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Geology of the basement rocks of Andorra, central Pyrenees

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ABSTRACT
In this work we present a 1:50,000 geological map of the basement rocks of Andorra that is the harmonization of the results of two decades of field work and data analyses in the frame of the 1:25,000 Geological Map of Andorra Project by CENMA–IEA (at present AR + I, Andorra Research + Innovation). The study area lies entirely in the Axial Zone of the Pyrenees, where only late Neoproterozoic and Paleozoic rocks and Quaternary deposits crop out. The map is produced at 1:25,000 scale and Quaternary deposits have been removed, in order to obtain a continuous basement map that can be used as the basis for stratigraphical and structural works. The main results of this work are the publication of new cartographic and structural data, as well as a better understanding of the stratigraphy in this sector.

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1. Introduction

1.1. Geological setting

Andorra is a country of about 470 km^2, with an average elevation of about 1900 m.a.s.l. located in the Pyrenees, an Alpine orogen in southwestern Europe, straddling the border between France and Spain (Figure 1(a)). The Pyrenees were originated by the convergence between Iberian and Euroasiatic plates from Late Cretaceous to early Miocene and constitute a thrust-dominated continental collision orogen (Muñoz, 1992; Pedrera et al., 2023). The Alpine deformation gave rise to E–W trending thrust sheets, some of which involved basement Neoproterozoic and Paleozoic rocks, forming an antiformal stack, which constitutes the so-called Axial Zone (Figure 1(b)). The Axial Zone is flanked by the North and South Pyrenean Zones, which are mainly composed of Mesozoic and Cenozoic rocks (Figure 1(a)) (Mattauer, 1968). Alpine metamorphism remains local and is weak enough, preserving the polyphased inherited structures (Muñoz, 1992; Pedreira, 2004). The Variscan deformation on the basement rocks of the Pyrenees changes from west to east. In the western and southern parts of the Pyrenees, the Variscan folds and thrusts developed under non-metamorphic or very low-grade metamorphic conditions, whereas towards the east of the Axial Zone, where Alpine erosion was more significant, deeper rocks are cropping out, and Variscan deformation occurred mainly under low-grade metamorphic conditions (García-Sansegundo et al., 2011). In some sectors, as in Andorra, located in the central-eastern part of the Pyrenean Axial Zone, rocks with high-grade metamorphic conditions and partial melting conditions (migmatites) are recognized (Figure 1(c)).

1.2. Previous work

In the middle twentieth century, Solé Sabarís and Llopis Lladó (1947) made the first geological map of Andorra. Later, during the 1960s and 1970s the geologists of Leiden University carried out a systematic mapping of the Central Pyrenees (see Zwart and De Sitter (1979) and references therein). The Dutch geologists published 10 map sheets (1:50,000 scale) of the Central Pyrenees in which, for the first time, some Ordovician and Devonian formations were described. Andorra was included in two of these maps: sheet 6 (Zwart, 1965) and sheet 10 (Hartevelt, 1970) that constituted the basis for the mapping during the following twenty years.

After two decades, the BRGM (Bureau de Recherches Géologiques et Minières) edited the Fontargente sheet (Besson, 1991) as part of the French geological mapping plan at 1:50,000 scale. This map includes the Andorra territory and introduced some new data with respect to the previous Dutch maps. Ten years later, the Earth Sciences Research Centre (CRECIT) (currently Andorra Research + Innovation) produced the first digital geological map of Andorra

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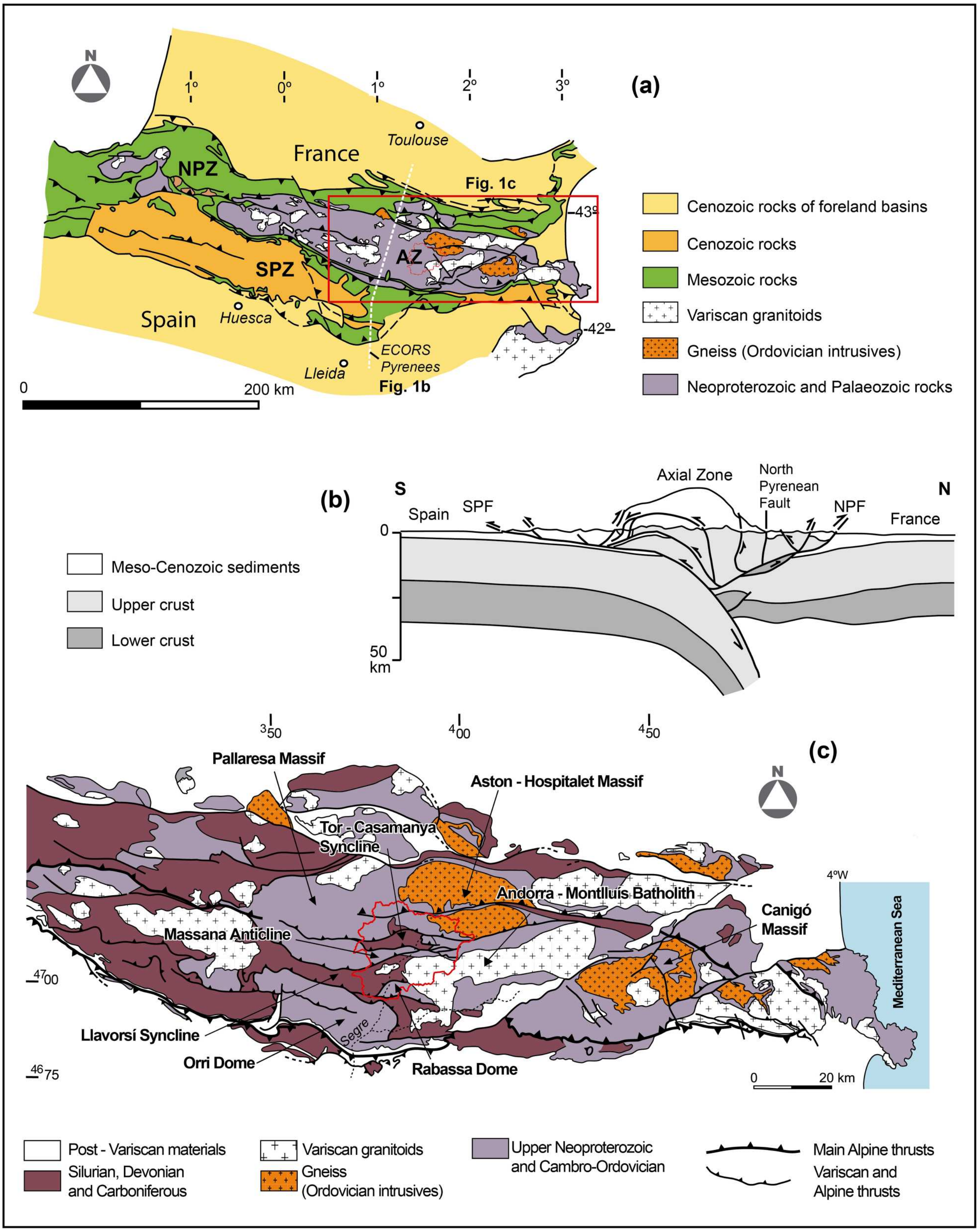

Figure 1. (a) Geological sketch of the Pyrenees with the location of the ECORS – Pyrenees profile (Figure 1b) (b) Geological interpretation of the ECORS Pyrenees seismic profile, from Muñoz (1992); AZ, Axial Zone; SPF, South Pyrenean front; NPF, North Pyrenean front. (c) Geological sketch of the Eastern Axial Pyrenees with indication of the main structures and the Andorra border in red, modified from Casas & Fernández, 2007.

(Casas et al., 2002). This map was a synthesis of the previous geological maps and added new data from detailed works carried out by Van den Eeckhout (1986), Poblet (1991) and Alías (1995). Nevertheless, this digital map did not provide significant changes.

In 2004, the CRECIT started 1:25,000 geological mapping of Andorra. In the frame of this project, several works were carried out (Clariana et al., 2004; Clariana & García-Sansegundo, 2009; Margalef et al., 2012, 2014) which concluded with the PhD

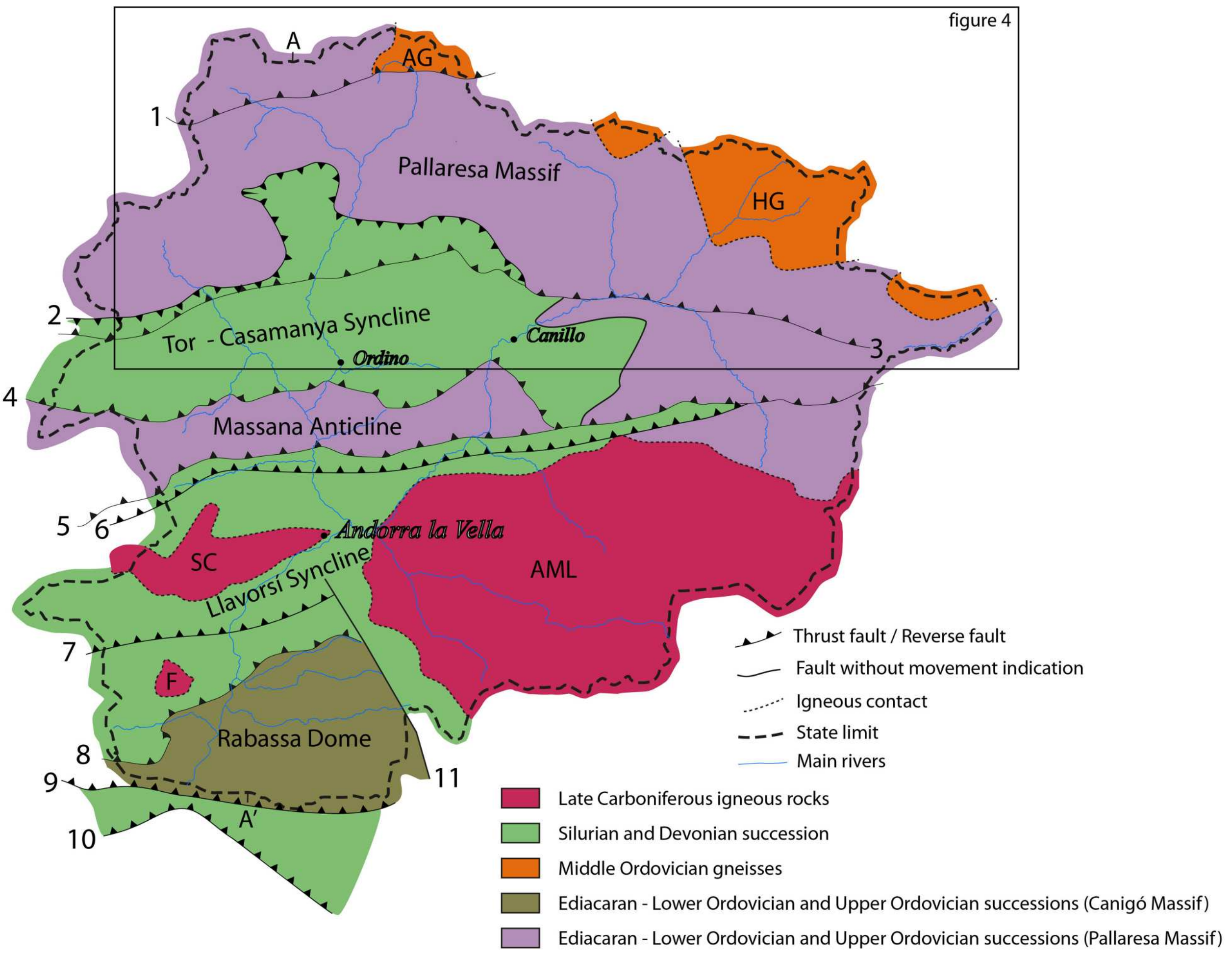

Figure 2. Sketch of the structural units defined in Andorra. AG: Aston gneiss, HG: Hospitalet gneiss; SC: Santa Coloma pluton; AML: Andorra–Montlluís Granodiorite; F: Fontaneda stock. 1. Mérens Fault; 2. Arinsal Fault; 3. Soldeu Fault; 4. Pal Thrust; 5. Estaron Thrust; 6. Encamp Thrust; 7. Bixessarri Thrust; 8. Sant Julià Thrust; 9. Arcavell Thrust; 10. Llavorsí Thrust; 11. Claror Fault.

thesis of Clariana (2015) and Margalef (2015). Both theses provided new data concerning stratigraphy, geochronology, metamorphism and structure of Andorra, as well as detailed geological mapping of the whole area. The geological map presented in this work is the result of the harmonization of the two geological maps that resulted from these PhD theses, which later have been revised and refined during several field campaigns.

In Andorra, the following structural units have been recognized based on rock ages and stratigraphical and structural features (Figure 2): (i) The northwest of Andorra is constituted by the eastern end of la Pallaresa Massif, made up by late Neoproterozoic (Ediacaran) to Lower Ordovician rocks; (ii) The northeast area is made up by the western end of the Aston and Hospitalet gneissic domes; (iii) In the central part, the Massana Anticline and the Llavorsí and the Tor–Casamanya synclines can be recognized; the first made up by Cambrian and Ordovician rocks and the two synclines by Silurian and Devonian rocks in their core; and (iv) In the southern area of Andorra, the Rabassa Dome is cropping out, that shows Cambrian and Ordovician rocks at its core and represents the western termination of the Canigó Massif (Hartevelt, 1970), an E–W oriented braquiantiformal dome mainly made up by a gneissic core surrounded by late Neoproterozoic (Ediacaran) to Upper Ordovician metasediments (Guitard, 1970). The Llavorsí Syncline and the Rabassa Dome are intruded by the Andorra–Montlluís Granodiorite, a late-Variscan batholith, which extends through the southeastern part of the territory.

2. Methodology

The Andorra geological map was prepared at a scale of 1:25,000, although it is presented at a scale of 1:50,000 to facilitate its visualization. Field mapping was mainly carried out at a scale of 1:10,000, although, when necessary, a more detailed scale was chosen (1:5000 scale). We used aerial photographs of the 1995 Andorran Government's flight at a scale of 1:16,000, the 2018 Andorran Government's orthophotography and the cartographic basemap of the topography of Andorra at a scale of 1:10,000, all of which can be downloaded from the server https://www.ideandorra.ad/geodades/index.jsp?lang=ca.

Structural data collected during field campaigns have been geolocated using a GPS system. Around 2400-point measurements (S_0 bedding, S_1 and S_2 cleavage, S_1/S_0 and S_2/S_0 intersection lineations and fold axes) were collected to perform the structural analysis, although only a selection of these data is displayed on the map. All the information compiled in the field campaigns has been integrated into a GIS project (ArcMap from ESRI's ArcGIS Pro, over the 1995 5×5 DTM base). Working in a 3D environment allowed constraining the 3D orientation of the macrostructures with limited outcrop access. The map is represented in the WGS 1984 UTM coordinate system, Zone 31N.

The Quaternary deposits, mainly influenced by glacial and fluvial-torrential dynamics (debris flow deposits, major landslides, screes, glacial drifts), often cover the bedrock. As the aim of this map is to represent the pre-Alpine basement rocks, the Quaternary deposits have not been represented, and the geology of the covered basement areas has been deduced based on the detailed geology of these areas.

3. Results

3.1. Stratigraphy

Pre-Alpine basement rocks cropping out in Andorra range in age from late Neoproterozoic (Ediacaran) to pre-Variscan Carboniferous (Figure 3). Below, the main features of the different lithostratigraphic units are described.

3.1.1. Ediacaran – Lower Ordovician succession

One of the first descriptions of this succession was made by Cavet (1957), in the Eastern Pyrenees. This author defined two series, from bottom to top, the 'Canaveilles series' and the 'Jujols schists'. Later on, Laumonier and Guitard (1986) and Laumonier et al. (2004) re-defined the Canaveilles and Jujols series as Groups. In the study area, three formations belonging to the Jujols Group are cropping out, from bottom to top: Alòs d'Isil, Lleret–Baiau and Alins formations. Recently, Padel et al. (2018) updated and revised the Ediacaran–Lower Ordovician successions of the Eastern Pyrenees and divide the Jujols Group into three formations; the Err, Valcebollère and Serdinya formations. These authors proposed that these formations can be correlated with the Alòs d'Isil, Lleret-Baiau and Alins formations respectively. We will use Serdinya Formation (equivalent to the Alins Formation) when referring to the Rabassa Dome.

The Ediacaran–Lower Ordovician succession of Andorra is mainly siliciclastic and can be recognized in three areas: (i) the northern sector, in the eastern Pallaresa Massif and the western–southwestern edge of the Aston and l'Hospitalet gneissic domes; (ii) the central sector, in the Massana Anticline; and (iii) the southern sector, in the core of the Rabassa Dome (Figure 2, Main Map).

In the northern sector, the Alòs d'Isil, Lleret–Baiau and Alins formations can be distinguished, while in the central and southern sectors only the Alins/Serdinya Formation is cropping out (See Main Map). The Alòs d'Isil Formation, with a minimum thickness of 400 m (Clariana, 2015), is composed of an alternation of white to light grey sandstones and dark grey shales of cm to dm thickness. Quartzite beds intercalated of 50–60 cm thick have also been identified. Above, the Lleret–Baiau Formation is made up of white limestone and black shales. The limestone horizons can reach 50 m thick and show an important recrystallization that does not allow the observation of sedimentary structures, only flat lamination is occasionally observed. The maximum thickness of this unit is 150 m (Clariana, 2015). Finally, the Alins/Serdinya Formation consists of mm to dm layers of grey to greenish grey shales and white sandstones, although the thickness of the alternating levels decreases towards the top of the formation. Several quartzite horizons, a few meters thick, are observed (Fontfréde Member, Padel et al., 2018). The thickness of this formation is difficult to estimate because its upper limit is eroded at different levels and unconformably covered by the Upper Ordovician succession. From the geological sections Clariana (2015), proposed a thickness of ca. 600 m. Acritarchs recovered from the uppermost part of this formation in the southern slope of the Canigó massif have yielded a broad Furongian–Early Ordovician age (Casas & Palacios, 2012), coincident with a maximum depositional age of *ca.* 475 Ma for the top of this succession based on the youngest detrital zircon population collected in the Rabassa Dome (Samples RB10-01; 02 and 03 in Margalef et al., 2016) (Figure 3).

3.1.2. Upper Ordovician succession

An unconformable Upper Ordovician succession overlies the Ediacaran–Lower Ordovician rocks (See Main Map). Significant erosion before the Late Ordovician sedimentation has taken place since in the Central and Eastern Pyrenees Upper Ordovician rocks overlie different parts of the pre-Upper Ordovician succession (Casas & Fernández, 2007; den Brok, 1989; García-Sansegundo et al., 2004; García-Sansegundo & Alonso, 1989; Kriegsman et al., 1989; Santanach, 1972; Puddu et al., 2019, amongst others). Margalef et al. (2016) proposed a time gap of about 20 Ma and Casas et al. (2023) a gap of 23 Ma in the Rabassa Dome by for the Upper Ordovician unconformity ('Sardic'), where Upper Ordovician rocks lie above the quartzites of the uppermost part of the Serdinya Formation.

In Andorra and in adjacent areas, Hartevelt (1970) defined five formations in the Upper Ordovician succession. From bottom to top, these are the Rabassa Conglomerate, Cava, Estana, Ansobell and Bar

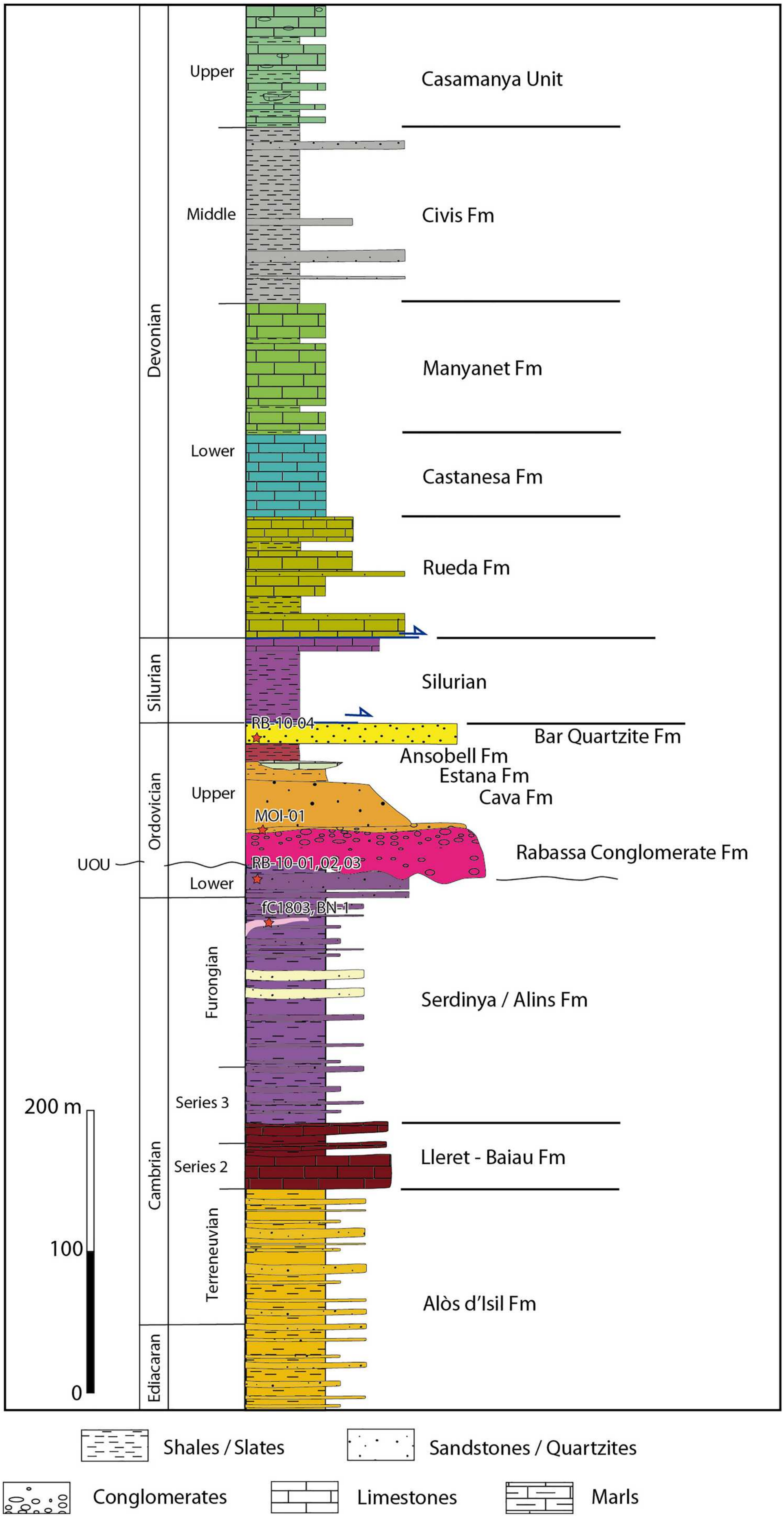

Figure 3. Stratigraphic log of the study area with location of the recently dated samples. Sample RB-10-04 from Margalef et al. (2016); MOI-01 from Casas et al. (2023); RAB-10-01, 02, 03 from Margalef et al. (2016); fC1803 from Clariana et al. (2018); and BN-1 from Casas et al. (2023). UOU, Upper Ordovician Unconformity.

Quartzite formations, which can be recognized with some thickness and facies variations over a wide area of the central and eastern Pyrenees (Figure 3). The Rabassa Conglomerate Formation consists of a broad fining-upward sequence of conglomerates made of heterometric, rounded to subrounded clasts of quartz, slate and schist, some of which of the Serdinya/Alins Formation. Its maximum thickness is about 20 m in the Rabassa Dome, and it gradually decreases towards the north, and in the northern half of Andorra it is not present. Hartevelt (1970) attributes a Sandbian (former Caradoc) age to this formation. The conglomerates transitionally turn to coarse sandstones of the overlying Cava Formation that consists of a fining upward sequence beginning with conglomerates that turn into coarse-grained feldspathic sandstones, and gradually into layers of fine-grained sandstones, shales and siltstones. This formation presents a characteristically greenish (when fresh) or reddish-purple colouring when altered. In some areas of Andorra Hartevelt (1970) and Silvério (2021) described abundant brachiopods, crinoids and bryozoans and Belaústegui et al. (2016) found Arthrophycus in the upper part of the Cava Formation, on the southern slope of the la Rabassa Dome, close to the Andorra–Spain border. Hartevelt (1970) and Gil-Peña et al. (2004) attributed a Katian age (former late Caradoc–early Ashgill) to this formation, in accordance with a maximum depositional age of around 453 Ma (Katian) based on the youngest detrital zircon population for the basal part of the Cava Formation (Casas et al., 2023). Its thickness ranges from about 250 m on the southern limb of the Rabassa Dome to 50 m on the northern limb of the Tor–Casamanya Syncline. These changes are probably related to syn-sedimentary extensional tectonics, as recorded in adjacent areas by Casas and Fernández (2007) and Puddu et al. (2019). The Cava Formation is overlain by the Estana Formation, cropping out only in several areas in Andorra and consists of brown to reddish-brown marls and slates, with abundant brachiopods, bryozoans, echinoderms and conodonts (Hartevelt, 1970; Silvério, 2021). Its thickness attains a maximum of 70 m in the western part of the Massana Anticline and, in neighbouring areas, a late Katian age was attributed to on the basis of its conodont content (Gil-Peña et al., 2004). The Ansovell Formation consists of monotonous unfossiliferous grey to black slates, with a thickness ranging between 30 and 200 m. Finally, the Bar Quartzite Formation consists of dark-grey, medium-rounded grained quartzites with ripples on its top. Its thickness ranges between 5 and 20 m in the study area. Sanz-López et al. (2002) and Štorch et al. (2019) attributed a Hirnantian age for this formation, based on conodont content from carbonate nodules on equivalent lateral sequences.

3.1.3. Silurian

The Silurian is represented by the characteristic black graphitic-bearing shales alternating with fossiliferous black limestones in its upper part. Silvério (2021) describes abundant graptolites in the black shales of the bottom of the sequence, while the limestones at the top are rich in gastropods, brachiopods, corals, crinoids and cephalopods (Orthoceras). Due to its plastic behaviour, Silurian shales act as an important décollement level (Hartevelt, 1970; Poblet, 1991) and as they are strongly deformed it is difficult to establish its thickness. Poblet (1991) estimated that it is about 110 m in the la Massana Anticline, while Margalef et al. (2023) proposed 200 m based on a cross-section.

3.1.4. Devonian succession

The modern studies of Devonian in the Central Pyrenees were made by the Dutch geologists of Leiden (Boersma, 1973; Hartevelt, 1970; Mey, 1967; Zwart & De Sitter, 1979). These authors defined most of the formations used nowadays. During the 1990s, other authors modified and refined some formations or stablished their age for the first time (García-López et al., 1990, 1991; García-Sansegundo, 1992; Palau, 1998; Poblet, 1991; Valenzuela-Ríos, 1994). Subsequently, García-Sansegundo et al. (2011) and Sanz-López (2002, 2004, 2019) proposed a division into sedimentary domains, based on the sedimentological characteristics, that made it possible to correlate different lithostratigraphic units along the Pyrenees. In Andorra, four of these Devonian formations are identified, from bottom to top: the Rueda, Castanesa, Manyanet and Civis formations (See Main Map). The Rueda Formation can reach 60 m thick and consists of an alternation of grey shales, carbonaceous shales and brown and grey limestones in which crinoids and orthoconic cephalopods remains are abundant. In its upper part, the limestone layers become more abundant, indicating a progressive boundary with the overlying Castanesa Formation. The conodont record from this unit in nearby sectors provided a Lochkovian–Praguian age (Valenzuela-Ríos, 2006). Above, the Castanesa Formation, 100 m thick, is characterized by grey massive limestones and marly limestones giving rise to characteristic ridges in the landscape. Crinoid, coral and trilobite bioclasts can be observed and conodonts from nearby sections provides Praguian age for the bottom and lower Emsian age for the upper part of this formation (Sanz-López et al., 2002). The upper boundary of this formation is sharp with the Fonchanina Formation, as can be observed westward of Llavorsí Syncline. Nevertheless, in the eastern end of this syncline and in the Tor–Casamanya syncline (Andorra sector), where the Fonchanina Formation does not crop out, a gradual transition to greenish marly limestones of Manyanet Formation is observed (Hartevelt, 1970; Poblet, 1991). The Manyanet Formation can reach 90 m in thickness and is composed of green marly limestones and beige to pinkish limestones containing crinoid and tentaculite remains. Its conodont content indicates an age ranging from the Middle Emsian to the Emsian–Eifelian boundary (Sanz-López, 2002). Above, the Civis Formation consists of a monotonous succession of micaceous grey shales with centimeter layers of marly limestone and sandstone interbedded with parallel lamination and ripples. Sanz-López (2002) proposed an Eifelian age for this unit based on conodont biostratigraphy. Recently, detailed geological mapping and biostratigraphic study have made it possible to identify an uppermost unit characterized by limestone, nodular limestone, calcareous shales, and shales (Clariana, 2015), named Casamanya Unit, which overlies the Civis Formation in the central–eastern part of the Tor–Casamanya Syncline (see Main Map). The conodont record of this unit indicates a Givetian to Famenian age (Valenzuela-Ríos et al., 2009).

3.1.5. Igneous rocks

The oldest metaigneous rocks that crop out in the area are the orthogneisses of the Hospitalet Dome. Its protolith (ca. 472 Ma, U-Pb on zircon, Denèle et al., 2009) is part of a widespread intrusion of voluminous granitic bodies present throughout the Central and Eastern Pyrenees, at the core of antiformal massifs, with ages ranging from late–Early Ordovician (Floian) to Late Ordovician (Sandbian–Katian) (Casas et al., 2010; Castiñeiras et al., 2008; Cocherie et al., 2005; Denèle et al., 2009; Liesa et al., 2011; Martínez et al., 2011; Mezger & Gerdes, 2016; Navidad et al., 2018). Volcanic and subvolcanic sills are interbedded within the pre-Upper Ordovician to Silurian sedimentary sequence. Up to now, two samples of subvolcanic rocks of Andorra have been dated. The first one is a rhyodacite sill interbedded in the Alins Formation from the Pallaresa Massif, giving an age of 453 ± 2Ma (Sandbian) (U–Pb CA-ID-TIMS in zircon, sample fC1803 from Clariana et al., 2018, figure 3). The second one is a rhyolite sill interbedded in the Serdinya Formation from the Massana Anticline, giving also a Sandbian age of 457 ± 1,4 Ma (U – Pb CA-ID-TIMS in zircon, sample BN-1 from Casas et al., 2023, figure 3). This volcanism is interpreted to be the last step of the Ordovician magmatic event responsible for the emplacement of the protolith of the gneiss (Aston and Hospitalet domes), coeval with the formation of the Upper Ordovician (Sardic) unconformity (UOU) and the development of extensional faults affecting the lower part of the Upper Ordovician succession (Casas et al., 2023; Puddu et al., 2019).

The most recent igneous bodies of Andorra are Andorra–Montlluís biotite-bearing granodiorite intrusion (*ca.* 305 Ma, U–Pb in zircon; Maurel et al. (2004); Romer and Soler (1995); and *ca.* 301 Ma U–Pb in zircon; Pereira et al. (2014)). Apart from the Andorra–Montlluís Granodiorite, two small bodies, the Santa Coloma pluton and the Fontaneda stock, are located in the southwestern part of the area. These bodies were emplaced coeval with the Variscan regional metamorphic peak (310–290 Ma, Vielzeuf et al., 2021; Cochelin et al., 2021) and the main Variscan deformation (Arranz & Lago, 2004), and cut through all previous Variscan structures (Casas et al., 1989, 2002; Margalef et al., 2023).

3.2. Structure

3.2.1. Structural units

As mentioned above, six structural units can be distinguished in Andorra, from north to south: the Hospitalet gneissic dome, the Pallaresa Massif, the Tor–Casamanya Syncline, the Massana Anticline, the Llavorsí Syncline and the Rabassa Dome (Figure 2). Except for the Hospitalet Dome, each structural unit thrust southwards by a set of approximately E–W-oriented south-directed north-dipping thrusts, that cut through previous folds (See Main Map) (Clariana, 2015; Losantos et al., 1988; Margalef, 2015; Poblet, 1991). These structural units are briefly described below:

3.2.2. The Hospitalet Dome

The Hospitalet Dome is an E–W elongated orthogneiss cored dome enveloped by metasedimentary rocks, affected by Variscan medium-grade HT–LP metamorphism (amphibolite facies). Metamorphic grade increases towards the core of the dome where the gneiss present a flat-lying foliation. The Mérens Fault, located to the north and at the western termination of the Hospitalet Dome, separates it from the Aston Dome. High-grade metasediments cropping out at the northernmost part of Andorra underlie the orthogneiss of the Aston Dome (Mezger et al., 2012) (Figure 4). In the metasedimentary succession around the domes a subhorizontal schistosity (S1) is occasionally associated with recumbent folds (Casas et al., 2019and references therein).

3.2.3. The Pallaresa Massif

The Pallaresa Massif is a large antiformal structure that its eastern end crops out north of Andorra, in contact with Aston and Hospitalet gneissic domes. It is crossed by the Mérens Fault, that separates a high-grade metamorphic pre-Upper Ordovician succession to the north from a low-grade metamorphic pre-Upper Ordovician succession to the south (Clariana & García-Sansegundo, 2009) (Figures 4 and 5). To the south, between the Mérens Fault and the Tor–Casamanya Syncline, the most conspicuous structure is a foliation (S1) (Figure 6(a)) associated with E–W recumbent north-verging folds (D1) (Figure 6(a)), observed south of the Mérens Fault. The S1 foliation

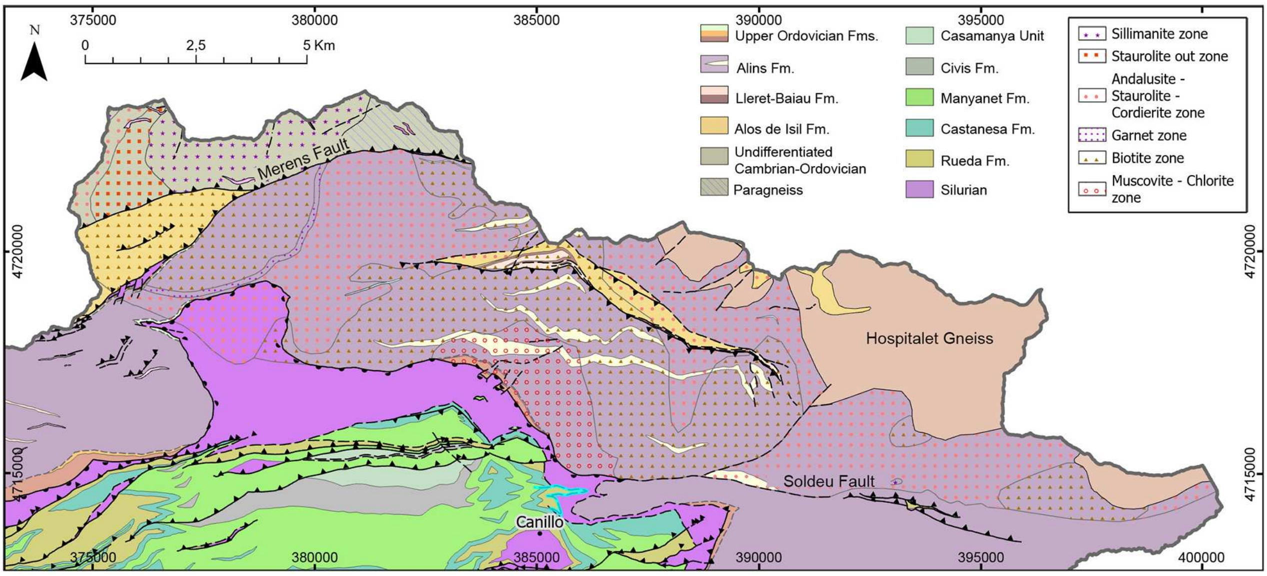

Figure 4. Metamorphic zonation sketch of the northern half of Andorra showing the areal distribution of the identified metamorphic zones (modified from Clariana, 2015).

corresponds to a crenulation cleavage since it deforms a previous slaty cleavage (SE) observed under the microscope (Figure 7). Close to the Tor–Casamanya Syncline the D1 folds are folded by E–W upright folds (D2) (Figure 6(b)) that develop axial plane cleavage (S2) (Figure 6(b)) and cut by thrusts whose orientation coincides with that of the upright D2 folds. These folds and their associated cleavages are described in detail by Clariana and García-Sansegundo (2009; 2016), Clariana (2015) and Casas et al. (2016).

Based on previous studies (Alías, 1995; Mezger, 2005) and on new field and microscopic data, six metamorphic zones have been differentiated in this sector (muscovite-chlorite zone, biotite zone, garnet zone, andalusite-staurolite-cordierite zone, and sillimanite zone) (See Main Map).

Deformation–metamorphism relationships have allowed to characterize a main HT–LP metamorphism episode subsequent to D1 and D2 structures and coeval with non-coaxial deformation restricted to the vicinity of the gneissic domes, such as rotated porphyroblast and subhorizontal foliation (S3) (Clariana and García-Sansegundo, 2016). The crystallization–deformation relationships observed in this sector of the Pallaresa massif are described in Clariana & García-Sansegundo, in press.

3.2.4. The Tor–Casamanya Syncline

The Tor–Casamanya Syncline is E–W oriented. Its northern limb is cut by the Arinsal Fault, affecting the contact between the Silurian and Devonian (Zandvliet, 1960; Zwart, 1965). The Pal Thrust (Cirés et al., 1990; Zandvliet, 1960) places the Silurian–Devonian rocks of southern limb of this syncline over different Cambrian–Ordovician and Upper Ordovician units of the Massana Anticline. E–W trending crenulation cleavage (S2) related to upright folds (D2) and Silurian-detached southwards directed thrusts are the most prominent structures (Figure 7) (Casas et al., 1989; Casas & Poblet, 1989; Clariana, 2015, 2023; Margalef, 2015; Poblet, 1991).

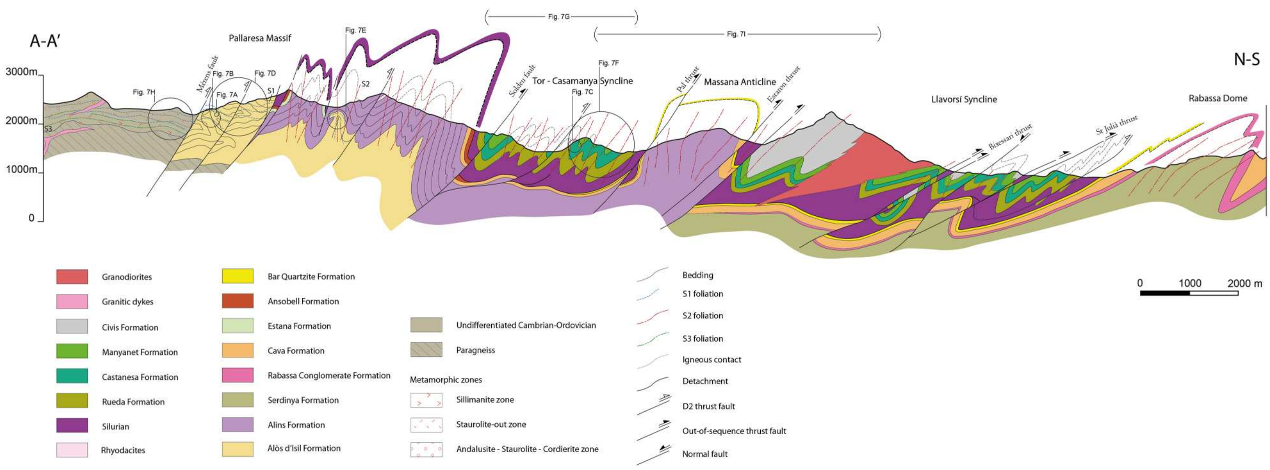

Figure 5. A-A′ geological cross-section. Same legend than in map. See main map and Figure 2 for location. Adapted from Clariana (2015) and Margalef et al. (2023).

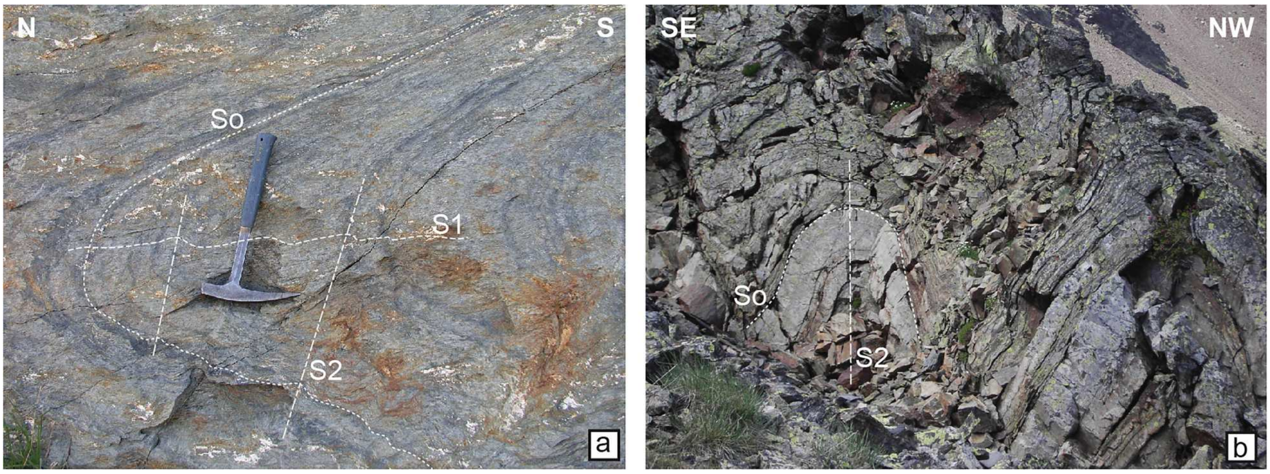

Figure 6. (a) Recumbent north-verging fold (D1) developed in the Alòs d'Isil Formation, notice the axial plane foliation associated with this fold (S1); location: 1° 29′ 14,13″E; 42° 37′ 23,78″N. (b) Aspect of well-developed upright D2 folds in Alins Formation; location: 1° 36′ 21,65″E; 42° 37′ 12,14″N.

The relationships between D2 folds and thrusts are analysed in Margalef et al. (2023) and Clariana (2023).

3.2.5. The Massana Anticline

The ENE–WSW to ESE–WNW trending Massana Anticline constitutes the southeastern end of the Pallaresa Massif (Hartevelt, 1970). This exhibits a box-fold geometry deduced from cross-section (Margalef et al., 2023). Its northern limb dips subvertical or steeply to the north, while the southern limb is overturned and dips moderately to the north. To the south, the Estaron Thrust (Losantos et al., 1988) places the Cambrian and Ordovician rocks of the Massana Anticline on top of the Silurian shales of the Llavorsí Syncline (Figure 5) (Poblet, 1991). Its main feature is an E–W trending crenulation cleavage (S2), which dips vertical in the northern part of the anticline and progressively decreases its dip to moderately north in the southern part (Figure 5). The S2 cleavage can be observed associated with D2 upright folds, both described in Margalef (2015) and Margalef et al. (2023).

3.2.6. The Llavorsí Syncline

The Llavorsí Syncline ranges in WNW–ESE direction and presents similar characteristics than those of the Tor–Casamanya Syncline. Its northern boundary is the Estaron thrust, described above, and its southern boundary corresponds to the Llavorsí thrust (Poblet, 1991), which places different Devonian formations and Silurian shales in contact with Cambrian–Ordovician and Upper Ordovician rocks of the Orri dome (Figure 5). The main structures in this syncline are ENE–WSW trending south-directed thrusts and a S2 cleavage related to E–W to ENE–WSW south verging folds (D2) (Clariana, 2015, 2023; Margalef, 2015; Margalef et al., 2023). Some out-of-sequence thrusts detached in the Cambrian–Ordovician succession or at deeper levels (i.e. Pal, Estaron, Encamp, Bixessarri and St Julià thrusts) cut previous D2 folds and Silurian detached thrusts (Margalef et al., 2023; Poblet, 1991). Margalef et al. (2023) proposed an Alpine age for these thrusts (Figure 7).

3.2.7. The Rabassa Dome

The Rabassa Dome is an E–W oriented antiformal structure with a north-dipping southern limb and a NE–SW oriented northwest dipping northern limb (Figure 5). At its eastern termination, the Claror fault cuts the Rabassa Dome and puts it in contact with the Andorra–Montlluís Granodiorite (Hartevelt, 1970; Poblet, 1991). South of Andorra, the Arcavell Thrust places the Rabassa Dome over the Segre Unit (Hartevelt, 1970) and over the southern limb of the Llavorsí Syncline. E–W to ENE–WSW directed S2 cleavage dips moderately to the north. The features of this cleavage are thoroughly described by Margalef (2015) and Margalef et al. (2023).

4. Conclusions

The 1:25.000 geological map presented in this work is the first geological map of the Principality of Andorra produced at this scale resolution. This map improves the precision of the existing geological maps and provide new data as: (a) deepening the knowledge of the stratigraphy and age of the Ediacarian and Paleozoic successions; (b) the differentiation of the Devonian formations in the Tor–Casamanya Syncline; (c) the refinement of the geological mapping of the Upper Ordovician succession; (d) the definition of new thrusts and the internal structure of the Llavorsí Syncline; (e) the new age data of the Upper Ordovician felsic volcanics (rhyolites and rhyodacites) and the Upper Devonian Casamanya Unit and (f) the compilation of new structural data that has allowed the description of the Variscan and Alpine structure of the study area.

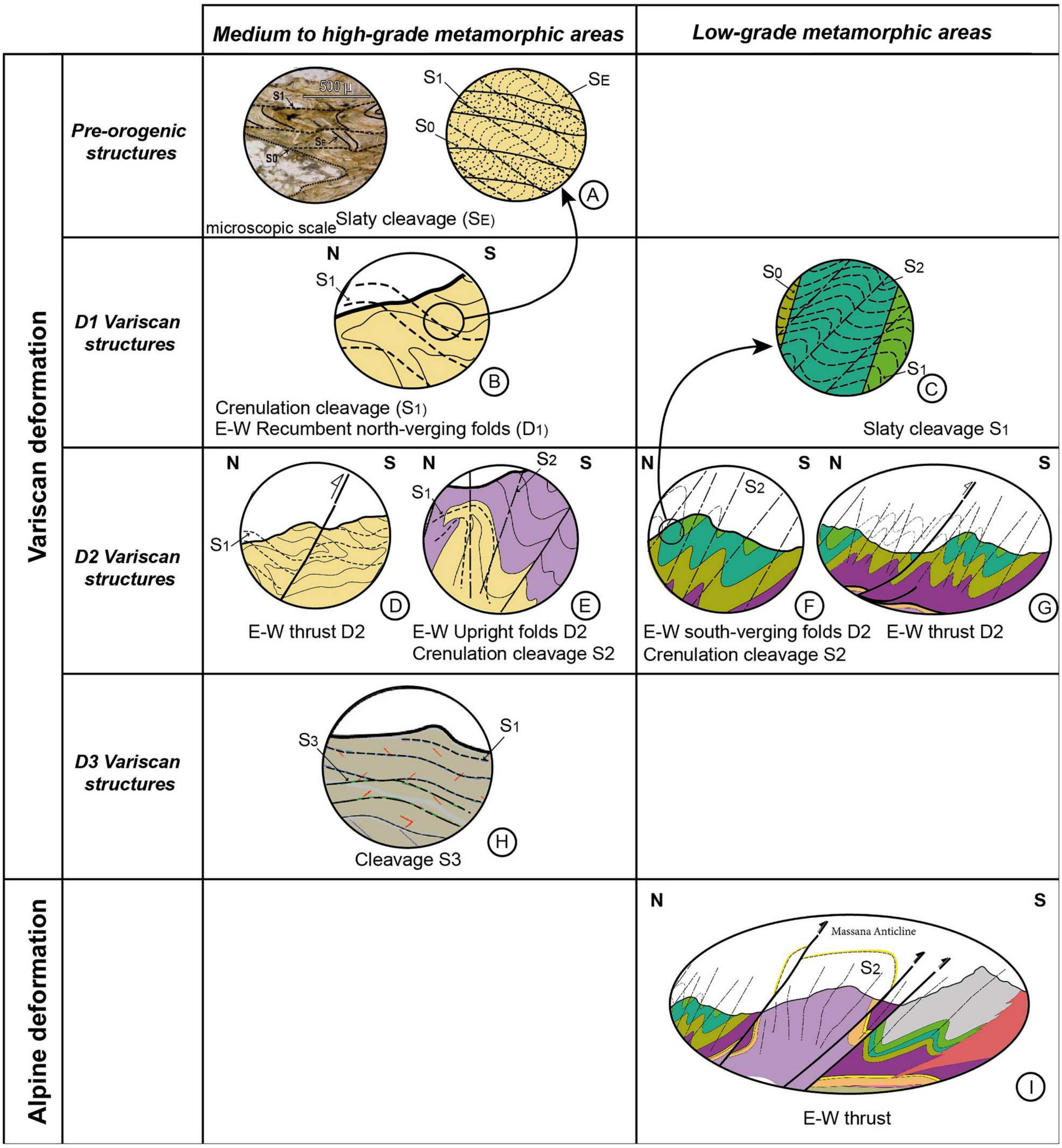

Figure 7. Scheme of the characteristic structures of the different deformation phases identified in Andorra and their chronological order, deduced from superposed structures relationships and their spatial distribution depending on metamorphic grade. The different cases are located in Figure 5.

Data acquired during the elaboration of this geological map, as well as their integration in GIS geodatabases, may also facilitate further research, especially in the field of structural geology, but also in other, such as hydrothermalism, neotectonics or palaeontology.

Software

Geological map has been designed using ESRI ArcGIS Pro Software and polished using Adobe Illustrator CC 2019. Tectonic sketch map and other figures are designed using Adobe Illustrator CC 2019.

Geolocation information

The study area is located in the Eastern Pyrenees, between approximately 1° 40’ E and 1° 79’ E; and 42° 42’ N and 42° 67’ N. We have used WGS 1984 UTM coordinate system, zone 31N.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article or its supplementary materials.

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