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Bartonian-Priabonian rotational evolution of the central Jaca-Pamplona Basin, Southern Pyrenees

Evolución rotacional del sector central de la Cuenca de Jaca-Pamplona durante el Bartoniense y Priaboniense (Pirineo meridIonal)

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ABSTRACT

Orogenic zones often exhibit vertical axis rotations (VAR) due to the accommodation of shortening differences along the main structural. In this work, we focus on the central Jaca-Pamplona Basin, where a Bartonian-Priabonian sequence crops out. There two magnetostratigraphic sections, Izaga and Berdún (2800 m), record about 5 Myr of the tectonic and sedimentary evolution of the basin. They have been discretized every 150 m to evaluate the rotational kinematics (spatio-temporal variations of the VAR). In the Izaga section the rotation is non-significant and noisier (dec=003°; inc=39°; a95=18°; k=23) than in the Berdún section, eastern sector, where the clockwise VAR is slightly larger (dec=008°; inc=46°; a95=10°; k=29) although it still overlaps the reference direction. Additional work is needed to refine this paleomagnetic record.

Key-words: *Vertical-Axis-Rotations, Pyrenees.*

RESUMEN

Las zonas orogénicas a menudo exhiben rotaciones de eje vertical (VAR) debido a la acomodación de diferencias de acortamiento a lo largo de la tendencia estructural principal. En este trabajo, nos centramos en la parte central de la cuenca de Jaca-Pamplona, donde aflora una potente secuencia Bartoniense-Priaboniense. Allí dos secciones magnetoestratigráficas, Izaga y Berdún (2800 m), registran unos 5 Ma de la evolución tectónica y sedimentaria de la cuenca. Han sido discretizadas cada 150 m para evaluar la cinemática rotacional (variaciones espacio-temporales del VAR). En la sección de Izaga la rotación no es significativa y es más ruidosa (dec=003°; inc=39°; a95=18°; k=23) que en la sección de Berdún, sector oriental, donde el valor de VAR en sentido horario es algo mayor (dec=008°; inc=46°; a95=10°; k=29) aunque todavía se solapa con la dirección de referencia. Serán necesarios trabajos adicionales para precisar este registro paleomagnético.

Palabras clave: *Rotaciones de eje vertical, Pirineos.*

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Introduction

Orogenic zones often exhibit vertical axis rotations (VAR) due to the accommodation of shortening differences along strike, both at local and regional scales. Paleomagnetism is the only geophysical tool that allows accurate quantification of VAR, that is, the angular difference between the declination of the expected paleomagnetic field (reference for a given age and plate) and the one of the actual paleomagnetic record at a given location. Since the pioneering work of Norris and Black (1961) in the Rocky Mountains, paleomagnetic results in several orogenic regions worldwide have shed light on understanding the 3D and 4D evolution of deformation.

The Pyrenees have been the focus of numerous paleomagnetic studies over the last sixty years due to the presence of well exposed oblique structures whose kinematics has been recorded by syntectonic sedimentation (Pedrera et al., 2023 and references therein). Among the many results derived from the vast network of paleomagnetic sites along the chain, the characterization of the rotational velocities of the thrust structures of the western southern front (External Sierras and Aínsa Oblique Structures Zone) stands out (see a recent review by Pueyo *et al.*, 2022). Yet, an accurate dating of the age of the rotation is still pending (Muñoz *et al.*, 2013).

In this work, we focus on the central sector of the Jaca-Pamplona Basin, a key area to fully understand the 4D geometry and kinematics of the rotational movements in the Western Pyrenees, where this type of information is almost lacking.

Geological Setting

The Pyrenees are a doubly-verging orogen formed during the Late Cretaceous to the Early Miocene by the collision between the Iberian and Eurasian plates (Muñoz, 1992; Teixell, 1996).

The southwestern part of the Pyrenean Zone is represented by the Jaca-Pamplona Basin, an ESE-WNW oriented basin filled by marine and continental

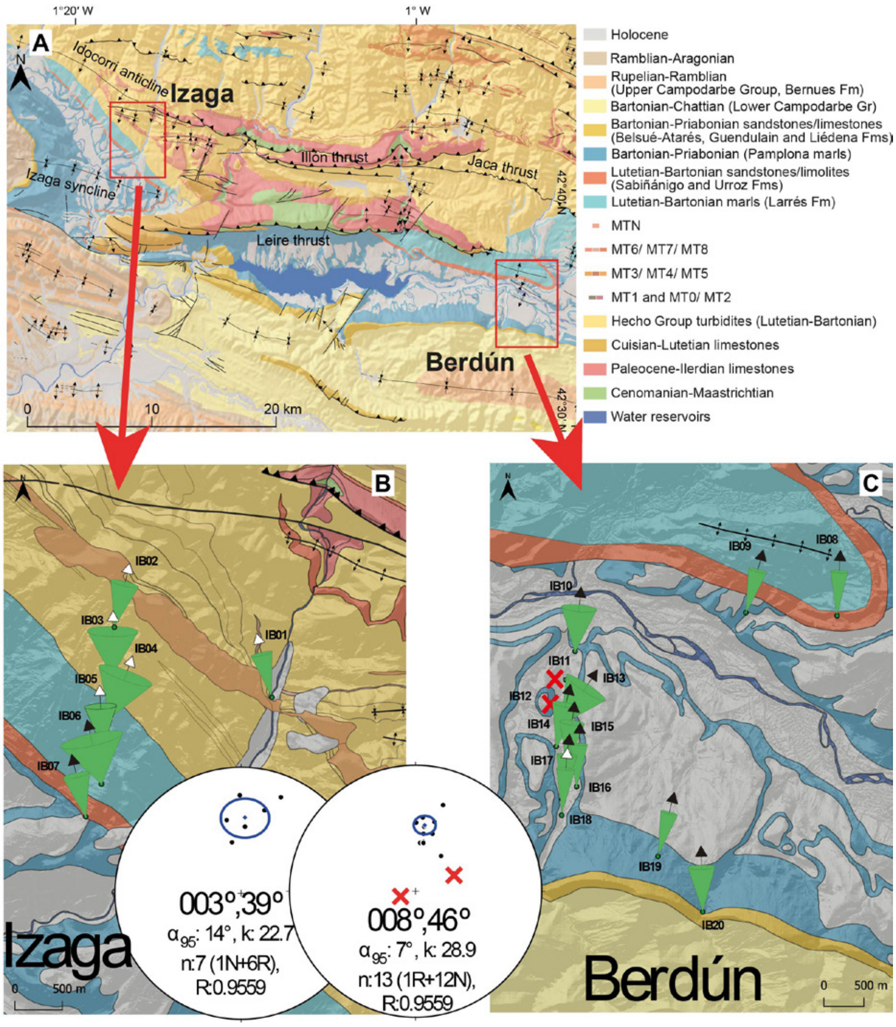

Fig. 1.- A) Geological Map of the central part of the Jaca-Pamplona Basin (modified from Robador Moreno et al., 2024) with the location of the sampling sections. B) Detail of the Izaga section with the rotation cones discreted. C) Detail of the Berdún section with the rotation cones discreted. Small circles and statistics are represented. Red crosses are directions not considered to statistics. See color figure in the online version.

Fig. 1.- A) Mapa geológico de la Cuenca de Jaca Occidental (modificado de Robador Moreno et al., 2024) con la localización de las series muestreadas. B) Detalle de la sección de Izaga con los conos de rotación discretizados. C) Detalle de la sección de Berdún con los conos de rotación discretizados. Se representan los círculos menores y la estadística. Las cruces rojas son direcciones no consideradas en la estadística. Ver figura en color en la versión web.

Eocene-Oligocene syn-tectonic deposits (Puigdefàbregas, 1975). This basin, developed at the footwall of the Lakora-Eaux-Chaudes thrust, was affected by the Larra and Gavarnie basement thrusts, and was transported, and exhumed, southwards as a piggyback basin atop of the Guarga basement thrust, which represents the South Pyrenean basal thrust in this part of the orogen (Labaume and Teixell, 2018; Muñoz *et al.*, 2013). This study is focused on the central sector of the Jaca-Pamplona Basin (JPB), where a thick sequence of Bartonian-Priabonian sediments crops out (Hogan and Burbank, 1993; Payros *et al.*, 1999, Oms *et al.*, 2003) (Fig. 1A). The studied sections are made up by the marls and turbidites of the Hecho Group, the marls and limolites of the Larrés, Urroz and Arguis-Pamplona formations, the deltaic sandstones of the Martes Formation and the continental materials of the Campodarbe Formation. These sediments record the evolution of the JPB, from its beginning as an underfilled turbiditic marine trough to its continentalization.

Sampling and methods

Two magnetostratigraphic sections were sampled, the Izaga section, Bartonian in age, in the northern limb of the Izaga syncline, and the Berdún section, Bartonian-Priabonian in age, across the Canal de Berdún. A sedimentary succession, more than 2800 m-thick, recording about 5 Myr of tectonic and sedimentary evolution of the JPB, was studied. A total of 387, evenly distributed sites, were sampled, 173 in the Izaga section with 6.5m spacing and 214 in the Berdún section with 9.5m spacing. Two oriented samples were collected in every site with an electrical power drill cooled by water. Stepwise demagnetization was conducted in the Paleomagnetic Laboratory of Barcelona (CCiTUB-GEO3BCN CSIC) and in the Palaeomagnetiklabor Gams of the Montanuniversität Leoben, Austria. One specimen per site was stepwise thermally demagnetized (TH), and a superconducting rock magnetometer (2G Enterprises) was utilized to measure the Natural Remanent Magnetization from room temperature up to 650ºC (at least 11 steps with increments of 25º-50ºC).

The Characteristic Remanent Magnetization directions (ChRM) were estimated by means of the VPD software (Ramón *et al.*, 2017) using standard methodologies for the fitting of the most stable paleomagnetic components.

A discretization routine (Mochales et al., 2012), was applied to establish the evolution of VAR along the two sections; average paleomagnetic directions for stratigraphic intervals spanning ~150 m were calculated including only ChRMs with maximum angular deviation (MAD) angles <20° and ensuring geographical continuity within each interval (e.g., not merging samples from different subsections). Reverse ChRM directions were converted into their antipodal directions. Standard spherical statistics were applied using the software Stereonet (Allmendinger *et al.*, 2011). Mean geographic coordinates (Lat and Long), bedding attitude as well as natural remanent magnetization were also averaged out (Table I).

The Eocene reference direction used to calculate VAR comes from the compilation by Pedrera *et al.*, (2023) of Eocene-Miocene data from the Ebro Basin: n=119; dec=002.3º; inc=42.8º; $\alpha95$=3.0°; K=38.1; R=0.9740. To calculate the associated error, the correction factor $\Delta D = \alpha95/\cos(Inc)$ was used.

Results and discussion

ChRM directions show both normal and reverse polarities after bedding correction. Folds and reversal test from previous studies (Pueyo *et al.*, 2002, Larrasoaña *et al.*, 2003; Oliva-Urcia et al., 2012; Pueyo-Anchuela et al., 2012) agree with

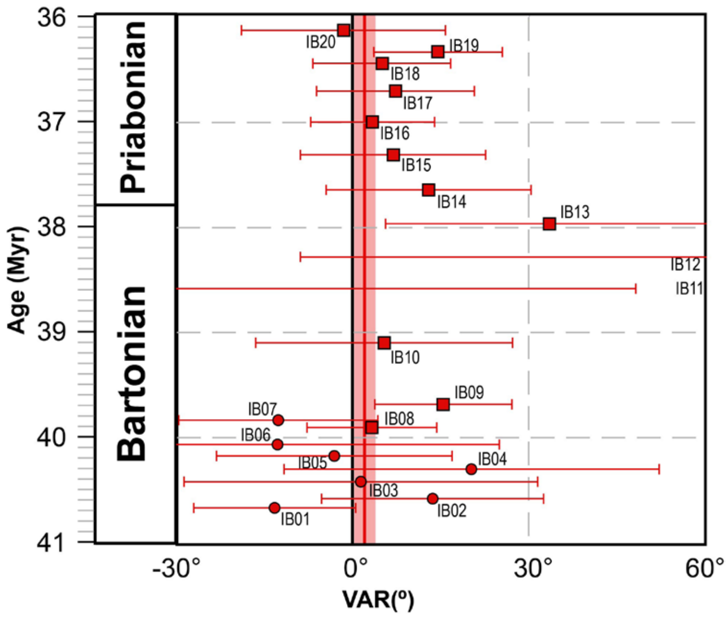

Fig. 2.- Vertical axis rotation (°) along Bartonian and Priabonian times in the Central sector of the Jaca-Pamplon Basin. Red stripe represents the paleomagnetic reference direction. Circles: Izaga section; Squares: Berdún section. See color figure in the online version.

Fig. 2.-Rotaciones de eje vertical durante el Bartoniense y Priaboniense en el sector central de la Cuenca de Jaca Pamplona. La banda roja representa la dirección de referencia paleomagnética. Círculos: sección de Izaga; Cuadrados: sección de Berdún. Ver figura en color en la versión web.

a primary origin of the studied ChRM. The results obtained show non-significant VAR in the Izaga section, west of the Leyre-Illón thrusts, (Fig. 1B), which is consistent with previous results obtained in the Pamplona sector (Larrasoaña *et al.*, 2003). East of the Leyre-Illón thrusts, in the Berdún section (Fig. 1C), results yield a small clockwise rotation (6º) that cannot be considered as significant in light of its associated error (Fig. 2). However, these results are also consistent with those obtained by Pueyo-Anchuela et al. (2012) and Pedrera et al., (2023) and references therein north and south of the Berdún section, where moderate (≈8-20º) CW and statistically significant VAR were also reported.

Conclusions

The results presented in this work demonstrate the absence of statistically significant VAR in the Eocene marine marls

Site	Latitud (º)	Longitud (º)	Z (m)	Strat H (m)	P	NRM (10-6 A/m)	NRM SD	K (10-6 S.I.)	K SD	Strike (º)	Dip (º)	DD	N	n	DEC (º)	INC (º)	ΔD (º)	a95 (º)	k	R	Age (Myr)	VAR (º)
IB01	42.709712	-1.2626024	496	50	R	158.6	79	111.3	27	106	23	S	9	7	169.0	-40.2	13.7	10.5	34.3	0.9750	40.7	-13.3
IB02	42.716336	-1.2827994	557	216	R	200.4	170	119.8	30	120	29	S	27	16	195.8	-31.8	18.8	16	6.3	0.8505	40.6	13.5
IB03	42.711826	-1.2830631	525	366	R	298.9	364	115.9	28	122	28	S	21	13	183.6	-45.6	30.0	21	4.9	0.8107	40.4	1.3
IB04	42.707930	-1.2832136	500	522	R	344.5	404	144.1	27	119	29	S	14	9	202.4	-18.1	31.8	30.2	3.9	0.7699	40.3	20.1
IB05	42.704820	-1.2842085	487	683	R	219.9	114	142.1	13	127	27	S	14	10	179.1	-23.0	20.0	18.4	7.9	0.8855	40.2	-3.2
IB06	42.701524	-1.2844382	490	857	R+N	197.5	55	168.1	22	125	25	S	25	18	349.5	56.0	37.6	21	3.7	0.7435	40.1	-12.8
IB07	42.698483	-1.2864703	438	1042	N	229.4	65	135.0	18	130	25	S	21	21	349.6	56.2	16.9	9.4	12.5	0.9239	39.8	-12.7
IB08	42.600204	-0.8715699	544	980	N	308.6	54	148.1	15	110	23	S	16	15	5.5	40.5	11.0	8.4	21.8	0.9571	39.9	3.2
IB09	42.600632	-0.8855765	512	1163	N	294.3	111	156.9	17	121	29	S	26	22	17.6	28.7	11.6	10.2	10.2	0.9062	39.7	15.3
IB10	42.596552	-0.9114972	486	1279	N+R	754.9	1904	162.3	16	86	23	S	22	19	7.6	51.7	21.8	13.5	7.1	0.8673	39.1	5.3
IB11	42.593161	-0.9130094	446	1446	N+R Bad Q	2333.4	3094	183.9	21	86	26	S	11	10	250.0	79.5	160.2	29.2	3.7	0.7564	38.6	-112.3
IB12	42.590363	-0.9131729	445	1599	N+R Bad Q	778.1	852	178.6	10	86	26	S	10	10	65.9	62.3	72.5	33.7	3	0.7020	38.3	63.6
IB13	42.588041	-0.9136129	419	1746	N	608.3	1288	166.8	13	86	26	S	15	12	35.6	61.6	27.8	13.2	11.7	0.9218	38	33.3
IB14	42.585615	-0.9144999	527	1898	N	621.5	631	190.2	13	86	26	S	14	13	15.1	42.3	17.4	12.9	11.2	0.9177	37.7	12.8
IB15	42.583529	-0.9130846	289	2043	N	353.7	116	168.5	26	93	35	S	13	13	9.1	57.2	15.7	8.5	25	0.9631	37.3	6.8
IB16	42.581050	-0.9112982	339	2197	N	251.7	71	174.0	17	93	41	S	11	11	5.6	58.4	10.5	5.5	69	0.9868	37	3.3
IB17	42.579553	-0.9136084	378	2352	N	445.0	152	148.6	21	100	45	S	13	12	9.5	58.0	13.4	7.1	38	0.9758	36.7	7.2
IB18	42.577730	-0.9134775	304	2508	R	320.2	91	192.3	21	101	43	S	9	9	187.2	-46.8	11.7	8	42.2	0.9789	36.5	4.9
IB19	42.573323	-0.8988229	280	2623	N	414.5	193	188.1	10	97	39	S	13	13	16.7	50.6	10.9	6.9	37.3	0.9753	36.4	14.4
IB20	42.566971	-0.8920067	238	2778	N	1011.7	646	185.6	50	104	39	S	17	17	0.7	44.6	17.3	12.3	9.3	0.8992	36.1	-1.6

Table I.- Paleomagnetic rotations in the Western Jaca Basin (IB01-IB07: Izaga section; IB08-IB20: Berdún section). Z: elevation; Strat H: stratigraphic level; P: polarity; NRM: Natural Remanent Magnetization; NRM SD: standard deviation of the NRM; K: susceptibility; K SD: standard deviation of the susceptibility; Strike, Dip and DD: bedding attitude; N: number of analyzed samples; n: number of considered samples; DEC: declination after bedding correction; INC: inclination after bedding correction; α95, k and R: Fisher's statistics parameters; Age: age of the site; VAR: Vertical Axis Rotation. In red, data not considered to VAR. See color figure in the online version.

Tabla I.- Rotaciones paleomagnéticas en el oeste de la Cuenca de Jaca (IB01-IB07: sección de Izaga; IB08-IB20: sección de Berdún). Z: elevación; Strat H: situación en la columna sedimentaria; NRM: Magnetización Remanente Natural; NRM SD: desviación estándar de la NRM; K: susceptibilidad; K SD: desviación estándar de la susceptibilidad; Strike, Dip and DD: dirección y buzamiento; N: número de muestras analizadas; n: número de muestras consideradas; DEC: declinación , INC: inclinación (ambas tras la corrección tectónica); α95, k y R: parámetros de la estadística de Fisher; Age: edad de las muestras; VAR: Rotación de Eje Vertical. En rojo, datos no considerados para el VAR. Ver figura en color en la versión web.

of the central sector of the Jaca-Pamplona Basin. In agreement with previous studies, it seems that this area is separating two sectors of the basin with a different tectonic evolution: 1) a western sector undergoing no VAR in response to homogeneous shortening along the south Pyrenean basal thrust; and 2) an eastern sector characterized by moderate-small clockwise VAR undergone in response to the westward increase of tectonic shortening occurred along the south Pyrenean basal thrust.

Author's contribution

EP and PSC organised the structure of the paper. PSC, EP, PC and JCL developed the methodology and together with MM, GB, AL, MPM and EB took the data. PSC and EP developed the figures and with PC and JCL wrote the manuscript. BB and RS supervised the laboratory analyses.

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