnetization's age is not critical for an attempt to retrieve small rotations. The different site positions in the selected area imply a maximum of 0.6 degrees of deviation compared to the predicted directions at its centre for an age of 30 Ma. This deviation is negligible compared to the uncertainty of the pole position (see Tab. 2).

In Table 1, the entries are sorted in four categories. Category I corresponds to primary directions with paleohorizontal. It includes mostly Tertiary sediments (3 out of 21 entries are from volcanics). Category II corresponds to secondary directions with paleohorizontal. It groups mainly pre-folding remagnetizations in sedimentary cover. Category III corresponds to primary directions without paleohorizontal. It includes mainly tertiary intrusive rocks. Category IV corresponds to secondary directions without paleohorizontal. It groups mainly metamorphic rocks, even if in some cases the bedding can be retrieved, as the folding may predate magnetization.

Each data is associated to the classical parameters (Fisher, 1953; Demarest, 1983): site number N (or sample number: n if only one site), declination: D, inclination: I, confidence angle: $\alpha 95$, predicted rotation (R) and associated error (dR), and age of the used pole (age-R). These rotations are represented at their site location on Figure 1 using a simple qualitative representation according to the nature of remanence. The uncertainty (dR) is indicated by a pie slice with an opening equal to two dR.

In a collision zone, the rigid body plate tectonics scheme should be taken with care, so that the map of paleomagnetic rotations (Fig. 1) must not be interpreted in a rigid way. Several studies show large variations of block rotations within the same formation due to differential transport of thrust units (*e.g.*, Muttoni *et al.*, 2000). As our aim is to delineate regional block rotations we provide regional mean direction by averaging at least 4 localities when available. This calculation is performed mainly using the regional structural pattern and the type of study (*i.e.* mostly one study = one reference even if several sites are described). We used also magnetostratigraphic studies, based on one or two sections, and some regional means with limited number of localities ($N < 4$) to strengthen our demonstration.

Two criteria have been used to categorize the dataset: (1) primary or secondary magnetizations, both combined with (2) the knowledge of a paleohorizontal at the time of magnetization is referenced or not. Then four categories (labelled I to IV, see Tab. 1) are defined. Category I is the ideal one as it contains primary magnetization with bedding attitude, which in principle concerns sedimentary and volcanic studies. However, the number of flows necessary to average out paleosecular variation (PSV), several tens at least (see Rochette *et al.*, 1993 where 30 sites still do not average PSV), is never achieved in the studied area. Therefore, the scarce available volcanic data is discarded in our analysis,

Table 2. Predicted directions at 45N and 7E for stable Europe *versus* time. A: Synthetic APWP (Besse and Courtillot, 2002), B: APWP results from post-filtering process and spline regression analysis (Schettino and Scotese, 2005) and C: APWP from Torsvik *et al.* (2012).

A					
Expected direction 2002 “Synthétique” APWP					
Age in Ma	Dec	Inc	a95	dDec	dInc
0	0.6	60.7	2.0	4.0	2.6
5	1.3	60.5	1.7	3.5	2.2
10	3.4	59.8	2.1	4.1	2.7
15	4.0	59.2	2.1	4.2	2.9
20	6.6	57.3	3.1	5.7	4.2
25	4.5	59.0	3.5	6.9	4.8
30	0.7	56.1	6.6	5.1	5.1
35	2.6	55.9	3.2	5.7	4.5
40	6.1	54.3	5.2	8.9	7.4
45	6.7	57.0	3.6	6.7	5.0
50	6.3	57.1	2.9	5.3	4.0
55	3.4	56.2	2.9	5.2	4.0
60	0.4	55.0	3.0	5.3	4.3
B					
Expected direction 2005					
Age in Ma	Dec	Inc	a95	dDec	dInc
0	0.5	62.8	2.6	5.6	3.3
5	0.2	62.2	2.1	4.4	2.6
10	0.2	61.5	2.6	5.4	3.4
15	0.6	60.7	3.7	7.6	4.9
20	1.0	60.0	2.8	5.6	3.7
25	1.3	59.2	7.9	15.5	10.5
30	1.5	58.5	10.5	7.4	7.4
35	1.6	57.8	4.1	7.7	5.6
40	1.7	56.9	4.1	7.6	5.7
45	1.7	56.1	3.7	6.7	5.2
50	1.7	55.4	4.2	7.4	5.9
55	1.6	54.8	5.6	9.8	8.0
60	1.6	54.4	4.2	7.2	5.9
C					
Expected direction 2012					
Age in Ma	Dec	Inc	a95	dDec	dInc
0	0.5	62.2	1.2	2.8	1.5
5	1.2	61.5	1.1	2.7	1.4
10	2.3	60.7	1.1	2.7	1.3
15	3.1	59.6	1.3	3.4	1.6
20	4.0	58.5	1.6	4.1	1.9
25	5.0	57.9	1.5	4.2	1.8
30	6.0	57.3	4.2	1.8	1.8
35	7.1	56.5	1.6	4.5	1.9
40	8.2	55.7	1.7	4.9	2.0
45	7.5	53.4	1.6	5.1	1.9
50	5.5	51.0	1.6	5.3	1.8
55	3.1	49.2	1.4	4.9	1.5
60	0.3	47.5	1.2	4.4	1.3

A: Synthetic APWP (Besse and Courtillot, 2002)

B: APWP results from post-filtering process and spline regression analysis (Schettino and Scotese, 2005)

C: APWP from Torsvik *et al.* (2012)

except the volcanic data from Northern Sardinia), synthesized by Muttoni *et al.* (1998) or the extensive work of Gattacceca *et al.* (2007), entries [14] and [16] respectively in Table 1. The category II contains mainly remagnetizations in sedimentary

fold and thrust belts. In this case, the fold test is a crucial tool and often not well documented in publications. For primary magnetization in intrusives (category III) and secondary magnetization without paleohorizontal (category IV), the lack

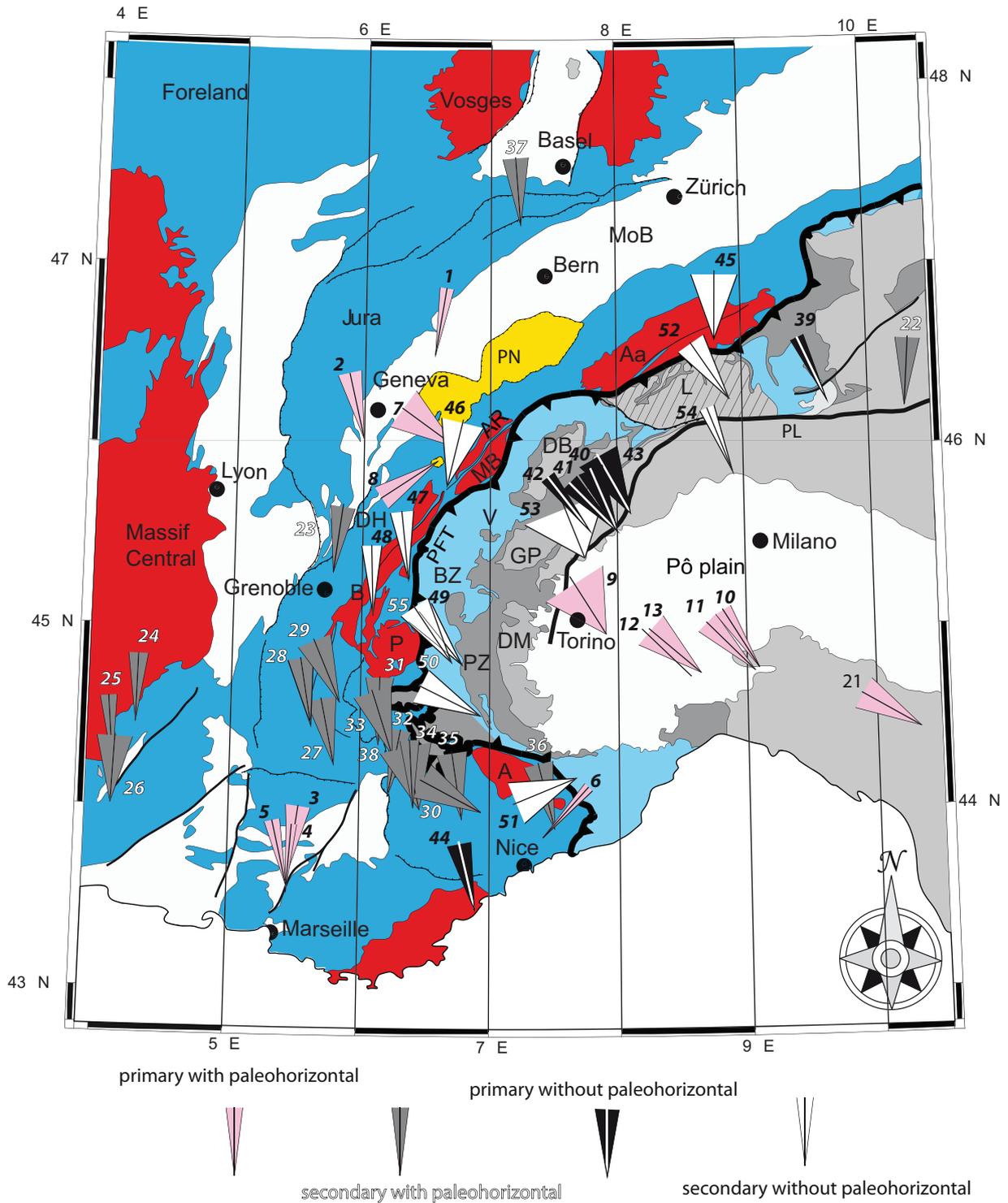


Fig. 1. Synthetic structural map of the Western Alps. Major thrust and strike slip faults are indicated, with the Penninic frontal thrust (PFT) highlighted in bold (after [Vialon *et al.*, 1989](#)). Tertiary paleomagnetic rotations *versus* north are represented according to the code described in the insert. Uncertainty is shown as a pie slice. Number corresponds to the entry in [Table 1](#). A: Argentera Massif, AR: Aar Massif, B: Belledonne crystalline Massif, BZ: Briançonnais zone, DB: Dent Blanche Massif, DH: Delphino-helvetic zone, DM: Dora Maira Massif, L: Lepontine Massif, MoB: Molasse basin, MB: Mont Blanc Massif, PL: Peri-adriatic Line, PN: Prealps Nappes, PZ: Piemontaise zone, PFT: Penninic frontal Thrust, V: Vanoise Massif.

of a paleohorizontal reference let open discussion on tectonic interpretations (*i.e.* vertical axis rotation or tilting around a horizontal axis) as it is always possible to find a tilt value and axis that fits the reference and observed directions (*e.g.*, in the Alps: Heller, 1980 [45]; Lamarche *et al.*, 1988 [48]; Ménaud and Rochette, 1992 [47], Crouzet *et al.*, 1996 [48], Rosenberg and Heller, 1997, Cairanne *et al.*, 2002; Dumont *et al.*, 2008 [48]). However, coherent tilt on a large horizontal extension is not so easy to explain as it would imply very large uplift or subsidence. Therefore, such data, if regionally coherent, cannot be dismissed.

The compiled database is detailed and discussed below, separating a) the European cover including the Subalpine massifs and the external crystalline massifs, west of the Penninic front; b) the internal Alpine units (Penninic and Austro-Alpine) plus the Piemonte basin and, c) the N Apennine and Corsica-North Sardinia sites.

3 European platform and external units

3.1 Tertiary sediments

Successful studies of Tertiary sediments are quite scarce. Kempf *et al.* (1998), as a by-product of extensive magnetostratigraphic work in the Oligo-Miocene Molasse sequence reported a small ($12.4 \pm 5.0^\circ$) although significant clockwise (CW) rotation of the Swiss Molasse basin [1]. In the southern part of the molasse basin, a seemingly contradictory counterclockwise (CCW) rotation ($-12.8 \pm 9.1^\circ$) is observed by Burbank *et al.* (1992) [2]. As Burbank *et al.*'s magnetostratigraphic study is only based on two sites, this CCW rotation may be related to local effects linked to the Vuache fault. The retrodeformation and displacement field of Affolter and Gratier (2004) performed using surface-balanced model, suggest counterclockwise rigid rotations up to 30° in the southern Internal Jura and a 10° clockwise, vertical axis rotation of the molasse basin in Switzerland. These predicted rotations are broadly consistent with those documented by paleomagnetic data. The observed paleomagnetic rotations may result from a substantial decrease in shortening at the southern Jura end, which would only reflect the deformation of detached cover.

Few sites were collected by Cardello *et al.* (2015) in Tertiary formations from the Helvetic nappes of Switzerland. As the Characteristic Remanent Magnetization (ChRM) is pre, syn or post folding, results are difficult to interpret. They represent more probably mainly local deformation linked to the Rawill depression structuration rather than a regional block rotation significance. These results are not reported in our database.

Two sites collected in Priabonian marls of the Arc de Nice massif have preserved a primary (or at less a pre-folding) remanence (Sonnette, 2012 [6]). It provides an important CW rotation of $42.0 \pm 4.4^\circ$. This important value probably reflects local effects during the polyphased deformation (Laurent *et al.*, 2000) and salt tectonic activity (Brooke-Barnett *et al.*, 2020; Célini *et al.*, 2020).

Other available data from Provence concern the lower Paleocene with a 5 to 9° insignificant clockwise rotation (Westphal and Durand, 1989; Cojan *et al.*, 2000) [3–4] and the Oligocene with $-16.5 \pm 6.0^\circ$ CCW rotation (Kechra *et al.*, 2003) [5]. Several assumptions may explain those contradictory results. (1): To explain the two previous results we have to

imagine $23.5 \pm 8.0^\circ$ CW rotation before Oligocene time and $16.5 \pm 6.0^\circ$ CCW rotation since the Oligocene. (2) Unsuspected important small scale (kilometric) rotations may affect some provençal data. While this is out of the scope of the present review, it is noticeable that the Late Cretaceous dinosaur site from Villeveyrac-Mèze Basin (Languedoc area) shows a significant vertical axis CCW rotation of about $15.1^\circ \pm 8.3^\circ$ with respect to the expected Late Cretaceous direction (Benammi *et al.*, 2006). This suggests that local block rotation is possible.

The special case of the so-called “ultra-Helvetic flysch” [7, 8] (Piquet *et al.*, 2000) will be discussed with the internal units because it comes from the Penninic klippen tectonically emplaced on the top of the Subalpine massifs.

3.2 Tertiary intrusive

The Esterel massif is mainly constituted of late Carboniferous and Permian rocks in which the only tertiary intrusive (locally named esterellite) site available over the European platform was found. The age of the esterellite rocks was initially estimated as Tertiary (Michel-Lévy, 1912), and later on subjected to controversies until an Ar/Ar dating at 31–33 Ma (Giraud, 1983; Féraud *et al.*, 1995). Early paleomagnetic study (Roche, 1957) comparing esterellite to Permian surrounding rocks, demonstrates that its direction is close to the one usually found in Tertiary and Quaternary rocks and away from those expected for a Permian magnetization. Later, the paleomagnetic study performed by Zijdeveld (1975) [44], has been revisited by Vlag *et al.* (1997), confirming the reliability of this data. A CCW rotation ($-17.6^\circ \pm 9.6^\circ$) is observed through the sampled area of several kilometre width. Therefore, tilting around horizontal axis is unlikely.

3.3 Remagnetized sediments

Several paleomagnetic studies conducted in the Mesozoic blue grey marls and limestones of the Alpine European margin have revealed a normal pre-folding remagnetization, carried by magnetite or pyrrhotite. The consistent normal polarity observed in rocks from Liassic to Cretaceous ages, together with the high inclination, definitely exclude that the observed directions are primary. It is tempting to assign this remagnetization to the long normal Cretaceous superchron as suggested by Katz *et al.* (1998 and 2000 [28]), but this would lead to a clockwise rotation of the obviously undeformed Massif Central sedimentary cover and a discrepancy in inclination. The southern sites: Cévennes [25–26] (Henry *et al.*, 2001; Kechra *et al.*, 2003) and Ventoux [27] (Kechra *et al.*, 2003), have been folded during the Upper Eocene Pyrenean phase (see Bilotte and Canerot, 2006; Peybernès *et al.*, 2007, for the age of the deformation) while the northern sites in the Subalpine massifs of Vercors and Chartreuse [23], showing positive fold tests (Aubourg and Rochette, 1992), have been folded during Miocene (Gidon, 1981). Assuming that magnetization reported by Aubourg and Rochette (1992) is a Tertiary remagnetization, it leads to an insignificant clockwise rotation [23].

The early synfolding nature of the remagnetization in Provence and Cevennes led Kechra *et al.* (2003) to propose a

Pyrenean age (40 Ma) for the widespread remagnetization of all these rocks. Although the northern part of the area remained undeformed, this age corresponds to the onset of collision, final marine retreat and uplift of the area and may have sufficiently modified the fluid-rock equilibrium condition to provoke crystallization of new magnetic grains at the expense of pre-existing iron rich grains. The corresponding chemical remanent magnetization (ChRM) would be acquired on a time span of the order of 1 Ma, thus recording the average polarity of the geomagnetic field. As this polarity appears normal during 80% of the time in between 42 and 38 Ma, the unique polarity of the remagnetization is not contradictory with the presence of several reversals in that time span. Whether this widespread remagnetization is linked to large scale orogenic fluid movements (D'Agrella-Filho *et al.*, 2000; Elmore *et al.*, 2006; Kim *et al.*, 2009) or to interaction with the *in situ* fluids remains to be discussed, although the second explanation seems more likely in the present context. On the other hand, the burial remagnetization invoked by Katz *et al.* (1998, 2000) is clearly excluded as a general mechanism as very little burial have affected the Jura or Massif Central sites compared to their Vocontian trough sites [28]. The Berrias case (Galbrun, 1985 [24a/b]) is special in the sense that it has been claimed as representing a primary lower Cretaceous magnetostratigraphic signal. However, the normal polarity mean direction perfectly fits the predicted Tertiary field and failed the reversal test with the reversed polarity direction (Tab. 1 – 24a/b) which is more in agreement with the Cretaceous age of the rocks. Therefore, we propose that the normal polarity samples (indeed coming from more reduced limestone layers than the reversed sandy layers) of the Berrias study are remagnetized, thus implying that the proposed magnetostratigraphy is not significant.

Many sites collected from the southern Subalpine chains exhibit syn-folding remagnetization (Cairanne, 2004; Sonnette, 2012). All these syn-folding sites are discarded from this study. Indeed, the superposition of 2 or 3 deformation phases forbids any hope of finding an original direction using only a tilting to restore the bedding back to the horizontal.

The study carried out on the sedimentary cover of the Barrot dome (Sonnette *et al.*, 2014; [30]) suggests a secondary magnetization acquired during or after folding. Its directional analyse shows an apparent large CCW rotation ($65.1^\circ \pm 15.0^\circ$). As the Permian substratum recorded no rotation (Bogdanoff and Schott, 1977), the rotation is mainly accommodated by the cover–substratum decoupling on the sliding of the Triassic gypsum décollement layer. This large rotation is therefore not representative of crustal bloc motion.

Cairanne in his PhD (2004) studied the remagnetization in several areas of the southern Subalpine massifs. In two sectors, (Esparon [31] and Gaubert [32]), the fold test is negative. As Pliocene strata are folded (Gidon and Pairis, 1992), the remagnetization is younger than 10 Ma. Similar results are observed for the Bès area [33] and the Barrême anticline [34] where Oligocene strata are folded. It implies that remagnetization is younger than 23 Ma. In the Subalpine Arc de Castellane and Arc de Nice, post folding remagnetization occurred in few areas (Sonnette, 2012). As the last folding event occurred during Miocene (Dardeau, 1988; Laurent *et al.*, 2000; Giannerini *et al.*, 2011), a significant rotation is observed in Arc de Nice ($13.1^\circ \pm 12.2^\circ$ [36]), while in Arc de Castellane insignificant CCW rotation ($7.2^\circ \pm 12.7^\circ$ [35]) occurred.

The northern sites in Jura Mountains [37] present a post folding (*i.e.* Miocene) remagnetization associated to alteration of primary pyrite and magnetite (Johnson *et al.*, 1984). This remagnetization presents no significant rotation ($-3.2^\circ \pm 10.5^\circ$).

3.4 Remagnetization without paleohorizontal constrain

Finally, several remagnetized crystalline or metamorphic units are reported in this section, even if in some cases bedding can be retrieved. Indeed, the ChRM is assumed to be of thermo-chemical origin and acquired during the metamorphism of the metamorphic units. The Aar Massif data [45] show small but consistent rotations that could be explained by a tilting. However, the coherent rotation of the Aar and Swiss molasse data are in favour of a vertical axis clockwise rotation. The directions of the entries in the Eastern Dauphinois area ([46, 47, 48] Tab. 1) have been calculated using all the published directions separated in three areas spreading in N-S over more than 100 km. Then even if some sites are tilted around horizontal axis (see Ménard and Rochette, 1992; Crouzet *et al.*, 1996; Dumont *et al.*, 2008), the regional mean could be considered reliable for a regional scale rotation around vertical axis discussion.

All the units, west of the Penninic front, yield small or unresolved rotations. The exception of the Digne nappe (Aubourg and Chabert-Pelline 1999 [38]) showing a significant departure from the expected direction (CCW rotation = $17.6^\circ \pm 22.2^\circ$) can be explained by rotation during thrusting and nappe emplacement. This was suggested by several authors such as Sonnette *et al.* (2014).

If we except the entries with probable local block rotation (*ie.*: 2, 3, 4, 38), and those close to the central part of the Alps (*i.e.*, longitude > 7°) where the E-W structures become linear, we observe that CW rotations are mainly present north of Grenoble, while CCW rotations concentrate to the south (Fig. 2A). Plotting rotation *vs.* latitude (Fig. 2A) suggests a visual trend from clockwise rotation in the North to a counterclockwise rotation in the South. We must notice that this trend is determined by a linear regression with a very low coefficient of determination ($R^2 \sim 0.26$) that imply it is not statistically significant. So instead of a trend one may identify two different rotation regimes north and south of latitude 45. The data from Cevennes, which are assumed to be on the stable European platform and the data with evidence of local rotation are not included in the trend, nor in the oroclinal test (Fig. 2B). In order to have a more classical view of the paleomagnetic data, the usual oroclinal test was performed using Paleomagnetism.org2 software online (Koymans *et al.*, 2016; Pastor-Galán *et al.*, 2017). It uses bootstrapped linear regressive techniques to determine the relationship between strike of geological structures and rotation. The result indicate a coefficient of determination $R^2=0.377$ and a Pearson coefficient $\tilde{I}=0.614$ suggesting respectively a trend and a high correlation. Notice that rotations are small or unresolved and that the oroclinal fold test indicate a best grouping between 6 and 17% of unfolding. This point suggests that bending has few impact on rotations. The conclusion is that whatever is the tectonic mechanism that produce the arcuate shape of the Subalpine massifs, paleomagnetic data does not evidenced similar shape.

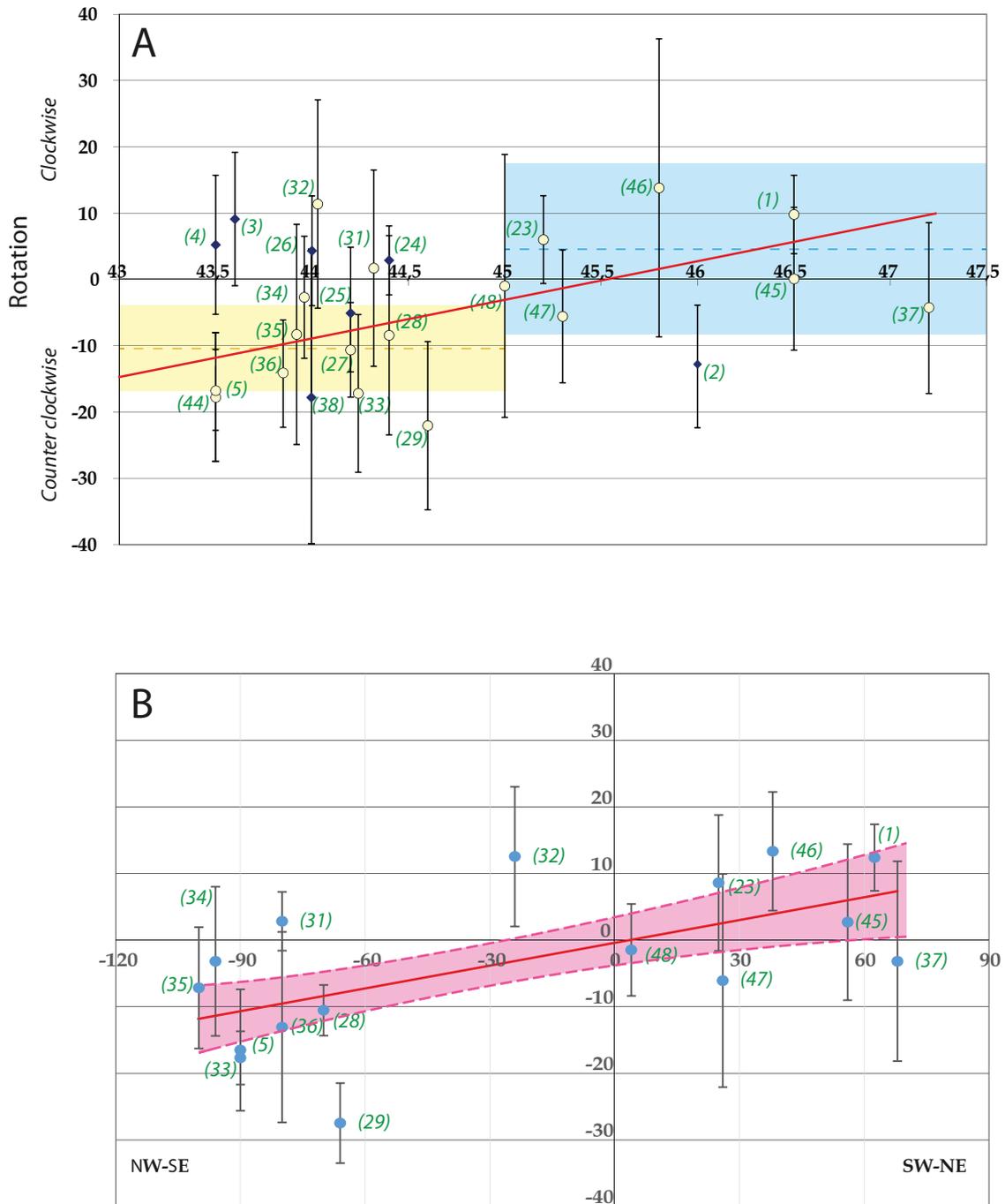


Fig. 2. A- Rotation *versus* latitude for the External zones of the western Alps. An apparent N-S trend of rotation is highlighted by the regression line calculated excluding possible local rotations ($R^2 \sim 0.26$). Full dots: probable local rotations (see discussion in the text). Numbers in brackets correspond to entries in Table 1. Rotations calculated south (yellow) and north (blue) of 45° latitude are indicated. In the South counter clockwise rotation for an age of 25 (10) Ma is $10.3^\circ + -6.4^\circ$ ($7.6^\circ + -5.9^\circ$). In the North, insignificant rotation for an age of 25 (10) Ma is observed: $4.5^\circ + -12.8^\circ$ ($7.2^\circ + -12.6^\circ$). B- Oroclinal test (rotation *versus* strike of the fold axis) for the Subalpine Massifs. The red line shows the total least squares regression for the data. The surrounding shaded pink area illustrates the confidence interval for 1000 bootstrapped regressions.

4 Alpine internal units: the Briançonnais block and the Piemonte – ligurian areas

There is little hope to retrieve primary magnetization in sedimentary rocks from the metamorphic internal belt due to strong deformation and metamorphism. Also, without fold test these data must be taken with great caution. As an example, the Permian paleomagnetic direction from the Guil valley (Roche and Westphal, 1969 [55]) are quite close to those from the Amonitico Rosso from the same area (Thomas *et al.*, 1999 [49]). Also, the 8 sites of Roche and Westphal (1969) are all of reverse polarity. Therefore, we assume that the direction of Roche and Westphal (1969) is more likely representative of an Eocene remagnetization than a primary magnetization.

4.1 Tertiary sediments

In the present database, all the reported primary directions in sedimentary rocks are from the unmetamorphosed and slightly deformed Tertiary Piemonte Basin [9 to 13] (Vandenberg, 1979; Thio, 1988; Bormioli and Lanza, 1995; Carrapa *et al.*, 2003 and Maffione *et al.*, 2008) or from the Ultra Helvetic Flysch (Piquet *et al.*, 2000) [7–8]. As important rotations occurred during sedimentation (see below), we will only use the oldest sediments (*i.e.* Oligocene to lower Miocene) in order to not bias the total global rotation. Bormioli and Lanza (1995) who studied the Monferrato and Torino Hills (the northern outcrops of the Apennine block) have concluded that their data are showing a ca $32^\circ \pm 29^\circ$ CCW rotation [9]. This conclusion is only based on the result from 2 sites over 17 studied. From the 17 sites, 6 gives scatter results, 7 presents directions close to the present day expected direction, 2 showing 100° CCW rotation are interpreted as local block rotations and 2 showing ca 32° rotation are compared to the rotation of the Adriatic block. Besides, the age of the sediments ranges from Burdigalian to Seravallian and the primary character of ChRM is not well evidenced. Therefore, the data from Bormioli and Lanza (1995) should not be considered regionally significant until a new study is performed on this key area.

Surprisingly, the other paleomagnetic results [10 to 13] exhibit an important and very similar CCW rotation (44 to 54°). Using different strata, Carrapa *et al.* (2003) and Maffione *et al.* (2008) were able to demonstrate that most of the rotation occurred between 23 and 13 Ma. Preliminary results from Vandenberg (1979) [10] have to be discussed in the light of other published data. The late Eocene to early Oligocene data present a CCW of $32^\circ \pm 8^\circ$ while Early Miocene data present a CW of $9^\circ \pm 10^\circ$. One can argue that the CW rotation is not significant, but it may also be a local effect as Vandenberg's work is only based on one site. If we apply to the Eocene-Oligocene the local CW deduced from the lower Miocene direction, we can argue for a ca 40° CCW, *i.e.* the same magnitude than in the data from Maffione *et al.* (2008), Carrapa *et al.* (2003) and Thio (1988).

The Eocene-Oligocene Ultrahelvetic flysch from the Prealps nappes exhibits a primary or pre-tilting remanence [7–8] (Piquet *et al.*, 2000) showing important CCW rotations ($54^\circ \pm 19^\circ$ and $123^\circ \pm 11^\circ$ for Dérochoir and Marais area respectively). As the different areas (Dérochoir and Marais)

are not in the same klippe and as they underwent different amount of rotation, they have been separated in the database. These rotations cannot have occurred after the nappe emplacement over the Subalpine massifs because the latter do not rotate more than few degrees. In the Prealpine nappes, the rotations may have occurred before emplacement for [7] and complicated during emplacement [8] as the structural data orientation are similar with the Penninic units and the rotations largely differ from the Subalpine massifs.

4.2 Tertiary intrusives

From the deformed units, only five studies with primary directions are available on the Eastern side of the Penninic front, all of which lacking a full paleohorizontal reference but consistently pointing toward large CCW rotations. A few primary Oligocene directions have been reported from the Bergell [39] and Traversella [42] intrusions (Heller, 1980; Lanza, 1984 respectively), and from andesitic dikes and flows in the Sesia zone (Lanza, 1977 and 1979) [40–41] and in the Biella zone (Bigioggero *et al.*, 1981) [43]. In several cases a tilt correction has been made assuming that the dikes were initially vertical (Lanza, 1977). However, this assumption may not be correct, thus explaining why these data are listed in category III and not I. Except the data from the Bergell massif, the others present low (30 to 40°) to very low (0 – 10°) inclination. This has been explained by a rotation around a N20 horizontal axis (*i.e.* tilting) of about 60° (Schmid *et al.*, 1989). Using such tilting leads to avoid rotation (around vertical axis). Also, in order to explain the data, an infinite number of solutions can be produced by combining tilting and rotation. In the case of the Western Alps, it must be mentioned that 2 sites from the Traversella intrusion [53] are carrying a secondary component with no inclination anomaly and showing a CCW rotation of about $22^\circ \pm 39^\circ$ (Lanza, 1984). If we take into account this quite poorly constrained data, the CCW rotation from the Sesia zone discussed above must be younger than the tilting.

The Tertiary ChRM reported from the Adamello contact aureole (Kipfer and Heller, 1988) [22] was probably acquired during the post intrusion cooling and deformation that occurred in between 42 and 30 Ma (Pennacchioni *et al.*, 2006). Therefore, and according to the surrounding data, it is quite surprising that this ChRM presents a direction close to the present day expected direction. There we suspect a recent remagnetization and discard these data.

4.3 Remagnetized rocks

Among category IV, the Briançonnais data [49] have also been “untilted”, not based on stratigraphic bedding (the fold test is negative) but on the reconstitution of tilted block formed in a late extensional phase, post-dating the remagnetization (Thomas *et al.*, 1999). Associated with data from Ubaye [50] and Liguria [51], the large rotation inferred is well defined and again not possible to explain by coherent tiltings (Collombet, 2001). The age of the remagnetization is unclear but most probably corresponds to the end of the major synmetamorphic deformation phase during the Oligocene. The strong rotation of the post-metamorphic magnetization of the Lepontine zone (Heller, 1980) [52] has been reinterpreted as an effect of tilting

(Rosenberg and Heller, 1997). This point of view is not consistent with the secondary directions reported by Lanza (1984) in the Traversella intrusion [53]. Moreover, the Triassic section from Besano Monte San Giorgio in the Dolomites massif [54] shows a consistent post-folding ChRM interpreted as due to thermo-chemical remagnetization during Eocene time (Dallanave and Muttoni, 2007). It presents a CCW rotation ($22^\circ \pm 7^\circ$) very similar to the one reported for the Traversella intrusion. Therefore, the coherency between rotations within Lepontine area and rotations from the surrounding area reinforced the original vertical axis interpretation of Heller (1980).

5 The Apennine and Corsica-North Sardinia paradox

The Italian peninsula and the Corsica-Sardinia paleomagnetic data will not be discussed at full length as its complex rotational history was clearly exposed by several papers (see discussion and references in Siravo *et al.*, 2023 and in Maffione *et al.*, 2008). In this section, we would like to point out some paleomagnetic data that appear to be important in the Alpine scheme of block rotations.

The Early to middle Miocene sediments from the Epiligurian sites (Muttoni *et al.*, 1998) [21] show a $\sim 61^\circ \pm 14^\circ$ CCW rotation *versus* stable Europe. This value is in the same magnitude than the one from the Tertiary Piedmont Basin ($55^\circ \pm 16^\circ$ CCW). The northern Apennine data from Speranza *et al.* (1997) and Lanci and Wezel (1995) show a post-Miocene CCW of $\sim 27^\circ$ (vs stable Europe). This may imply, if we consider North Apennine and Epiligurian as a rigid bloc, that it underwent half of the total rotation ($\sim 30^\circ$ CCW) during only the upper Miocene.

The age of the Corsica – North Sardinia rotation is now well defined (see Edel *et al.* (2001), Gattacceca *et al.* (2007) and Siravo *et al.* (2023) for discussion). Most of the 45° CCW rotation occurred between 21.0 and 17.5 Ma. Only less than 10° remain until 15 Ma. The 60° CCW rotation reported by Siravo *et al.* (2023) for Corsica – North Sardinia is mainly deduced from Permian volcanics and these data are therefore excluded from our study.

The magnetization from the Middle Miocene sediments of the St Florent Basin (Vigliotti and Kent, 1990) show antipodal directions [17]. As the fold test is negative, the authors claim for a secondary remanence ($D=9.8$; $I=62.8$; $\alpha_{95}=6.6$; $k=192$). But as the number of sites is limited ($N=4$), we can suspect the accuracy of the fold test and if we assume a primary remanence ($D=342.6$; $I=47.0$; $\alpha_{95}=9.3$; $k=99$), it gives a consistent CCW rotation of $21^\circ \pm 11^\circ$, very similar to the one deduced from pyroclastites of Bonifacio area [19] (Ferrandini *et al.*, 2003). But due to low number of flows, we can doubt that secular variations are averaged. Also Vigliotti and Kent (1990), report a post 40 Ma CCW rotation of $37^\circ \pm 6^\circ$ [18] based only on one site. Confirmation of the large ($44^\circ \pm 6^\circ$) post 25 Ma CCW rotation of Corsica, previously inferred only from Permian data and continuity with Sardinia came from only one site [20]. Therefore, it can also be interpreted as a local rotation.

The amount of Tertiary rotation of the Corsica-North Sardinia block has been a long-lasting debate. The study of Gattacceca *et al.* (2007) based on numerous and precisely date

lava flows, conclude for a ca 45° CCW rotation for North Sardinia. For Corsica, the debate is still open as the data of Vigliotti and Kent (1990) $\sim 34^\circ$ CCW and of Ferrandini *et al.* (2003) $\sim 44^\circ$ CCW rotation are only based on few sites. It must be noticed that South Sardinia was submitted to $86^\circ \pm 7^\circ$ CCW rotation (Siravo *et al.*, 2023).

6 Discussion on tectonic consequences

The post Eocene rotations depicted on Figure 1 delineate block domains with rotations of variable sense and amplitude whose limits do not follow the classical African-European plate boundary. These blocks can be regarded as microplates delimited by major crustal tectonic discontinuities. Following several analogue modelling (Collombet, 2001; Martinod *et al.*, 2024) the block rotations should mainly be driven by lithospheric processes such as subduction and consecutive slab break-off. The size, origin and thickness of these blocks is a question that is not currently solved.

In front of the Alpine wedge, the non-metamorphosed subalpine massifs and the molassic basin show small to unresolved rotations. Also, even when rotations are significant, they come from sedimentary cover usually detached from their crustal basement. The general decoupling of the sedimentary cover from the basement was first suspected by Gidon (1956), and since the advent of balanced geological sections and the ECORS seismic profile has been widely adopted (Gratier *et al.*, 1989; Guellec *et al.*, 1990; Mosar, 1999). Nevertheless, looking at sites located south of 45° latitude (with NW-SE orientation of main geological structures), a small but significant counter-clockwise rotation is observed. Its amount is respectively $-10.3 \pm 6.4^\circ$ and $-7.6 \pm 5.9^\circ$ for a magnetization age of 25 Ma and 10 Ma (Fig. 2A). On the other hand, looking at sites located north of 45° latitude (with NE-SW orientation of main geological structures), no significant rotation is observed. Keeping these points in mind, the more external European basement slices and cover may be transported without rotation (case of Belledonne and central subalpine massifs) or subject to a wrenching and lateral escape or a partial dragging. The first mechanism is suggested if we consider that no significant rotations are evidenced on the European part of the belt. The other mechanism may also be taken into account in order to explain the rotational pattern evidenced in the southern subalpine massifs and in the Provence area. Such mechanisms are compatible with the punching of the European margin by an "Apulian" (or Padanian) block rotating while moving towards the W or NW. A complete review on kinematic models can be found in Brunsmann *et al.* (2024). Whatever the mechanism is, the rotations are small.

Lateral escape of the Provence area may be facilitated by the opening of the Provencal basin, which started in the Oligocene, even if the main Corsica-Sardinia rotation is limited to the lower Miocene. A remaining compatibility problem concerns the possible rotation of Provence with respect to its western border. It can be solved assuming that the rotation is mainly of Oligocene age. Indeed, this period is characterised in the area by huge triangular semi-grabens that indicated a strong southward gradient of extension (Benedicto, 1996). Conversely, 3D balanced cross sections (Gratier *et al.*, 1989) imply an eastward gradient of shortening with the right rotation angle. If this shortening is synchronous with basin

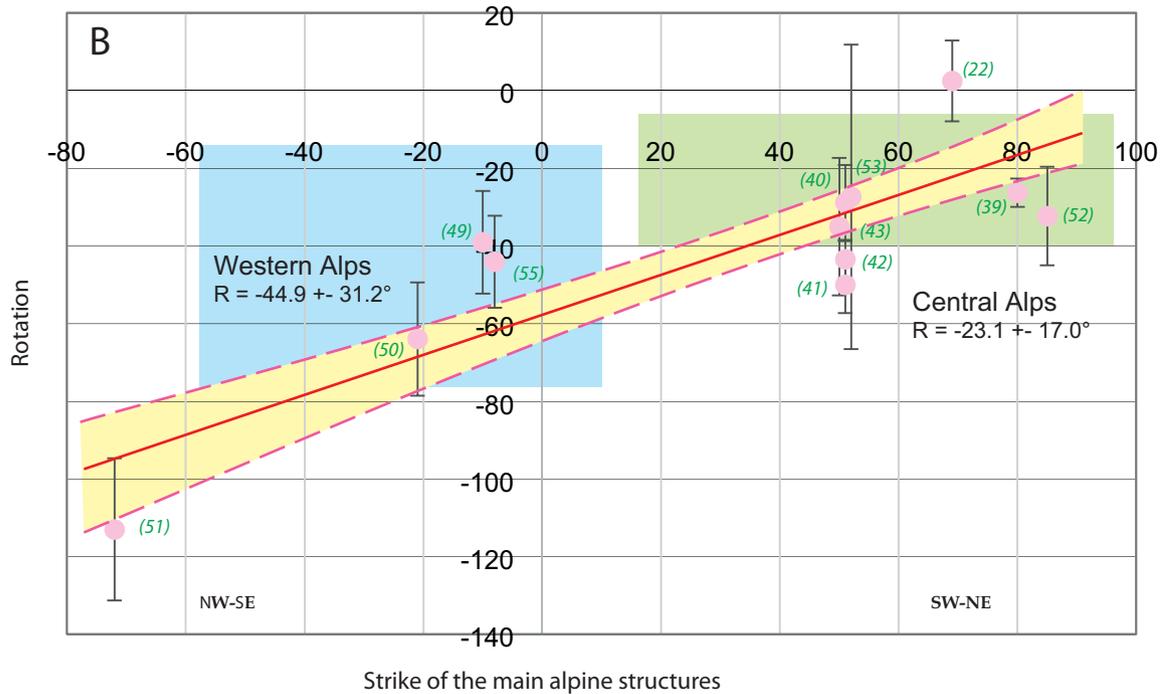
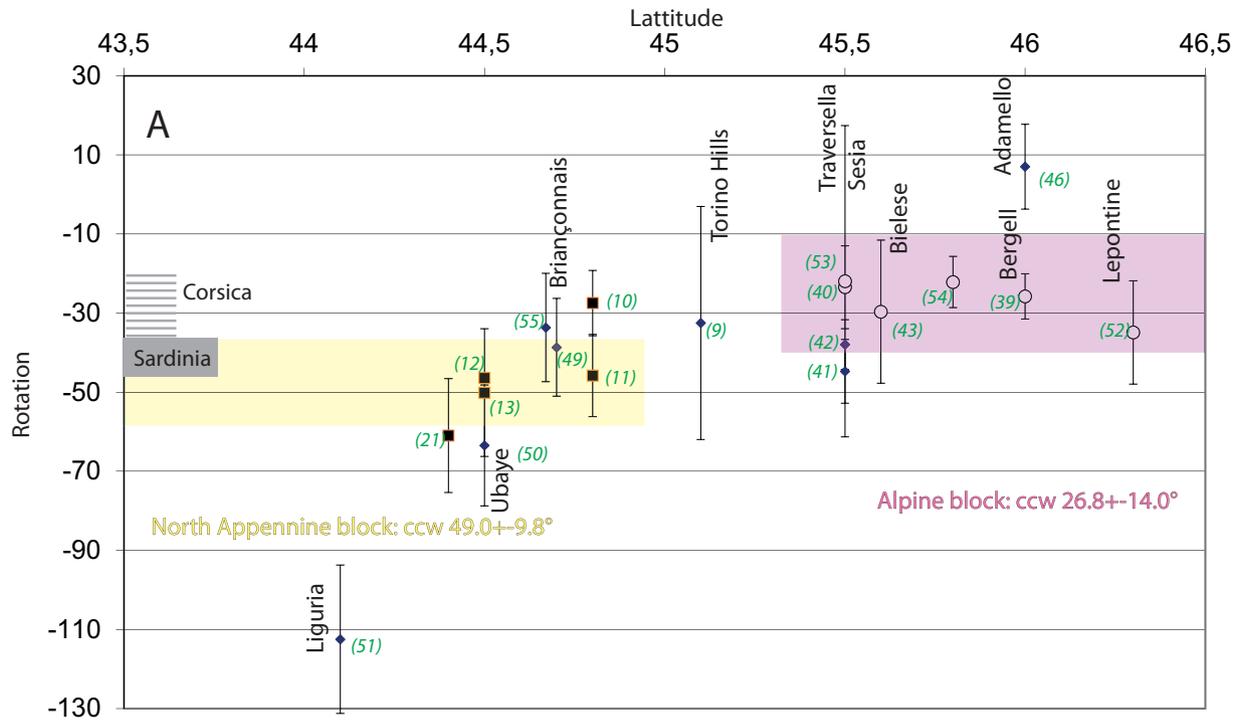


Fig. 3. A- Rotation *versus* latitude for the Internal zones and Piemont area; Full square: data used for calculation of “N Apennine block” rotation. Open circle: data used for calculation of “Alpine block” rotation. Amount of rotation for Corsica and Sardinia is graphically indicated on the left of the graph. B- Oroclinal test (rotation *versus* strike of the main alpine structures) for the Internal zones. The red line shows the total least squares regression for the data. The surrounding shaded yellow area illustrates the confidence interval for 1000 bootstrapped regressions. Rotations of the Western Alps in blue ($-44.9 \pm 31.2^\circ$) and the Central Alps in green ($-23.1 \pm 17.0^\circ$) are indicated.

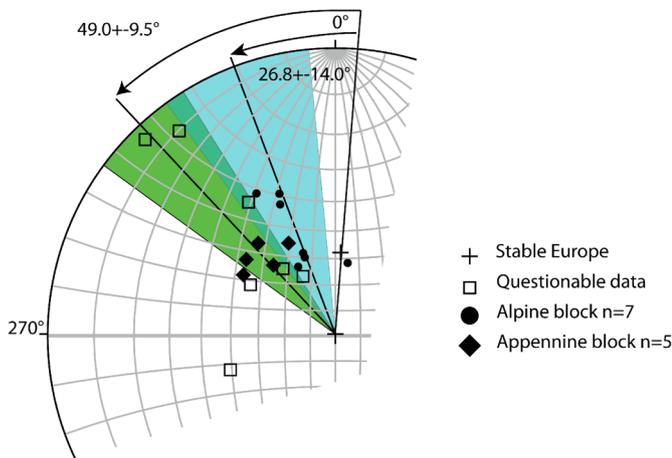


Fig. 4. Stereoplot of paleomagnetic data north (open circle) and south (closed square) of the Pôplain. Means are also indicated.

extension, all limits of the rotating Provençal zone are accounted for.

A large zone of important (25 to 50°, Figs. 3 and 4) CCW rotation appears, involving the internal units of the Alps (including the Prealps klippen) and the Piemonte basin. The Periadriatic line separates two blocs of different amount of rotation (Fig. 1). As previously underlined by Schmid *et al.* (1989) this post-Oligocene deformation results from dextral motion.

The oroclinal test performed using paleomagnetic data from the internal Alps (Fig. 3B) indicates a coefficient of determination $R^2=0.671$ and a Pearson coefficient $\bar{I}=0.819$ suggesting a high correlation. These statistical parameters are strongly influenced by the rotation of the Ligurian site ([51] – Collombet *et al.*, 2001). By not using this site, $R^2=0.389$ and $\bar{I}=0.624$. The rotation calculated from the Central Alps (CCW $23.1 \pm 17.0^\circ$) is not significantly different from the one calculated for the Western Alps (CCW $44.9 \pm 31.2^\circ$).

These rotations are denied by Brunsmann (2023). In order to explain the arcuate shape of the belt, this author invokes a proto-arc inherited from the subduction period. The existence of such a proto-arc is also supported by restoration of collisional shortening around the arc (Bellahsen *et al.*, 2014; Rosenberg *et al.*, 2021).

In the context of the rotations highlighted by the present study, the Corsica-North Sardinia block can also be fitted with the mainland scheme. According to Siravo *et al.* (2023), the Corsica – North Sardinia block was submitted to $\sim 60^\circ$ CCW rotation since possibly starting close to the Eocene/Oligocene boundary (~ 34 Ma). According to Gattacceca *et al.* (2007), between 20.5 and 15 Ma the Corsica – North Sardinia block rotated $\sim 45^\circ$ counterclockwise with respect to stable Europe, around a pole located north of Corsica. This implies that a rotation of $\sim 15^\circ$ occurred during the Oligocene phase of rifting. Similar amount and age of rotation for Corsica – North Sardinia block and Appennine – Tertiary Piemonte Basin block (ca 45–50° CCW and 22 to 17 Ma) suggests that all the domain moves simultaneously together (Maffione *et al.*, 2008).

We can also add the Penninic area to this highly rotated domain. However different results, found in allochthonous cover units, do not mean that the underlying Apulian lithosphere did not rotate as a whole. The proposed generalized rotation is also compatible with the study of Thöny *et al.* (2006) in the central and eastern Alps.

These strongly rotated units are separated from the less to non-rotated units by the Penninic front in the North, implying about 100 km of right-lateral strike slip movement on this major structure. In the South, the limit should be placed in the Ligurian basin. The Eastward limit of the rotated block is still controversial (Thöny *et al.*, 2006). It must be noticed that the amount of rotation is different on both sides of the Po plain (Fig. 3): $26.8 \pm 14^\circ$ in the North ("Alpine bloc": Dec = 339.3, Inc = 48.6, $\alpha 95 = 11.6$, N=7) and $49.0 \pm 9.5^\circ$ in the South ("North Apennine bloc": Dec = 317.0, Inc = 48.9, $\alpha 95 = 7.8$, N=5). The paleolatitudes deduced from the inclination of the unquestionable data of the two blocks are close to $29\text{--}30^\circ$ N. It can be deduced a N-S displacement of these blocs of about 1700 ± 400 km since the time of remanence acquisition (mainly since upper Oligocene). Assuming an Oligocene magnetization age and comparing to the Oligocene expected direction for stable Europe a difference of about 10° is observable. While the difference does not exceed the confidence cone, it may suggest a minimal N-S shortening across the Alps of ca 500 km since the Oligocene, compatible with the Schmid *et al.* (1996) view. These results also imply that the Monferrato-Torino Hills north verging thrust is a major structure accommodating the differential rotation between a "Liguria – Corsica – North Sardinia" block and a "Southern Alpine" block. This point was already raised by Vandenberg and Wonders (1976) from the study of Mesozoic primary remanences in Tuscany and Southern Alps. It is also well established according to several plate-tectonic reconstructions (Handy *et al.*, 2010). The eastward prolongation of this major fault zone, now buried under a thick Late Tertiary to Quaternary sedimentary cover, is probably in connection with the north Apennine frontal thrust. This is also in very good agreement with the paleomagnetic data from the Colli Euganei (Soffel, 1972) exhibiting a ca 55° CCW rotation between the Eocene and the Miocene. In the opposite direction, the differential motion between the two blocks (Alpine and North Apennine) may be transferred into the Ligurian basin where the Alpine block disappears.

According to Stampfli *et al.* (1998), incorporation of the Briançonnais terrane in the accretionary prism is diachronous from East ($\sim 50\text{--}45$ Ma) to West ($\sim 37\text{--}34$ Ma). The final stages of the continental collision between the European and Adriatic continental margins were accomplished by $\sim 35\text{--}32$ Ma (e.g., Berger and Bousquet, 2008; Stampfli and Hochard, 2009; Handy *et al.*, 2010). At this time, the Penninic units underwent a HP or UHP metamorphism (Rosenbaum and Lister, 2005). Also at ca 30 Ma, a thickened crustal bridge was already built up across the European-African suture (Jolivet and Faccenna, 2000) and a similar rotation of both sides can be supported. This rotation may have occurred synchronously with the rotation of the Corsica – North Sardinia block in between 22 and 17 Ma as suggested by Maffione *et al.* (2008) or partly accommodated during Oligocene. The synchronism of all these rotations is still matter of debate as the crustal blocks involved are probably not

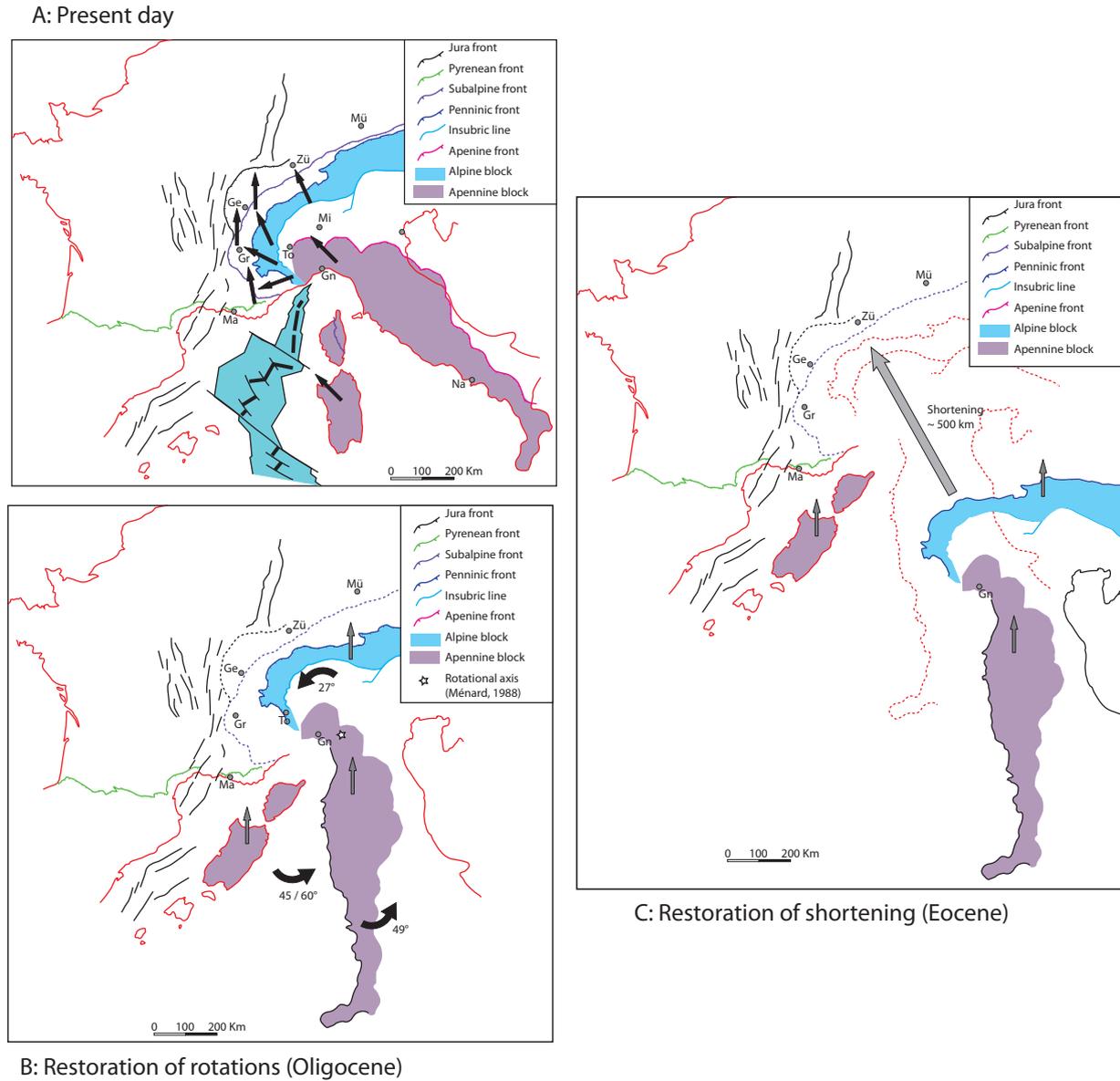


Fig. 5. Schematic maps explaining the alpine rotations and showing – A: the present day situation. The main observed rotations are indicated. Restoration – B: Syn to Post Oligocene rotations and – C: the Eocene shortening. The drawing of the Italian peninsula in the Eocene clearly does not represent the situation at that time as the Apennine develop and deform during and after this period.

the same. In this context, the very large rotations from the southern Briançonnais [51–52] have to be explained. We suggest following [Collombet *et al.* \(2002\)](#) and [Ford *et al.* \(2006\)](#) a late Miocene sinistral transpressive shear zone located north of the Argentera massif. This shear zone accommodates the excess rotation of 25 to 60° compared to the Penninic – North Liguria – Corsica – North Sardinia blocs (who rotate only 40–60°). This implies the punching of the European margin by a block moving toward NW that may also explain the observed rotation pattern of the external zones.

Another speculative interpretation resides in the assumption that the southern Briançonnais was subjected to successive CCW rotations. The first one, documented north of the Po plain (25 to

30° CCW) occurring during Oligocene. Then this area is incorporated to the southern block and subjected to a second CCW rotation of ca 50° during lower Miocene. The remaining rotation (ca 30°) may be explained by local tectonic displacements.

Between metamorphism and intrusion emplacement and the occurrence of rotation, a major tectonic event must have occurred in order to explain the horizontal axis tilting observed in several data with low to very low inclination (40, 41, 42 and 43 in [Tab. 1](#)) as already suggested by several authors ([Schmid *et al.*, \(1989\)](#), [Rosenberg and Heller \(1997\)](#)). According to secondary magnetization in the Traversella intrusion [53], this tilting around horizontal axis is followed by 25–30° CCW rotation ([Fig. 5](#)).

7 Conclusions

Based on the present synthesis of paleomagnetic rotations since 40 Ma in the western Alpine realm, areas including oceanic domains (*i.e.* Corsica- North Sardinia and North Apennine) can play as rigid bodies, while in contrary, internal deformation deduced from paleomagnetic studies evidence that Apulia (Apennine + Southern Alps) cannot be anymore regarded as a rigid body. An important limit occurs below the Po plain.

In the Western Alps, the plate boundary, first localised at the ophiolitic suture, later shifted along the Penninic Frontal Thrust. Since Miocene, the major motions between stable Europe and “Africa” are accommodated along the Penninic Frontal Thrust which in consequence became the new plate boundary. This is currently still the case as evidenced by the present-day seismicity distribution (Larroque *et al.*, 2021; Mathey *et al.*, 2021).

A reappraisal of the internal Alps kinematic scheme seems mandatory to take into account these generalized large rotations. For example, all the westward Eocene transport directions recognized in the internal Alps (Choukroune *et al.*, 1986; Dumont *et al.*, 2011) are no longer in contradiction with the northwestward convergence predicted by plate tectonic reconstruction. Nevertheless, initial pre-Eocene to Eocene N to NW tectonic transport (see for example Dumont *et al.*, 2022) have to be restored according to block rotations depicted by paleomagnetic data.

Tectonic models of the Alps must take into account the observed rotations. In particular, models that preferentially involve slab retreat or slab breakoff due to frictional forces of the slab in the asthenosphere should prohibit any rotation. Taken with care, paleomagnetic data are a powerful tool to better understand the most studied collision belt of the world. In fact, it clearly highlights that 4D view of the alpine dynamics and 3D balanced crustal restoration are needed and should be encouraged.

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