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U-Pb zircon age of Ordovician magmatism in the Albera Massif (Eastern Pyrenees)

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ABSTRACT

New geochronological data from the Albera Massif confirm the presence of an Early – Mid Ordovician igneous event (472 - 465Ma) recorded in the pre-Variscan rocks of the Pyrenees. This event resulted in the emplacement of a large granitic body in the lower part of the pre-Upper Ordovician metasedimentary succession and in the intrusion of a series of metric sized dykes in the middle and upper parts of it. The two types of igneous rocks were gneissified during subsequent Variscan deformation. The geochronological data confirm the occurrence of the gneiss as having derived from an Ordovician intrusive sheet, as in other Pyrenean massifs. The dykes are considered to be the subvolcanic equivalent of the intrusive sheet. The data also provide insight into the age of the metasedimentary series of the massif and enable us to correlate the dated rocks with other gneissic and subvolcanic bodies of the Variscan massifs of the Pyrenees and Iberia.

KEYWORDS **Pre-Variscan. Early-Mid Ordovician magmatism. SHRIMP geochronology. U-Pb zircon dating. Eastern Pyrenees.**

INTRODUCTION

The origin and significance of the large gneissic bodies that crop out at the core of metamorphic massifs in the Pyrenees has long been a subject of debate. Initial studies conclude that large granitic orthogneisses represent a Cadomian basement overlain by a lower Paleozoic cover (Autran et al., 1966; Autran and Guitard, 1969; Guitard, 1970; Vitrac-Michard and Allègre, 1975). In contrast, pioneering geochronological work suggests an Ordovician age for the protoliths of the orthogneisses (Jäger and Zwart, 1968; Majoor, 1988). Although some works based on structural field data, (Sebastián et al., 1982; Liesa, 1988; Vilà, 2003) have challenged the basement - cover interpretation, recent geochronological data have provided evidence contradicting this interpretation. These studies conclude that an Early – Mid Ordovician magmatic event (477-467Ma) gave rise to the protoliths of the Canigó, Roc de Frausa and Aston - Hospitalet gneisses (Cocherie et al., 2005; Castiñeiras et al., 2008a and Denele et al., 2009, respectively). The absence of a Cadomian granitic basement and the presence of an Ordovician magmatism in the Pyrenees is comparable to the one described in other areas of northern Gondwana (Pin and Marini, 1993; Valverde-Vaquero and Dunning, 2000) and have been extensively discussed (e.g. Barbey et al., 2001; Deloule et al., 2002; Laumonier et al., 2004; Cocherie et al., 2005; Castiñeiras et al., 2008a).

In this scenario, the Albera massif played a prominent role, given that the basement-cover model was defined in this massif (Autran et al., 1966). This model was subsequently applied to other gneissic cored massifs of the Pyrenees (Guitard, 1970). However, no geochronological data on the Albera gneiss has been available to date. In this work, we present new geochronological data that furnish evidence of a well defined Early – Mid Ordovician magmatic event in this massif. The significance of the event is discussed and compared to other gneissic bodies of the Variscan massifs of the Pyrenees and the Iberian realm.

GEOLOGICAL SETTING

The Albera massif is located at the easternmost end of the Pyrenees where Variscan basement rocks crop out extensively (Fig. 1). It presents a half dome structure resulting from a set of E-W trending Neogene normal faults that cross cut the central part of the massif. The faults also account for the cropping out of the lowermost rocks (Figs. 1, 2). To the west, the massif is bounded by La Jonquera fault; to the south, the Valleta Fault marks the boundary between the low-grade metamorphic rocks of the Albera massif and the medium to high-grade rocks of the Cap de Creus massif (Fig. 2). Three main lithological units can be distinguished: i) a pre-Upper Ordovician metasedimentary sequence including acidic

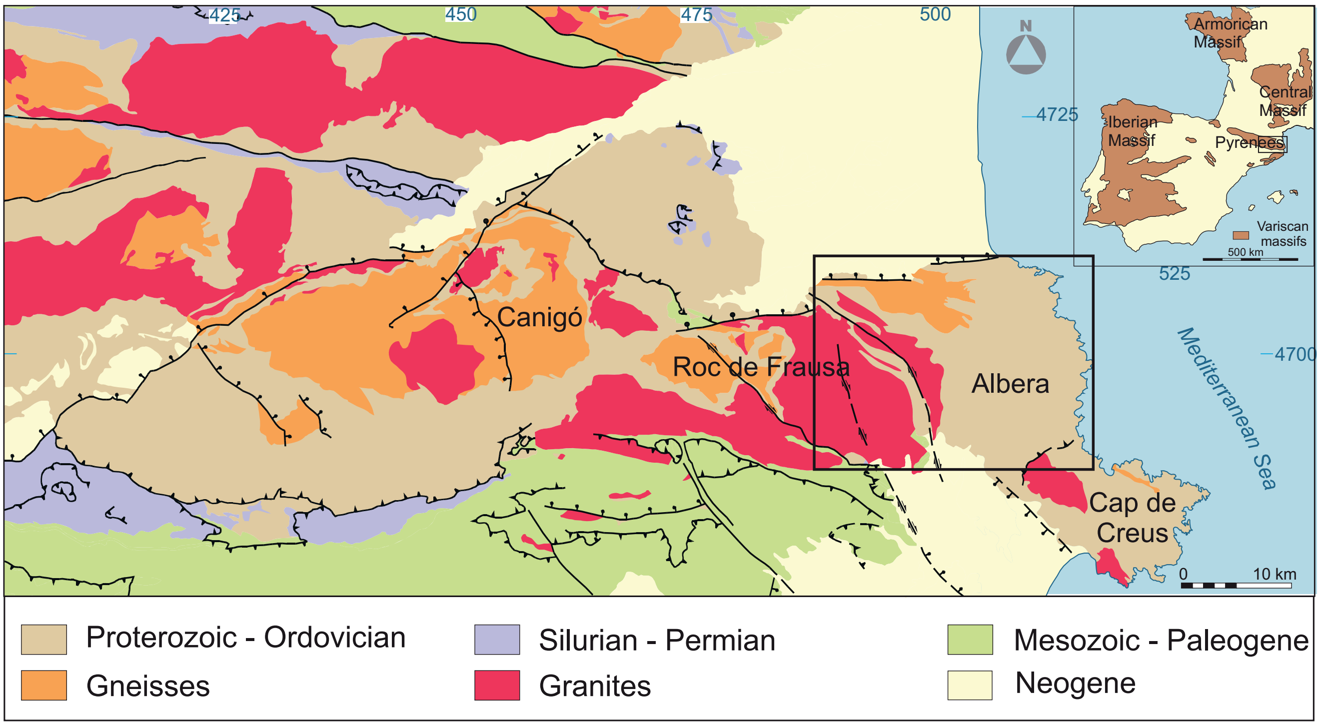

FIGURE 1 | **Geological sketch-map of the Variscan basement of the Eastern Pyrenees and location of the Albera massif.**

metaigneous rocks, ii) a large orthogneiss body, and iii) Variscan plutonic rocks, mainly granitoids.

The pre-Upper Ordovician metasedimentary sequence is divided into a Lower Series and an Upper Series separated by a characteristic layer of black metapelites that constitutes the top of the Lower Series (Fig. 2) (Cirés et al., 1994; Vilà et al., 2005, 2007). The Lower series is composed of alternating layers of metagreywackes and metapelites with abundant centimetric discontinuous layers of white plagioamphibolic rocks. Discontinuous layers of metabasites, calc-silicate rocks, quartzites and marbles crop out throughout the whole Lower series. The Albera orthogneiss constitutes the main interlayered unit in the Lower series which is up to 500m thick. The series below the orthogneiss is migmatitic with alternating leucosomes, mesosomes and melanosomes. Plagioamphibolic and metasedimentary layers are also present. These characteristic layers and the abundance of pelitic minerals in the migmatites enable us not only to relate the two series but also to term these migmatites paragneisses after Autran et al. (1966). Towards the upper stratigraphic levels, the metasediments become gradually darker and more pelitic until they form a continuous unit of black metapelites known as the Black Series. The black metapelites are interbedded with white quartzites and blue-grey marble beds. The Upper Series is formed by alternating layers of metapelites and metapsammites with thin microconglomerate (2m thick), marble and black metapelite intercalations (Cirés et al., 1994; Laumonier et al., 1996; Vilà et al., 2005, 2007). Acidic metaigneous rocks form discontinuous bodies cross cutting the Upper Series and the Black Series. They correspond to gneissified subvolcanic dykes and sills or discontinuous lense–shaped layers of lava flows and volcaniclastic tuffs. They contain quartz and feldspar porphyroclasts in a finer grained matrix and their composition corresponds to that of peraluminous leucogranites and granites (Vilà, 2003). In this paper they will be termed rhyolithic metaporphyries.

The age of the sequence remains to be resolved because of its azoic character, although a Cambro-Ordovician (pre-Caradocian) age has been suggested (Fontboté, 1949; Cavet, 1957). A Mid/Late Cambrian age (Laumonier, 1988; Perejón, et al., 1994) or a Late Cambrian/Early Ordovician (Guitard et al., 1998) has been proposed for its upper part. Recent radiometric dating of interlayered metatuffs in neighbouring massifs (Cap de Creus, Roc de Frausa and

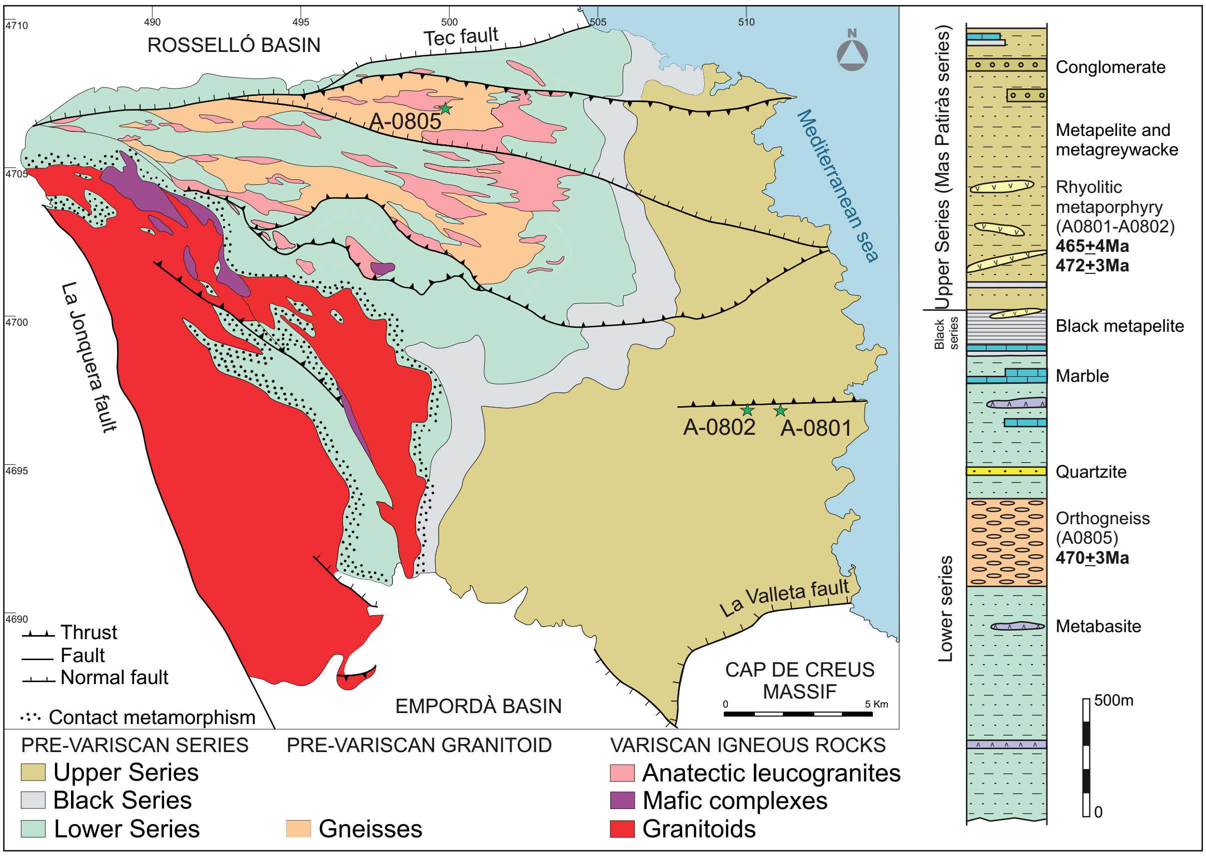

FIGURE 2 | **Geological sketch-map and synthetic stratigraphic column of the Albera Massif with location of the samples (the coordinates of the sites are in Table 1).**

Canigó massifs) has yielded a Late Neoproterozoic-Early Cambrian age (580-540Ma) for the lower part of the succession (Cocherie et al., 2005; Castiñeiras et al., 2008a). Lithological similarities of the Cap de Creus and Albera sequences allow us to correlate the series, which suggests a Late Neoproterozoic-Early Cambrian age for the Lower series of the Albera Massif though no pre-Variscan interlayered igneous rocks of the Albera massif have been dated so far.

The Albera orthogneiss is formed by K-feldspar porphyroclasts surrounded by a matrix rich in quartz, feldspar and biotite. It is derived from a large pre-Variscan sheet-shaped granitoid intrusion. Guitard (1970) considered this gneiss to be equivalent to the G2 Canigó gneiss on the basis of its mineralogy and texture. According to Vilà (2003), it is derived from a peraluminous granodiorite.

Variscan intrusives are represented by three main groups of rocks: an anatectic leucogranite, a composite intrusion, namely the Sant Llorenç - La Jonquera batholith and El Castellar leucogranite. The anatectic leucogranite is formed by peraluminous dykes and stocks emplaced at the deepest outcropping tectonic levels in the anatectic and perianatectic domains (Autran et al., 1970; Vilà, 2003). It intruded synchronously with the main tectonic phase and regional metamorphism. The Sant Llorenç - La Jonquera intrusion is a sheet-shaped body made up of calc-alkaline granodiorites, tonalites and granites with associated small mafic complexes composed of diorite-gabbro stocks and ultramafic rocks, and leucogranite dykes (Autran et al., 1970; Cocherie, 1985; Liesa and Carreras, 1989). The more mafic rocks are emplaced at lower structural levels in high-grade metamorphic domains whereas the acidic rocks, which form the top of the pluton, are intruded at higher structural levels in low-grade metamorphic domains. The Sant Llorenç - La Jonquera and the mafic complexes develop a contact metamorphic aureole overprinting the main foliation but show a fabric that is related to a later folding phase.

The El Castellar leucogranite forms a small elongated pluton intruded into the metasediments close to the La Jonquera plutonic complex. It represents one of the peripheral intrusions (Debon et al., 1995) of the La Jonquera complex and it is peraluminous and heterogeneous with numerous metasedimentary enclaves and pegmatite dykes (Vilà, 2003; Vilà et al., 2005).

SHRIMP U-Pb ZIRCON GEOCHRONOLOGY

Sample and zircon description

The samples collected for U-Pb zircon analysis correspond to two rhyolithic metaporphyries (samples A-08-1, A-08-2) and to an orthogneiss (sample A-08-5) (Fig. 2). Samples A-08-1 and A-08-2 are white – orange aphanitic massive rocks with discontinuous green to grey coloured thin foliated layers. They are mainly constituted by quartz and minor feldspar porphyroclasts (1-5mm) that are prominent in a fine-grained groundmass (0.02-0.05mm) composed of quartz, altered feldspar and phyllosilicates (muscovite and scarce chlorite). The phyllosilicates define an anastomosing foliation that wraps the porphyroclasts. Quartz outlines are rounded with deep embayments characteristic of magmatic corrosion. The field relations together with the compositional and textural features of these rocks allow us to interpret them as former hypabissal or subvolcanic rocks, probably granitic porphyries.

Sample A-08-5 is an augen orthogneiss of granitic composition made up of quartz, microcline, plagioclase, biotite and small amounts of muscovite and opaque ore. Biotite and muscovite define a coarse discontinuous foliation separating quartz-feldspar layers, 2-3mm thick. Quartz constitutes the groundmass and shows both undulose extinction and subgrains. It displays a relatively uniform grain size of 0.4mm. Microcline and plagioclase constitute porphyroclasts that range from 1-4cm. Microcline is perthitic and exhibits tartan twinning owing to deformation.

Zircons from the three samples were isolated using gravimetric and magnetic techniques. About 40 zircon grains per sample were handpicked under a binocular microscope. They were selected from the most idiomorphic crystals to avoid all possibility of inheritance. The preferred zircons were mounted in epoxy resin together with some chips of zircon standard R33 (Black et al., 2004). Prior to isotopic analysis, the zircons were imaged with transmitted and reflected light on a petrographic microscope, and with cathodoluminescence on a JEOL JSM 5600 electron microscope housed at SUMAC (Stanford-US Geological Survey micro analysis centre). After the analysis, secondary electron images were taken to locate the exact position of the spots.

Zircon crystals from sample A-08-1 may be colourless, pale yellow or light purple and may contain few inclusions. Mineral habit is variable, commonly plain prisms with differently shaped pyramid terminations and length-to-breadth ratios between 1:3 and 1:5. In some cases, the prisms are composite, resulting in stubbier zircons (aspect ratios of 1:1 or 1:2). Broken and moderately rounded grains are common irrespective of their habit. Under cathodoluminescence, they exhibit clear core-rim structures with abundant inherited cores mantled by magmatic oscillatory zones (Fig. 3). The zircon yield from sample A-08-2 was poor, less than a hundred grains extracted from ~20 kg of rock, compared with the previous sample. Zircons are mainly brownish and practically free of inclusions. The most frequent habits are dipyramidal prisms and equant grains due to the presence of composite faces (Fig. 3). Cathodoluminescence reveals a luminescent oscillatory zoning in most grains commonly surrounded by non-luminescent rims. The sharp limit between areas with different luminescence suggests that the rims are magmatic rather than metamorphic in origin. Xenocryst cores are rare. The orthogneiss (sample A-08-5) provided the most abundant zircon yield. Zircon grains can be colourless or coloured in different yellow tones with few inclusions. The most common habit is dipyramidal prisms with aspect ratios between 1:3 and 1:5, but more complex habits or rounded grains can also be found. Under cathodoluminescence, zircons display broad oscillatory zones, typical of magmatic environments (Fig. 3).

U-Th-Pb analyses of zircon were conducted using the Bay SHRIMP-RG (Sensitive High-Resolution Ion Microprobe - Reverse Geometry). The analytical procedure followed for zircon dating is described elsewhere (e.g., Premo et al., 2008). The concentration of U was calibrated with zircon standard CZ3 (550ppm U, Pidgeon et al., 1995), and isotopic compositions were calibrated against R33 (419 Ma, Black et al., 2004) which was analyzed every fourth analysis. Squid and Isoplot software (Ludwig, 2002, 2003) were used for data reduction following the methods described by Williams (1997) and Ireland and Williams (2003). Ages are based on $^{206}Pb/^{238}U$ ratios corrected from common Pb using the ^{207}Pb method. Analytical results are presented in Table 1 and plotted in Figure 4.

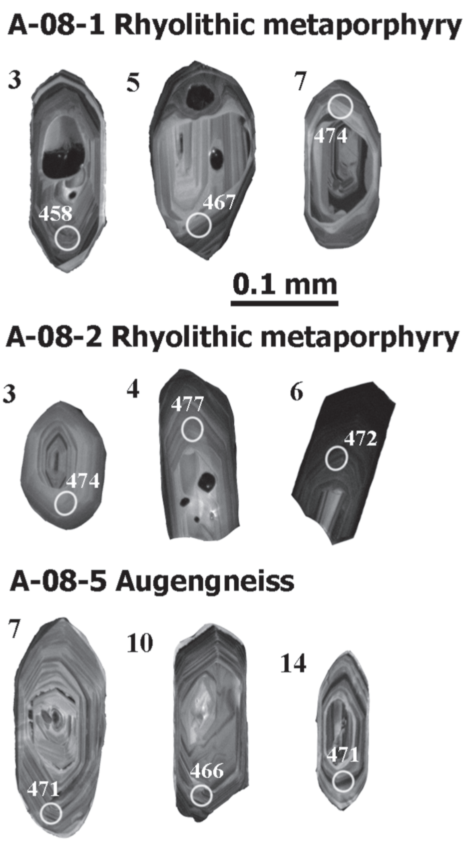

FIGURE 3 | **Cathodoluminescence images for selected zircons.**

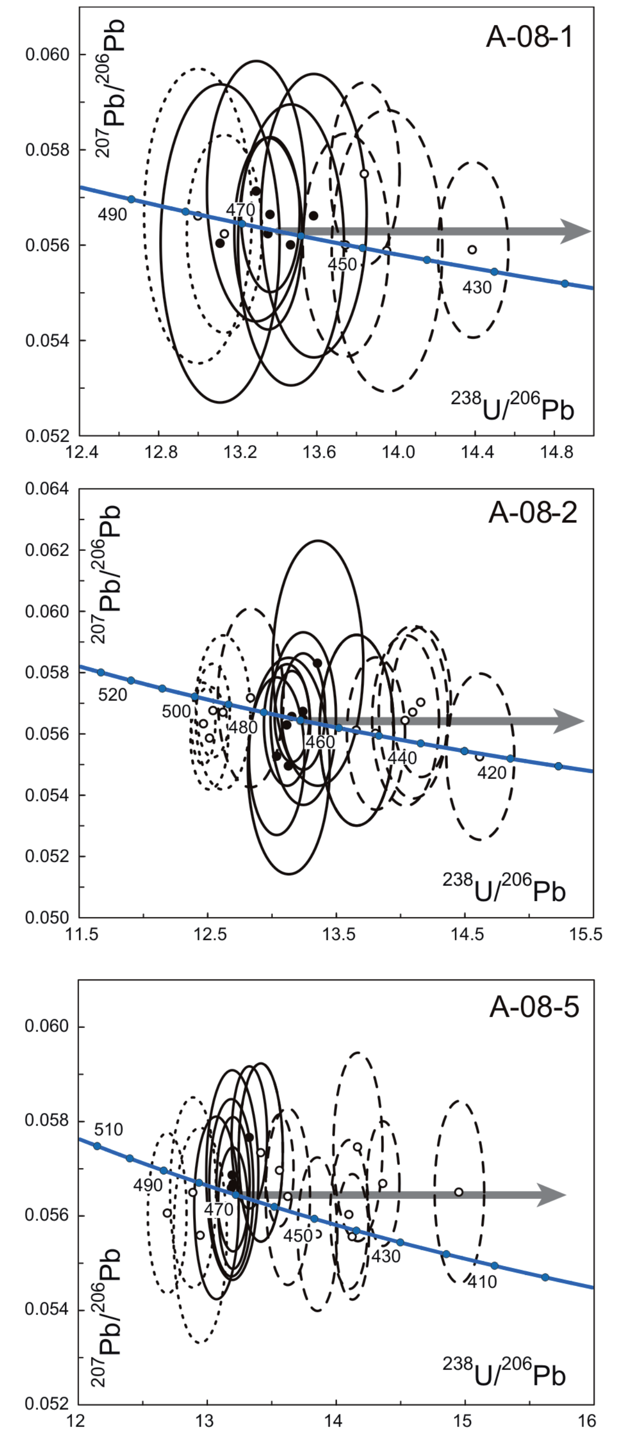

FIGURE 4 | **Tera-Wasserburg plot showing the distribution of SHRIMP zircon analyses for samples A-08-1, A-08-2 and A-08-5. Dashed and dotted ellipses represent analyses not considered for the mean age calculation. Grey arrows indicate modern Pb-loss track. Error ellipses are ±2σ.**

TABLE 1 | **SHRIMP U-Th-Pb zircon data of the samples from the Albera massif**

Spot number and description		Common ^{206}Pb (%)	U (ppm)	Th (ppm)	Th/U	^{207}Pb corrected: $^{206}Pb/^{238}U$ age	^{207}Pb corrected: $^{206}Pb^*/^{238}U$	Uncorrected ratios: $^{238}U/^{206}Pb$	Uncorrected ratios: $^{207}Pb/^{206}Pb$	^{204}Pb corrected ratios: $^{238}U/^{206}Pb^*$	^{204}Pb corrected ratios: $^{207}Pb^*/^{206}Pb^*$
A-08-01:Rhyolithic metaporphyry. UTM: 511471, 4694026, 118											
1	om	0.05	562	63	0.11	433.0 ± 2.2	0.0695 ± 0.0004	14.39 ± 0.5	0.0559 ± 1.3	14.40 ± 0.5	0.0551 ± 1.5
2	om	0.20	524	259	0.51	448.9 ± 2.3	0.0721 ± 0.0004	13.84 ± 0.5	0.0575 ± 1.4	13.84 ± 0.5	0.0575 ± 1.4
3	om	0.06	221	51	0.24	**457.7 ± 3.6**	0.0736 ± 0.0006	13.58 ± 0.8	0.0566 ± 2.1	13.58 ± 0.8	0.0566 ± 2.1
4	om	0.04	696	62	0.09	**465.0 ± 2.1**	0.0748 ± 0.0003	13.36 ± 0.5	0.0566 ± 1.2	13.38 ± 0.5	0.0557 ± 1.4
5	om	0.09	231	20	0.09	**467.2 ± 3.5**	0.0752 ± 0.0006	13.29 ± 0.8	0.0571 ± 2.0	13.29 ± 0.8	0.0571 ± 2.0
6	om	-0.03	168	71	0.43	**461.9 ± 3.7**	0.0743 ± 0.0006	13.47 ± 0.8	0.0560 ± 2.1	13.47 ± 0.8	0.0560 ± 2.1
7	om	-0.06	126	25	0.21	**474.1 ± 4.4**	0.0763 ± 0.0007	13.11 ± 0.9	0.0560 ± 2.4	13.11 ± 0.9	0.0560 ± 2.4
8	om	0.00	162	70	0.45	477.8 ± 4.1	0.0769 ± 0.0007	13.00 ± 0.9	0.0566 ± 2.2	13.09 ± 0.9	0.0512 ± 4.5
9	om	-0.01	397	136	0.35	**465.6 ± 2.4**	0.0749 ± 0.0004	13.35 ± 0.5	0.0562 ± 1.5	13.36 ± 0.5	0.0560 ± 1.5
10	om	0.00	167	60	0.37	446.2 ± 3.6	0.0717 ± 0.0006	13.95 ± 0.8	0.0559 ± 2.2	13.95 ± 0.8	0.0559 ± 2.2
11	om	0.00	274	137	0.52	452.7 ± 2.9	0.0728 ± 0.0005	13.74 ± 0.6	0.0560 ± 1.7	13.75 ± 0.6	0.0556 ± 1.8
12	om	-0.04	323	61	0.20	473.3 ± 2.8	0.0762 ± 0.0005	13.13 ± 0.6	0.0562 ± 1.5	13.14 ± 0.6	0.0557 ± 1.6
A-08-02:Rhyolithic metaporphyry. UTM: 510562, 4696333, 260											
1	om	0.08	203	83	0.42	443.3 ± 3.3	0.0712 ± 0.0006	14.03 ± 0.8	0.0564 ± 2.0	14.05 ± 0.8	0.0558 ± 2.2
2	om	0.01	250	107	0.44	450.8 ± 3.0	0.0724 ± 0.0005	13.80 ± 0.7	0.0560 ± 1.8	13.81 ± 0.7	0.0555 ± 1.9
3	om	-0.20	110	45	0.43	**474.2 ± 4.7**	0.0763 ± 0.0008	13.13 ± 1.0	0.0550 ± 2.6	13.13 ± 1.0	0.0550 ± 2.6
4	om	-0.17	246	96	0.40	**477.2 ± 3.2**	0.0768 ± 0.0005	13.04 ± 0.7	0.0553 ± 1.9	13.05 ± 0.7	0.0546 ± 2.0
5	om	0.04	401	107	0.27	**469.2 ± 2.5**	0.0755 ± 0.0004	13.24 ± 0.5	0.0567 ± 1.4	13.24 ± 0.5	0.0567 ± 1.4
6	om	0.01	660	136	0.21	**472.3 ± 2.0**	0.0760 ± 0.0003	13.15 ± 0.4	0.0566 ± 1.1	13.15 ± 0.4	0.0566 ± 1.1
7	om	-0.04	249	70	0.29	491.8 ± 3.4	0.0793 ± 0.0006	12.62 ± 0.7	0.0567 ± 1.8	12.63 ± 0.7	0.0562 ± 1.9
8	om	-0.10	1308	168	0.13	497.9 ± 1.5	0.0803 ± 0.0003	12.47 ± 0.3	0.0563 ± 1.0	12.47 ± 0.3	0.0561 ± 1.0
9	om	-0.03	365	86	0.24	**473.8 ± 2.6**	0.0763 ± 0.0004	13.11 ± 0.6	0.0563 ± 1.4	13.11 ± 0.6	0.0563 ± 1.4
10	om	0.01	186	82	0.45	**469.3 ± 3.6**	0.0755 ± 0.0006	13.24 ± 0.8	0.0565 ± 2.0	13.24 ± 0.8	0.0565 ± 2.0
11	om	-0.16	522	145	0.29	496.3 ± 2.3	0.0800 ± 0.0004	12.51 ± 0.5	0.0559 ± 1.2	12.51 ± 0.5	0.0559 ± 1.2
12	om	0.25	118	41	0.35	**464.4 ± 5.0**	0.0747 ± 0.0008	13.35 ± 1.1	0.0583 ± 2.8	13.35 ± 1.1	0.0583 ± 2.8
13	om	0.01	147	53	0.37	455.6 ± 3.9	0.0732 ± 0.0006	13.66 ± 0.9	0.0561 ± 2.3	13.66 ± 0.9	0.0561 ± 2.3
14	om	0.17	252	89	0.36	439.3 ± 2.9	0.0705 ± 0.0005	14.16 ± 0.7	0.0570 ± 1.8	14.17 ± 0.7	0.0561 ± 2.0
15	om	0.05	183	64	0.36	483.5 ± 3.9	0.0779 ± 0.0006	12.83 ± 0.8	0.0572 ± 2.1	12.83 ± 0.8	0.0572 ± 2.1
16	om	-0.04	622	120	0.20	494.7 ± 2.1	0.0798 ± 0.0004	12.54 ± 0.4	0.0568 ± 1.1	12.54 ± 0.4	0.0568 ± 1.1
17	om	-0.01	205	74	0.37	426.7 ± 3.2	0.0684 ± 0.0005	14.61 ± 0.7	0.0553 ± 2.0	14.64 ± 0.7	0.0538 ± 2.4
18	om	0.12	182	68	0.39	441.4 ± 3.4	0.0709 ± 0.0006	14.09 ± 0.8	0.0567 ± 2.0	14.11 ± 0.8	0.0561 ± 2.2
A-08-05:Orthogneiss. UTM: 499168, 4707108, 144											
1	om	0.14	1110	85	0.08	433.3 ± 1.6	0.0695 ± 0.0003	14.36 ± 0.4	0.0567 ± 0.9	14.36 ± 0.4	0.0567 ± 0.9
2	om	0.10	1292	120	0.10	458.2 ± 1.5	0.0737 ± 0.0003	13.56 ± 0.3	0.0570 ± 0.9	13.56 ± 0.3	0.0570 ± 0.9
3	om	-0.14	344	45	0.14	480.3 ± 3.1	0.0774 ± 0.0005	12.95 ± 0.6	0.0556 ± 1.7	12.95 ± 0.6	0.0556 ± 1.7
4	om	0.04	790	67	0.09	441.6 ± 1.9	0.0709 ± 0.0003	14.10 ± 0.4	0.0560 ± 1.1	14.10 ± 0.4	0.0560 ± 1.1
5	om	1.32	1158	45	0.04	437.3 ± 1.6	0.0702 ± 0.0003	14.06 ± 0.4	0.0663 ± 0.9	14.24 ± 0.4	0.0559 ± 2.4
6	om	-0.03	470	40	0.09	481.9 ± 2.7	0.0776 ± 0.0005	12.89 ± 0.6	0.0565 ± 1.5	12.89 ± 0.6	0.0562 ± 1.5
7	om	0.01	526	37	0.07	**471.1 ± 2.5**	0.0758 ± 0.0004	13.19 ± 0.5	0.0566 ± 1.4	13.19 ± 0.5	0.0563 ± 1.4
8	om	0.22	474	56	0.12	438.8 ± 2.4	0.0704 ± 0.0004	14.17 ± 0.5	0.0575 ± 1.4	14.17 ± 0.5	0.0575 ± 1.4
9	om	-0.02	1075	72	0.07	441.1 ± 1.6	0.0708 ± 0.0003	14.12 ± 0.4	0.0556 ± 1.0	14.12 ± 0.4	0.0559 ± 1.0
10	om	0.16	811	90	0.11	**465.7 ± 1.9**	0.0749 ± 0.0003	13.33 ± 0.4	0.0577 ± 1.1	13.33 ± 0.4	0.0577 ± 1.1
11	om	0.05	363	42	0.12	**470.8 ± 2.9**	0.0758 ± 0.0005	13.19 ± 0.6	0.0569 ± 1.6	13.19 ± 0.6	0.0569 ± 1.6
12	om	0.17	556	22	0.04	416.7 ± 2.2	0.0668 ± 0.0004	14.95 ± 0.5	0.0565 ± 1.4	14.95 ± 0.5	0.0565 ± 1.4
13	om	-0.04	557	46	0.09	449.4 ± 2.0	0.0722 ± 0.0003	13.85 ± 0.5	0.0556 ± 1.2	13.86 ± 0.5	0.0550 ± 1.3
14	om	-0.04	805	56	0.07	**470.9 ± 1.7**	0.0758 ± 0.0003	13.20 ± 0.4	0.0562 ± 0.9	13.20 ± 0.4	0.0562 ± 0.9
15	om	0.13	424	58	0.14	462.9 ± 2.4	0.0744 ± 0.0004	13.41 ± 0.5	0.0573 ± 1.3	13.41 ± 0.5	0.0573 ± 1.3
16	om	-0.11	560	40	0.07	489.5 ± 2.3	0.0789 ± 0.0004	12.69 ± 0.5	0.0561 ± 1.2	12.69 ± 0.5	0.0561 ± 1.2
17	om	-0.05	394	30	0.08	**475.4 ± 2.5**	0.0765 ± 0.0004	13.07 ± 0.5	0.0562 ± 1.4	13.05 ± 0.5	0.0574 ± 1.7
18	om	0.04	425	33	0.08	456.4 ± 2.4	0.0734 ± 0.0004	13.62 ± 0.5	0.0564 ± 1.4	13.63 ± 0.5	0.0561 ± 1.4
19	om	0.03	662	43	0.07	**470.6 ± 1.9**	0.0757 ± 0.0003	13.20 ± 0.4	0.0567 ± 1.0	13.20 ± 0.4	0.0563 ± 1.1

All errors are 1s.
Zircon description: om=oscillatory magmatic.
Bold ages used to obtain the mean age.

U-Pb results

Twelve zircon grains from sample A-08-1 were analyzed, using cathodoluminescence images to target oscillatory zones that were considered as magmatic in ori-gin. Xenocryst cores were avoided whenever possible. Six analyses generated a mean age of 465.0±4.3 Ma (Fig. 4) with a mean square of weighted deviates (MSWD) of 1.9. This age is interpreted as the crystallization age of the igneous protolith. In sample A-08-2, eighteen zircons were analyzed in magmatic areas with oscillatory zoning using cathodoluminescence images to avoid non-luminescent rims. Seven analyses yielded a mean age of 472.0±3.0 Ma, MSWD=1.3 (Fig. 4). In the orthogneiss (sample A-08-5) nineteen analyses were obtained from magmatic areas with a mean age of 470.4±3.1 Ma (Fig. 4). The MSWD=2.0 was calculated by pooling together six analyses and was interpreted as the crystallization age of the igneous protolith.

DISCUSSION AND CONCLUSIONS

New geochronological data on the Albera massif furnish evidence of a well defined Early-Mid Ordovician magmatic event that brought about the intrusion of granitic bodies (ca. 470Ma) and acid subvolcanic porphyritic dykes (465-472Ma) into the pre-Upper Ordovician sequence. These ages range within error to the Floian, Dapigian and the lower part of the Darriwilian, which are roughly equivalent to the Arenig in the British regional series division (see Finney, 2005). The ages also fit in well, within error, with those obtained for the protoliths of other Pyrenean orthogneisses: Canigó gneiss (467±7 to 477±4Ma, Cocherie et al., 2005) Roc de Frausa gneiss (476±5Ma, Castiñeiras et al., 2008a) and Aston and Hospitalet gneisses (470±6Ma and 472±2Ma, Denele et al., 2009). Late Cambrian/Early Ordovician ages are also frequent in the gneisses of the Iberian Massif (Guadarrama orthogneiss: 470 to 480 Ma, Vialette et al., 1987; Cardoso gneiss: 480±2Ma, La Morcuera gneiss: 477±4Ma, Valverde-Vaquero and Dunning, 2000; Miranda do Douro gneiss: 483±3Ma, Bea et al., 2006 and 496±3Ma, Zeck et al., 2007; Sotosalbos anatectic gneiss: 465 to 480Ma, Castiñeiras et al., 2008b, among others) However, it should be noted that the magmatic episode recognized in the Pyrenees encompasses a shorter period (10Ma) and that no evidence of Late Cambrian or Early Tremadocian magmatic activity has been recorded. Thus, the igneous activity related to the Cambrian rifting episode, widespread in the Iberian Massif (Simancas et al., 2004) and in other European Variscan massifs (Linnemann et al., 2007), has not been recognized in the Pyrenees.

The intrusive bodies located in the middle and upper parts of the successions can be regarded as the subvolcanic equivalent of the large granitic body coevally emplaced in the lower part of the succession. It should be stressed that the Albera massif is the only Pyrenean massif that has preserved shallow depth intrusive porphyries of Ordovician age to date. On the other hand, rhyolitic and rhyodacitic volcanic rocks and crystal-tuff porphyroids of Early Ordovician age occur in the Iberian massif (Ollo de Sapo and related facies: 480±2Ma, Valverde-Vaquero and Dunning, 2000) and in Sardinia (Lula porhyroid: 474±13 Ma, Helbing and Tiepolo, 2005; metarhyolite and metadacite: 491.7±3.5 Ma to 479.9±2.1 Ma, Oggiano et al., 2009). According to the age obtained for these subvolcanic rocks, Early Ordovician (older than 472Ma) is the youngest age that can be assigned to the Upper series of the Albera massif.

Our data confirm present day interpretations that consider the protoliths of all the orthogneisses to be intrusive and not part of an eroded Cadomian basement. Thus, the boundary between the gneisses and the overlying metasediments does not represent the basement-cover boundary that corresponds to the Upper Proterozoic – Cambrian boundary. Although further research and geochronological work is needed to assess the age of the pre-Upper Ordovician sequence (Vilà, 2003) the base of the Cambrian is probably located close to the top of the so-called Black Series of the Albera Massif (Vilà, 2003) or at the base of the Upper series in the Cap de Creus and Albera Massifs (see discussion in Castiñeiras et al., 2008a).

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