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Deciphering the Sardic (Ordovician) and Variscan deformations in the Eastern Pyrenees, SW Europe

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Abstract: Detailed geological mapping of the La Cerdanya area (Canigó unit, Eastern Pyrenees) provides new data characterizing the different structural styles exhibited by Cambrian-Lower Ordovician (Jujols Group) and Upper Ordovician successions. Their unconformable contact, related to the Sardic Phase, ranges from 0° (paraconformity) to 90° (angular discordance). The Jujols Group rocks topped by the unconformity are affected by Sardic foliation-free open folds. The pre-Sardic succession, the Sardic Unconformity and the lower part of the post-Sardic succession (Rabassa Conglomerate and Cava formations) are cut and offset by several Late Ordovician NNE-SSW-trending synsedimentary extensional faults associated with hydrothermal activity, which dramatically affected the thickness of the lower part of the Upper Ordovician succession. We relate (i) the Mid-Ordovician Sardic uplift and erosion, and (ii) a Mid-Late Ordovician upward propagating extensional fault system bounding the outline of half-grabens, subsequently infilled by alluvial deposits, to a thermal doming event (about 475–450 Ma) that led to the uplift and stretching of the Ordovician lithosphere. Thermal doming may be caused by mafic magma underplating and responsible for the coeval calc-alkaline magmatic activity broadly developed in the Eastern Pyrenees. We discuss the similarities between the Mid-Ordovician Sardic Unconformity and other Early Palaeozoic unconformities described in neighbouring areas. Finally, we suggest a geodynamic scenario in which a regional-scale thermal event was related to the opening of the Rheic Ocean that led to the drift of Avalonia from the SW-European margin of Gondwana.

Introduction

The Pyrenees **are** a WNW-ESE trending Alpine fold and thrust belt that contains pre–Variscan basement rocks, late Neoproterozoic–to–Carboniferous in age (Fig. 1). The pre–Variscan basement forms a large strip in the core of the cordillera and provides evidence of Cadomian, Sardinic and Variscan magmatic episodes (Cocherie *et al.* 2005; Castiñeiras *et al.* 2008; Casas *et al.* 2010, 2015; Navidad *et al.* 2010; Pereira *et al.* 2014; Martínez *et al.* 2016; Padel *et al.* 2018a), and Variscan and Alpine deformation events (Guitard 1970; Zwart 1979; Muñoz 1992). The onset and significance of the Ordovician deformation has been matter of debate since the pioneer work of Llopis Lladó (1965). After Santanach (1972), it is widely accepted that the Upper Ordovician succession unconformably overlies either the Cambrian–Lower Ordovician Jujols Group or the Ediacaran–Terreneuvian Canaveilles Group (García-Sansegundo & Alonso 1989; Den Brok 1989; Kriegsman *et al.* 1989; Poblet 1991; Muñoz & Casas 1996; García-Sansegundo *et al.* 2004; Casas & Fernández 2007). However, the origin of this unconformity has been object of several interpretations. Santanach (1972) in the Canigó massif and García-Sansegundo *et al.* (2004) in the Garona dome attributed the unconformity to basement tilting, related to a Late Ordovician faulting episode and subsequent erosion. In the Lys-Caillaouas massif, Den Brok (1989) and Kriegsman *et al.* (1989) proposed the existence of a pre–Variscan deformation event. A pre–Late Ordovician folding episode has been also suggested as related to the unconformity on the southern Canigó massif (Casas 2010; Casas *et al.* 2012). However, the geodynamic **significance** of this deformation episode is not yet well established: it is related neither to metamorphism nor cleavage development, although it seems related to uplift, widespread emersion and considerable erosion before the onset of Upper Ordovician deposition (Casas 2010). As a result, the Upper Ordovician rocks onlap a palaeorelief formed by different pre–Upper Ordovician formations, ranging from the upper Neoproterozoic to the Lower Ordovician in the Central and Eastern Pyrenees (Santanach 1972; Laumonier & Guitard 1986; Cirés *et al.* 1994). This intra–Ordovician unconformity may be interpreted as equivalent to the “Sardinic Phase” described in Sardinia (Teichmüller 1931; Stille 1939), which separates the Cambrian–Ordovician from the Upper Ordovician successions (Pillola *et al.* 2008).

In this paper we present new data on the structural style exhibited by the Cambrian–Ordovician and Upper Ordovician successions of the La Cerdanya area, in the Eastern Pyrenees. **The data provide clear evidence** of well-expressed Ordovician deformations in the **form of** extensional faults and folds, the latter only affecting the Cambrian–Ordovician succession. The interpretation of these pre–Variscan deformation structures should contribute to a better understanding of the **origin and** meaning of the Sardinic **Unconformity**, and thus, to discuss the geodynamic setting of this fragment of North Gondwana during Ordovician times, bracketed between the Cadomian and Variscan orogenies.

Geological setting

The study area crops out in the southern flank of the Canigó Unit, which represents an antiformal Alpine **structure** with exposures ranging in age from Late Neoproterozoic to Carboniferous-(Fig. 1). The Alpine floor thrust of this unit is the Orri thrust (Muñoz 1992).

In the study area (Fig. 2), the Cambrian–Lower Ordovician succession **consists of** a thick package (ca. 1500 m) of grey to greenish shales alternating with subsidiary **cm-scale** sandstone interbeds. This succession represents the Serdinya Formation (Padel *et al.* 2018b) of the Jujols Group (Laumonier 1988). Acritarchs recovered from the uppermost part of this succession, close to the Sardinic **Unconformity** at La Molina locality (Fig. 1) (southern slope of the Canigó massif), indicate a Furongian–earliest Ordovician age (Casas & Palacios, 2012). This **age** is coincident with a maximum depositional age of ca. 475 Ma for the uppermost part of the Jujols Group in the La Rabassa dome, on the basis of the youngest detrital zircon population (Margalef *et al.* 2016). To the east, in the Albera massif, metapelites and metapsammites from the uppermost part of a metasedimentary succession that can be correlated with the Jujols Group are crosscut by acidic subvolcanic dykes, which constrain its minimum depositional age to 465–472 Ma (Liesa *et al.* 2011). All these data suggest a depositional age for the uppermost part of the Jujols Group at ca. 475 Ma. On the other hand, a ca. 455 Ma U–Pb age for the Upper Ordovician volcanic rocks directly overlying the Sardinic **Unconformity** has been proposed in the Eastern Pyrenees (Martí *et al.* 2014), in the Les Gavarres (455±1.8 Ma, Navidad *et al.* 2010) and Les Guilleries (452±4 Ma, Martínez *et al.* 2011) areas. This **suggests** a time gap of about 20 m.y. for the Sardinic Phase in the Pyrenees, similar to the gap found in SW Sardinia, the type area where the original unconformity was described; **there**, the unconformity separates the Cambrian–Ordovician from the Upper Ordovician successions, marking a stratigraphic gap of **ca. 18 m.y.** that includes part of the Floian (Pillola *et al.* 2008), the entire Dapingian and Darriwilian, and part of the Sandbian (Hammann 1992; Leone *et al.* 2002).

In the Eastern Pyrenees, the overlying Upper Ordovician succession (Cavet 1957; Hartevelt 1970) forms a broad fining-upward siliciclastic package that comprises some limestone key levels and displays significant thickness variations, ranging from 100 to 1000 m (Fig. 3). This succession was originally described by Hartevelt (1970), who **distinguished** five formations; **i.e.** from base to top, the Rabassa Conglomerate, Cava, Estana, Ansobell and Bar Quartzite formations. The Rabassa Conglomerate Formation, up to 100 m thick, consists of reddish-purple, polygenic conglomerates with **heterometric** clasts composed of quartzite and slate derived from underlying rocks and vein quartz. The overlying Cava Formation, 0–850 m thick, is made up of conglomerates, sandstones and shales with volcanic intercalations; one coquina punctuating their shale interbeds have yielded brachiopods (*Svobodaina havliceki*, *Rostricellula* sp. and *Rafinesquina* sp.) and bryozoans, suggesting a Katian (former late Caradoc–early

Ashgill) age (Hartevelt 1970; Gil-Peña *et al.* 2004; Puddu & Casas 2011). The Estana Formation, 5–200 m thick, is composed of limestone and marly limestone rich in brachiopods, bryozoans, echinoderms and conodonts of late Katian age (Gil-Peña *et al.* 2004). The top of the carbonate succession is unconformably capped by the black-grey shales of the Hirnantian Ansobell Formation, 20–320 m thick, which in turn is overlain by the Bar Quartzite, 2–20 m thick and dated as Hirnantian on the basis of their fossiliferous content (Sanz López & Sarmiento 1995; Sanz López *et al.* 2002; Roqué Bernal *et al.* 2017; Štorch *et al.* 2018).

In several areas of the Pyrenees, from Pierrefite to the west (Calvet *et al.* 1988) to the Ribes de Freser area to the east (Robert & Thiebaut 1976; Robert 1980; Ayora 1980; Martí *et al.* 2014) volcanic rocks have been reported interbedded in the Upper Ordovician sediments. These volcanic rocks consist of pyroclastic deposits with subsidiary lavas and subvolcanic intrusive rocks (Martí *et al.* 1986, 2019). They include andesite, rhyodacite and rhyolite that make up a small fraction of the corresponding Ordovician. Additionally, the Ribes area includes a subvolcanic granitic body, the Ribes granophyre, emplaced in the lower part of the Sandbian–lower Katian succession and dated at 458 ± 3 Ma by Martínez *et al.* (2011), and several granitic orthogneissic bodies emplaced in the lower part of the pre–Variscan succession (the Núria gneiss with a protolith age of 457 ± 4 Ma, Martínez *et al.* 2011; and the Queralbs gneiss, with a protolith age of 457 ± 5 Ma, Martínez *et al.* 2011).

All these pre–Variscan rocks display a polyphase deformation linked to the Variscan deformation and a low-pressure/high-temperature metamorphism (Guitard 1970; Zwart 1979). A pervasive foliation is the main deformational structure in the medium- to high-grade metasediments and the gneissic bodies derived from Ordovician and Cadomian granitoids. This foliation (S_{1-2}) is a composite fabric developed prior to coeval with the Variscan regional metamorphism, being associated with an E–W to NE–SW oriented stretching lineation. S_{1-2} is folded by later E–W to NW–SE upright folds, forming the mesostructure that depicts the Aston-Hospitalet, Canigó, Roc de Frausa and Albera gneissic domes all along the backbone of the chain. According to Clariana & García-Sansegundo (2009) and García-Sansegundo *et al.* (2011), in the Garona dome and the Pallaresa massif, S_1 is a slaty cleavage only developed in the Cambro-Ordovician succession and not related to folds; and S_2 is associated with N-verging recumbent folds formed at Carboniferous time. In the eastern part of Pallaresa massif (central Pyrenees), south of Aston massif and north of the Tor-Casamanya syncline, Clariana *et al.* (2009) and Clariana & García-Sansegundo (2009) described a subvertical S_3 crenulation cleavage, axial plane of E–W trending upright folds, deforming S_{1-2} . This S_3 becomes the main cleavage in the Pallaresa massif, the Tor-Casamanya and Llavorsí synclines and the Rabassa and Orri domes (Speksnijder 1986; Poblet 1991; Clariana & Sansegundo 2009; Margalef & Casas 2016). S_3 exhibits a fan-like attitude close to the southern contact with the post-Variscan

rocks due to the Alpine rotations linked to thrust sheet stacking (Muñoz 1992) The Devonian and the Carboniferous Culm rocks of the study area exhibit a well-developed cleavage that can be correlated with this S₃ mesostructure (Martín-Closas *et al.* 2018). Additionally, to the south of the study area, several thrust sheets involving Devonian and Carboniferous rocks can be observed (Hartevelt 1970; Domingo *et al.* 1988; Casas *et al.* 1989; Martín-Closas *et al.* 2018). Their basal detachment is located at the base of the Silurian black shales; although most of the thrusts are south-directed, some north-directed thrusts can be observed. In the southern limb of the D₃ megastructures, as the Rabassa dome, thrusts and the lower detachment dip to the south. In turn, thrusts cut the fold-related cleavage. Thus, thrust development in the post-Silurian rocks must have been broadly coeval with the onset of D₃ folds in the low-grade pre-Silurian rocks (Martín-Closas *et al.* 2018). In the Eastern and Central Pyrenees this deformation episode occurred at 330–319 Ma, according to the age of syn-orogenic Carboniferous Culm deposits (latest Visean to Serpukhovian by Sanz-López *et al.* 2006; Namurian by Delvolvé 1981; Delvolvé & Perret 1989; Delvolvé *et al.* 1993; Martín-Closas *et al.* 2018). This age is coincident with the maximum deposition ages of 336±2 and 356±9 Ma obtained from U–Pb on detrital zircon from Carboniferous rocks (Martínez *et al.* 2016). A minimum age, in turn, is provided by the age of the crosscutting Andorra-Montlluís granodiorite, dated as 305±3 Ma by Romer & Soler (1995), 305±5 Ma by Maurel *et al.* (2004), and 301.5±1.9 Ma by Pereira *et al.* (2014).

Structure

We performed a detailed (1:5,000 scale) geological map of the Talitendre area and measured a stratigraphic log of the Upper Ordovician succession cropping out along the road near Ordén village (Fig. 2). This study area constitutes the WNW-ESE oriented vertical-to-subvertical southern flank of the Canigó antiform that joins southwards with a synformal megastructure, where Silurian, Devonian and pre-Variscan Carboniferous successions are extensively exposed (Fig. 1). Together with this subvertical arrangement, excellent outcrop conditions allow the recognition of the Sardic Unconformity, a system of extensional faults and several deformation mesostructures chronologically subdivided into three different episodes. To better visualize and reconstruct the fault geometry, cartographic data were integrated into a 3D environment (MOVE software), which also facilitated the geometric analysis of the Sardic Unconformity.

Sardic Unconformity

The Cambrian–Lower Ordovician outcrops are onlapped, at angles ranging from a few to 90°, by both the Rabassa conglomerate and the Cava formations (Figs 2-4). The angular

discordance separates the Upper Ordovician succession on its southern side from underlying Cambrian–Ordovician strata on its northern side. This contact shows a planar to weakly undulated, locally irregular **surface capping** the Cambrian–Ordovician strata, and can be considered as an unconformity laterally ranging from a paraconformity to an angular discordance. The unconformity exhibits a roughly WNW-ESE trend (194/75) although, locally, the orientation ranges from E-W to NW-SE (Fig. 5a-b).

The Upper Ordovician succession shows a NW-SE trend of vertical to subvertical strata. Upper Ordovician beds may be either overturned or strongly dipping northwards or dip eastwards in the eastern **part** of the study area (Fig. 6). In contrast, Cambrian–Ordovician bedding surfaces exhibit a wide range of orientations (see below).

Polyphase folding

The most visible mesostructures of the Cambrian–Ordovician and Upper Ordovician rocks are bedding surfaces. Field data show that bedding surfaces exhibit different **orientations** (Fig. 7). Orientation of the Cambrian–Ordovician succession presents a marked dispersion and dip values **rang**ing from subvertical to subhorizontal (Fig. 7a). In contrast, the Upper Ordovician bedding poles exhibit a more regular NW-SE trend (Fig. 7b). As we will discuss below, the marked dispersion of the bedding poles in Cambrian–Ordovician **strata** suggests the superposition of several fold systems. In the description that follows, L_1 and L_3 refer to different fold axes, and L_{0-2} **and** L_{0-3} to bedding/cleavage intersection lineation.

D_1 structures. The existence of D_1 folds can be inferred from the arrangement of bedding surfaces at outcrop and **different** map scales, and from the pattern displayed by D_3 linear elements, intersection lineations **s** and fold axis in the Cambrian–Ordovician sequence. That is, D_3 folds developed over initially non-horizontal surfaces and D_1 folds control the geometry of D_3 mesoscale folds (e.g., [Turner & Weiss 1963: p. 130](#); [Mey 1967: p. 194](#); [Ramsay 1967: p. 539](#)). The existence of previous D_1 folds may also explain the distribution of D_2 mesostructures on the Cambrian–Ordovician rocks. Concerning the initial orientation of D_1 fold axes, the map analysis suggests that: (i) despite dispersion, Cambrian–Ordovician bedding exhibits two maxima in their orientations at WNW-ESE and NE-SW (Fig. 7a); (ii) WNW-ESE orientations predominate over NE-SW ones; and (iii) especially interesting are the outcrops in which the Cambrian–Ordovician beds are NE-SW oriented, and are both vertical and normal to the unconformity horizon (Fig. 8a). In such a situation, after **unfolding** the Upper Ordovician sequence using WNW-ESE horizontal rotational axis parallel to the Upper Ordovician unconformity, the NE-SW vertical Cambrian–Ordovician beds still remain vertical and with a similar NE-SW orientation (Fig. 8b). This observation suggests that D_1 fold axes presented an initial subhorizontal NE-SW

orientation, with a short limb oriented NE-SW subvertical or strongly dipping, and a long limb subhorizontal or gently dipping towards the SE or NW. However, the effect of superposed D_3 folds precludes to assess whether D_1 folds have a NW or SE vergence. Analysis of the areas where subvertical WNW-ESE and NE-SW orientations coexist allows the estimation of 10 to 100 m-scale dimensions of D_1 folds (Fig. 9). It should be noted that there is no evidence of an axial planar cleavage development or other mesostructures related to D_1 fold formation.

D_2 structures. A not very pervasive cleavage (S_2) is observable at outcrop scale in the Cambrian–Ordovician rocks, while S_2 is well developed in the fine fraction of the Upper Ordovician, being deflected by coarser deposits (such as conglomerates and sandstones), where it develops irregularly. S_2 surfaces generally dip 20° to 80° towards the E-ESE (Fig. 7c–d) and are commonly deformed by D_3 folds. In the Upper Ordovician rocks, S_2 exhibits dispersion along a N-S oriented girdle (Fig. 7d). Neither folds nor other mesostructures related to this event have been clearly identified in the field. As D_3 linear mesostructures, L_{0-2} exhibits a wider dispersion in the pre- than in the post-unconformity rocks (Fig. 7c–d).

D_3 structures. A north-dipping S_3 cleavage is the dominant deformation structure recognizable in the exposures of the study area. S_3 cleavage is observable from outcrop down to microscopic scale, and is correlated with the dominant cleavage observed in the Silurian and Devonian rocks cropping out to the south of the area. S_3 is oriented NW-SE with variable dips towards the NE. In the eastern area, it is subvertical or strongly dipping, whereas in the western sector it dips gently to moderately towards the NE (Fig. 2).

S_3 is related to D_3 folds affecting both the pre- and post-unconformity rocks. As the S_3 surfaces, the D_3 fold axial surfaces are generally gently dipping (10° – 45°) towards the N-NE in the western part of the study area, while to the east they have the same orientation, though steeply dipping or subvertical. D_3 folds are SW vergent, open to tight and generally 1–100 m scale with cm-scale minor folds (2nd or 3rd order folds) on the limbs of the main folds. D_3 folds show mildly curved hinges that generally developed harmonic folding, especially in the Upper Ordovician rocks. D_3 fold axes exhibit different orientations in the pre- and post-unconformity rocks (Fig. 7e–f). In the Upper Ordovician succession, L_3 axes and L_{0-3} intersection lineations are grouped forming a maximum with a moderate plunge to the WNW or ESE (Fig. 7f). The bedding/cleavage relationship indicates that the study area constitutes the southern flank of a south-facing first-order D_3 fold oriented WNW-ESE (Fig. 2b).

In contrast, the minor L_3 axes and L_{0-3} intersection lineations of the Cambro–Ordovician rocks display a wide range of orientations. L_{0-3} plunge ranges from sub-horizontal to 45° (Figs. 7e), and no simple distribution pattern may be deduced from map analysis (Fig. 2). If L_{0-3} and L_3 are

plotted together, they are mainly distributed along a great circle coincident with the S_3 average plane, although two maxima oriented ca. $20^\circ\text{--}40^\circ/000$ and $25^\circ/115$, respectively, can be envisaged with predominance of low plunge values (Fig. 7e).

Extensional faults and tectonically induced sedimentation

At the map scale, several extensional faults affecting the Cambrian–Ordovician strata, the Sardinian unconformity and the lowermost part of the Upper Ordovician succession can be recognized (Figs 2-5) (Casas & Fernández 2007; Casas 2010). At present, the faults trend broadly N-S to NNE-SSW, and their hangingwall generally appears to be the eastern block, despite the presence of some antithetic faults (Fig. 2). The faults are steep, domino-style and their surface dips range from 48° to 90° towards the WNW and ESE. This variation in orientation together with the changes in strike along a fault plane detected in 3D analysis suggest that the faults are slightly folded around a subhorizontal NNE-SSW axis ($189/00$) (Fig. 5c). Maximum throws vary between 200 and 750 m. The NNE-SSW fault orientation could have prevented the inversion of the faults during the Variscan and Alpine deformation events, but the orientation did not prevent their rotation following horizontal E-W axes during the former events. The faults are associated with synsedimentary hydrothermal activity, represented by dense networks of quartz veins encased in the uppermost part of the Jujols Group and subparallel to the trace of the extensional faults. These served as source for huge amounts of vein quartz clasts that form the Rabassa conglomerate (Fig. 10 a-b).

The displacement of some of these faults diminishes progressively up-section and vanishes in the upper part of the Upper Ordovician rocks, especially in the lower part of the Cava Formation, indicating that the faults became inactive before deposition of the overlying Estana strata (Fig. 2). Thus, the Rabassa Conglomerate and the lower part of the Cava formations are syn-tectonic sediments, whereas the upper part of the Cava Formation and the overlying Estana, Ansobell and Bar formations are post-tectonic sediments. As a result, the whole Upper Ordovician succession shows sharp changes in total thickness ranging between 190 m and 900 m, with a general increase from W to E. Perpendicular to these faults, the Rabassa Conglomerate Formation displays sharp changes in thickness (from 0 to 100 m) and facies associations. Deposits of the Rabassa Conglomerate Formation neighbouring the extensional faults consist of chaotic breccias ranging both laterally and vertically to matrix- to clast-supported conglomerates (Fig. 11d-e). These include massive to weakly stratified, unsorted, pebble-dominated deposits of sandstone, shale, vein quartz and mafic phenocrysts (Fig. 11a-b). Contacts are commonly scoured and grading is both normal and inverse. Breccias and matrix-supported conglomerates show either chaotic or amalgamated patterns; they interfinger laterally with packages of clast-supported conglomerates and pebbly sandstones that pinch out or

change abruptly, both laterally and vertically, into sandstone/shale alternations (Cava Formation). Clast-supported conglomerates show massive to weakly imbricated pebbles and cobbles (Fig. 11f), subrounded, moderately sorted and grade upsection and laterally into litharenites; the latter display centimetre- to decimetre-scale trough and low-angle cross-stratified sets alternating with shales (Fig. 11g), irregularly burrowed. Lithostratigraphically, the occurrence of shale interbeds marks the base of the Cava Formation. Three facies associations can be recognized: (i) Breccias and matrix-supported conglomerates are interpreted as having undergone different types of downslope transport by basal sliding of plastic to semi-rigid sediment masses that included contemporaneous hydrothermal dykes of quartz (Fig. 11e). Amalgamation of debris-flow deposits indicates the presence of neighbouring slopes close to synsedimentary extensional faults. (ii) Packages of clast-supported conglomerates and pebbly sandstones represent in-channel gravel bars that graded into straight to sinuous crested bedforms in shallow, braided systems. During high-discharge events, sediments were reworked and accumulated as channelized conglomerates. (iii) Finally, sandstone/shale alternations reflect the influence of marine shoreface-to-offshore conditions with local development of burrowing by soft-bodied metazoans

It should be noted that as the Upper Ordovician unconformity is cut by these normal faults, significant pre–Upper Ordovician erosive processes took place preceding the normal faulting event.

Synsedimentary faults are planar, either non-rotational or with small amounts of rotation affecting the beds in the hangingwall. The geographical distribution of these normal faults allows subdivision of the Upper Ordovician succession into six domains (Fig. 6). In the four western domains (A_1 to A_4), the Upper Ordovician bedding planes exhibit an E-W or NW-SE trending orientation, ranging from N100E to N120E with subvertical or strongly dipping attitude. In domain A_5 , the Upper Ordovician bedding planes exhibit a wider range of dipping values, with bedding poles distributed in a NE-SW girdle, as a result of a 119/28 oriented fold axis (Fig. 6). In the easternmost domain A_6 , the Upper Ordovician bedding planes show a roughly NW-SE trending with variable dipping as a result of a 115/16 oriented fold axis. The divergence between the beds next to the hangingwall varies between a minimum value of 10° (A_5) and a maximum of 24° (A_4), with a main value of 18° (A_2) and 20° (A_3), which allows us to infer a ca. 20° fault rotation.

It is difficult to identify the faults as well as to recognize an eventual detachment horizon in the Cambrian–Ordovician rocks. This and the steep arrangement of the fault surfaces preclude an estimate of the amount of extension linked to fault movements. In any case, the small amount of bed rotation in the hangingwall of the faults, ca. 20°, indicates a small amount of E-W extension.

Discussion

Structure: age and significance of folds D_1 , D_2 and D_3

D_1 folds affecting the Cambrian–Ordovician succession are sealed by Upper Ordovician strata. Thus, it is assumed that the episode D_1 is earlier than the successions deposited above. An Early–Mid Ordovician age can be proposed for this folding event. Moreover, D_1 fold axes are parallel to subparallel to the direction of the Late Ordovician extensional faults. We noted the absence of microscale D_1 folds and the lack of either associated cleavage or metamorphism. We interpret that D_1 folds can form at the hangingwall blocks of extensional faults. Folds related to extensional faults have been extensively described, caused by slip on nonplanar normal faults (Xiao & Suppe 1992), on faults with ramp-flat-ramp fault geometry (Rotevatn & Jackson 2014), on localized zone of shortening between two fault trends (Abu Sharib *et al.* 2017) or as fault-propagation folds (Sharp *et al.* 2000). From these possibilities, we favour that D_1 folds formed as fault-propagation folds of upward-propagating normal faults. In this situation, vertical or steeply dipping pre–Sardic beds in the hangingwall near the fault surface are common as propagation of the fault tip to the surface results in breaching of a previous fold (Sharp *et al.* 2000). Therefore, two possibilities can be envisaged: either the fold formation is linked to pre–Sardic (Early–Mid Ordovician) movements of the mapped extensional faults, or they resulted from the movement of other extensional faults, not detected in the area due to the monotonous character of the Cambrian–Ordovician succession and the lack of cartographic marker beds. According to the first possibility, post–Sardic (Late Ordovician) upward fault propagation should led to normal faults cutting previous folds, the topographic surface and the unconformity, and post–Sardic sediments filling the hangingwalls thinning away from fault surfaces (Fig. 2). According to the second option, the faults would not reach the topographic surface, and normal faults would rest as blind faults in the pre–Sardic sequence. In any case, the Upper Ordovician unconformity changes from a paraconformity in the long limb of the D_1 folds or in the footwall of the faults, to an angular unconformity in the hinge zone or in the vertical limbs of the D_1 folds in the hangingwall of the faults (Fig. 9). As stated before, the outcrop conditions, together with the monotonous character and the lack of cartographic key levels in the pre–Sardic sequence, make it difficult to identify these blind faults as well as the continuation in the pre-unconformity sequence of the normal faults cutting the unconformity. The situation depicted above argues against a contractional origin for the Ordovician (Sardic) folds in the Pyrenees as previously proposed by Casas (2010) and Casas *et al.* (2012).

Equivalent D_1 pre-main cleavage folds were described by Casas (2010) to the north of the Canigó unit, in the El Conflent area, and more to the east, in the La Molina area. The former exhibit a similar N-S direction with axes strongly dipping to the north, whereas in the La Molina,

pre-main cleavage folds are mainly oriented NNW-SSE. As in the study area, the combination of both pre-main cleavage folds and syn-foliation folds with variable orientations gives rise to a complex disposition of bedding planes (Casas 2010).

The interpretation of the deformation episode D_2 is more difficult due to the lack of related mesostructures. It could be correlated with the S_2 cleavage associated with N-verging recumbent folds described in the Garona and Pallaresa domes by Clariana & García-Sansegundo (2009) and Clariana *et al.* (2009). However, the lack of related folds in the study area makes this correlation speculative. In any case, the age of this deformation should be post-Ordovician (Variscan) because it affects both the pre- and post-unconformity deposits.

The main foliation (S_3) recognized in the study area can be correlated with the pervasive axial plane crenulation cleavage (S_3) of E-W trending upright folds, which represents the main cleavage preserved in the Pallaresa massif, the Tor-Casamanya and Llavorsí synclines and the Rabassa and Orri domes (Speksnijder 1986; Poblet 1991; Clariana & Sansegundo 2009; Margalef & Casas 2016). It should be noted that the Cambrian–Ordovician succession of these Pyrenean massifs shares a common structural arrangement: a regional crenulation cleavage, regularly oriented and dipping to the north, associated with intersection lineations and minor fold axes displaying a significant dispersion. This arrangement, described for example in the Rabassa dome (Poblet 1991; Capellà & Bou 1997), the Massana anticline (Hartevelt 1970; Poblet 1991; Casas *et al.* 1998), the Orri dome (Hartevelt 1970; Speksnijder 1986; Poblet 1991) and the Lys-Caillaouas massif (Den Brok 1989), among others, has been attributed to the presence of pre-foliation (pre- D_3) deformations.

Origin of the Sardic Unconformity, extensional faults and D_1 folds

The angular unconformity described above represents the prolongation of those described westwards by Casas & Fernández (2007), and in the La Molina area by Santanach (1972) and Casas (2010). The unconformity can be attributed to the doming, tilting and erosion of a pre-Sardic succession, which preceded the deposition of the Upper Ordovician conglomerates and sandstones (Santanach 1972; García-Sansegundo *et al.* 2004). Doming, tilting and truncation of Cambrian–Ordovician strata suggest relative uplift, perhaps associated with a fall in the eustatic sea level.

The Sardic Unconformity was affected by a Late Ordovician extensional pulsation, responsible for the movement of the NNE-SSW oriented normal faults that led to the contemporaneous opening of grabens and half-grabens. These were infilled with the alluvial, fluvial and volcano-sedimentary deposits of the Upper Ordovician Rabassa Conglomerate and Cava formations,

which also reflected a significant **and stepwise** hydrothermal activity. Simultaneously, a Late Ordovician magmatic pulse yielded a varied suite of magmatic rocks: small granitic bodies are emplaced in the pre-unconformity strata of the Canigó massif and constitute the protoliths of the Cadí, Casemí, Núria and Canigó G-1 type gneisses (ca. 457–446 Ma, Casas *et al.* 2010; Martínez *et al.* 2011; Navidad *et al.* 2018), together with **metre-scale** thick bodies of metadiorite (ca. 453 Ma, Casas *et al.* 2010). Coeval calc-alkaline volcanic rocks (ignimbrites, andesites and volcanoclastic rocks) are interbedded in the Upper Ordovician of the Ribes de Freser area (Robert & Thiébaud 1976; Ayora 1980; Robert 1980; Martí *et al.* 1986, 2019); a granitic body **at Ribes** with granophyric texture, dated at ca. 458 Ma by Martínez *et al.* (2011), intrudes at the base of the Upper Ordovician succession. **Metre-scale** rhyodacitic to dacitic subvolcanic sills intercalated within the pre-unconformity succession close to the base of the Upper Ordovician have also yielded Late Ordovician ages in the La Pallaresa dome (ca. 453 Ma, Clariana *et al.* 2018).

Previously, a Floian–Dapingian magmatic pulse, coeval with the uplift and subsequent extensional activity related to D₁ fold formation took place. This pulse gave rise to the intrusion of voluminous peraluminous granites, about 500 to 3000 m thick and emplaced into the pre-unconformity strata. They constitute the protoliths of the large laccolith-shaped, orthogneissic bodies that punctuate the backbone of the Pyrenees, from west to east, the Aston (ca. 470–467 Ma, Denèle *et al.* 2009; Mezger & Gerdes 2016), Hospitalet (ca. 472 Ma, Denèle *et al.* 2009), Canigó (ca. 472–462 Ma, Cocherie *et al.* 2005; Navidad *et al.* 2018), Roc de Frausa (ca. 477–476 Ma, Cocherie *et al.* 2005; Castiñeiras *et al.* 2008) and Albera (ca. 470 Ma, Liesa *et al.* 2011) massifs. As a whole, the Ordovician magmatism in the Pyrenees lasted about 30 m.y., from ca. 477 to 446 Ma, a time span contemporaneous with the Ordovician deformations described above (Fig. 12).

Taken all together, uplift, **denudation**, extensional tectonics and magmatic activity may be related to a thermal doming caused by the underplating of hot mafic magmas (Fig. 13). This scenario has been invoked as the origin of the Furongian–Early Ordovician magmatism in the Central Iberian Zone of the Iberian Massif related to the so-called Toledanian Phase (Bea *et al.* 2007; Montero *et al.* 2009; Díez Montes *et al.* 2010). The latter is characterized by a Furongian gap associated with the onset of a remarkable magmatic activity of calc-alkaline affinity, giving rise to the the Ollo de Sapo and Urra formations, ca. 495–470 Ma (see summaries in Álvaro *et al.* 2007; García-Arias *et al.* 2018; Casas & Murphy 2018; ,Sánchez-García *et al.*, in press). In the Pyrenees, doming would start at ca. 475 Ma, causing regional uplift and emersion responsible for the end of the marine Jujols Group sedimentation, its erosion and the emplacement of a widespread calc-alkaline granitic magmatism (Fig. 13). Subsequent extensional episodes would be related to the **opening** of half-grabens **and their infill** with the

Rabassa Conglomerate Formation and the lower part of the Cava Formation. The latter sedimentation was coeval with magmatic activity until ca. 450 Ma, when thermal relaxation led to marine transgression and sedimentation (middle part of the Cava Formation) that overlapped an inherited Sardinic-related palaeorelief. After a glaciogenic transgression represented by the blanketing of the basin by the Ansobell Formation, isostatic rebound at ca. 445 Ma may be signalled by the progradation of the Bar Quartzite Formation, coincident with the end of the magmatic activity and with the final sealing of inherited Sardinic palaeotopographies at Silurian times. Later on, the Variscan deformation would overprint all these rocks and structures at Mid Carboniferous times.

Comparison with neighbouring areas

In Sardinia, the Sardinic Unconformity is associated with an intra-Ordovician stratigraphic gap in the autochthonous Palaeozoic basement of the Iglesiente-Sulcis area (southwestern Sardinia), which corresponds to the External Zone of the South-European Variscan Chain. Similar gaps (named Sarrabese Unconformity) are found in the External nappe Zone, associated with coeval igneous activities in the Sarrabus-Gerrei area (~ 465 Ma: Buzzi *et al.* 2007a, 2007b; Oggiano *et al.* 2010). The post-unconformity succession is related to Upper Ordovician magmatism in SW Sardinia (~ 457 Ma: Pavanetto *et al.* 2012) and central-northern Sardinia (~ 469 Ma up to ~ 456 Ma: Helbing & Tiepolo 2005; Giacomini *et al.* 2006; Boriani 2008). Indeed, in Sardinia, the pre-Sardinic sequence is affected by different E-W striking structures with neither regional metamorphism nor cleavage, displaying 1 to 100 m-scale folds without cleavage and faults, subsequently sealed by Upper Ordovician strata (Pasci *et al.* 2008; Cocco & Funedda 2012, 2019; Cocco *et al.* 2018). We can recall, for instance, the structure of the Su Scoffoni area in southeastern Sardinia, where Cocco & Funedda (2019) described the Sardinic Unconformity sealing folds affecting only the pre-Upper Ordovician succession. As a result, the Upper Ordovician succession in SE Sardinia overlies Cambrian-Ordovician beds with different attitudes, in a similar way than that described above from the Eastern Pyrenees. The occurrence of faults and the environment of half-grabens have been supposed by Brusca & Dessau (1968) and Martini *et al.* (1991), who associate them with a post-unconformity deposit (Monte Argentu Formation) in SW Sardinia.

In the Occitan Domain (Mouthoumet and Montagne Noire massifs) of southern France, the Ordovician is punctuated by two major gaps: a Sardinic Unconformity (ranging from paraconformable to angular discordant contacts) and a diachronous Silurian erosive unconformity that represents blanketing of an inherited glaciogenic palaeorelief (Álvarez *et al.* 2016). As in the case of the Eastern Pyrenees and Sardinia, the Montagne Noire includes emplacement of massive (Sardinic-related) Middle Ordovician granitic bodies. The migmatitic

Somail Orthogneiss of the southern Axial Zone, derived from an Ordovician metagranite that was emplaced at 471 ± 4 Ma and 450 ± 6 Ma (U–Pb zircon ages; Roger *et al.* 2004; Cocherie *et al.* 2005). Recent geochronological dating of these augen orthogneisses has updated the story of various generations of granitoids that form the core of the Axial Zone (e.g., Cocherie 2003; Roger *et al.* 2004; Faure *et al.* 2004; Bé Mézème 2005; Charles *et al.* 2009). A post–Sardic rifting reactivation is recorded in the Mouthoumet massif and the Cabrières klippe (southern Montagne Noire), where Late Ordovician fault-controlled subsidence and the record of rift-related continental tholeiitic lavas were coeval, in some areas, with the onset of the Hirnantian glaciation (Álvaro *et al.* 2016, 2018). Re-opening of rifting branches was followed by onlapping patterns and final sealing of Sardic palaeotopographies during Silurian and Early Devonian times. It led to fault-controlled subsidence and the generation of structurally controlled depocentres, at least in the Cabrières sector of the Montagne Noire and the Mouthoumet area. It was accompanied by marine transgression and extensional pulses that gradually led to flooding and onlapping on the shoulders of the rifting branches, which were finally sealed during Early Devonian times.

As a result, the Sardic Phase is shared by the Occitan Domain, the Eastern Pyrenees and Sardinia, all of them located along the eastern branch of the Variscan Ibero-Armorican Arc during Ordovician times. According to some authors (e.g., Stampfli *et al.* 2002), this margin of Gondwana faced the Proto-Tethys, also called Ran Ocean (Torsvik & Cocks 2009), and later on the Palaeo-Tethys Ocean (Torsvik & Cocks 2004; Von Raumer & Stampfli 2008). This geodynamic setting is different to that faced by the Iberian Massif, located along the western branch of the Ibero-Armorican Arc. In the Central Iberian and Ossa-Morena Zones of the Iberian Massif, a similar but earlier unconformity, the Toledanian unconformity is represented by an angular discordance that separates variably tilted Ediacaran–Cambrian Series 2 rift-related successions from an overlying Tremadocian–Floian passive-margin succession. The involved gap (at least ~ 22 m.y) includes, at least, most of the Furongian and basal Ordovician, although the erosion can incise into the entire Cambrian and the upper Ediacaran Cadomian basement (Gutiérrez Marco *et al.* 2002). The Toledanian Phase has been recently interpreted (Sánchez-García *et al.* 2008) as representing the rift/drift transition that led to the opening of the Rheic Ocean (Díez Montes *et al.* 2010; Thomson *et al.* 2010; Nance *et al.* 2010; Álvaro *et al.* 2014, 2018; Casas *et al.* in press). Neither metamorphism nor penetrative deformation related to this unconformity have been described, except in the Marão Anticline and the Amêndoa-Carvoeiro Synform of the Central-Iberian Zone. In these areas, cleavage-bearing folds with steep axial planes at high angles to Variscan structures have been described and related to transient compression and dextral strike-slip features along the Central-Iberian/Ossa-Morena contact lineament (Romão & Ribeiro 1993; Correia Romão *et al.* 2005; Romão *et al.* 2005, 2013; Amaral *et al.* 2014). A similar volcanic-free “Furongian gap” related to a break-up unconformity

has been reported in the central Anti-Atlas of Morocco, and related to the above-reported Toledanian Phase (Álvarez & Vizcaíno 2018).

The magmatism associated with the Toledanian and Sardic Phases is dominantly felsic and calc-alkaline, and exhibits an arc-like signature that some authors have interpreted as linked to subduction conditions (Castro *et al.* 2002; Del Greco *et al.* 2016). However, other authors have interpreted this signature as an inherited character caused by the fast melting of a subduction-related Neoproterozoic crust (Díez Montes *et al.* 2010; Navidad *et al.* 2010; Sánchez-García *et al.* in press). This fast melting may also explain the great amount of inherited zircons, the highly porphyritic character and the virtual absence of mafic bodies in these magmas. These may have resulted from the partial melting of granitoids or sediments in the continental lower crust caused by the underplating or intrusion of hot mafic magmas that produced a great heat input during an extensional event (Bea *et al.* 2007; Montero *et al.* 2009; Díez Montes *et al.* 2010).

Conclusions

In the Eastern Pyrenees, the Sardic unconformity separates two successions with different structural features. The Cambrian–Lower Ordovician and the Upper Ordovician succession are affected by Late Ordovician extensional tectonics and by two Variscan deformation events. Moreover the Cambrian–Lower Ordovician succession is also affected by an Early–Mid Ordovician fold system that we relate to extensional faults. Upward propagation of some of these extensional faults during Sandbian–Katian times, caused that faults affect the Sardic Unconformity and the lowermost part of the Upper Ordovician succession.

We relate the extensional fault formation to a thermal doming developed between 475 and 450 Ma. The doming should have produced stretching of the Ordovician lithosphere, together with emersion, uplift and erosion of the Cambrian–Ordovician sequence giving rise to the formation of the Sardic Unconformity. Thermal doming may be also responsible of coeval magmatic activity well developed in the same area and caused by hot mafic magma underplating. We compare the Mid Ordovician Sardic unconformity in the Pyrenees with contemporaneous gaps recognized in Sardinia and the Occitan Domain, and also discuss the similarities with the Furongian Toledanian gap described in the neighbouring Iberian Massif, which may have been originated in similar scenarios.

We suggest a regional-scale thermal event ranging in age from Early–Mid to Late Ordovician, which affected several areas of the Northern Gondwana margin. Their role in the geodynamic scenario that originated other significant Early Palaeozoic events, as the opening of the Rheic

569 Ocean and the drift of Avalonia (*sensu lato*) from the western part of North Gondwana, has to
570 be investigated.

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FIGURE CAPTIONS

Fig. 1. Geologic sketch of the Eastern Pyrenees with the location of the study area.

Fig. 2. (a) Detailed geologic map of the study area. (b) Geological cross-section of the study area. Location on Fig. 1.

Fig. 3. Cambrian-Ordovician and Upper Ordovician stratigraphic log measured near Ordén (top at GSP point). Location on Fig. 2. 1) shales; 2) siltstones; 3) sandstones; 4) conglomerates; 5) quartzites; 6) marlstones; 7) fossils; 8) ripples; 9) plane lamination; 10) bioturbation.

Fig. 4. Examples of the Upper Ordovician unconformity in the study area. **UO**, Upper Ordovician; **CO**, Cambrian-Ordovician. Angular unconformity, 78° (a), 69° (b), and 34° (c) respectively. Location on Fig. 2.

Fig. 5. (a) 3D representation of the study area with estimation of the orientation of the unconformity surface and the extensional faults; (b) equal area lower hemisphere stereoplot of the unconformity and (c) equal area lower hemisphere stereoplot of extensional faults from cartographic data using MOVE software.

Fig. 6. (a), (b), (c), (d), (e) and (f) Equal area lower hemisphere stereoplots of the disposition of the Upper Ordovician bedding surfaces in the six domains (D1, D2, D3, D4, D5 and D6) individuated from west to east between the extensional faults. The Upper Ordovician unconformity surface is shown (red dashed line) in the stereoplots together with the average bedding planes (black lines) in (a, b, c, d), or the best-fit girdle (blue line) in (e) and (f). *n* indicates the number of measurements.

Fig. 7. Equal area lower hemisphere stereoplots of bedding (S_0), D_2 related mesostructures (S_2 cleavage and L_{0-2} intersection lineation), and D_3 related mesostructures (S_3 cleavage and L_{0-3} intersection lineation) from the Cambrian–Ordovician (a, c and e) and Upper Ordovician successions (b, d and f) in the study area. In (c) and (d), the L_{0-2} intersection lineations are distributed along a great circle that is coincident with the S_2 average plane (in green) and in (e) and (f) the L_{0-3} intersection lineations are distributed along a great circle that is coincident with the S_3 average plane (in red). *n* indicates the number of measurements.

Fig. 8. (a) Sketch and equal area lower hemisphere stereoplot of the Upper Ordovician unconformity (83/033) overlying Cambrian–Ordovician subvertical beds (296/77 and 178/86);

(b) disposition of the Cambrian–Ordovician beds after a ca. 90° rotation about a horizontal axis parallel to the unconformity (00/123).

Fig. 9. (a), (b), (c) and (d), detailed sketches showing the disposition of S_0 bedding planes in the Cambrian–Ordovician rocks. Inset, location of the different zones.

Fig. 10. Breccia levels of the Rabassa Conglomerate Formation neighbouring synsedimentary normal faults at La Molina. (a) Clast-supported angular cobbles of sandstone and shale (derived from the underlying Jujols Group) mixed with hydrothermal quartz clasts sourced from synsedimentary veins (arrowed). (b) Thin-section photomicrograph of previous sample showing reworked hydrothermal polycrystalline quartz (pQ), siltstone (s), claystone (cl) and mafic phenocryst (v) clasts embedded in an unsorted sandy-to-clayey matrix; scale = 1 mm.

Fig. 11. (a) Sardinian angular discordance separating the Jujols shales (left) from the Rabassa breccia deposits (right) at Talltendre. (b) Subvertical dyke of hydrothermal quartz representing a synsedimentary fault marking the Jujols/Rabassa contact at La Molina; scale = 10 cm. (c) Folded dykes of hydrothermal quartz encased in the Jujols shale neighbouring a synsedimentary normal fault that separates it from the Rabassa Formation at Talltendre. (d) Basal part of the Rabassa Formation close to the unconformity of Figure 11a, showing a breccia of clast-supported polymictic blocks rich in shales and sandstones of the underlying Jujols Group and hydrothermal quartz clasts sourced from the dykes (arrowed) that crosscut the outcrop at Talltendre. (e) Matrix-supported breccia of the Rabassa Formation with folded dykes of hydrothermal quartz (arrowed) at Talltendre. (f) Typical clast-supported polymictic conglomerate of the Rabassa Formation at La Molina. (g) Amalgamated trough cross-stratified sets of a lenticular sandstone package, up to 2.2 m thick and 8 m of lateral continuity, embedded in shales; lower part of Cava Formation at Talltendre.

Fig. 12. Relative probability plot of the geochronological ages (U-Pb on zircon) of the Ordovician magmatism of the Pyrenees. Data after Deloule *et al.* (2002), Cocherie *et al.* (2005), Castiñeiras *et al.* (2008), Denèle *et al.* (2009), Casas *et al.* (2010), Liesa *et al.* (2011), Martínez *et al.* (2011), Mezger & Gerdes (2016), Navidad *et al.* (2018) and Liesa *et al.* (unpublish.); n=25

Fig. 13. Sketch showing the geodynamic evolution described in the text (not to scale).

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Dear Editor,

Barcelona, June 13th 2019

We submit the revised version of the manuscript: **“Deciphering the Sardinian (Ordovician) and Variscan deformations in the Eastern Pyrenees, SW Europe”** that we would like to publish in your journal. We would like to acknowledge the two reviewers for their detailed work and constructive criticisms. We have incorporated most of their suggestions, which we feel has significantly improved the manuscript. We hope that with all the incorporated changes (in red in the manuscript) this contribution will be now suitable for publication in your journal.

We have incorporated the formal suggestions and the comments of the reviewer#1 about shortening the text. Some reorganizations of the text have also been done to avoid repetitions. Discussion chapter have been reorganized. Also we enlarged Conclusions chapter and the structural domains defined in the study area have been renamed.

We have also acted positively on most of the comments of reviewer#2 concerning the text and the figures. However, there are some points in which our opinion differs from that of the reviewer. The changes introduced are detailed below together with some responses to their suggestions:

ABSTRACT

As the work talks about the Paleozoic rocks and Variscan deformation of the Pyrenees, the Axial Zone should be named in the abstract and described in the introduction or geological setting. It is mentioned in line 531 for first (and unique) time.

Revision: No, because the Axial Zone refers to the Alpine structure of the Pyrenees, not the Variscan one. In line 531 we are talking about the “Axial Zone” of the Montagne Noire.

Line 20: Say better "The Jujols Group", instead "Cambrian-Lower Ordovician" to avoid repetitions, because is already said that the Cambrian-Ordovician rocks are the Jujols Group.

Revision: Done

INTRODUCTION

Lines 38-62 (first paragraph of the introduction) starts mentioning the deformation events of the pre-Variscan rocks. I recommend add cites here (line 41). However, then only describe

the antecedents of the Ordovician deformation. As the text talks about the Variscan structure too in the text (D2 and D3), antecedents about that should be included in the text.

Revision: Done

Line 64: New structural data

Revision: We disagree because this would be repetitive.

Line 65: La Cerdanya should be localized on map of Fig. 1 and reference it on the text.

Revision: Done

Line 69: origin and meaning, instead of meaning and origin.

Revision: Done

GEOLOGICAL SETTING

More references to the figures to better follow the text, especially figs. 2 and 3.

Revision: Done

Line 77: The Orri thrust should be depicted in the maps.

Revision: No, because this thrust is not cropping out in the Eastern Pyrenees

Line 83: Show La Molina locality in maps.

Revision: Done

Line 84: Age instead of datum.

Revision: Done

Line 96: Include cite for the gap found in Sardinia.

Revision: Done

Line 105: I think it is not necessary to include the words "conglomerate" and "quartzite" because the formations are going to be described after.

Revision: No because they are the formal names of the formations described

Line 120: I consider it is not necessary to start the paragraph with "Moreover". It can start with "The presence of volcanics...".

Revision: Done

Line 134: Delete the comma after Zwart to homogenize the cites.

Revision: Done

Lines 133-155: Last paragraph of geological setting introduces main deformation in the studied area by previous authors. D3 seems to be the main deformation phase, but a better description for the D1-D2 citing previous authors should be done. Thus, restructure this paragraph for better understanding.

Revision: Done

STRUCTURE

This section only should include structure description and observations made by the authors. However, in some cases, they also include interpretations (e.g. line 206, 213, 279, ...). Please, move all the interpretations to the discussion section and show better your own results, especially in subsections D1, D2 and D3 structures, and extensional faults. I also consider that in these subsections, the authors should better remark the vergency of the structures.

Revision: this chapter has been modified

Line 167: Delete ". ". Add "software" after MOVE.

Revision: Done

Line 173: Reference fig. 3 too.

Revision: Done

Line 189: "trends" or "orientations" instead of "attitudes".

Revision: Done

Lines 194-195: It is confusing talk about cleavage surfaces before the descriptions in the next paragraphs.

Revision: Done

Line 230: I consider that the comment about the S2 deflection is obvious and unnecessary.

Revision: We disagree. No structuralists can find this comment necessary to follow the argument.

Line 256: Where the axe of this fold should be?

Revision: In some part in the middle of the Canigó massif, North of the study area

Line 280: "peter out" is informal. Use decrease, or other synonym.

Revision: Done

Line 298: Fig. 6e.

Revision: Done

DISCUSSION

Line 318: The discussion should be better introduced, with sentences presenting the interpretation of the deformation phases, and not in the description above. Discussion section should be last section before Conclusions. However, there are three sections (Tectonically induced sedimentation; Origin of the Sardic unconformity, extensional faults and D1 folds; and Comparison with other neighbouring areas) that is not clear that are included inside the discussion, and they should, because authors compare with previous works.

Revision: Done, this chapter has been reordered

Line 327: Why Alpine? Cite references or explain it.

Revision: Deleted to avoid ambiguities.

From line 329 talks about the unconformity in the subsection of "Age and significance of D1 folds" and it is confusing mixing both structures. Please, separate them. Also, in this paragraph (and other parts of the text) doubt words as "perhaps" or "seems be" are included. I recommend do not use them and use more consistent sentences.

Revision: Done

Lines 344-348: This sentence is too long and also some words are repeated (faults, as a result). Rewrite it to better understanding.

Revision: Done

Line 352: "As a result" again.

Revision: Done

Lines 338-366: This paragraph is difficult to follow. Maybe some sketches or more references to figures make it easier to understand.

Revision: This paragraph has been rewritten

Lines 386-390: There are some repetitions in this sentence and can be simplified. For example, it is said twice that S1 is the main cleavage in the studied area and other massifs.

Revision: This paragraph has been rewritten

Line 408: As said above, it is not clear that this section is included or not in the discussion. And, in my opinion, it should.

Lines 416-428: This paragraph includes a very good description of the Rabassa conglomerates, however should be in the geological setting with the description of the units and not in the discussion.

Line 430: The beginning of this paragraph is confusing: Where are recognized the facies? The "Rabassa fm." has to be mentioned there.

Revision: This chapter has been reorganized and repetitions avoided

Line 441: Interpretations of the Sardic unconformity and D1 folds are also in the first subsection of the discussion. It should be reorganized for better understanding.

Lines 443-455: This paragraph seems a detailed introduction of next ones. It should be shorter, and not repeat ages that be cited below.

Revision: The chapter has been reorganized

Line 468: Affected or originated?

Revision: Done

Line 489: Maybe add a sentence about the Toledanian phase, that is in lines 554-556.

Revision: Done

Lines 505-510: This sentence is too long, should be separated in two shorter sentences to better understanding.

Revision: Done

Line 521: "Grabbens" instead of "granbens".

Revision: Done

Lines 525-530: Cite references.

Revision: Done

Lines 539-541: Same, cites would help.

Revision: Done

Lines 547: Do not recommend start a paragraph by "As a result". It should be continuation of the previous because continues talking about the same.

Revision: Done

Lines 557-559: The Toledanian phase should be described the first time is mentioned.

Revision: Done

Lines 566-572: Long sentence.

Revision: Done

Lines 576-577: What the felsic and calc-alkaline magmatic rocks imply? Explain in a few of words.

Revision: This is explained in the lines below.

CONCLUSIONS

Line 591: It is better to be consistent and do not use doubt words as "may" (same in line 596). And "Ma" instead of "m.y."?

I suggest add a short paragraph (a couple of sentences) about the structure and deformation phases of the studied area because is it detailed on the text and appear in the title.

Revision: Done

ACKNOWLEDGEMENTS:

Line 611: Software packages/programs.

Revision: Done

FIGURES

1: Smooth the line of the thrust. Add more coordinates in the vertical axe. Line up the squares of the legend. Also add some localities I mention above.

Revision: Done

2: Line 1095: through? Add to the legend the blue thrust of the map and the dotted weave (NE of the map). Also add some localities I mention above.

Revision: Done

3: This stratigraphic column is very detailed for this work. I suggest to a simpler one. Moreover, all the data on the right side is unnecessary, and this legend is not explained. Is that all the Silurian thickness that there is in the area? If not, close with a discontinuous line.

Revision: The discontinuous line is added in gap of the Silurian and the figure captions enlarged to explain all the legend

4: Add in the figure caption "CO" and "UO". Is there creep in picture B?

Revision: Done. No it is a visual effect probably.

5: *Numbers in B and C are very small. And also points, it is not easy to see. Line 1105-1106 "unconformity and normal faults surfaces; (b) stereographic projection of the unconformity, and (c) the extensional faults from cartographic data using MOVE software.*

Revision: Done

6: *What "1%" means in the stereoplots? As is always the same value I recommend add the data to the figure caption. In comparison, too many measures in D5 domain. The map (that is the same that is in fig. 2) is very big in the figure. As the only new information is the domains, I suggest add them to fig. 2 and reference it. This figure would be smaller and simpler, with all the importance on the stereoplots.*

Revision: Done

7: *Same of fig. 6 about the 1%, it is repetitive. Add to the legends of each stereoplot a dot with the foliations, to see that dots are S0/2/3 and the triangles are the lineations.*

Revision: Done

8: *I suggest not repeat the map again. If not, do it simpler: here, the topography in the inset is not necessary.*

Revision: Done

10: *Locate La Molina. Line 1136: "probably"?*

Revision: Done. Deleted.

11: *Locate La Molina. Line 1141: The Jujols/Rabassa contact is the unconformity. Line 1144: fig. 11A. Lines 1144-1147: Long sentence.*

Revision: Done

12: *It seems that there are too many publications for only 25 datations. Is it well? I suggest add a sentence to the figure caption with the isotops (U/Pb?) and mineral (zircons?).*

Revision: Done

13: *This figure is not very clear, and it is crucial for the text. Add all the colours to the legend (blue, dark green, red) even if it is obvious. a, b, c) should be at the left of the sketches. Arrows are very big too. To make it easier, I recommend add other sketch between the magmatism and the end. It seems that there are a lot of subsidence.*

Revision: Done. We don't consider necessary to add another sketch to the figure

Looking forward to hearing from you soon,

Yours sincerely,

Josep Maria Casas

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