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Discerning Variscan from Alpine deformation in the Pyrenean Axial Zone; insights from geochronologic and structural data

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Abstract. The Axial Pyrenean Zone constitutes the axis of the Pyrenees, an Alpine orogen. The ~~precambrian~~ and ~~p~~aleozoic rocks outcropping in this zone underwent two orogenies (the Variscan and Alpine orogenies). Within this zone, distinguishing Variscan from Alpine structures represents a very complicated task due to the scarcity ~~both of~~ geochronological data constraining the age of deformation and units younger than Permian which would be only affected by Alpine deformation. In this work we have dated a rhyolitic sill interspersed within the regional Variscan foliation (S1) by zircon geochronology with U-Pb ion probe (SHRIMP). This sill is located in the central part of the Axial Zone, between the Garone Dome and the Aran Valley Syncline, and it is folded by open and upright folds that also deform Variscan structures. The results indicate that the sill ha~~ve~~ an Early-Middle Permian age of 274±1.5 Ma. This age postdates the Variscan deformation that occurred between 380 and 290 Ma and indicates that the folds deforming the sill must be ~~of Alpine age.~~ Moreover, these folds are associated with a penetrative crenulation lineation recognized in the Garonne Dome that points to a possible Alpine origin for the macrostructural configuration of this dome. This work highlights the necessity of incorporating geochronological data to correctly interpret deformation in complex areas as the Axial Pyrenean Zone affected by two orogenies.

1 Introduction

The superposition of different tectonic stages represents a very common phenomenum affecting most orogens and sedimentary basins worldwide. In the Iberian Peninsula two important orogenies spaced in more than 200 million years, the Variscan (Middle-Late Carboniferous) and Alpine (Late Cretaceous-Miocene) orogenies, took place and only areas showing pre-Cambrian to Carboniferous rocks underwent their superposition. The Pyrenean Axial Zone, in the core of the Pyrenees (Fig. 1A), represents an area where would be possible to analyse the overlap of both orogenies and the influence of the Variscan orogeny on the final Alpine structural frame as it mainly consists of Paleozoic rocks. However, this task is not easy due to the total or partial reactivation of structures, presence of two main rifting stages between the two orogenies, limited geochronologic data and lack of stratigraphic markers. With respect to this last point, a jointed analysis of deformation in Paleozoic and nearby Mesozoic-Cenozoic (pre-Miocene) rocks would help to distinguish Variscan from Alpine deformation, but unfortunately the presence of the younger rocks within the Pyrenean Axial Zone is very scarce. Thus, to discern between Variscan and Alpine deformation in the Pyrenees constitutes a major challenge in order to fully understand its overall geodynamic evolution and the Variscan fold belt.

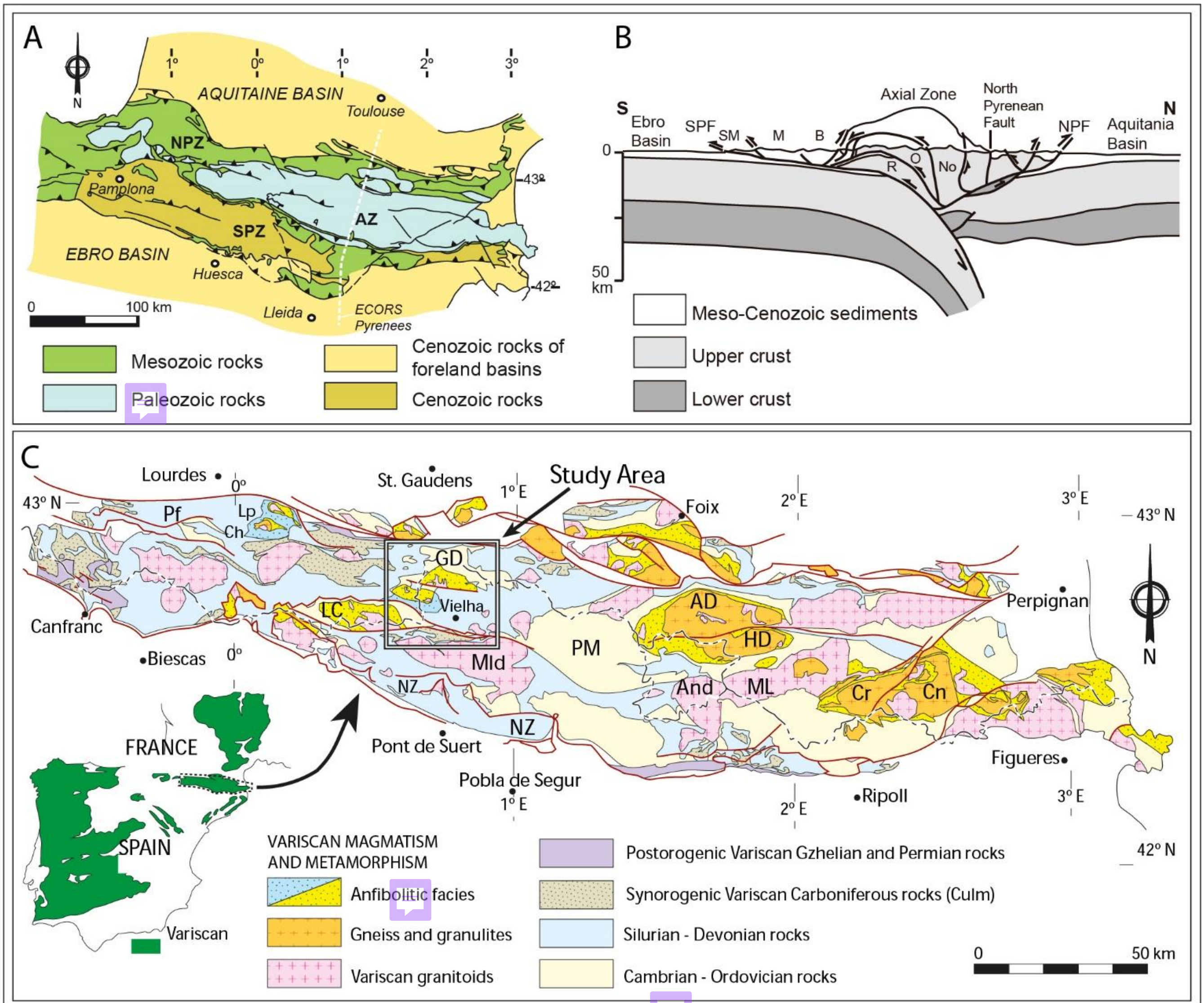

Figure 1: (A) Geological sketch of the Pyrenees with location of the ECORS-Pyrenees profle. Structural Units: SPZ, South Pyrenean Zone; AZ, Axial Zone; NPZ, North Pyrenean Zone. (B) Geological interpretation of the ECORS-Pyrenees seismic profle according to Muñoz (1992) (C) Geological map of the study area. (1) Jujols Series, (2) Bentaillou Limestone, (3) Upper Ordovician succession, (4) Silurian black slates, (5) Devonian rocks, (6) Carboniferous rocks, (7) Mesozoic rocks, (8) Granitoids, (9) Biotite Zone, (10) Cordierite-Andalusite Zone, (11) Sillimanite Zone, (12) Variscan thrust, (13) Alpine fault, (14) Zn-Pb-mine. GD: Garona Dome, AVS: Aran Valley Sinclinorium, LCM: Lys–Caillaouas Massif, NPF: Northpyrenean Fault, NPZ: Northpyrenean Zone, SPZ: Southpyrenean Zone (modified of Autran and García-Sansegundo, 1996).

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The present configuration of the Pyrenean Axial Zone responds to an antiformal stack formed by several Alpine basement thrusts (Fig. 1B) (e.g. Fischer, 1984; Déramond et al. 1985; Willians, 1985; Muñoz, 1985; Cámara and Klimowitz, 1985; Vergés et al., 1995 and Teixell, 1998). The structural architecture of the Axial Zone is rather heterogeneous highlighting strong differences along- and across-strike on its petrophysics, structure and metamorphism. The Variscan inheritance has played a major role controlling these variations (e.g. García-Sansegundo et al., 1992; Cochelin et al., 2018; Waldner et al., 2021), but also crustal thickness variations and the non-cylindrical crustal stretching between the European and Iberian plates during the Mesozoic have influenced (e.g. Banda et al., 1995; Bond and McClay, 1995; Soto et al., 2006). Some of the features varying through the Pyrenean Axial Zone are; (i) number and distribution of Alpine thrust sheets involving basement (e.g. Parish, 1984; Williams, 1985; García-Senz et al., 2020), (ii) Alpine cleavage, better developed in the western and southern parts of the Pyrenean Axial Zone (Muller and Roger, 1977; García-Sansegundo, 1992; Gil-Peña, 2004; Gutiérrez-Medina et al., 2012), (iii) metamorphism, which shows higher grade at its central-eastern part (e.g. Gil-Peña and Barnolas, 2004), (iv) age of ~~the~~ rocks, older towards the East of the Axial Zone, (v) heterogeneous distribution of the Silurian shales, which acted as an effective detachment level for Variscan and Alpine basement thrust sheets (e.g., Matte, 1969; García-Sansegundo, 1990; García-Sansegundo et al., 2011; Casas et al., 2019; Cochelin et al., 2017; Marcén et al., 2018), and (vi) presence of ESE–WNW elongated structural antiforms or domes, also increasing in number towards the East whose origin is still not well understood (Zwart, 1979; Soula, 1982; Van den Eeckhout, 1986; Kriegsman et al., 1989; Pouget, 1991; Abalos et al., 2002; Mezger et al., 2004; Denèle et al., 2014; Carreras and Druguet, 2014; Mezger and Gerdes, 2016; Cochelin et al., 2017) (Fig. 1C).

In this work, we ~~realize~~ a throughout revision of the structure and chronological succession of Variscan and Alpine deformational events in an area located in the central Pyrenean Axial Zone thanks to zircon U–Pb dating of a sill interspersed in the regional foliation. The study area is located between the Garona Dome, one of the ESE–WNW enlogated antiforms characterizing the Pyrenean Axial Zone, and the Aran Valley Synclinorium (Fig. 1C). Moreover, it shows three types of structures formed and/or reactivated during the Alpine orogeny (Fig. 2A); (i) inverted Ordovician normal faults, as the E-W Bossots Fault which runs across the study area cutting all previous Variscan structures (García-Sansegundo and González-Santano, 2023) (Fig. 2A), (ii) inverted Mesozoic normal faults, such as the North Pyrenean Fault (Teixell et al., 2018) limiting the Garona Dome to the North, and (ii) Alpine thrusts as the Gavarníe Thrust, developed on the southern limb of the Aran Valley Synclinorium (García-Sansegundo, 1992; Ortuño et al., 2008; Soler et al., 1998, Teixell et al. 2018). The importance of distinguishing between Variscan and Alpine deformation is crucial for fully understanding the geodynamic evolution of the Pyrenees and solid evidences must be derived from properly dated stratigraphic markers as done here.

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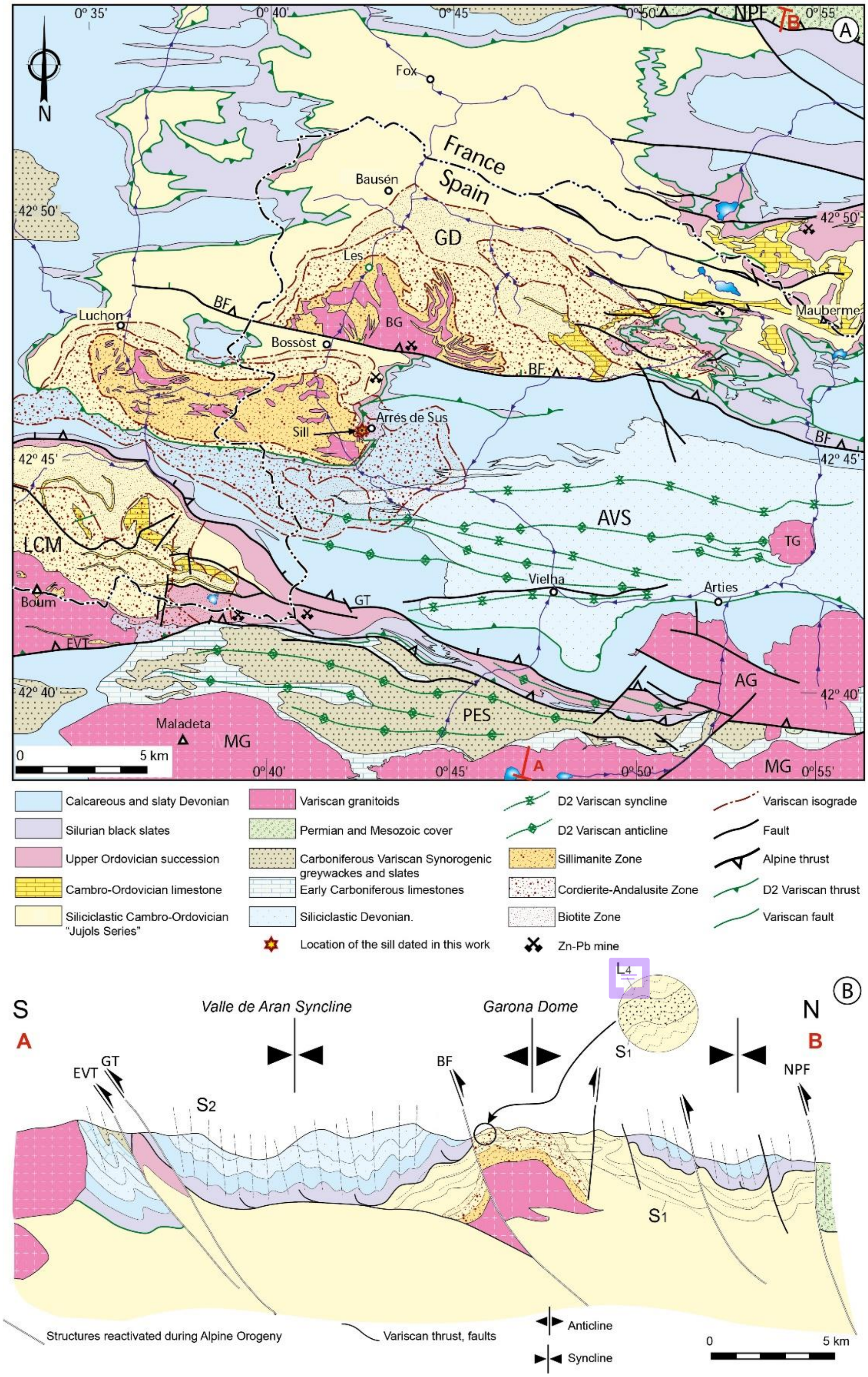

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Figure 2: (A) Geological map of the study area. The metamorphic zones correspond to Variscan metamorphism. In the Alpine thrust the green triangle and segment indicate reverse or normal Variscan movement, respectively and the black segment indicates a normal Alpine movement. AG: Arties Granite, BF: Bossòst Fault, BG: Bossòst granitois, AVS: Aran Valley Synclinorium, GD: Garona Dome, Sinclinorium, LCM: Lys–Caillaouas Massif, MG: Maladeta Granite, NPF: Northpyrenean Fault, PES: Plan d' Estan Synclinorium, TG: Tredós Granite, GT: Gavarnie Thrust, EVT: Eriste-Vallarties Thrust. Location in figure 1. (modified from García-Sansegundo and Ramírez Merino, 2013; Sanz López, J. and Palau, 2013). (B) geological cross section of the study area located in the figure 2a.

2 Geological setting

The Pyrenees formed due to the convergence between the Iberian and European plates from Late Cretaceous to Miocene (Savostin et al., 1986). This process originated an asymmetric double vergence orogen whose general structure is determined by Alpine thrusts. The Pyrenees are divided into three structural zones across strike from north to south (Mattauer, 1968; Séguret, 1972): the North Pyrenean Zone, the Axial Zone and the South Pyrenean Zone. Mesozoic and Cenozoic rocks crop out mainly in the Northern and Southern Pyrenean Zones while the Axial Zone is composed of Late Proterozoic and Paleozoic rocks. To the north and south, the range is flanked by the Aquitaine and Ebro foreland basins, respectively (Fig. 1A).

The Pyrenees underwent two orogenies, the Variscan (Middle-Late Carboniferous) and Alpine (Late Cretaceous-Miocene) ones, and two main rifting cycles during the Mesozoic affecting the Variscan basement. The Late to post-Variscan orogenic stage was characterized by extension and thinning linked to orogenic collapse and calc-alkaline magmatism (e.g. Faure et al., 2002; López-Gómez et al., 2019; Lloret et al., 2021). This extensional stage was characterized by the formation of small basins limited by normal faults and WNW-ESE grabens and/or half grabens, parallel to the direction of previous Variscan structures (e.g. Saura and Teixell, 2006). At present, most of these basins are located along the southern edge of the Axial Zone. The filling of these basins consists of thick volcanic (andesitic and dacitic lavas and ignimbrites) and volcano-sedimentary (conglomerates, sandstones, siltstones and lacustrine limestones) rocks (e.g. Gisbert, 1981; Simón-Muzas, 2022). This effusive event was chronologically coeval with the intrusion of the Late Carboniferous-Permian igneous bodies (granodiorites, sills and dikes) located in the Axial Zone (Pereira et al. 2014, Lloret et al., 2021). In the Axial Zone, the Alpine thrusts gave rise to an antiformal stack of basement thrust–sheets involving Late Proterozoic and Paleozoic rocks previously affected by Variscan deformation and metamorphism (Fig. 1B) (e.g. Fischer, 1984; Willians, 1985; Muñoz, 1992; Vergés et al., 1995; Teixell, 1998).

The study area is located in the central Pyrenean Axial Zone. The principal macrostructures that can be identify there from north to south are (Fig. 2A): the North Pyrenean fault, the Garona dome, the Bossots fault, the Aran Valley Sinclinorium, the Gavarnie thrust, the Plan d' Estan Synclinorium and the Eriste-Vallarties thrust. These structures were originally described by Danolli (1913, 1930), Kleinsmiede (1960), Sitter and Zwart (1962), Zwart (1965), Matte (1969) among others. The sampled rock for further chronological analysis is located close to the locality of Arrés de Sus (Spain), at the northern half of the Aran Valley Synclinorium (Fig. 2A). The Aran Valley Synclinorium is filled with Silurian and Devonian rocks. It is located in the footwall of the Bossost fault, which transported southwards Cambro-Ordovician rocks involved in the Garona dome (Fig. 2B).

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2.1 Stratigraphy of the study area

The stratigraphy of the study area is characterized by Cambrian to Devonian metasedimentary rocks of low to high metamorphic grade, Carboniferous rocks, a Late Carboniferous-Permian granitic body and Mesozoic rocks outcropping to the north of the North Pyrenean fault (Fig. 2A).

Cambrian to Devonian metasedimentary rocks can be grouped into four units: (I) Jujols Serie (Cavet, 1957), which have a Cambro-Ordovician age and are made up of centimeter to meter alternations of quartzite and slates, (II) the Upper Ordovician succession (Hartevelt, 1970), which is unconformable to the previous one and is made up of sandstones, microconglomerates and slates, with an interbedded limestone level (García-Sansegundo and Alonso, 1989; García-Sansegundo et al., 2004), (III) the Silurian black slates, whose fossil content has allowed to attribute them to the middle Llandovery–Lockchovian (Donnot, 1974; Dégardin, 1988), and (IV) the Devonian rocks, with frequent facies changes, which are formed by a thick serie of limestones and slates in the lower part and sandstones and slates in the upper part (García-López et al., 1991; Kleinsmiede, 1960). Above, the Carboniferous rocks consist of Lower Carboniferous white limestones (Bouquet and Stoppel, 1975) and a siliciclastic succession formed by sandstones, shales and occasionally conglomeratic levels attributed to the Pennsylvanian (Waterlot, 1969; Dalloni, 1910, 1913; Arche, 1971). At the northern sector of the study area, north of the North Pyrenean Fault, Upper Cretaceous rocks outcrop, which consist of flysch made up by marls, slates and conglomerates.

One of the features of the Pyrenean Axial Zone is the presence of several Late Variscan granitic bodies (Esteban et al., 2015) that intruded Cambrian to Carboniferous rocks. The Late Variscan granitic rocks outcropping in the study area correspond to the Bossòst Granitoid in the central part and in the southern part, the Lys–Caillaouas, Tredós, Artiés and La Maladeta granites (Fig. 2A). The Bossòst Granitoid has a general leucocratic and pegmatitic composition (Debon et al. 1996) and it is formed by a main granite body made up of several small stocks located at the central part and numerous sills parallel to the subhorizontal regional foliation (Fauré, 1963). The host rocks of the Bossòst Granitoid are usually the Cambro-Ordovician rocks of the Jujols Series. They are affected by a high temperature and low pressure metamorphism (HT–LP) reaching the Sillimanite Zone (Fig. 1 and Fig. 2). Some facies of the Bossòst Granitoid provided ages between 327 and 338 Ma (Mezger and Gerdes, 2016), although recently in one of the small stocks of the main body, two populations of zircons have been obtained yielding two age groups (317–329 Ma and 295±2 Ma), which has been interpreted related to two magmatic pulses (López-Sánchez et al., 2019); the first one at the beginning of the Variscan deformation, during the Early Carboniferous (Viseense–Serpukhoviense) and the second one, Late Variscan, in the Early Permian.

3 Variscan deformation and metamorphism

The Variscan orogeny took place during the Middle-Late Carboniferous and gave rise to a collisional orogen in central and southwestern Europe (Matte y Ribeiro, 1975; Matte, 2001). In the Pyrenees, the Variscan deformation can be only found in the Axial Zone, in the core of the belt (Fig. 1A). The tectonic imprint of the Variscan orogeny on both the deformation of

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affected rocks and the general configuration of the Pyrenean Axial Zone has been long studied and nowadays is receiving much attention.

The work by Zwart (1963) represents one of the first studies analysing the Variscan deformation in the Pyrenean Axial Zone. This author proposed a vertical variation of the structural style distinguishing two structural domains in function of the different metamorphic grade and attitude of the main cleavage; infrastructure and suprastructure domains. In the infrastructure domain, the main cleavage has a flat-lying attitude and is usually associated with middle to high grade HT-LP metamorphism, whereas in the suprastructure domain, the cleavage is subvertical and was generated in low grade metamorphic conditions (Zwart, 1979; Carreras and Capella, 1994 and references therein). The space-time relationships and the geological setting where these two domains developed are still controversial and two end-members models have been proposed to explain them; continuous versus polyphase deformation.

Models interpreting a single and continuous deformation period are mainly based on structural studies on calc-alkaline plutons and gneiss domes. They interpret the formation of both steep and flat-lying structures under a dextral transpression setting (e.g. Bouchez and Gleizes, 1995; Gleizes et al., 1998; Mezger and Passchier, 2003; Aurejac et al., 2004; Vilà et al., 2007; Denèle et al., 2007; 2008; 2009; Mezger, 2009; Cochelin et al., 2017; 2018). They distinguish early and late deformation events and consider that during this second event, the formation of domes in the middle crust was contemporaneous with the development of steep foliation and emplacement of large plutons in the upper crust.

On the other hand, polyphase deformation models suggest the occurrence of at least two main Variscan deformational events in a general compressive tectonic scenario based on structural studies in various sectors of the central Pyrenees (e.g. Poblet, 1991; García-Sansegundo, 1996; Clariana and García-Sansegundo, 2009; García-Sansegundo et al., 2011; Pérez-Cáceres et al., 2023; Margalef et al., 2016; Clariana and García-Sansegundo, 2016; Casas et al., 2019; Margalef et al., 2023). The first deformational event consisted on the formation of north verging folds and associated planar tectonic foliation. The second main deformational event was characterized by the formation of south-verging to upright folds with a subvertical axial plane cleavage.

In the studied area, detailed structural analyses (see synthesis in García-Sansegundo, 1990, 1992, 1996) have revealed the next serie of structures developed in the following chronological order:

(a) Pre-orogenic Variscan structures. They consist of slaty cleavage (SE), vergent to the South, not associated with folds. This cleavage only affects the Cambro-Ordovician rocks of the Jujols Serie and has been interpreted related to a pre-orogenic Variscan event. In the study area, this cleavage SE has been related to the Upper Ordovician unconformity (García-Sansegundo and Alonso, 1989; García-Sansegundo et al., 2004), whose origin was interpreted as related with an extensional tectonic context (García-Sansegundo et al., 2014).

(b) D1 Variscan structures. They correspond to north-verging E–W trending folds. To the north of the Garona Dome, these folds are recumbent, very tight and kilometer in scale, while to the south of the Dome, in the Valle de Aran Synclinorium, the folds are inclined, smaller and with a greater angle between limbs. A tectonic foliation (S1) is associated with these D1 folds, which when it affects the Cambro-Ordovician rocks of the Jujols Series, corresponds to a crenulation cleavage (it gives rise to

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SE microfolding), while when it develops in more modern rocks, it occurs as a penetrative slaty cleavage (García-Sansegundo, 1996).

(c) D2 Variscan structures. They consist of south-directed thrusts that deform S1, detached at the base of the Silurian rocks, which upwards pass to upright E–W folds associated with a subvertical crenulation cleavage (S2) (Matte, 1969; García-Sansegundo, 1990; García-Sansegundo, 1992; García-Sansegundo, 1996). In the Garona Dome, below the Silurian detachment level, practically no D2 structures are developed. To the south of the Aran Valley Synclinorium, the D2 structures are cut by the La Maladeta Granodiorite, dated between 298±2.4 Ma (Evans et al., 1998) and 301.7±7 Ma (Martínez et al., 2016).

(d) D3 Variscan structures. They are only developed within the metamorphic aureole of the Bossòst Granitoid. It is a discontinuous band, between 3–5 km wide, dipping to the North, into which rotated andalusite, staurolite and cordierite porphydoblasts are occasionally observed including a folded S1. A local tectonic foliation (S3) develops around these porphyroblasts, generalized throughout the band and whose position is coincident with S1, thus overlapping it. Cordierite and staurolite porphyroblasts are observed in the Aran Valley Synclinorium, near the Bossòst Granitoid, including S1 deformed by D2 folds and surrounded by the S3 foliation (García-Sansegundo and González-Santano, 2023).

Regarding metamorphism, two main Variscan metamorphic episodes, identified by Mezger and Passchier (2003), have been recognized in the study area:

(i) M1 Metamorphic episode. It is recorded by the growth of staurolite and garnet on the Cambro-Ordovician slates of the Jujols Series. The porphyroblasts of this first metamorphic episode include S1 inside and their growth may be related to the intrusion of dikes and/or sills related to the first magmatic pulse recorded in the Bossòst Granitoid, with ages between 338 and 317 Ma. (Visean-Serpukhovian) (Mezger and Gerdes, 2016; López-Sánchez et al., 2019).

(ii) M2 metamorphic episode. It is characterized by the synkinematic growth of staurolite, cordierite and andalusite and the development of the S3 foliation. It is contemporary with the D3 structures and the second magmatic pulse of the Bossòst Granitoid during the Early Permian.

4 Methodology

The methodology included sampling, field and laboratory work to perform a geochronology analysis of a sill outcropping in the study area and a structural analysis and comparison with structures observed in the study area.

The geochronological study was done using zircon U–Pb dating in the Ibersims Laboratory of the University of Granada using an ion probe (SHRIMP). The analytical protocol is published at the web address: https://www.ugr.es/~ibersims/ibersims/Zircon_U_Pb_analysis.html. ~~Sampling was done in one sample and a~~ total of 16 zircons were separated from ~~the studied rock~~. The methodology used in the laboratory was as follows, hand-picked zircons from the studied samples, several grains of the TEMORA-1 standard (for isotope ratios; Black et al., 2003), one grain of the SL13 zircon standard (for U concentration, Claoué-Long et al., 1995), plus a few grain of the REG zircon (plenty of common lead, for calibrating the masses) are cast on a 3.5 cm diameter epoxy mount (megamount), polished and documented using optical (reflected and transmitted light) and scanning electron microscopy (secondary electrons and cathodoluminescence). After extensive cleaning, mounts are coated with ultra pure gold (8 - 10 nanometers thick) and inserted into the SHRIMP for analysis. The analytical method follows that described by Williams and Claesson (1987). Each selected spot is rastered with the primary beam for 120 s prior to the analysis, and then analysed 6 scans, following the isotope peak sequence 196Zr2O, 204Pb, 204.1background, 206Pb, 207Pb, 208Pb, 238U, 248ThO, 254UO. Every peak of every scan is measured sequentially 10 times with the following total counting times per scan: 2 s for mass 196; 5 s for masses 238, 248, and 254; 15 s for masses 204, 206, and 208; and 20 s for mass 207. The primary beam, composed of single charged, double 16O ions, is set to an intensity of about 5 nA, with a 120 microns Kohler aperture, which generates 17 x 20 micron elliptical spots on the target. The secondary beam exit slit is fixed at 80 microns, achieving a resolution of about 5000 at 1% peak height. All calibration procedures are performed on the standards included on the same mount. Mass calibration is done on the REG zircon (ca. 2.5 Ga, very high U, Th and common lead content). Every analytical session starts measuring the SL13 zircon, which is used as a concentration standard (238 ppm U). The TEMORA-1 zircon (416.8 ± 1.1 Ma), used as isotope ratios standard, is then measured every 4 unknowns. Data reduction is done with the SHRIMPTOOLS software (available from www.ugr.es/~fbea), specifically developed for IBERSIMS by F. Bea. This software is a new implementation of the original PRAWN software developed for the SHRIMP, and has been extensively checked against PRAWN and Ludwig's SQUID. SHRIMPTOOLS is platform-independent and runs on any Windows, Mac or Unix computer regardless of language, time, and date system settings. It has been written in the programming language of the STATA commercial package which implements powerful algorithms for robust regression, outlier detection and time-series analysis. The software calculates the intensity of each measured isotope in two steps. First, it uses the STATA letter-value display algorithm to find outliers in the ten replicates measured in each peak during each scan, discarding them and averaging the rest. Then, the blank, measured at 204.1 mass is subtracted from each peak. This may produce negative values in mass 204 when it recorded next to zero counts. Once normalized to the SBM measurements, the software calculates the 204/206, 207/206, 208/206, 254/238 ratios using Dodson's (1978) double linear interpolation method. The 206/238, 206/195, 238/195, and 248/254 ratios are calculated by dividing the value at the mid-time of the analysis of each isotope calculated from the robust regression lines of the peak average of each scan vs the time at which it was measured. Errors for Dodson interpolated ratios are calculated as the standard error of the (scans-1) interpolations for each ratio. Errors for the isotope ratios calculated by regression result from propagating accordingly the standard error of the linear prediction at the mid-point of the analysis. 206Pb/238U is calculated from the measured 206Pb+/238U+ and UO+/U+ following the method described by Williams (1998). The error reported for 206Pb/238U includes (1) the error in UO+/U+ (2) the error in the regression line ln (UO+/U+) vs ln (206Pb/238U) (3) the standard error in the replicate measurements of the TEMORA zircon. For high-U zircons (U > 2500 ppm) 206Pb/238U is further corrected using the algorithm of Williams and Hergt (2000). Though seldom necessary, the software also permits correction for instrumental drift with time using the sequence of replicate measurements of the TEMORA zircon.

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5 Results

5.1 Sill and structure description

The sampled rock consists of a rhyolitic sill of 35 – 40 centimeters thickness located on the northern half of the Aran Valley Sinclinorium and in the footwall of the Bossòst thrust (Fig. 4). It appears intruding Silurian ampelites.

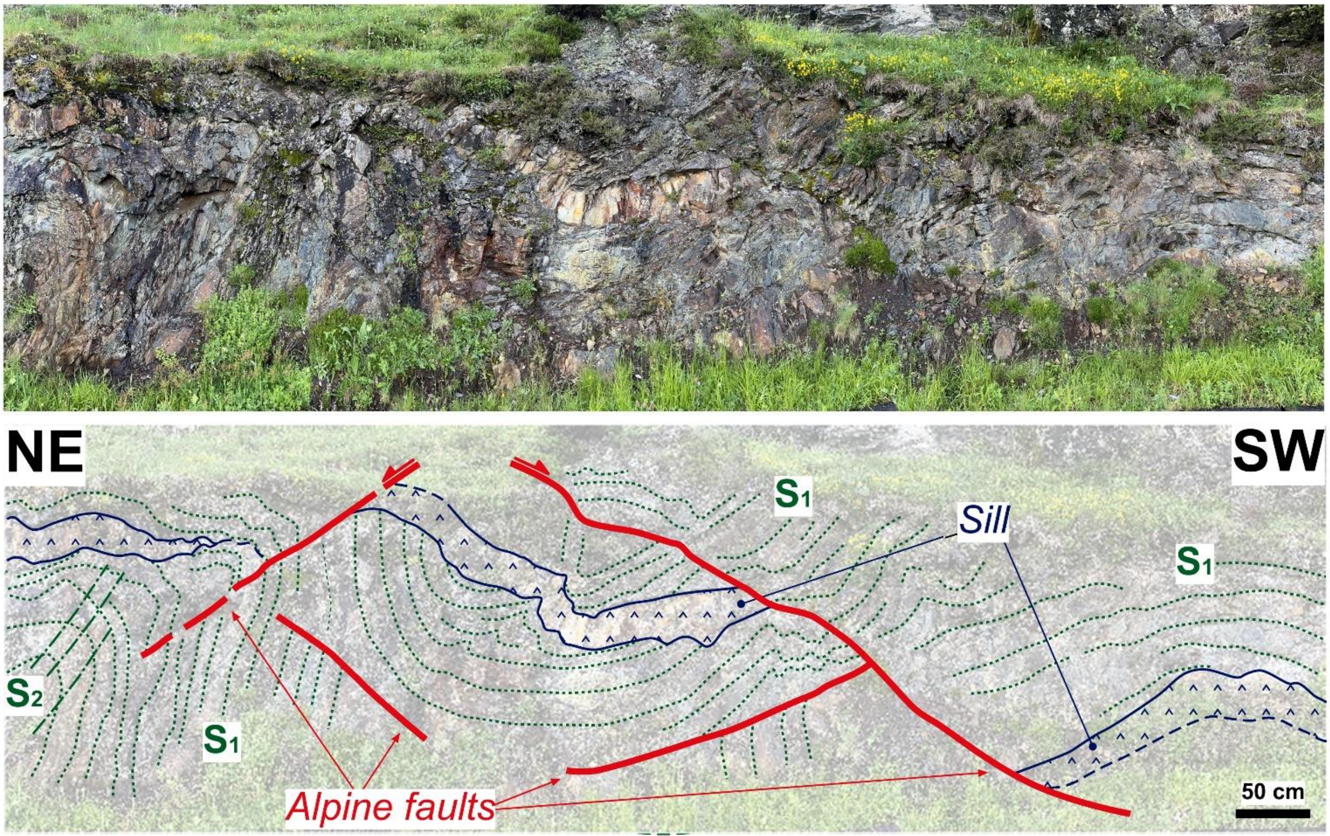

Figure 4: Outcrop of the Permian sill dated in the present work (42º45'30.1"N; 0º42'25.5"E, see location in figure 2A). Notice the S1 Variscan foliation, deformed by tight D2 folds. The sill cross-cut the S1 foliation and is deformed by open folds, some of which result from the flattening of Variscan D2 folds. The S1 foliation and the sill are also affected by normal faults.

The sill consists of a coarse-grained and leucocratic rock with a porphyritic texture that shows evidence of hydrothermal alteration. The primary mineralogy was totally replaced by a secondary paragenesis that includes carbonates and sericite as pseudomorphs, possibly plagioclase, and a matrix of carbonates, sericite, and quartz, with occasional opaque minerals. The studied sill probably corresponds to an original dike of intermediate-acid composition (andesite–dacite), based on this secondary paragenesis and the presence of plagioclase as phenocryst within quartz.

The studied sill appears interspersed within a subhorizontal foliation (S1 in Fig. 4). This foliation S1 affects the Silurian rocks outcropping between the Garona Dome and the Aran Valley Synclinorium. Close to the sill, an incipient second foliation (S2) can be recognized in the hinge zone of south-directed vergence folds (D2 structures). This S2 foliation affects the foliation S1

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identified in the Silurian rocks and it has been also recognized in rocks of the Garonne Dome and the Aran Valley synclinorium being the dominant foliation in the latter. The sill, however, cross-cuts foliation S1. The sill, and also the Silurian rocks in the study area, are deformed by open upright E-W folds. A penetrative E-W trending crenulation lineation appears associated with these open upright E-W folds that can be observed in the Silurian ampelites (Fig. 4). It is worth highlighting that these last folds have also been recognized in the Garona Dome, where produced re-tight of D2 folds and that the observed penetrative E-W trending crenulation lineation coincides with lineation L4 defined by García-Sansegundo (1992) and also identified in Paleozoic metasedimentary units within the Garona Dome. Finally, both the sill and Silurian rocks are affected by small and ~~fragile~~ normal faults.

Therefore, it turns that at least two tectonic episodes must occur after the intrusion of the sampled sill dated as Early-Middle Permian (Kungurian-Roadian); (1) the deformational event producing the open upright E-W folds associated with a penetrative E-W trending crenulation lineation, and (2) an extensional stage to account for the normal faults.

5.2 Geochronological data

The results of isotopic analysis of zircons show a population of concordant ages of varied zircons (Fig. 3A, C) ca. 850 Ma, 650, 560, 470 and 270 Ma, the latter being the most abundant and most recent age, with a concordant population of 20 points that give a concordant age of 274±1.5 Ma (Fig. 3B). Therefore, this sill is dated as Early-Middle Permian (Kungurian-Roadian). This dating has strong consequences as it post-dated the Variscan orogeny and ~~can be used as stratigraphic marker of~~ the Alpine deformation.

This crystallization age is consistent with those obtained by different authors for other sectors of the Pyrenean Axial Zone in calc-alkaline magmatic rocks (Aguilar et al., 2014; Denèle et al., 2012; Schnapperelle et al., 2020), while the inheritances are consistent with those previously described in other works (Mezger and Gerdes, 2016).

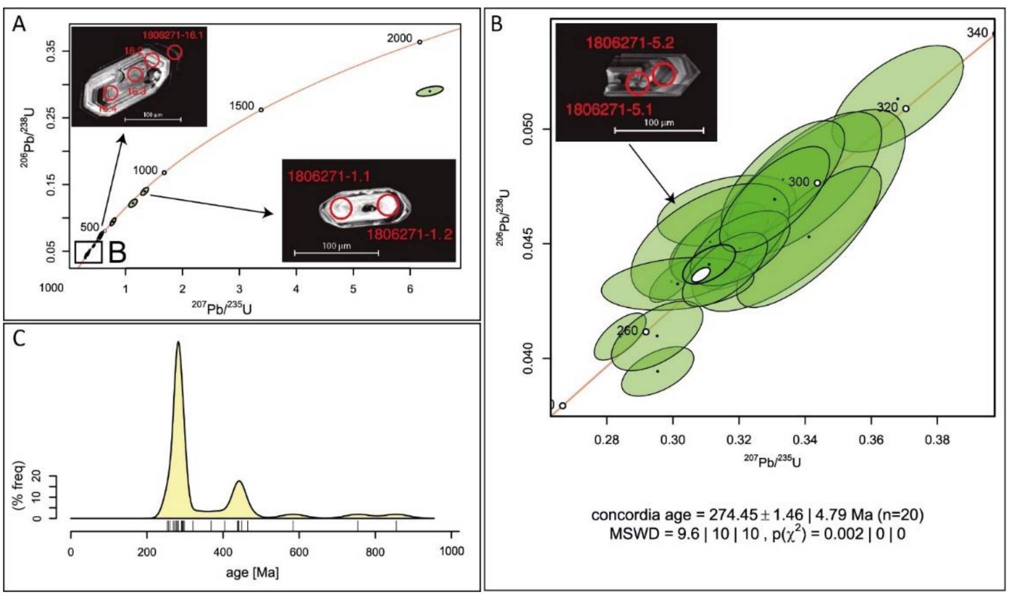

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Figure 3: U–Pb SHRIMP data from the zircon population analyzed from the sill. A) Concord curve with the total data and two of the zircons analyzed. B) Concord age U–Pb on 20 data and example of one of the zircons analyzed. C) Modal distribution of Pb206/U238 ages of the analyzed data population, showing a main inheritance age around 480 Ma.

6 Interpretation and discussion

6.1 Variscan and Alpine deformation

Taking into account the Permian age of the sampled rock, a detailed revision of the structure and metamorphism of the study area has been done in terms of interpreting the chronological succession of tectonic events (Table 1).

AGE	DEFORMATION EVENT	STRUCTURES	FEATURES	REFERENCES
Upper Cretaceous - Miocene	Alpine deformation →←	- Crenulation lineation (L4) - Upright E-W folds	- Tightening pervious D2 folds - Open upright E-W folds - Development of the Dome geometries	- This work
Mesozoic	Rifting stages ←→	- Normal faults	- Major normal faults. E.g. Gavarnie Thrust.	- García-Sansegundo and Ramírez-Merino (2013)
Late Carboniferous - Permian	D3 Variscan Event ←→	- Rotated porphiroblast - Tectonic foliation (S3)	- Ductil deformation in de Middle crust - Normal faults in the Upper crust	- Saura and Teixell (2006) - Casas (2007) - Clariana and García-Sansegundo (2016) - García-Sansegundo and González-Santano (2023)
Carboniferous	D2 Variscan Event →←	- D2 folds - S2	- Scarce bellow Silurian detachment level - Upright E-W folds - S2, Crenulation clevage	- Matte (1969) - García-Sansegundo (1996)
Carboniferous	D1 Variscan Event →←	- D1 folds - S1	- E-W North verging folds - S1, Crenulation clevage (Jujols Serie), Slaty clevage (Ord. Sup, Sil and Dev. rocks)	- Matte (1969) - García-Sansegundo (1996)
Pre-Carboniferous	Pre-Variscan Event ←→	- Slaty Clevage (SE)	- Not associated with folds - Only affects the Jujols Serie	- García-Sansegundo et al. (2014) - Casas et al. (2019)

Table 1: Deformation events and related structures identified in the study area.

In the study area, the polyphasic model describing two main Variscan compressional events explains and satisfies the observed structures and associated foliation. A general consensus exists postulating that the compressive Variscan deformation of the Pyrenean Axial Zone ends after the development of the D2 structures (Carreras and Druguet, 2014; Casas et al., 2019). Afterwards, the final stage of the Variscan cycle has been described linked to extensional tectonics related to the collapse of the Variscan orogen and associated to calc-alkaline magmatism (García-Sansegundo et al., 2011; Lloret et al., 2021). ~~Within the uppermost crust, evidences~~ of this Late Variscan extensional tectonic context have been found in the southern part of the Pyrenean Axial Zone, where normal faults have been recognized cutting structures comparable to the D2 Variscan structures described in this work (Casas et al., 2007). These normal faults, in turn, are cut by the Andorra Granitoid of 305+3 Ma in age (Romer and Soler, 1995). In addition, to the South of the Pyrenean Axial Zone, the Permian outcrops are found deposited in

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small, narrow E–W basins, limited by normal faults in the same direction (e.g. Saura and Teixell, 2006; Lloret et al., 2021; Simón-Muzas, 2022). This Late Variscan extensional stage has been also characterized by ductile extensional structures as stretching lineations, boudins and rotated porphyroblasts. These structures, conversely, are restricted to the surroundings of Late Carboniferous-Permian granitic bodies inferring a possible genetic relationship between these two processes (i.e. extensional deformation and intrusion of igneous bodies) (García-Sansegundo et al., 2011; Clariana and García-Sansegundo, 2016; Pérez-Cáceres et al., 2023). In the studied area, this type of structures is represented by structures ~~D3~~ and they are restricted to the metamorphic zones related to the Bossòst Granit~~iod~~. Therefore, a Late Variscan extensional stage has been detected in the Pyrenean Axial Zone characterized by the formation of normal faults in superficial zones of the crust and extensional ductile structures in deeper zones, as that appearing close to the Bossóst Granitoid in the Garona Dome and Aran Valley Synclinorium (Mezger, 2005, 2009; Mezger et al., 2004).

With respect to the Alpine compressive structures, in the Pyrenean Axial Zone they have traditionally been interpreted as south–directed thrusts displacing and rotating units of Paleozoic rocks with Variscan deformation to configurate an antiformal–stack (e.g. Muñoz, 1992; Williams, 1985). Some of these Alpine thrusts are easily recognizable, as they jointly deform Paleozoic basement rocks and Permian, Mesozoic and/or Cenozoic rocks of the cover (Fig. 5). This is the case of the Gavarnie Thrust which, to the west of the study area, appears as a tectonic window, with Paleozoic rocks in the hanging wall and Mesozoic rocks in the foot wall. To the east, the Gavarnie Thrust is folded by an anticline. In the study area, the northern limb of this anticline shelters Permo–Triassic rocks (Mattauer and Séguret, 1966; Soler et al., 1998) and it appears as a normal fault (García-Sansegundo and Ramírez-Merino, 2013). This indicates its nature as a Mesozoic extensional fault reactivated as thrust during the Cenozoic (see also Teixell et al. 2018), although there the reverse fault displacement did not compensate that of the normal fault (Fig. 5).

Based on data obtained in this work, the smooth upright E–W folds that deform the sill and the associated penetrative crenulation lineation post-date the sill. Taking into account that the sill has been dated as Early-Middle Permian, this deformation event must be posterior and associated with a compressive event that in the study area would take place in the Late Cretaceous-Miocene compressional stage of the Alpine cycle. The occurrence of E-W penetrative crenulation lineation post-dating a Permian sill has important consequences as it indicates that this Alpine compressive deformation could also have a ductile character. Ductile Alpine structures, similar to those described here, have recently been recognized in other sectors of the Pyrenean Axial Zone, where Helvetic-type nappes were described deforming Silurian–Devonian rocks in relation to the Eaux–Chudes Alpine Thrust, located to the NW (Caldera et al., 2020). Moreover, the occurrence of this deformation within the Garona Dome could imply a genetic relationship as we will explain below.

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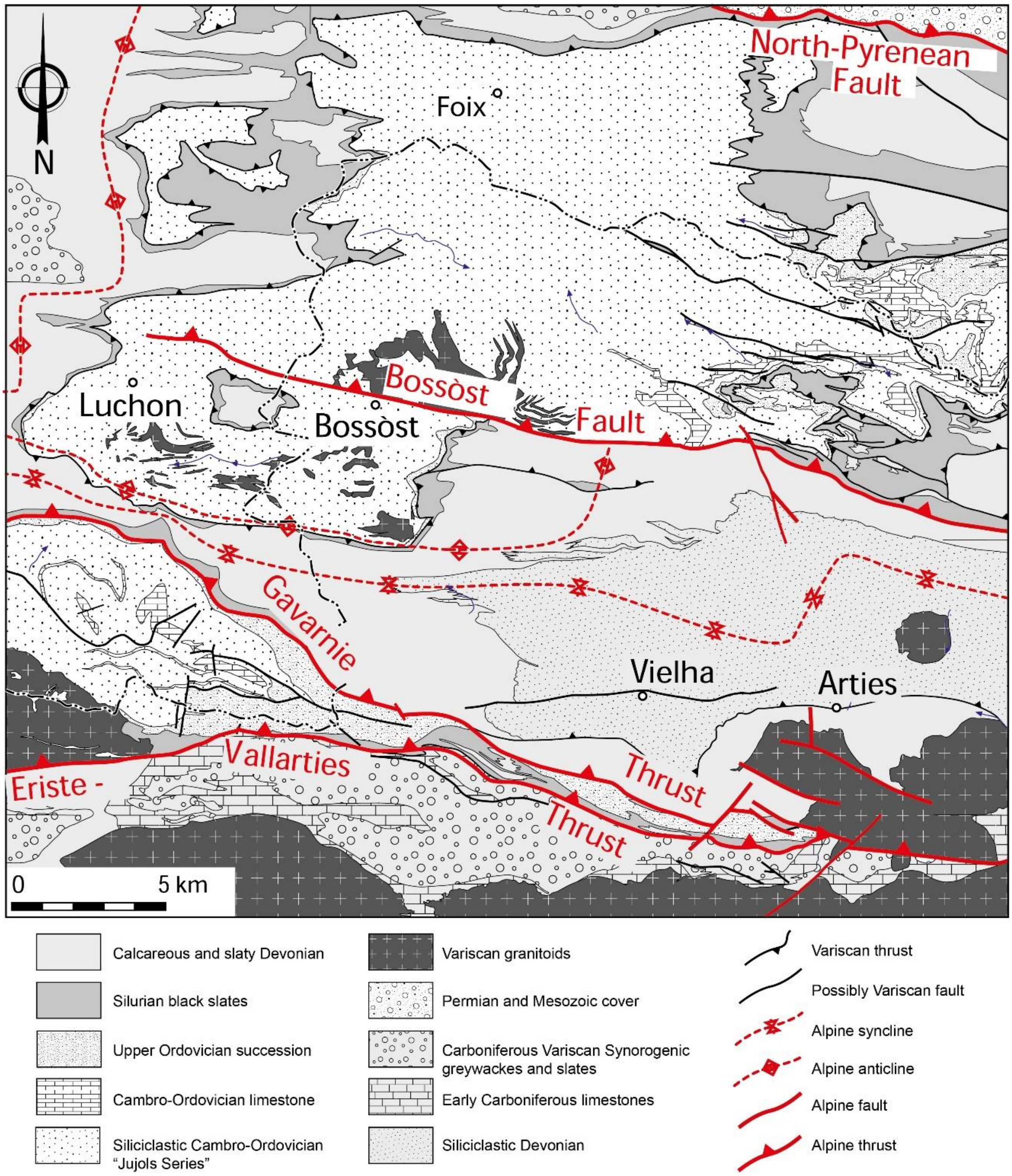

320 **Figure 5: Geological map of the study area ~~showing~~ the main Alpine structures.**

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6.2 Origin of the Pyrenean Axial Zone structural domes

The Pyrenean Axial Zone is characterized by the presence of several WNW-ESE elongated structural antiforms or domes, which number increases towards the East. Their origin is still a matter of debate (Zwart, 1979; Soula, 1982; Van den Eeckhout, 1986; Kriegsman et al., 1989; Pouget, 1991; Abalos et al., 2002; Mezger et al., 2004; Denèle et al., 2014; Carreras and Druguet, 2014; Mezger and Gerdes, 2016; Cochelin et al., 2017). The domes are ubiquitous structures in the hinterland of all exhumed orogens and their origin is still not well understood (Díez-Montes, 2006 and references therein). They have been interpreted in relation to compressional (Amato et al., 1994; Burg et al., 1984; Lee et al., 2000; Takeshita and Yagi, 2004) and extensional contexts, in the latter case linked to processes of fusion of the crust (Coney, 1980; Davis, 1988; Harris et al., 2002; Lister and Davis, 1989; Vanderhaeghe et al., 1999). In compression contexts, the causes that originate them can be fold interference, buckling or antiformal-stack formation. In extensional contexts, they can be related to metamorphic core complex formation processes (Díez-Montes, 2006 and references therein), although an intermediate origin is also proposed with the implication of compressional or extensional processes (Lee et al., 2000). In the study area, in the hanging wall of the Bossòst thrust, the Garona Dome crops out (Fig. 2B). It has a general WNW-ESE trend and it is characterized by two strongly dipping limbs separated by a wide hinge zone that configures the dome itself and deforms the metamorphic isogrades linked to the Bossòst Granitoid (Carreras, J. & Debat, P. (coord.), 1996).

In many works carried out in the Pyrenean Axial Zone, it has been interpreted that domes similar to that of the Garona originated during the emplacement of granitoids in intermediate levels of the crust (Denèle, 2007; Denèle et al., 2009, 2014; Mezger, 2005; Mezger and Gerdes, 2016; Zwart, 1979) or as a result of the superposition of two folding phases (Carreras and Druguet, 2014). Other interpretations have considered they formed as structural-metamorphic domes during the Variscan deformation (Pouget, 1991; Soula, 1982) or as in the case of the l'Hospitatet (Van den Eeckhout, 1986) or the Lys–Caillaouas massifs (Kriegsman et al., 1989), they formed as a product of extensional tectonics contemporaneous with the development of Variscan subhorizontal foliation.

In general, the core of the Pyrenean Axial Zone domes is constituted by rigid bodies of igneous rocks; Ordovician ~~augen~~gneises in the Canigó, Carança, l´Hospitalet and Astón domes and Variscan granitoids in the Garona, Lys–Caillaouas, Chiroulet and Lespone domes. Around these rigid igneous rocks forming the domes, the Paleozoic metasedimentary units are deformed by Variscan structures and in the Garone dome open folds accompanied by a penetrative crenulation lineation (L4 in García-Sansegundo, 1992) have been identified. This crenulation lineation coincides with that described in this work associated with folds deforming the Permian sill and therefore, interpreted as formed during the Alpine compressive deformation. Thus, we interpret that the formation of the Pyrenean Axial Zone domes took place during the Alpine compression. The rheological contrast between the igneous rocks located in the core of the domes and the surrounding Paleozoic metasedimentary units could play a major role to account for the observed deformation (i.e. limbs of folds in the Paleozoic metasedimentary units coincide with the termination of the rigid igneous bodies) and the current domed geometry. Previous Variscan structures could be deformed ductility, folded or flattened and acquire higher dips thanks to this deformation and the vertical attitude of the

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northernmost Alpine thrusts of the Pyrenean Axial Zone could be related to the formation of the domes (Fig. 2B). In the study area, to the south of the Garona Dome, the Aran Valley Synclinorium, dominated by D2 Variscan structures (Fig. 2B), could have been tightened during the Alpine Orogeny.

Thus, in this part of the Pyrenean Axial Zone, the Alpine compressive deformation not only consists ~~of~~ the development of thrusts that displace and rotate the Paleozoic units, but ~~also~~ it is ductile, capable of producing open folds, at all scales, with wide hinges and strongly dipping limbs, associated with a penetrative crenulation (L4) developed in the Lower Paleozoic rocks themselves (Fig. 2B). In the same way that the Garonne Dome has been interpreted as an Alpine structure, it is possible to consider an Alpine origin for the rest of the domes in the Pyrenean Axial Zone, thus evidencing the development of ductile deformation in the Palaeozoic rocks of the Pyrenean basement related to Alpine compression.

7 Conclusions

- In the transition between the Garona Dome and the Aran Valley Synclinorium, a rhyolitic sill ~~interspersed in the~~ Variscan subhorizontal foliation (S1) has been dated at 274±1.5 Ma (Kungurian - Roadian; Early-Middle Permian) by zircon geochronology with U-Pb ion probe (SHRIMP). This sill is affected by open ~~and~~ upright folds that must be considered Alpine in age.
- The folds that deform the sill are associated with a penetrative crenulation lineation (L4) and with the structures responsible for the current configuration of the Garona Dome, which must therefore also be an Alpine structure.
- In the the Aran Valley Synclinorium, the Alpine deformation could have given rise to a tightening and flattening of the D2 Variscan structures and consisted of upright or south-verging folds, oriented in an E–W trending and to which the S2 crenulation cleavage was associated.

Author contribution

JGS and PC: have carried out the search and research process and data collection in the field. ARO: carried out the analysis of geochronological dating. JGS, PC and RS: original draft preparation with contributions from all co-authors. RS and JGS: Acquisition of the financial support for the project leading to this publication.

Competing interests

The authors declare that they have no conflict of interest.

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