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## Polyphased rare-element magmatism during late orogenic evolution: geochronological constraints from NW Variscan Iberia

Jérémie Melleton<sup>1,3,\*</sup>, Eric Gloaguen<sup>1,2</sup>, Dirk Frei<sup>3,4</sup>, Alexandre Lima<sup>5,6</sup>, Romeu Vieira<sup>7</sup> and Tania Martins<sup>8</sup>

<sup>1</sup> BRGM, Georesources Division, ISTO, UMR 7327, 3 avenue Claude Guillemin, B.P.6009, 45060 Orléans Cedex 2, France

<sup>2</sup> Université d'Orléans, ISTO, UMR 7327, 45071 Orléans, France

<sup>3</sup> Department of Earth Sciences, University of Western Cape, Cape Town, South Africa

<sup>4</sup> GEUS, Østervoldgade 10, DK-1350 Copenhagen K, Denmark

<sup>5</sup> Department of Geosciences, Environment and Spatial Planning, Faculty of Sciences, University of Porto, Porto, Portugal

<sup>6</sup> ICT (Institute of Earth Sciences), Porto pole, Portugal

<sup>7</sup> Fortescue Metals Group, Perth, Australia

<sup>8</sup> Manitoba Geological Survey, 360-1395 Ellice Av., Winnipeg, MB, Canada

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**Abstract** – Rare-element granites and pegmatites represent important sources of raw materials for “clean, green and high technologies”, such as lithium and tantalum, for example. However, mechanisms of rare-element granites and pegmatite’s origin are still far from being fully understood. Several rare-element pegmatite fields and a rare-element granite are known in the Variscan realms located in Iberia (Spain and Portugal), enhancing the interest of this area for studying the formation of these extremely fractionated melts. In situ U-Pb dating by LA-SF-ICP-MS of columbite-group minerals from rare-element granites and pegmatites of the Iberian Variscan belt provides new constraints on the generation of rare-element melts. Three events have been recognized: (i) Emplacement of the Argemela rare-element granite, in the Central Iberian Zone (CIZ), with an age of  $326 \pm 3$  Ma; (ii) Emplacement of rare-element pegmatites from the Galicia-Trás-os-Montes Zone (GTOMZ), at an average age of  $310 \pm 5$  Ma; (iii) Emplacement of rare-element pegmatites in the CIZ and in the southern GTOMZ at about  $301 \pm 3$  Ma. These two last events are coeval with the two peaks of ages for the late orogenic magmatism at ca. 308 Ma and 299 Ma, and all dated rare-element pegmatites clearly emplaced during the late-orogenic evolution of the Variscan belt. Contemporaneous fields of rare-element pegmatites are arranged in belts following those formed by similar granitoid suites. Pegmatite fields from both the GTOMZ and the CIZ reveal a southward propagation of ages of emplacement, which matches the observed propagation of deformation, metamorphism and magmatism in the two different geotectonic zones. Existence of three successive rare-element events in the Iberian Massif argues against the involvement of lower crustal HP-HT metamorphism in the generation of rare-element melts. Possible sources of rare-element-enriched melts are more likely located in the middle to upper crust, as are the major components of granitic magmatism. Analyses of U and Pb isotopes from columbite-group minerals are very robust and reproducible, making them good candidates for dating ore deposits related to peraluminous magmatism as well as REE- and Nb-bearing deposits.

**Keywords:** rare-element granite and pegmatite / columbite group minerals / LA-SF-ICPMS dating / Variscan orogeny / Iberian Massif

**Résumé – Magmatisme à métaux rares polyphasé au cours de l'évolution tardi-orogénique : contraintes géochronologiques depuis le NO de l'Ibérie varisque.** Les granites et pegmatites à métaux rares représentent des ressources importantes en matières premières minérales utilisées par les technologies de la transition énergétique et de la télécommunication, comme le lithium ou le tantale. Cependant, les processus géologiques à leur origine sont encore peu compris. Plusieurs champs de pegmatites et un granite à métaux rares sont connus dans les formations varisques de l'Ibérie (Espagne et Portugal), ce qui en fait une

\*Corresponding author: [j.melleton@brgm.fr](mailto:j.melleton@brgm.fr)

aire d'étude d'intérêt pour l'étude de la formation de ces magmas extrêmement différenciés. La datation U-Pb in situ par LA-SF-ICP-MS des minéraux du groupe de la colombite extraits de granites and pegmatites à métaux rares de la chaîne varisque ibérique apporte de nouvelles contraintes sur la genèse des magmas à métaux rares. En effet, trois événements distincts ont été reconnus : (i) La mise en place du granite à métaux rares d'Argemela dans la zone centre ibérique (CIZ) à  $326 \pm 3$  Ma ; (ii) La mise en place de pegmatites à métaux rares dans la zone de Galice-Trás-os-Montes (GTOMZ), à un âge moyen de  $310 \pm 5$  Ma ; (iii) La mise en place de pegmatites à métaux rares dans la CIZ et le sud de la GTOMZ à environ  $301 \pm 3$  Ma. Ces deux derniers événements sont contemporains des deux pics de magmatisme tardi-orogénique à environ 308 Ma and 299 Ma. Toutes les pegmatites à métaux rares datées au cours de cette étude se sont mises en place durant l'évolution tardi-orogénique de la chaîne varisque. Les champs de pegmatites à métaux rares contemporains sont organisés en ceintures similaires à celles des suites de granitoïdes. Les champs de la GTOMZ et de la CIZ montrent une propagation vers le sud des âges de mises en place, ce qui est cohérent avec la propagation observée pour la déformation, le métamorphisme et le magmatisme dans les deux domaines géotectoniques. L'existence de trois épisodes successifs de magmatisme à métaux rares dans le massif ibérique est un argument contre la participation de processus métamorphiques de hautes pressions et hautes températures infracrustaux dans la genèse des magmas à métaux rares. Leurs sources possibles sont plus probablement localisées dans la croûte moyenne à supérieure, comme le magmatisme granitique contemporain. Les analyses des isotopes de l'uranium et du plomb des minéraux du groupe de la colombite sont robustes et reproductibles, ce qui en fait un excellent outil pour la datation des gisements à métaux rares.

**Mots clés :** granites et pegmatites à métaux rares / minéraux du groupe de la colombite / LA-SF-ICPMS / orogénèse varisque / Massif Ibérique

## Introduction

Lithium and tantalum are key metals for the development of new technologies. Rare-element granites and pegmatites are amongst the most important sources of raw materials for these metals (Linnen *et al.*, 2012). They are also storehouses for many industrial minerals such as feldspar, quartz, mica and kaolin (Glover *et al.*, 2012). Rare-element granites and pegmatites generally form volumetrically small bodies, corresponding to small batches of enriched magma. Magmatic processes can lead to rare-element-enriched magma in two ways: (A) low melting rate resulting in small melt fractions from a crustal source with a restricted composition or partial melting of rare-element rich sediments in shear zone context (Stewart, 1978; Melleton *et al.*, 2012; Deveaud *et al.*, 2013, 2015; Shaw *et al.*, 2016; Simmons *et al.*, 2016; Müller *et al.*, 2017; Konzett *et al.*, 2018a, b; Gourcerol *et al.*, 2019; Webber *et al.*, 2019; Ballouard *et al.*, 2020; Lv *et al.*, 2021b); or (B) a late withdrawal of residual liquid from the crystallization of parent granite (Černý *et al.*, 2005; Novak *et al.*, 2013; London, 2018; Roda-Robles *et al.*, 2018; Neiva *et al.*, 2019; Garate-Olave *et al.*, 2020; Lv *et al.*, 2021a). This latter process is the most accepted genetic model for rare-element granites and pegmatites, although fractionation between “parent” granites and rare-element magmatic bodies still has to be explained (London, 2008).

Another explanation for rare-element enrichment has been proposed: the extraction of metasomatic fluids during lower crustal granulite metamorphic processes (High Pressure-High Temperature, HP-HT) was suggested to explain the abnormal enrichment of fluxing elements (Li, F, B, Be) and High Field Strength Elements (HFSE, mainly Nb and Ta) (Christiansen *et al.*, 1988; Marignac and Cuney, 1999; Cuney *et al.*, 2002; Cuney and Barbey, 2014; Simons *et al.*, 2016). This hypothesis is based mainly on the observation of extreme depletion of Cl, F, Large-Ion Lithophile Elements (LILE) and rare-metals in granulite and

on geochronological results ( $^{40}\text{Ar}$ - $^{39}\text{Ar}$  on lepidolite and muscovite) from the North French Massif Central, where rare-element bodies were emplaced contemporaneously at about 310 Ma, at the same time as HP-HT metamorphism affecting the lower crust of the French Massif Central.

In the northwestern Variscan realms of Iberia, rare-element pegmatites are widespread (Cotelo Neiva, 1944; Neiva, 1975, 1977; Gomes and Nunes, 1990; Charoy *et al.*, 1992; Martín-Izard *et al.*, 1992; Roda, 1993; Fuertes Fuente and Martín-Izard, 1998; Neiva *et al.*, 2008, 2012; Neiva and Ramos, 2010; Antunes *et al.*, 2013; Lima *et al.*, 2014; Roda-Robles *et al.*, 2016, 2018). In addition, the Argemela granite, studied by Charoy and Noronha (1991, 1996), Michaud *et al.* (2020) and Michaud and Pichavant (2020) presents all the characteristics of a rare-element granite. Rare-element pegmatites occur in geographically restricted fields and, for this reason, at least seven main rare-element pegmatite fields are recognized. Previous studies, based mainly on geochemical data, suggested a genetic relationship between rare-element pegmatites and surrounding granitoids (Gomes and Nunes, 1990; Fuertes Fuente and Martín-Izard, 1998; Lima, 2000; Almeida *et al.*, 2002; Neiva *et al.*, 2008, 2012; Neiva and Ramos, 2010; Roda-Robles *et al.*, 2018). Due to the very low number of available geochronological data on rare-element pegmatites in Iberia, as highlighted by Roda-Robles *et al.* (2018), one of the first questions is on the general timing of rare-element magmatism: is there one general event or is it polyphased? Currently, only three studies provided radiometric ages in an attempt to date emplacement of granitic pegmatites in the Iberian segment of the Variscan belt. Two of them focused on a single pegmatite field, the Fregeneda-Almendra field (Portugal and Spain) for the first one ( $^{40}\text{Ar}$ - $^{39}\text{Ar}$  on micas; Roda *et al.*, 2009; Vieira, 2010), the second at the Tres Arroyos field (CIZ, Spain) (U-Pb by LA-ICP-MS on columbite-group minerals; Garate-Olave *et al.*, 2020). The other study (U-Pb on zircon and monazite; Lima *et al.*

*al.*, 2012) focuses on the Pavia field composed of barren pegmatites (*i.e.*, without minerals typical of rare-elements pegmatites, Lima *et al.*, 2014) located in the Ossa-Morena zone. In the the Fregeneda-Almendra field, authors concluded that Li-bearing pegmatites are not genetically related to their nearest granite; their conclusion is also supported by earlier structural, geochemical and mineralogical data (Roda *et al.*, 1999). For the Pavia field, pegmatites are contemporaneous to some neighbouring granites (Lima *et al.*, 2012, 2014).

Age of rare-element pegmatite and granite is usually obtained using  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  method on micas. However, posterior disturbances can easily affect this isotopic system (Miller and Morton, 1980). Zirconium activity in rare-element granites and pegmatites is generally very low and, when zircon is present, it shows generally high U contents that lead to advanced metamictization (Raimbault, 1998). It is then difficult to use zircon to date emplacement of rare-element granite and pegmatite by U-Pb isotopes measurements. Monazite, another mineral widely used for U-Pb dating of magmatic rocks, is unfortunately rare in the pegmatites of the Li-Cs-Ta (LCT) family (Černý and Ercit, 2005) and related peraluminous rare-element granites. However, columbite group minerals (CGM) are common accessory phases of rare-element pegmatites and granites. They are ideally suited for U-Pb dating since they easily accept U in their structures and can therefore contain a significant amount of radiogenic Pb (Romer and Wright, 1992). Moreover, Pb diffusion is considered to be very low, making these minerals resistant to isotopic system resetting, together with generally very low amount of common Pb (Romer and Wright, 1992; Melleton *et al.*, 2012; Legros *et al.*, 2019). In this context, CGM are the most suitable magmatic minerals for constraining emplacement ages of rare-element granites and pegmatites and is more and more used (Romer and Wright, 1992; Romer and Smeds, 1994, 1996, 1997; Melcher *et al.*, 2008; Melleton *et al.*, 2012; Deng *et al.*, 2013; Van Lichtervelde *et al.*, 2017; Yan *et al.*, 2018; Legros *et al.*, 2019; Feng *et al.*, 2020; Garate-Olave *et al.*, 2020).

In this paper, we present new in-situ U-Pb ages obtained by laser ablation-single collector magnetic sectorfield-inductively coupled plasma-mass spectrometry (LA-SF-ICP-MS) on CGM (both columbite and tantalite) from selected rare-element granites and pegmatites of the Iberian Massif. We discuss the timing of rare-element magmatic events in the Variscan belt, temporal relationships between pegmatites and granites, and the crustal level of the magmatic sources involved. To conclude, we highlight the fact that all CGM compositions show similar behaviour of U-Pb isotopes, making the entire group suitable for dating several types of ore deposits.

## Geological setting

Located along the western border of the Iberian Peninsula, the Iberian Variscan belt represents a large segment of the European Variscan belt. The Variscan belt remnants extend for more than 8000 km from the Appalachians to the Caucasus. The belt was produced by the Paleozoic convergence and collision of two megacontinents, Gondwana in the south and Laurussia in the north, with the involvement of several

microcontinents and the closure of several oceanic domains (Matte, 1986, 1991; Martínez Catalán *et al.*, 2021 and references therein).

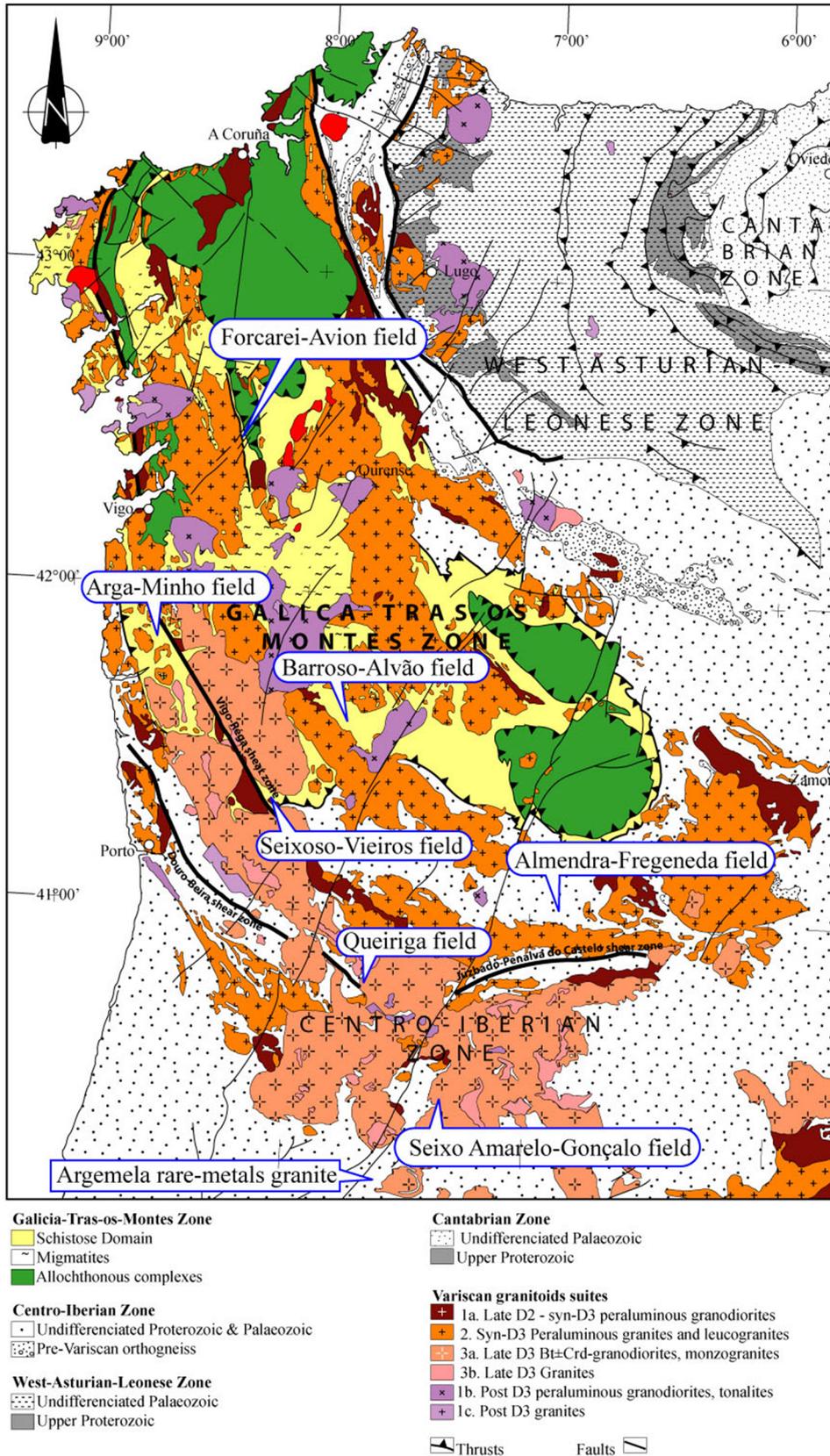
The northwest part of the Iberian Variscan belt is subdivided into four main zones (Fig. 1): (i) the Cantabrian domain; (ii) the West Asturian Leones Zone; (iii) the Galicia-Trás-os-Montes Zone (GTOMZ) (Farias *et al.*, 1987); (iv) the Central Iberian Zone (CIZ) (Julivert *et al.*, 1974; Farias *et al.*, 1987).

Northwestern Iberia records three main phases of deformation (D1, D2 and D3), part of a long-lived deformation history developed in response to Variscan subduction, continental collision and final post-thickening extension (Matte, 1986). The ages of the three main deformation events are diachronous in time and space as a result of deformation propagation (Dallmeyer *et al.*, 1997).

All pegmatites studied are emplaced within the GTOMZ or the CIZ. The GTOMZ (Fig. 1) comprises mainly schists of the para-autochthon and allochthonous complexes. In general, D1 and pre-D1 events are preserved in allochthonous complexes. Paleozoic metasedimentary rocks from the para-autochthon have been affected mainly by D2 and D3 events and by the emplacement of numerous granitoids. The D2 event (~ 375–340 Ma) is related chiefly to final nappe emplacement, prograde metamorphism and local extensional movements. The strong E-W compressive D3 event (~ 340–310 Ma) produced upright folds at all scales and local subvertical S3 foliation. This event is related to high-T and medium-P metamorphism producing partial melting.

The CIZ (Fig. 1) is characterized by autochthonous metasedimentary formations with the predominance of a thick, monotonous Precambrian to Cambrian metapelite and greywacke sequence (Schist-Greywacke Complex) covered by Lower Ordovician quartzite (Arenig facies). Three main Variscan tectono-metamorphic stages are recognized (Ábalos *et al.*, 2002): (i) the D1 event, corresponding to the formation of straight folds associated with prograde Barrovian metamorphism and dated to about 360 Ma (Dallmeyer *et al.*, 1997); (ii) the D2 extensional event (~ 340–325 Ma), marked by local development of extensive shear zones and sub-horizontal folds and associated with varying degrees of metamorphism; and (iii) the D3 stage (~ 325–305 Ma), related to dextral and sinistral strike slip and marked by development of vertical shear zones and emplacement of synkinematic granitoids.

In northwestern Iberia, Variscan granitoids have been classified according to their age or chemical composition (review in Ábalos *et al.*, 2002). Basically, they can be subdivided into three series: i) early and late peraluminous tonalites, granodiorites and biotite granites; ii) peraluminous leucogranites; and; iii) biotite ± cordierite granites. Early peraluminous granodiorites represent a syntectonic, late-D2 to syn-D3 event, peraluminous granites, a syn-D3 event, biotite ± cordierite granites, a late-D3 event, and late peraluminous granodiorites, a post-D3 event. This is coherent with the proposed classification by Roda-Robles *et al.* (2018), *i.e.*, the five following types: i) two-mica peraluminous leucogranites; ii) P-rich highly peraluminous granites; iii) P-poor moderately peraluminous granites; iv) moderately to low peraluminous granites and v) I-type low peraluminous granites.



**Fig. 1.** Location of sampled pegmatite fields within the Iberian Massif. Geology modified from Julivert *et al.* (1974); granitoid classification according to Castro *et al.* (2002).

**Table 1.** GPS location of studied samples (geographic co-ordinates, WGS84 datum) and summary of their main characteristics.

Sample	Longitude	Latitude	Name	Type	location	Tectonic zone
FO1001	W8°20'23.5"	N42°30'12.7"	Alfonsín	Spd-pegmatite	Avión-Forcarei field	GTOMZ
BA1002	W7°39'43.9"	N41°36'12.9"	Adagóí	Spd-pegmatite	Barroso-Alvão field	GTOMZ
BA1001	W7°49'48.4"	N41°37'20.3"	Lousas	Pet-pegmatite	Barroso-Alvão field	GTOMZ
SA1001	W8°37'32.9"	N41°50'00.3"	Formigoso	Pet-pegmatite	Arga-Minho field	GTOMZ
SE1001	W8°06'46.5"	N41°21'03.8"	Outeiro	Pet-granite	Seixoso-Vieiros field	GTOMZ
SE1003	W7°59'34.6"	N41°19'18.1"	Vieiros	Pet-Spd-pegmatite	Seixoso-Vieiros field	GTOMZ
QU1001	W7°44'18.7"	N40°47'11.9"	Mina do Rebentão	Pet-pegmatite	Queiriga field	CIZ
GO1001B	W7°20'01.6"	N40°26'11.5"	Gonçalo	Lep-pegmatite	Seixo Amarelo-Gonçalo field	CIZ
AR1001A	W7°36'10.0"	N40°09'21.8"	Argemela	Rare-element granite		CIZ

## Local setting of the study areas

Sampled ore bodies are emplaced within two different geotectonic zones and exhibit different relationships with respect to main deformation phases and emplacement conditions (ductile *versus* fragile). This section briefly describes the local setting of each pegmatite field. All pegmatites studied belong to the LCT family, following the scheme of Černý and Ercit (2005). Figure 1 shows the location of the pegmatite fields studied and of the Argemela rare-element granite. Details of sampled ore bodies including locations are presented in Table 1.

### Pegmatites from the Galicia-Trás-os-Montes Zone-Schistose Domain (GTOMZ-SD)

#### The Forcarei-Avión pegmatite field

The pegmatite fields of the Galicia-Trás-os-Montes area are emplaced within the Schistose Domain of the GTOMZ. This domain is a large, trapezoidal area bounded to the west and east by peraluminous syn-D3 granite batholiths. Autochthons and the bases of para-autochthon units were strongly affected by D3 metamorphism that caused partial melting, and migmatites are therefore observed on the edges of D3 synforms in the northwestern, southwestern and southeastern parts of the GTOMZ-SD. A large-scale, left-lateral, N170°E-trending shear zone, the Serra do Suido shear zone (Fig. 1), is developed at the contact between the two-mica Cerdedo granite and the para-autochthonous metasedimentary rocks west of the GTOMZ-SD (Gloaguen *et al.*, 2014). At least three pegmatite fields are currently recognized within the GTOMZ-SD: the Forcarei-Avión field, the Lalín field and the Boborás field (Fuertes-Fuente, 1996; Fuertes-Fuente and Martín-Izard, 1998). The most important one extends within the Forcarei-Avión region and contains numerous rare-element-bearing pegmatites. One petalite-subtype pegmatite from this field, which lies at the end of Devesa de Abaixo on the road to Alfonsín, was sampled for this work (Tab. 1).

#### The Barroso-Alvão pegmatite field

The Barroso-Alvão pegmatite field is also part of the GTOMZ, located close to the thrust that represents the southern boundary with the Central Iberian Zone and bounded to the east by the Vila Real fault (one of the major NNE-SSW

families of faults that affect the region). This pegmatite field has been extensively studied by several authors (Charoy *et al.*, 1992; Lima, 2000; Martins and Lima, 2011; Martins *et al.*, 2011; Silva *et al.*, 2018). Another remarkable feature is the proximity of the pegmatite field to the Vila Real fault, one of the major NNE-SSW families of faults that affect the region. Pegmatites intruded metasedimentary rocks, which exhibit N120°E-trending S2 subhorizontal cleavage locally overprinted by the D3 event. Deformation event D3 produces a locally strong, penetrative S3 crenulation cleavage that is preferentially associated with ductile shear zones (Noronha *et al.*, 1981). This event occurred during the final Variscan ductile upright folding event that resulted in the 120°-trending folds, which overprinted earlier deformation events.

For our geochronological study, we selected two pegmatite bodies classified as complex type, petalite and spodumene subtype: the Lousas petalite-subtype pegmatite and the Adagóí spodumene-subtype pegmatite (Tab. 1).

#### The Arga-Minho pegmatite field

The Arga-Minho pegmatite field extends north to Ponte de Lima, east to the Vila Verde thrust and west to the Vigo-Régua shear zone. It comprises mainly Silurian metasedimentary formations of the para-autochthon unit, mostly andalusite-bearing micaschists. It is intruded by the Serra de Arga peraluminous granite, which is considered to represent a syn-D3 event (Gomes and Nunes, 1990). Previous studies linked the development of the Arga-Minho pegmatite field with emplacement of the Serra de Arga peraluminous granite, mainly because of the presence of Li, F and Nb anomalies in the southwestern and southeastern parts of the pluton (Gomes and Nunes, 1990; Nunes and Gomes, 1994; Gomes, 1995). In this study, we collected samples from the Formigoso petalite-subtype pegmatite described by Gomes and Nunes (1990).

#### The Seixoso-Vieiros field

The Seixoso-Vieiros field contains numerous granitic pegmatite-aplite bodies (Seixoso and Vieiros pegmatites). The area is bordered to the northwest by the Variscan Celorico de Basto granitic massif, and to the southeast by the syntectonic Felgueiras granodiorite. In the Seixoso area, a specialized heterogeneous granitic intrusion also outcrops as two main apices in the Seixoso and Outeiro granite cupolas (Lima *et al.*,

2009). These apices have a biotite-bearing facies at depth and two-mica or muscovite  $\pm$  tourmaline facies on their roofs (Helal *et al.*, 1993).

During this study, we dated the Outeiro Mine specialized granite and the Vieiros Mine albite-type pegmatite (Tab. 1). The Outeiro granite contains granitic facies, heterogeneously distributed layered facies and pegmatitic segregations. Lithium-bearing minerals, petalite and spodumene have been observed in the pegmatitic segregations (Lima *et al.*, 2009). The mineral assemblage typically matches that of albite-type pegmatites (Černý and Ercit, 2005).

### Pegmatites and rare element granite from the Central Iberian Zone (CIZ)

#### The Queiriga pegmatite field: Mina do Rebentão

The Queiriga pegmatite field, like other pegmatite occurrences of this area (*e.g.*, Penalva do Castelo field: Venturinha beryl-pegmatite, Correia Neves, 1964), is located along the border of the large, left-lateral, N130°E-trending Douro-Beira crustal-scale shear zone (Valle Aguado *et al.*, 2005). We sampled the Mina do Rebentão pegmatite (Tab. 1), emplaced within the porphyritic Cota-Viseu late-D3 granite, which has been dated at  $306 \pm 4$  Ma (Valle Aguado *et al.*, 2005) by conventional U-Pb dating of zircon and monazite. The Mina do Rebentão pegmatite was likely emplaced under brittle conditions and contains numerous metric granodiorite enclaves with sharp contacts in its upper part.

#### The Seixo Amarelo-Gonçalo pegmatite field

The Seixo Amarelo-Gonçalo pegmatite field (Guarda-Belmonte area, east central Portugal) is located in the CIZ of the Iberian Massif. It was described extensively by Ramos (1998, 2007) and Neiva and Ramos (2010). In this area, numerous aplite-pegmatite sills intrude the porphyritic biotite > muscovite Guarda granite, which is classified as a late-D3 granite (Ferreira *et al.*, 1987; Neiva *et al.*, 2009; Neiva and Ramos, 2010). The last authors distinguished four two-mica granites in the Guarda-Belmonte area: the Guarda granite G1 is dated at  $304 \pm 4$  Ma (SHRIMP U-Th-Pb on monazite; Neiva *et al.*, 2009; Neiva and Ramos, 2010), the fine- to medium-grained porphyritic biotite > muscovite granite (G2) at  $300 \pm 1$  Ma, the coarse grained porphyritic biotite > muscovite granite (G3) at  $301 \pm 2$  Ma and the medium- to coarse-grained muscovite > biotite granite (G4) at  $299 \pm 3$  Ma (ID-TIMS on zircon and monazite; Neiva and Ramos, 2010; Neiva *et al.*, 2011). According to these authors, aplite-pegmatite sills would belong to a magmatic serie related to G2 and G3. However, the marked variation in geochemical results from their analyses of aplite-pegmatite (especially for Li, Sn, Rb and Ta) raises some doubts about their interpretations.

Because of the sharp contacts between pegmatite sills and the host granite and the scarcity of deformation patterns, emplacement likely occurred under brittle conditions at an upper level during compressive motion (reverse faulting).

For this study, we chose to date the Gonçalo lepidolite-subtype pegmatite, which outcrops about 1.5 km northeast of the town of Gonçalo.

### The Argemela rare-element granite

The Argemela rare-element granite is a small elliptical body in central Portugal and showing extreme enrichment in incompatible elements (Charoy and Noronha, 1996). This rare-element granite intruded into Upper Precambrian, low-grade schists and metagreywackes, along a N165°E-trending right-lateral vertical shear zone that also slightly deformed its eastern border (Michaud *et al.*, 2020). Its very fine texture and the presence of rounded quartz suggest very fast cooling consistent with upper-level emplacement (Charoy and Noronha, 1991). Several generations of steeply dipping quartz veins with montebrasite, wolframite, and scarce cassiterite, crosscut the granitic body (Michaud *et al.*, 2020). Genetic relationships between rare-element granites, intragranitic veins and with the neighbouring amblygonite-cassiterite-bearing quartz-vein swarm mined for tin in the past have been investigated recently (Michaud and Pichavant, 2020; Michaud *et al.*, 2020). These results highlighted the effect of the continuity of magmatic to hydrothermal processes for the origin of the different mineralizations. Following Michaud *et al.* (2020) interpretation, CGM disseminated in the granite crystallized at the magmatic stage whereas scarce CGM also occur in late intragranitic veins.

### Analytical methods

Pegmatites are usually very heterogeneous bodies and representative samples must be selected with care. However, the studied pegmatites are not all zoned, and in most cases, observed zoning mostly concerned crystal sizes rather than significant mineralogical changes. Macroscopic observations during fieldwork allowed us to recognize blocks with abundant oxides (mainly cassiterite and CGM). All study samples were selected from the oxide-rich zones of the pegmatites.

CGM grains were handpicked under a binocular microscope after densimetric separation. To distinguish these grains from cassiterite grains, they were tested (tinning test) by placing them inside a zinc cup and covering them with hydrochloric acid (Parfenoff *et al.*, 1970). CGM grains do not change during the tinning test, whereas cassiterite grains become covered by a thin layer of zinc, giving them a silvery aspect. Grains were mounted in epoxy blocks and subsequently ground and polished to obtain a uniform surface. Backscattered electron (BSE) images were acquired at the BRGM (Orléans, France) and at the Géosystèmes research unit (UMR 8217) in Lille, France.

In-situ U-Pb isotopic data on single grains of CGM were acquired by laser ablation (NewWave UP213)-single collector magnetic sectorfield-inductively coupled plasma-mass spectrometry (LA-SF-ICP-MS, ThermoFinnigan Element2) at the Geological Survey of Denmark and Greenland in Copenhagen. At the time of analyses, no CGM international standard was available, possibly because of the marked compositional variability of these minerals. However, Melcher *et al.* (2008) did not observe matrix-dependent U-Pb fractionation during CGM dating, and chose to use a zircon standard to correct the matrix effect on fractionation and an extensive study shows that matrix effect are mainly observed for tantalite crystals

(Legros *et al.*, 2019). Frei and Gerdes (2009) and Gerdes and Zeh (2006) described in detail the methods used for the analysis and processing of data from zircon U-Pb dating, and we applied these methods to process the U-Pb data acquired on CGM. All age data presented herein were obtained by single spot analyses with a spot diameter of 45  $\mu\text{m}$  and a crater depth of approximately 15 to 20  $\mu\text{m}$ . The Plešovice (Sláma *et al.*, 2008) and M127 (Nasdala *et al.*, 2008) zircon standards were repeatedly analyzed during data acquisition for quality control, and the results were consistently within  $2\sigma$  of the published ID-TIMS ages. Isoplot/Ex 3.0 (Ludwig, 2003) was used to calculate concordia ages and to plot concordia diagrams.

Electron-microprobe analyses of CGM grains from the studied pegmatites were carried out in the wavelength-dispersion mode on a CAMECA SXFive instrument (University of Orléans-CNRS-BRGM common laboratory). Analyses were performed with an accelerating voltage of 20 kV. The beam diameter was 2  $\mu\text{m}$ . All samples were examined for chemical heterogeneities by back-scattered electron imaging. The number of points and grains analysed per sample depended upon the degree and scale of chemical zoning. Matrix corrections were made with the phi-rho-Z computing program PAP (Pouchou and Pichoir, 1984). Major and trace element were analysed with a beam current of 200 nA. Ti K $\beta$ , Nb L $\alpha$ , Zr L $\alpha$  were measured on PET, Hf M $\beta$  on TAP, Fe K $\alpha$ , Mn K $\alpha$  on LiF, Sn L $\alpha$ , U M $\beta$ , Sc K $\alpha$  on LPET and W L $\alpha$ , Ta L $\alpha$  on LLiF. Counting times on peak and background were 10 s for Ti, Fe, Mn; 40 s for Sn, Nb, W, Zr, U, Hf and 60 s for Ta. Standards of calibration were natural mineral (cassiterite for Sn), synthetic oxides (MnTiO<sub>3</sub> for Ti, Fe<sub>2</sub>O<sub>3</sub> for Fe, LiNbO<sub>3</sub> for Nb, UO<sub>2</sub> for U, ScPO<sub>4</sub> for Sc), and pure elements (Ta, Zr, Hf and W). According analytical setting and element concentration within CGM for each analysis, detection limits were in between 267 and 305 ppm for Sn, 49 and 56 ppm for Sc, 198 and 223 ppm for Ti, 325 and 366 ppm for Fe, 125 and 142 ppm for Mn, 321 and 688 ppm for Nb, 266 and 347 ppm for Zr, 254 ppm for Hf, 382 ppm for W, 245 and 443 ppm for Ta, 306 and 348 ppm for U.

## Geochronological results

Isotopic data are presented in Tables S1 and S2 (e-components) and plotted in Figures 2–10. All age and error calculations were performed at the  $2\sigma$  level. Errors ellipses were plotted at the  $2\sigma$  level in all diagrams.

For most samples, few analyses produced strongly fractionated transient signals unusable for age calculations. Such signals are interpreted to be due to the presence of micro-inclusions (quartz, albite, micas or U-rich minerals such as uraninite) that were not detected during the examination of SEM pictures prior to the analyses.

### Pegmatites from the the Galicia-Trás-os-Montes Zone-Schistose Domain (GTOMZ-SD)

Forcarei-Avion pegmatite field: Alfonsín petalite-subtype pegmatite (FO1001): BSE images showed various types of grains: homogenous, with patchy zoning, or with dark cores surrounded by lighter rims (Fig. 2). Crystal sizes range from

300 to 500  $\mu\text{m}$ . In total, twenty-three analyses were performed on six columbite-(Mn) and columbite-(Fe) grains. Results from three analyses were rejected because of irregular, strongly fractionated, unusable transient signals. The remaining analyses gave concordant or nearly concordant results and yielded an age of  $312 \pm 4$  Ma, with an MSWD value of 0.73 ( $n = 20$ ) (Fig. 2). Uranium and lead concentrations range from 291 to 1248 ppm and from 15 to 61 ppm respectively (see Tab. S1, e-components).

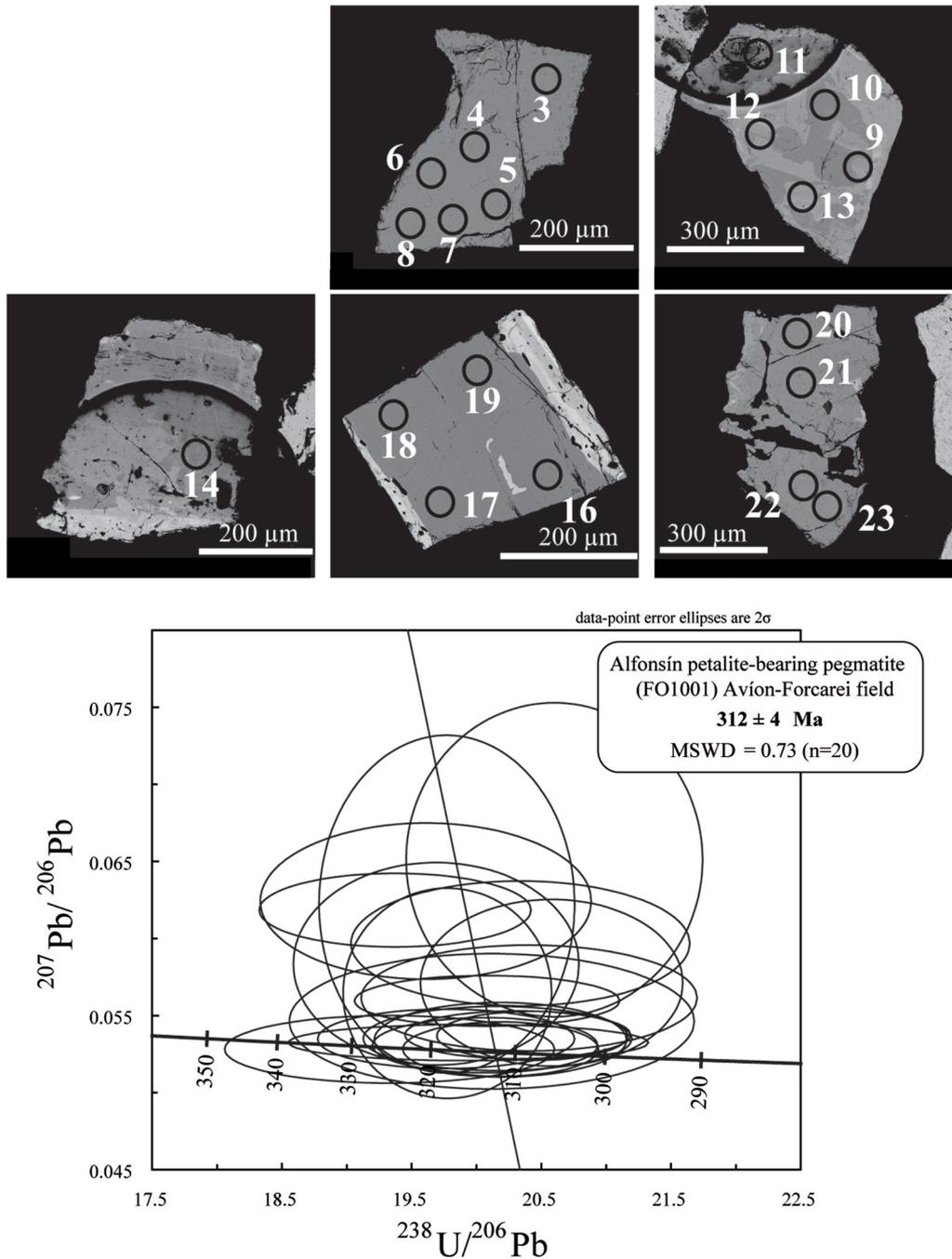
Barroso-Alvão pegmatite field: Three grain populations from the Lousas petalite-subtype pegmatite (BA1001) were observed in BSE images (Fig. 3). The first is represented by slightly homogenous grains, the second, by grains mainly showing patchy zoning, and the third, by grains with oscillatory zoning. Uranium-rich mineral inclusions are common and are particularly abundant in grain 22 (Fig.). Crystal sizes range from 300 to 800  $\mu\text{m}$ . In total, twenty-two analyses were performed on seventeen columbite-(Mn) and columbite-(Fe) grains (Fig. 3). Results from two analyses were rejected because of irregular and highly fractionated transient signals, and from three others because of significant radiogenic Pb loss. The remaining analyses yielded an age of  $311 \pm 4$  Ma (Fig. 3), with an MSWD of 0.19 ( $n = 16$ ). Uranium and lead concentrations range from 104 to 3241 ppm and from 5 to 156 ppm respectively (see Tab. S1, e-components).

Two populations of grains from the Adagó spodumene-subtype pegmatite (BA1002) were observed in BSE images (Fig. 4). The first is composed of heterogeneous grains with cores showing patchy zoning and rims with oscillatory zoning. The second comprises grains having homogenous cores and rims with oscillatory zoning. Uranium rich mineral inclusions are common. Crystal sizes vary from 100  $\mu\text{m}$  to 1 mm.

In total, twenty-one analyses were carried out on seventeen columbite-(Fe) and tantalite-(Fe) grains (Fig. 4). Three analyses were rejected because of irregular, highly fractionated transient signals, and four more because of significant radiogenic Pb loss. The remaining analyses yielded an age of  $307 \pm 5$  Ma (Fig. 4), with an MSWD of 0.30 ( $n = 14$ ). Uranium and lead concentrations range from 69 to 1390 ppm and from 3 to 69 ppm respectively (see Tab. S1, e-components).

Arga-Minho pegmatite field: Formigoso petalite-subtype pegmatite (SA1001): In total, eight analyses were carried out on one columbite-(Fe) grain and one tantalite-(Fe) grain. BSE imaging of the tantalite-(Fe) grain shows oscillatory zoning; the columbite-(Fe) grain shows sector zoning (Fig. 5). Crystal sizes are about 150  $\mu\text{m}$  (Fig. 5). Results from one analysis were rejected because of an irregular, highly fractionated transient signal, and from another because of small, but significant radiogenic Pb loss. One analysis provided concordant results, whereas five others provided results that plot along a mixing line with common Pb values (Fig. 5) that yield an age of  $304 \pm 9$  Ma, with an MSWD of 1.0 ( $n = 6$ ). Uranium and lead concentrations range from 240 to 1386 ppm and from 12 to 65 ppm respectively (see Tab. S1, e-components).

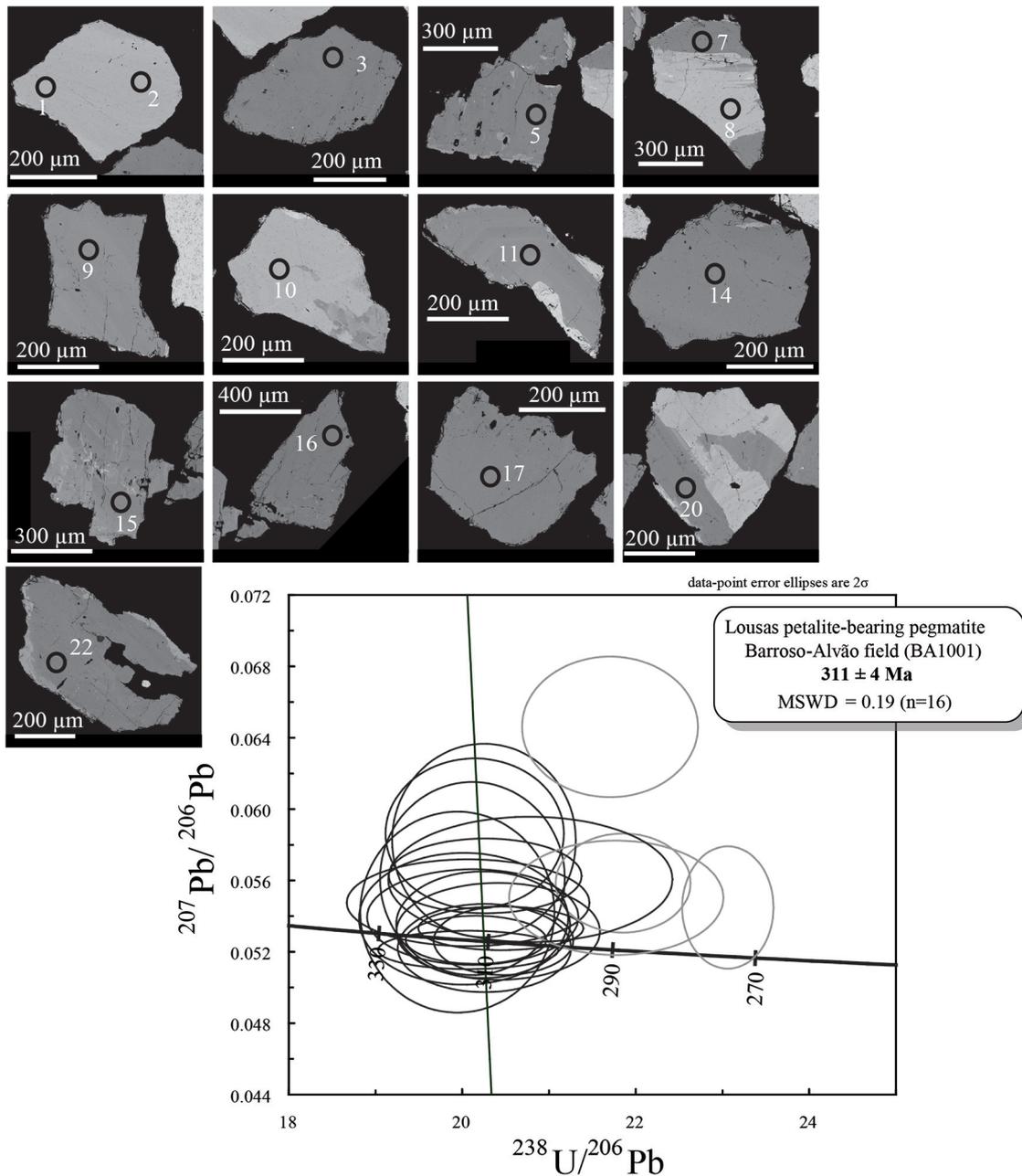
Seixoso-Vieiros pegmatite field: Two grain populations from the Outeiro Mine granite (SE1001) were observed in BSE images (Fig. 6). The first is composed of poikilitic grains with patchy and oscillatory zoning and numerous inclusions of U-rich minerals, and the second, of grains with mainly oscillatory



**Fig. 2.** Inverse concordia diagrams reporting CGM U-Pb data for the sample from the Alfonsín petalite-bearing pegmatite (FO1001A; Forcarei-Avión field). BSE images of the dated grains.

zoning and no inclusions. Crystal sizes range from 100 to 500  $\mu\text{m}$ . In total, fourteen analyses were performed on five columbite-(Fe) grains (Fig. 6). Two analyses (2 and 12) of grain cores (Fig. 6) yielded low U concentrations (between 225 and 266 ppm) and an age of  $316 \pm 9$  Ma. A second analysis population yielded an age of  $301 \pm 5$  Ma, with an MSWD of 0.43 ( $n = 9$ ). Uranium and lead concentrations range from 225 to 1129 ppm and from 8 to 54 ppm respectively (see Tab. S1, e-components).

Tantalite-(Fe) grains from the Vieiros pegmatite (SE1003) show patchy zoning and crystal sizes ranging from 700 to 900  $\mu\text{m}$  (Fig. 7). In total, nineteen analyses were performed on two tantalite-(Fe) grains (Fig. 7). Results from seven analyses were rejected because of irregular, highly fractionated transient signals. Results from the remaining analyses are concordant or plot along a mixing line with common Pb values and yield an age of  $301 \pm 4$  Ma (Fig. 7), with an MSWD of 0.44 ( $n = 12$ ). Uranium and lead concentrations range from 112 to 218 ppm



**Fig. 3.** Inverse concordia diagrams reporting CGM U-Pb data for the sample from the Lousas petalite-bearing pegmatite (BA1001; Barroso-Alvão field). BSE images of the dated grains.

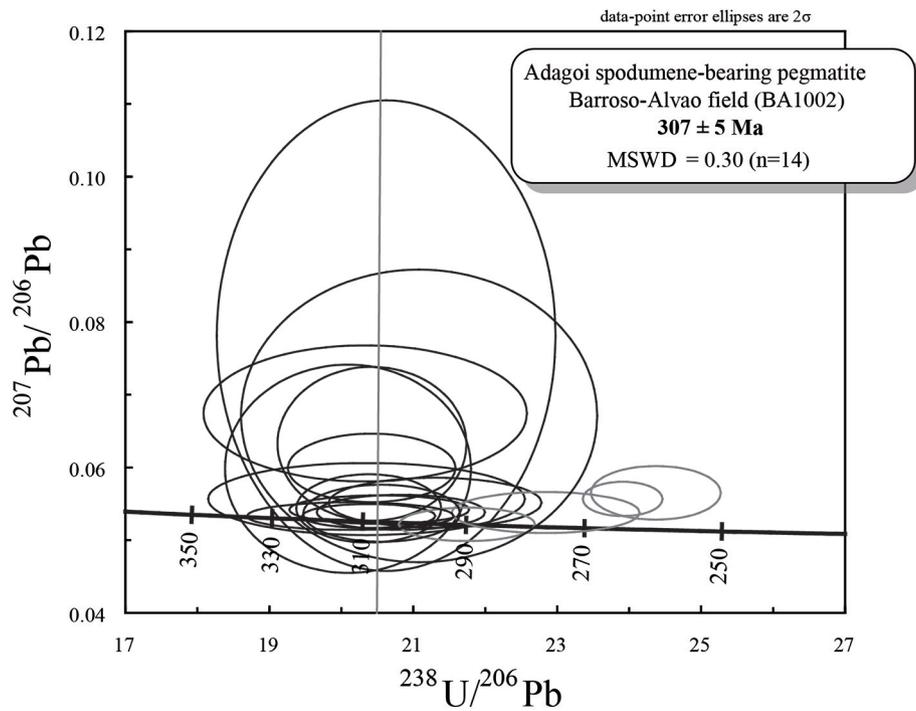
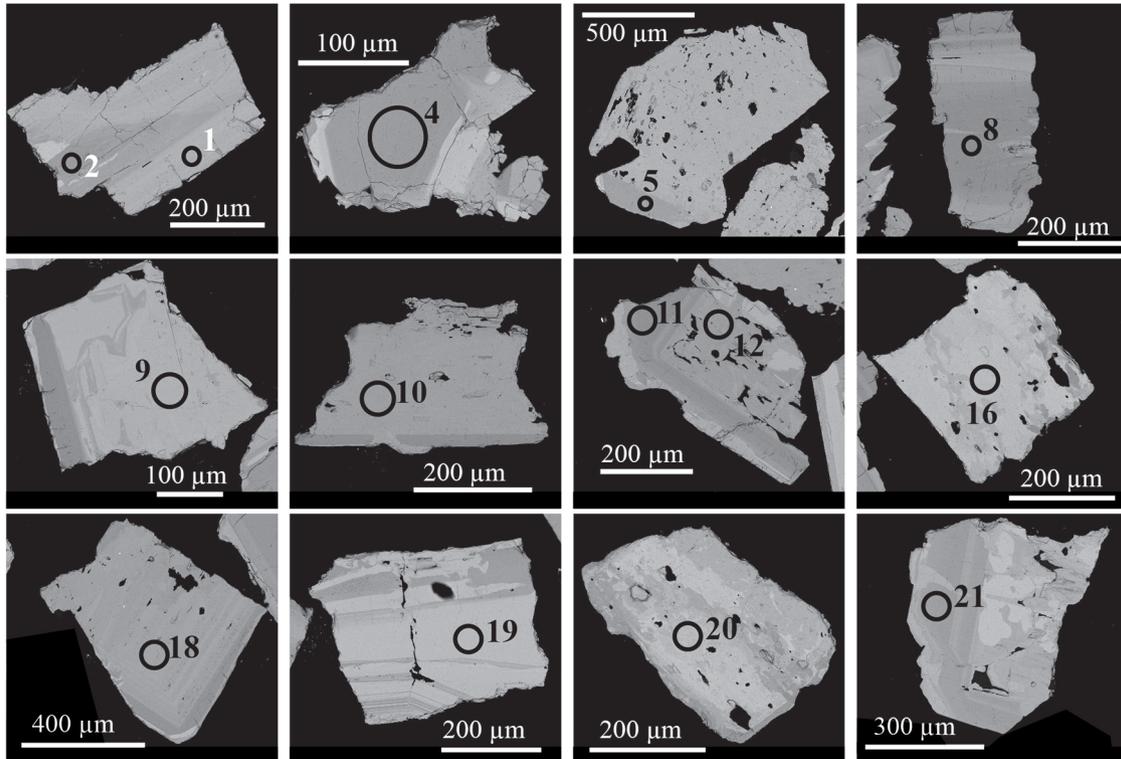
and from 5 to 11 ppm respectively (see [Tab. S1](#), e-components).

### Pegmatites from the Central Iberian Zone (CIZ)

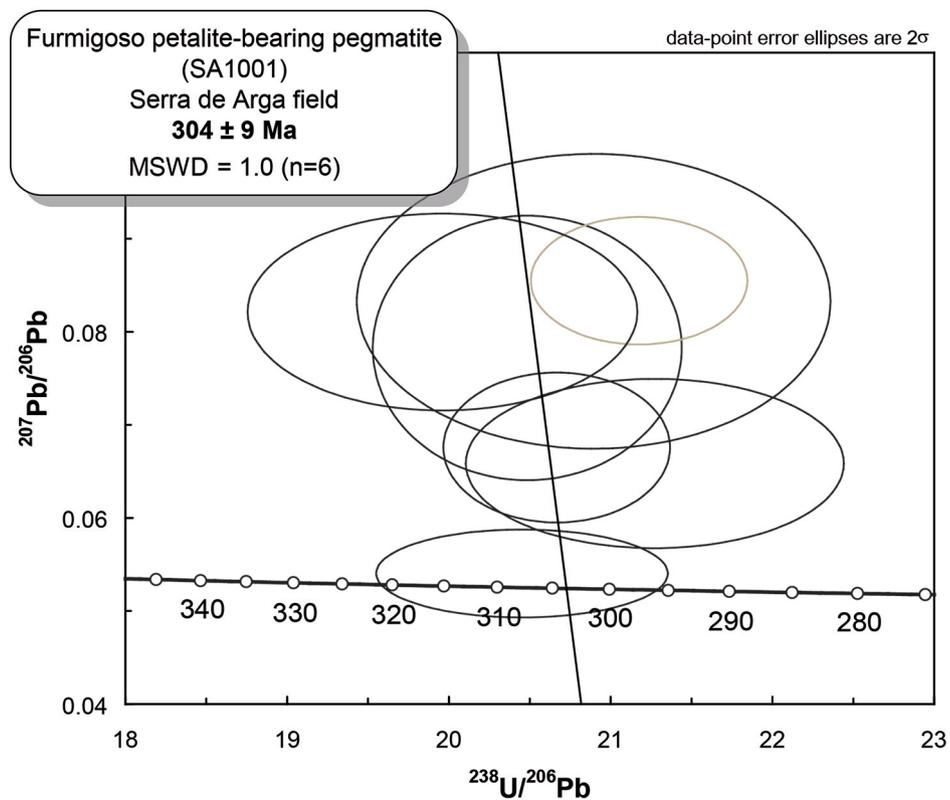
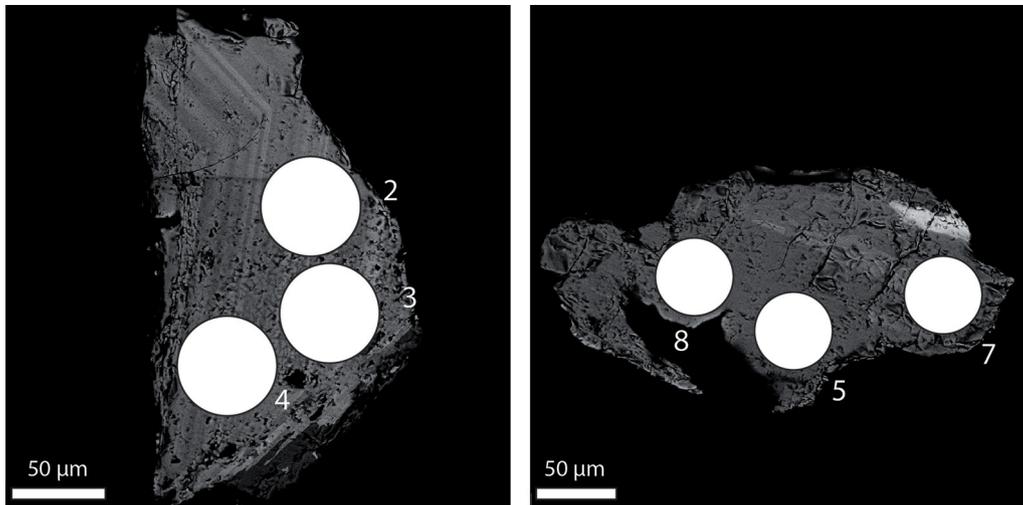
Mina do Rebentão petalite-subtype pegmatite (QU1001, Queiriga field): In total, nineteen analyses were performed on seventeen columbite-(Mn) and tantalite-(Mn) grains ([Fig. 8](#)). BSE images showed very heterogeneously textured grains. Homogenous grains or grains with slight rectilinear zonations seem to form a first population. Very complex grains with

patchy and/or oscillatory zoning form a second heterogeneous population ([Fig. 8](#)). Crystal sizes range from 200 to 500  $\mu\text{m}$  ([Fig. 8](#)). Results from three analyses were rejected because of irregular, highly fractionated transient signals, and from three more because of significant radiogenic Pb loss.

Results from the remaining analyses are concordant or plot along a mixing line with common Pb values and yield an age of  $300 \pm 4$  Ma, with an MSWD of 0.47 ( $n = 16$ ) ([Fig. 8](#)). Uranium concentrations range from 510 to 4453 ppm. Consequently, Pb concentrations range from 23 to 210 ppm (see [Tab. S2](#), e-components).



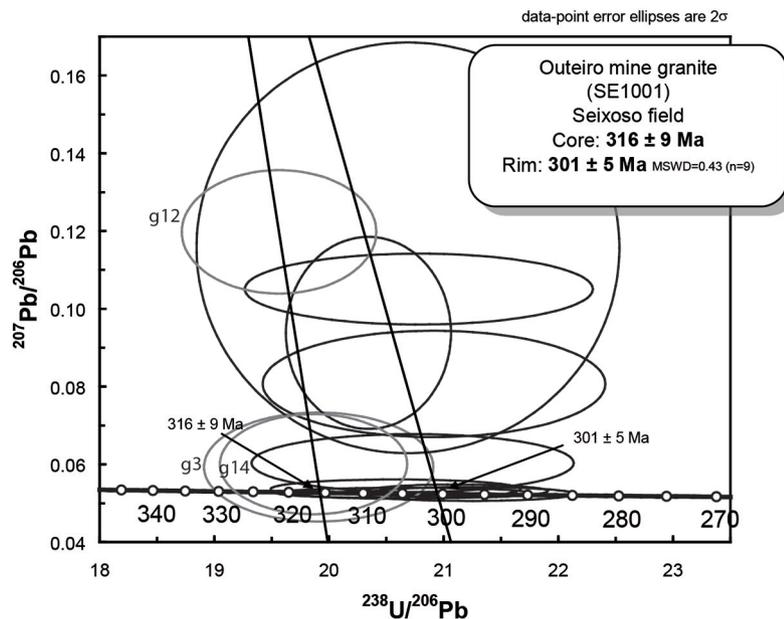
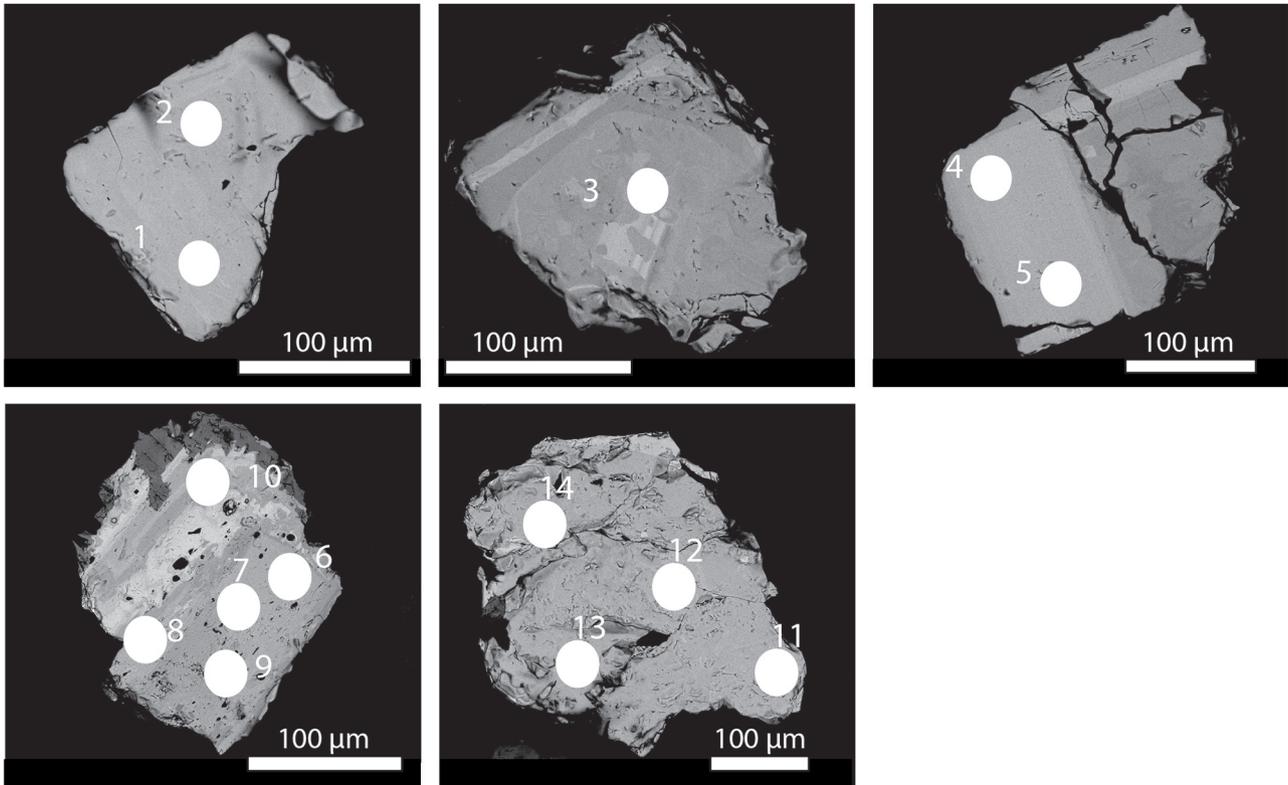
**Fig. 4.** Inverse concordia diagrams reporting CGM U-Pb data for the sample from the Adagói spodumene-bearing pegmatite (BA1002; Barroso-Alvão field). BSE images of the dated grains.



**Fig. 5.** Inverse concordia diagrams reporting CGM U-Pb data for the sample from the Formigoso petalite-bearing pegmatite (SA1001; Arga-Minho field). BSE images of the dated grains.

The Seixo Amarelo-Gonçalo pegmatite field: Two grain populations from Gonçalo lepidolite-subtype pegmatite (GO1001B) were observed in BSE images (Fig. 9). The first is slightly homogeneous, whereas the second is composed of complex grains with patchy and/or oscillatory zoning. Most of the grains analyzed are between 100 and 200 μm in size; one grain measured nearly 700 μm.

In total, twenty-nine analyses were performed on eighteen columbite-(Mn) and tantalite-(Mn) grains, representative of the two textural types. Results from three analyses were rejected because of irregular, highly fractionated transient signals, and from a fourth because of significant radiogenic Pb loss. The remaining analyses yielded an age of  $301 \pm 3$  Ma (Fig. 9), with an MSWD of 0.29 ( $n = 25$ ). Uranium and lead

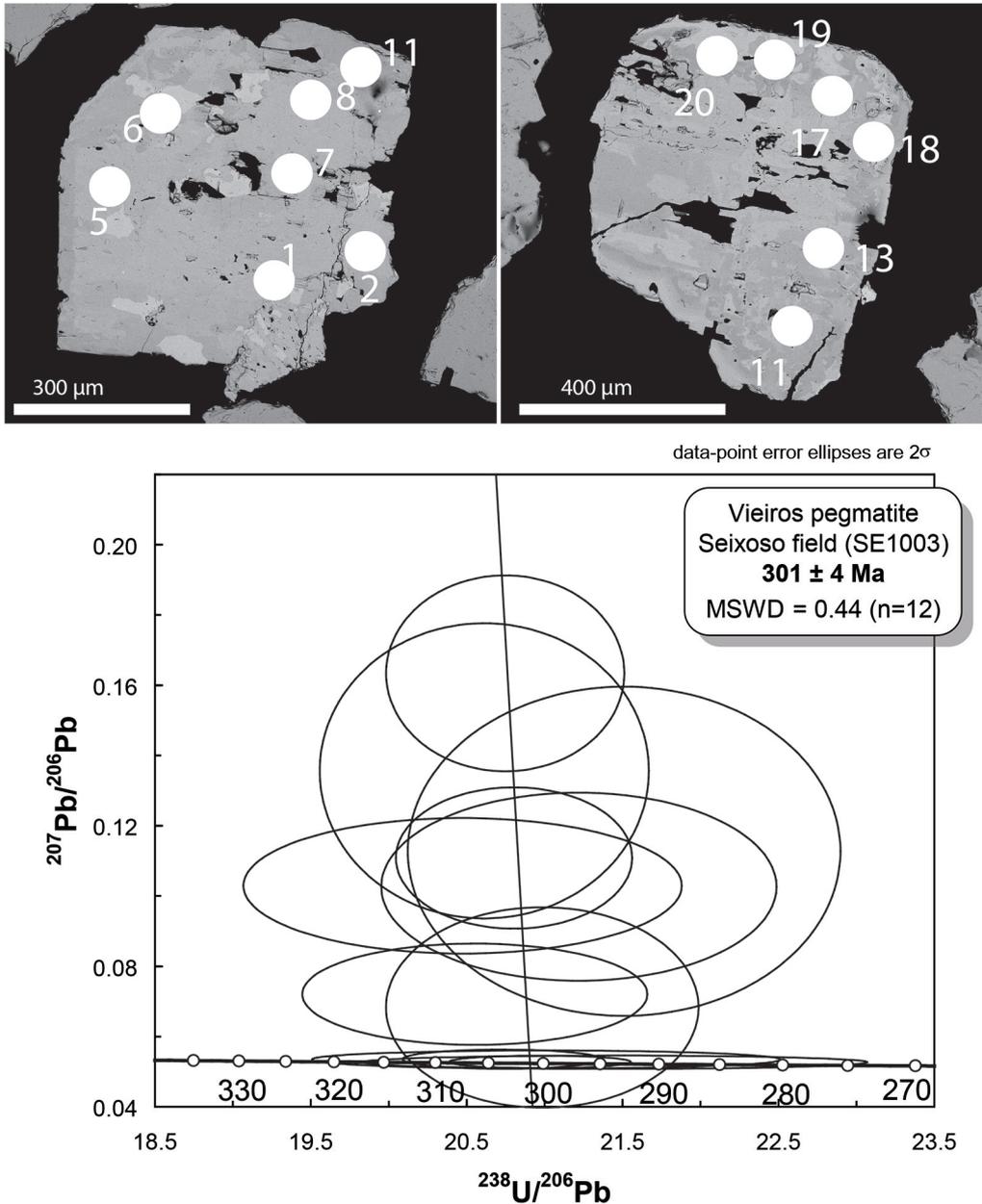


**Fig. 6.** Inverse concordia diagrams reporting CGM U-Pb data for the sample from the Outeiro Mine granite (SE1001; Seixoso-Vieiros field). BSE images of the dated grains.

concentrations range from 66 to 921 ppm and from 3 to 44 ppm respectively (see [Tab. S2](#), e-components).

Argemela granite (AR1001A): BSE images ([Fig. 10](#)) showed several types of columbite-(Mn) grains: homogenous grains, grains with a heavier rim and a dark core, and more complex grain populations with patchy zoning. Sizes range from

300 to 700  $\mu\text{m}$ . In total, twenty analyses were performed on eleven columbite-tantalite grains. Results from five analyses were rejected because of irregular, highly fractionated transient signals. Results from most of the remaining analyses are highly concordant, whereas results from three analyses plot along a mixing line with common Pb values and gave an age of  $326 \pm 3 \text{ Ma}$ ,



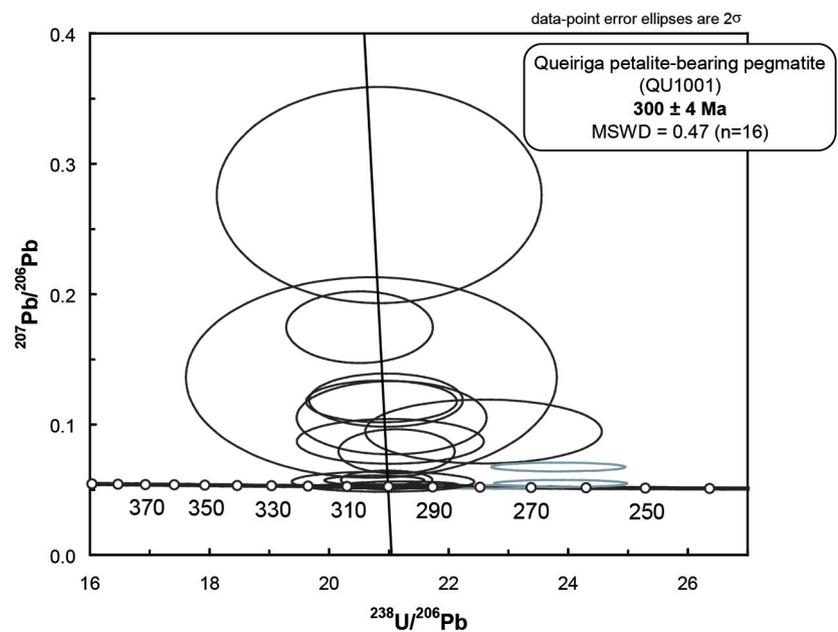
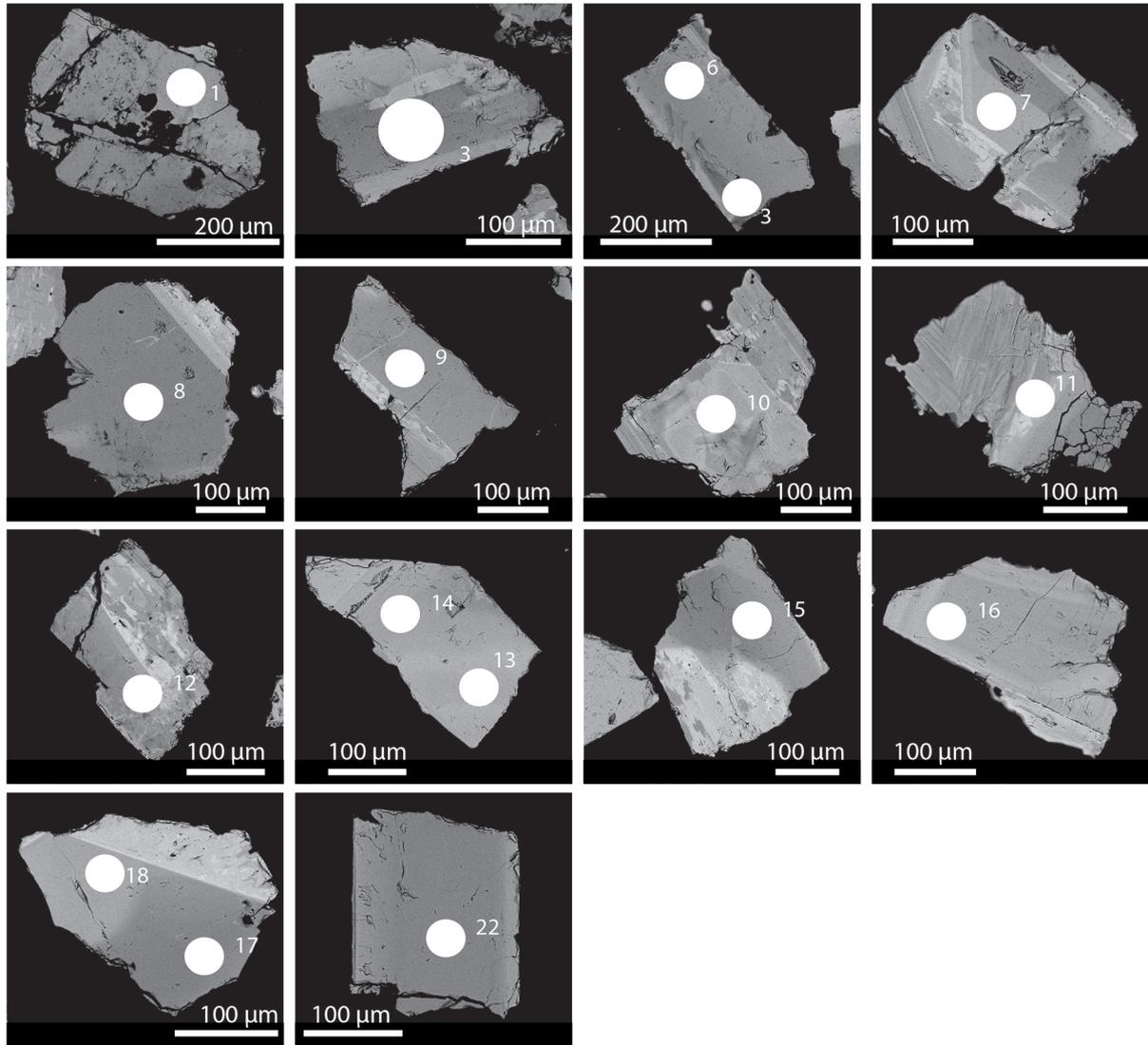
**Fig. 7.** Inverse concordia diagrams reporting CGM U-Pb data of the sample from the Vieiros petalite-bearing pegmatites (SE1003; Seixoso-Vieiros field). BSE images of the dated grains.

with an MSWD of 0.22 ( $n = 15$ ) (Fig. 10). Uranium and lead concentrations range from 72 to 969 ppm and from 4 to 50 ppm respectively (see Tab. S2, e-components).

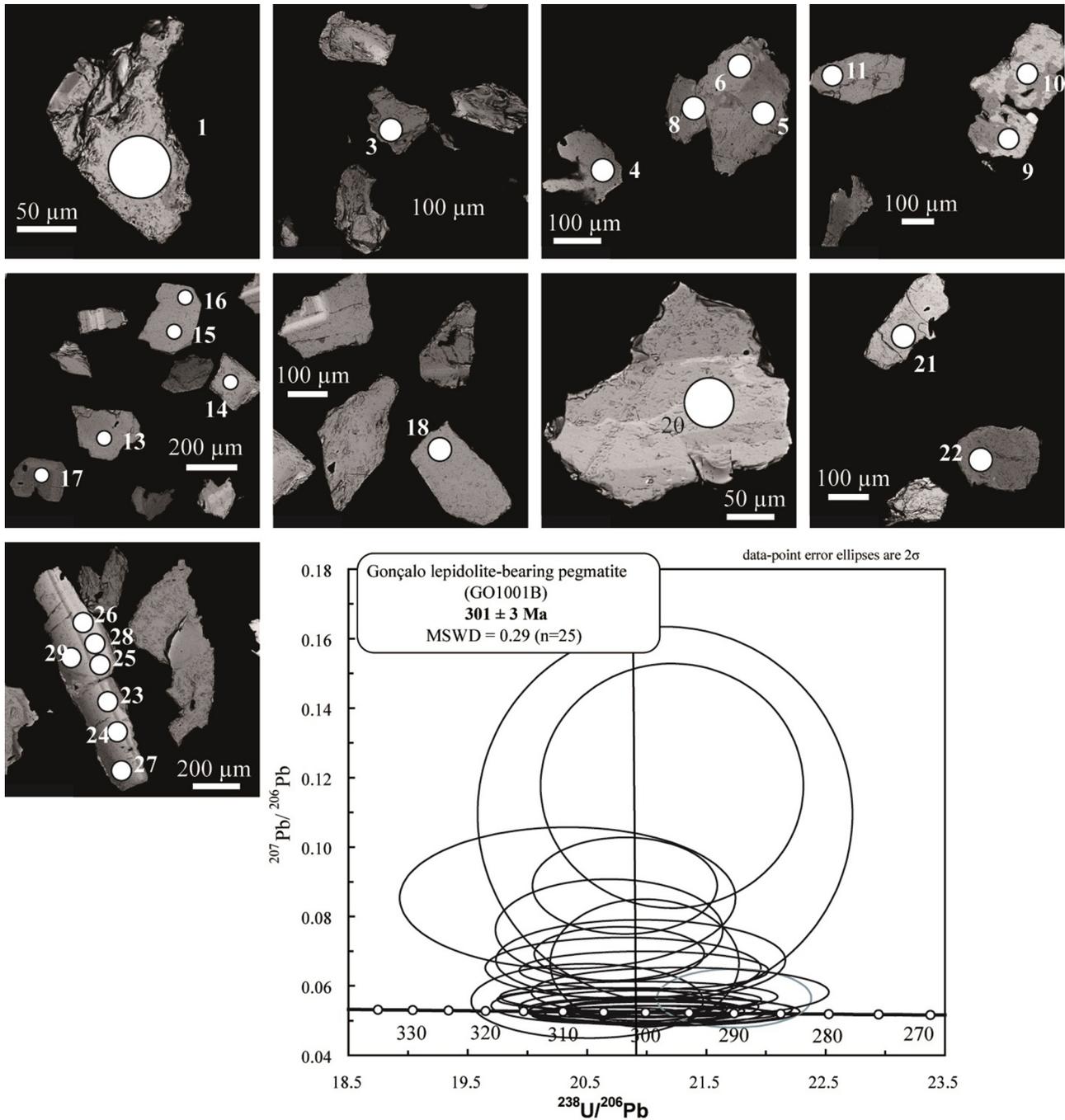
### Chemical compositions of dated CGM

Table S3. (e-components) and Figure 11A show that almost all parts of dated CGM grains correspond to columbite-(Mn) (Outeiro granite SE1001, Formigoso petalite-subtype pegmatite SA1001, Adagói spodumene-subtype pegmatite BA1002, Alfonsin petalite-subtype pegmatite FO1001A, Rebenção petalite-subtype pegmatite QU1001) or columbite-(Fe)

(FO1001A, AR1001, Lousas petalite-subtype pegmatite BA1001 and Gonçalo lepidolite-subtype pegmatite GO1001B). Only grains from the Vieiros pegmatite (SE1003) and scarce parts of grains correspond to tantalite-(Fe) (Adagói spodumene-subtype pegmatite BA1002) or tantalite-(Mn) (Rebenção petalite-subtype pegmatite QU1001, Argemela rare metal granite AR1001). The composition of some tantalite-(Fe) from the Vieiros petalite-subtype pegmatite (SE1003) located within the boundaries of the tantalite-tapiolite gap are probably the result of a disequilibrium growth, remaining metastable and not exsolved into ferrotapiolite-tantalite pairs (Cerny *et al.*, 1992). Trace



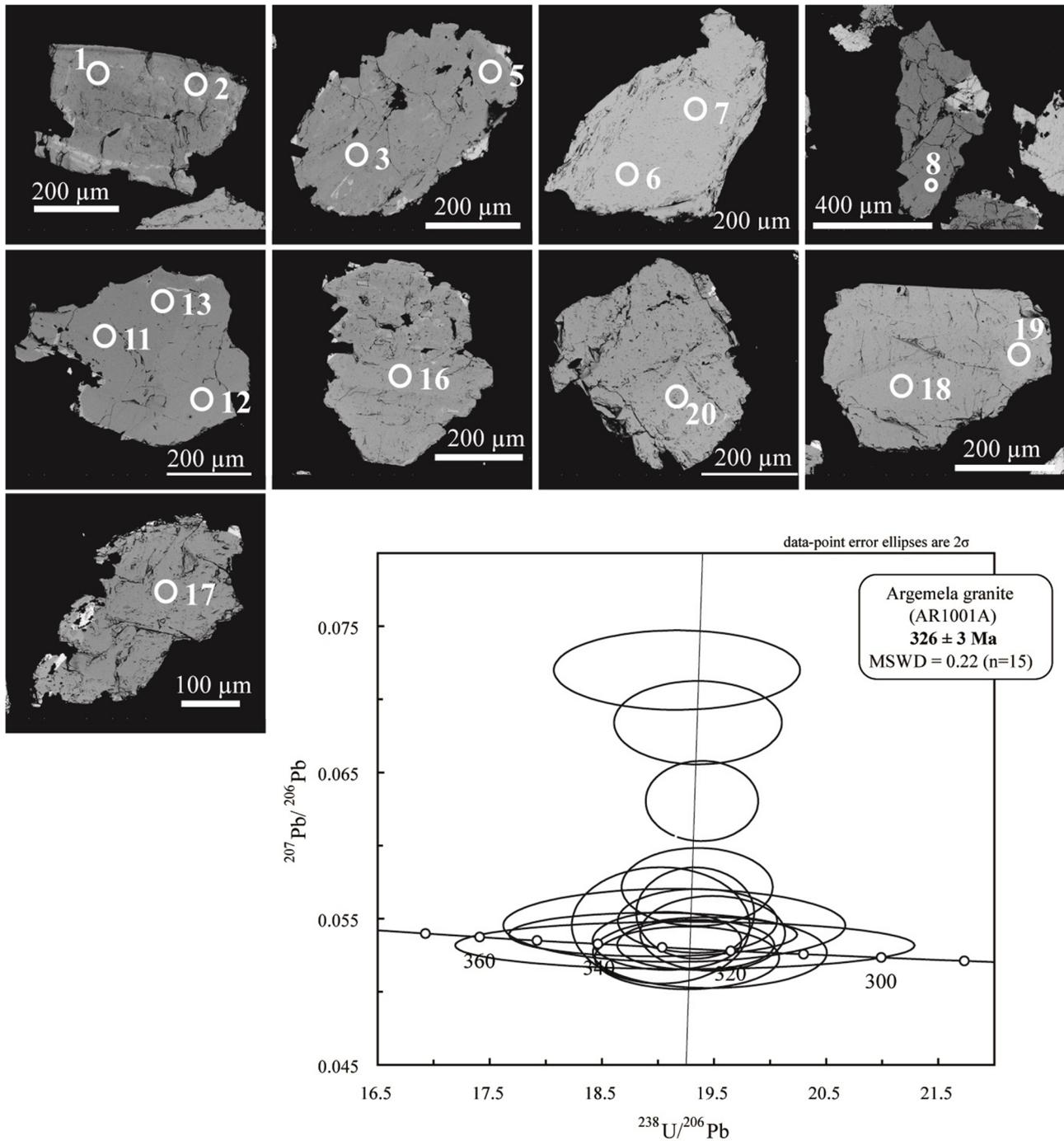
**Fig. 8.** Inverse concordia diagrams reporting CGM U-Pb data for the sample from the Mina do Rebentão pegmatite (QU1001; Queiriga field). BSE images of the dated grains.



**Fig. 9.** Inverse concordia diagrams reporting CGM U-Pb data for the sample from the Gonçalo lepidolite-bearing pegmatite (Seixo Amarelo-Gonçalo field). BSE images of the dated grains.

element within studied CGM are mainly represented by Sn, Ti, Zr, Sc and U. Elements Hf and W are generally below the detection limits. The major element *versus* trace element binary diagrams (Fig. 11C and zoom on Fig. 11D) underline the anti-correlation between the two groups. CGM grains from SA1001, SE1001, GO1001B and FO1001A follow the 1:1 substitution trend, indicating a  $M^{2+} + M^{5+} \rightarrow M^{3+} + M^{4+}$

substitution vector (e.g., Ercit, 1994; Černý *et al.*, 2007). Conversely, CGM grains from others samples follow the 3:2 substitution trend, indicating a  $M^{2+} + 2M^{5+} \rightarrow 3M^{4+}$  substitution vector. For all samples, Sn, Ti and Zr are well correlated and their quantities decrease with the Mn/(Mn + Fe) ratio (Fig. 11B) whereas U content is not correlated with Sn (Fig. 11F), thus not correlated with others  $M^{4+}$ .

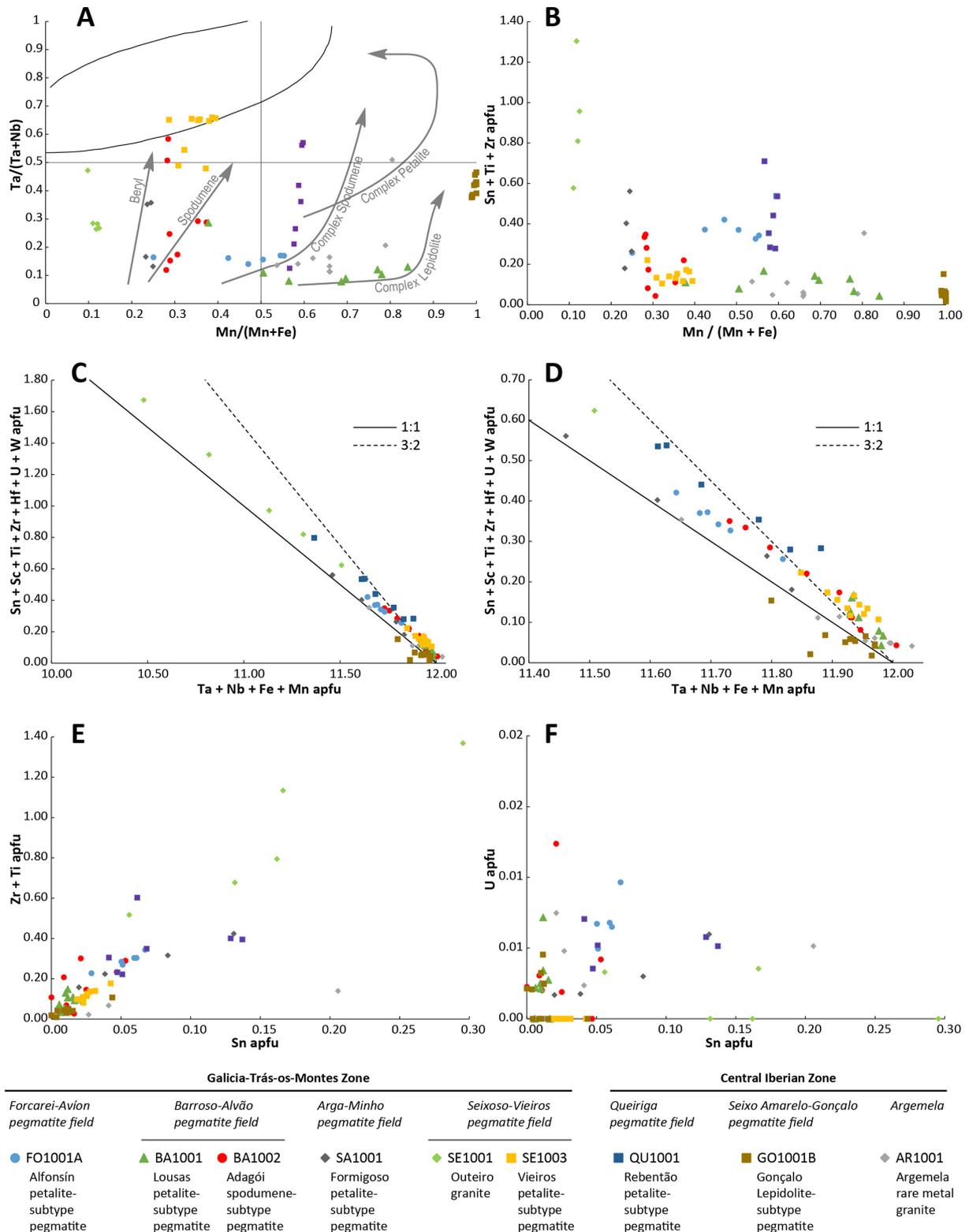


**Fig. 10.** Inverse concordia diagrams reporting CGM U-Pb data for the sample from the Argemela rare-element granite. BSE images of the dated grains.

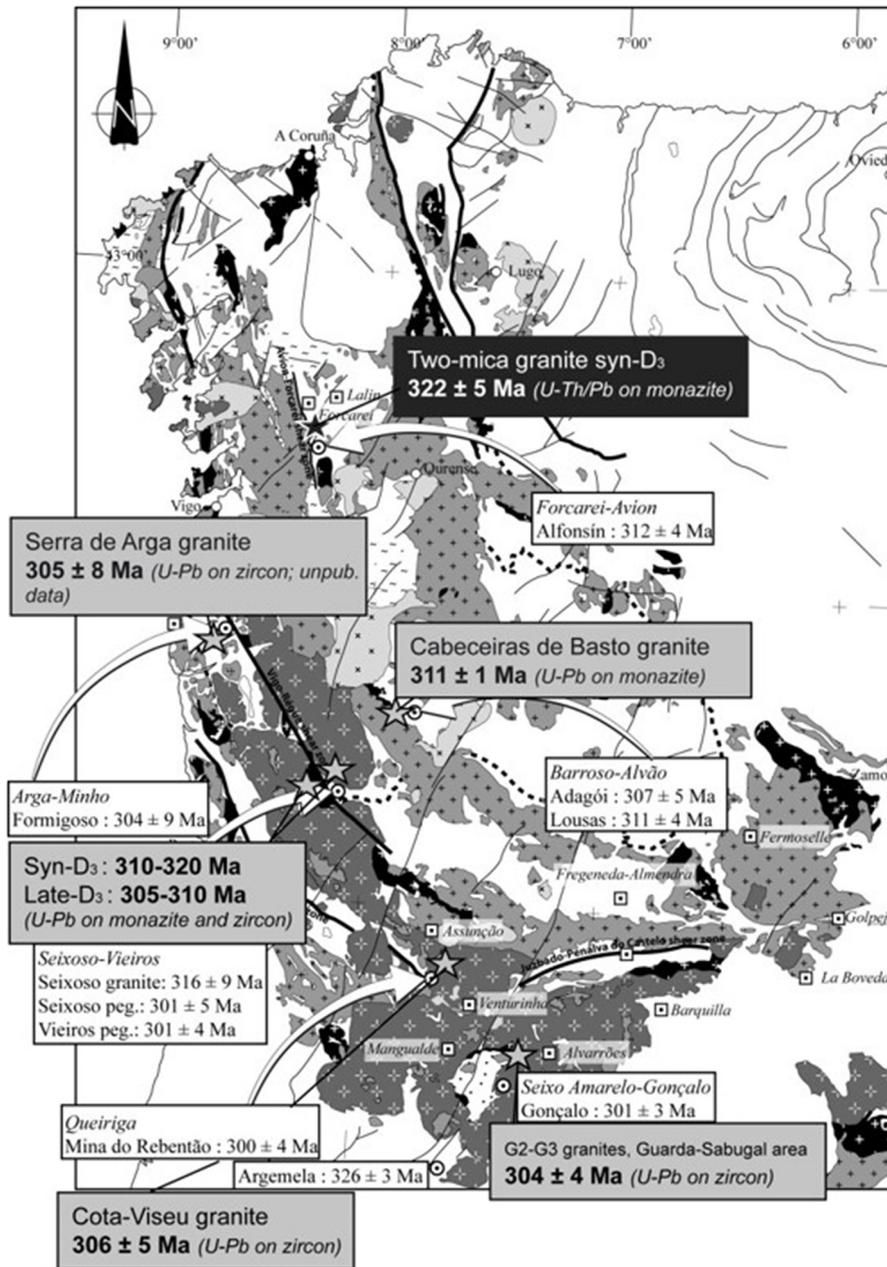
## Discussion

This paper provides ten new U-Pb ages on CGM from rare-element granites and pegmatites of the Iberian Variscan belt (summarized in Figs. 12 and 13). With the exception of the Outeiro Mine granite (Seixoso-Vieiros field), for which two different ages can be clearly established, all the samples provided homogeneous results (within error). For all the

studied samples (except Outeiro Mine), the absence of textural features that could indicate posterior disturbance events suggest that the age obtained for each sample corresponds to the age of magmatic emplacement. In the following section, we first discuss the implications of these results for the chronology of rare-element magmatism and the evolution of the Late Variscan continental crust. Consequences for rare-element enriched peraluminous melts are also debated. To



**Fig. 11.** (A) Composition of studied CGM grains in the quadrilateral Ta/(Ta + Nb) versus Mn/(Mn + Fe) diagram. Enrichment trends of Ta and Nb (grey arrows) observed for CGM from various types of pegmatites according to Černý (1989). (B) Sn + Ti + Zr vs. Mn/(Mn + Fe) (atoms per formula unit, apfu) binary diagram showing a poorly defined general trend of  $M^{4+}$  traces impoverishment with increase of (Mn/Mn + Fe) ratio. (C and D) Trace element vs. Ta + Nb + Mn + Fe (apfu). (E) Zr + Ti vs. Sn (apfu) binary diagram showing the correlation between Zr, Ti and Sn in columbite-tantalite grains within almost all pegmatites fields. (F) U vs. Sn (apfu) binary diagram showing the lack of correlation between the uranium and the tin contents within studied columbite-tantalite grains.



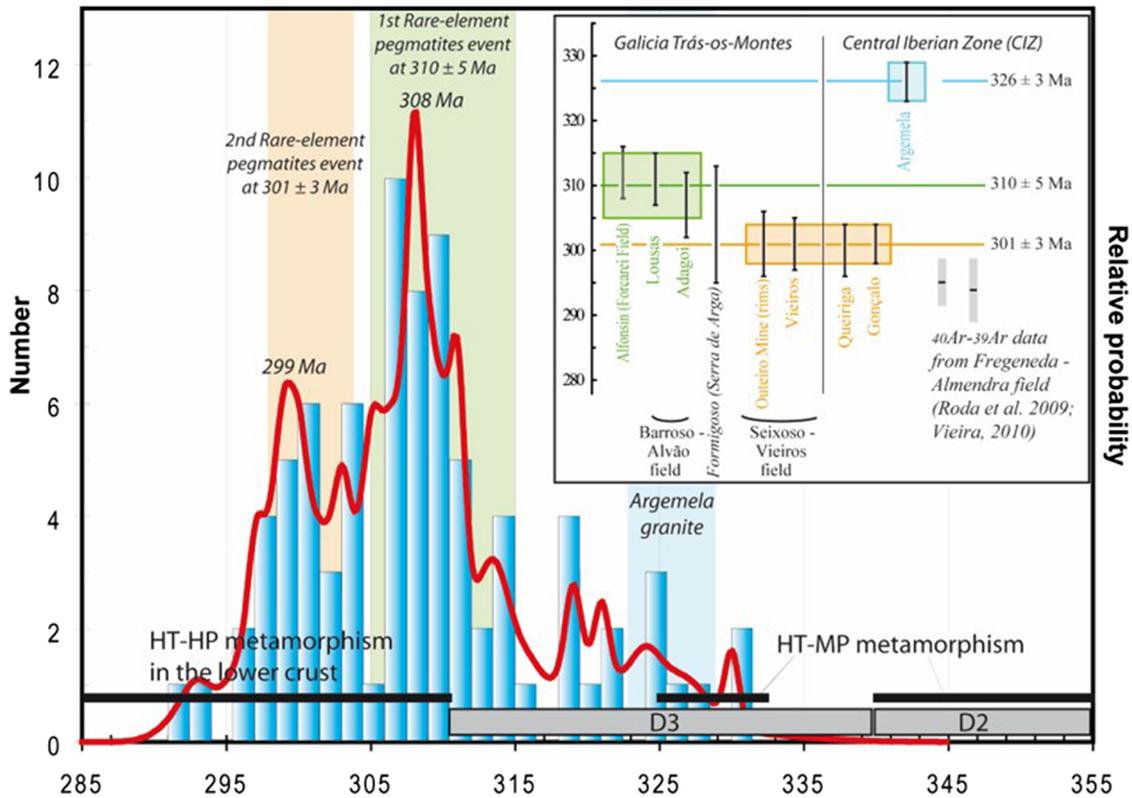
**Fig. 12.** Results from pegmatite dating showing a spatial organization of ages of emplacement. Other pegmatite fields are included to show the spatial relationship between most of the pegmatite fields and shear zones. Dark grey stars and boxes represent supposed “parent” granites that are not contemporaneous with neighbouring rare-element pegmatite fields. Light grey stars and boxes represent supposed “parent” granites that are contemporaneous with neighbouring rare-element pegmatite fields.

conclude, we argue for the relevance of using CGM to date ore deposits related to rare-element granite and pegmatite.

### Early rare-element granite emplacement

Granitoids emplaced during the last ductile deformation phase D3 predominate in the CIJZ. Given the current state of knowledge, geochronological data indicate two main periods

of rare-element pegmatite and granite emplacement, a first event at 330–320 Ma with a peak at 320 Ma, and a second event at 314–299 Ma, with a paroxysm at around 308 Ma (Fig. 12) (Dias *et al.*, 1998; Valle Aguado *et al.*, 2005; Zeck *et al.*, 2007; Ruiz *et al.*, 2008; Antunes *et al.*, 2008, 2013; Solá *et al.*, 2009; Carracedo *et al.*, 2009; Martins *et al.*, 2009, 2013; Neiva *et al.*, 2009, 2011, 2012; Diaz-Alvarado *et al.*, 2011; Teixeira *et al.*, 2011, 2012; Orejama *et al.*, 2012; Carvalho *et al.*, 2012).



**Fig. 13.** Summary of results from the geochronological study and comparison with emplacement ages of granites (compilation of geochronological data from [Dias \*et al.\*, 1998, 2002](#); [Valverde-Vaquero \*et al.\*, 1999](#); [Fernández-Suárez \*et al.\*, 2000](#); [Martin-Izard \*et al.\*, 2000](#); [Valle Aguado \*et al.\*, 2005](#); [Bea \*et al.\*, 2006](#); [Zeck \*et al.\*, 2007](#); [Ruiz \*et al.\*, 2008](#); [Antunes \*et al.\*, 2008, 2013](#); [Carracedo \*et al.\*, 2009](#); [Solá \*et al.\*, 2009](#); [Martins \*et al.\*, 2009, 2013](#); [Neiva \*et al.\*, 2009, 2011, 2012](#); [Diaz-Alvarado \*et al.\*, 2011](#); [Gutiérrez-Alonso \*et al.\*, 2011](#); [Teixeira \*et al.\*, 2011, 2012](#); [Orejama \*et al.\*, 2012](#)), tectonic phases, HT-MP metamorphic events (data from [Montero \*et al.\*, 2004](#) and [Bea \*et al.\*, 2009](#)) and the HT-HP metamorphic event ([Fernández-Suárez \*et al.\*, 2006](#)).

*et al.*, 2012). Three main granitic suites have been described: (i) the early syn-D3 peraluminous granodiorite-granite suite, derived from melting of mixed mafic and felsic lower crust components, or mixing of felsic crustal melts with mantle-derived magmas ([Valle Aguado \*et al.\*, 2005](#); [Teixeira \*et al.\*, 2011](#)); (ii) the syn-D3 peraluminous leucogranite suite, mainly originating from a moderate degree of partial melting under water-undersaturated conditions of metasedimentary crustal sources ([Beetsma, 1995](#); [Teixeira \*et al.\*, 2012](#)); and (iii) the late- to post-D3 biotite ± cordierite-bearing granodiorite-granite suite, forming large, composite batholiths and possibly originating from mixing of mantle-derived magmas and crustal felsic melts during petrogenesis ([Azevedo and Nolan, 1998](#); [Castro \*et al.\*, 1999](#); [Dias \*et al.\*, 2002](#); [García Moreno and Corretgé, 2007](#)).

Dating columbite-(Mn) from the Argemela rare-element granite gave an age of  $326 \pm 3$  Ma, which corresponds to the earliest rare-element event highlighted by our study (Fig. 13). Given the current state of knowledge about the chronology of Variscan magmatic activity within the CIZ, no other contemporaneous granitic body has been found in the vicinity of the Argemela rare-element granite. However, [Teixeira \*et al.\* \(2012\)](#) dated several two-mica granites near Carraceda de Ansiães, about 150 km to the North, and obtained similar ages of  $324 \pm 4$

Ma and  $324 \pm 2$  Ma. These granites are interpreted to be derived from partial melting of heterogeneous metasedimentary material. To the west, along the Porto-Tomar fault zone, migmatitization is dated at  $335 \pm 4$  Ma (U-Pb SHRIMP on zircon overgrowths ([Ordóñez-Casado, 1998](#)) and granites between 335 and 318 Ma ([Pereira \*et al.\*, 2010](#) and references therein).

[Charoy and Noronha \(1991, 1996\)](#) showed that the Argemela rare-element granite was emplaced at an upper level in the crust. This means that this portion of the Iberian Variscan Massif was not thickened during the Variscan orogeny. In the northern French Massif Central, the Beauvoir and Montebras rare-element granites were also emplaced at a high level in the crust, but are significantly younger with an age of  $308 \pm 2$  Ma ([Cheilletz \*et al.\*, 1992](#); [Cuney \*et al.\*, 2002](#)). Therefore, on the basis of our results, the Argemela granite was emplaced almost 20 Ma earlier and is the earliest rare-element granite currently known in the Variscan belt.

### Temporal relationships between rare-element pegmatites and granitic magmatism

The generally preferred genetic model for rare-element pegmatites recognizes a spatial and genetic relationship between fertile “parent” granite and a swarm of increasingly

fractionated pegmatites with distance from the granite (*e.g.*, Černý *et al.*, 2005; London, 2008). In this model, granites and pegmatites are supposed to have the same ages within the uncertainties of the currently available dating methods.

Granite batholiths can be built during several successive pulses spread over more than 10 Ma (Coleman *et al.*, 2004; Neiva *et al.*, 2012; Lima *et al.*, 2012; Teixeira *et al.*, 2012; Carvalho *et al.*, 2012). Conversely, several authors have argued for very fast emplacement and crystallization of granitic intrusions (Bea *et al.*, 2007; Michel *et al.*, 2008), *e.g.*, over less than 1 Ma. Because the uncertainties of U-Pb dating are generally greater than 1 Ma, we make the assumption that rare-element granites and pegmatites and their supposed “parent” granites, when their ages differ within uncertainties, are not petrogenetically related.

Most of the studied areas show contemporaneous emplacement of granitoids and pegmatites. The two types of rare-element pegmatites from the Barroso-Alvão pegmatite field provide ages of  $311 \pm 4$  Ma, for the Lousas petalite-bearing pegmatite, and of  $307 \pm 5$  Ma, for the Adagói spodumene-bearing pegmatite. Several authors consider the Cabeceiras de Basto granite, which shows little enrichment in Li, Sn W and F and is located south of the Barroso-Alvão pegmatite field, as a potential source for these rare-element pegmatites (Lima, 2000; Almeida *et al.*, 2002). The ages obtained are consistent with the  $311 \pm 1$  Ma (U-Pb on monazite) minimum age of crystallization of the Cabeceiras de Basto granite proposed by Almeida *et al.* (2002). However, mineral study and spatial statistical analyses discarded spatial relationships between the Barroso-Alvão pegmatite and the Cabeceiras de Basto granite (Martins *et al.*, 2012; Silva *et al.*, 2018).

CGM from the Formigoso pegmatite (Serra de Arga field) gave an age of  $304 \pm 9$  Ma. In this case, the greater uncertainties are due to the limited number of analyses (*i.e.*, six analyses). Previous work linked the development of the Arga-Minho pegmatite field with emplacement of the Serra de Arga granite (Gomes and Nunes, 1990; Nunes and Gomes, 1994; Gomes, 1995), however published geochronological data for the area are lacking. Gomes (1995) suggested an age of  $305 \pm 6$  Ma (unpublished data) for emplacement of the Serra de Arga granite. In this case, the two ages are coeval.

CGM from the Outeiro Mine granite gave ages of  $316 \pm 9$  Ma and  $301 \pm 5$  Ma. There are two possible interpretations for these two ages: (i) the Outeiro Mine granite was emplaced at  $316 \pm 9$  Ma and was affected by post-crystallization disturbance at  $301 \pm 5$  Ma that caused partial lead loss or solution/recrystallization; or (ii) the Outeiro Mine granite formed at  $301 \pm 5$  Ma and incorporated older inherited grains from its source or as a result of crustal contamination. Several arguments favour the first interpretation. CGM are not that common in crustal rocks. It is therefore very unlikely that the magma of the Outeiro Mine granite contained inherited xenocrysts. Moreover, older ages were obtained from two grains cores (Fig. 6) that have lower U concentrations than domains with younger ages. This is consistent with easier loss of radiogenic Pb in domains with high U concentrations during a later disturbance. The Vieiros pegmatite from the same field gave an age of  $301 \pm 4$  Ma, interpreted as the age of emplacement. The Seixoso pegmatite, located 100 m from the Outeiro Mine granite, shows structural and mineralogical

features similar to those of the Vieiros pegmatite. Therefore, emplacement of these pegmatites and associated fluids could have caused the disturbance that affected the Outeiro Mine columbite-tantalite. The Felgueiras syn-D3 granodiorite, located to the south, had not been dated directly. Dias *et al.* (2002) dated the Celorico de Basto late-D3 granite, located to the north, and obtained an age of  $308 \pm 4$  Ma, making it contemporaneous with the Vieiros pegmatite. The older Outeiro Mine granite could be related to syn-D3 magmatic activity.

CGM from the Gonçalo lepidolite-subtype pegmatite gave an age of  $301 \pm 3$  Ma. This pegmatite crosscuts the Guarda granite, which has been dated at  $304 \pm 4$  Ma (SHRIMP U-Th-Pb on monazite; Neiva *et al.*, 2009). However, Neiva and Ramos (2010) argue that these pegmatites are related to later porphyritic biotite > muscovite granites, which has been dated at about  $300 \pm 1$  Ma and  $301 \pm 2$  Ma (U-Pb on zircon and monazite; Neiva *et al.*, 2011). The data obtained are therefore in good agreement with these observations.

The Mina do Rebentão petalite-subtype pegmatite from the Queiriga pegmatite field was dated at  $300 \pm 4$  Ma, which is the same age as the Cota-Viseu granite ( $306 \pm 5$  Ma; Valle Aguado *et al.*, 2005) whose edge is crosscut by the pegmatite. However, the Mina do Rebentão pegmatite was emplaced under brittle conditions, which argues against the existence of a genetic link between this pegmatite and the host granite.

Finally, only one pegmatite lead to an age that suggests unrelated emplacement of pegmatites and granitoids. Indeed, analyses of CGM from the Alfonsín pegmatite (Forcarei-Avión field) provided an age of  $312 \pm 4$  Ma. Using geochemical arguments, several authors suggested that a relationship exists between aplites-pegmatites from the area and syn-D3 peraluminous two-mica granites (Fuertes-Fuente, 1998; Fuertes-Fuente and Martín-Izard, 1998). However, Gloaguen (2006) dated emplacement of the syn-D3 peraluminous two-mica granite at  $322 \pm 5$  Ma (U-Th/Pb on monazite). Thus, our results suggest that no temporal relationship exists between pegmatites and neighbouring granite.

In conclusion, our results suggest that there are no links between the rare-element pegmatites and their neighbouring late-D3 biotite  $\pm$  cordierite granites. This is in good agreement with field observations from the Barroso-Alvão field, where pegmatites are clearly deformed (Martins, 2009).

### Three rare-element events in the Iberian Massif

The U-Pb dating of CGM from nine rare-element pegmatites and granites from the Iberian Massif provides the first evidence that rare-element magmatism occurred at least during three temporal events in this part of the Variscan belt (Fig. 13).

In the CIZ, the Argemela granite was emplaced during an early event at  $326 \pm 3$  Ma. As highlighted previously, granitoids of this age are rare in the CIZ (Fig. 13) and are located more in the north. This magmatism was related to a first melting event that occurred at the beginning of the D3 deformation phase.

In the GTOMZ, dated pegmatites from both the Forcarei-Avión field and the Barroso-Alvão field gave an average age of  $310 \pm 5$  Ma (Fig. 13). Emplacement of these rare-element

pegmatites was contemporaneous with the main granitoid emplacement event, which occurred at the end of the D3 tectonic phase at about 308 Ma (Fig. 13). Given the uncertainties, this second event could be contemporaneous with either the early syn-D3 granodiorite-granite suites or the syn-D3 leucogranite suites. During our work, we did not observe any evidence of this event in the CIZ. However, obtained age at  $305 \pm 9$  Ma for the Tres Arroyos aplopegmatites (U-Pb on columbite group minerals; Garate-Olave *et al.*, 2020), localized in the southern part of the CIZ, could be part of this event or related to a third later event.

The third event corresponds to the emplacement of pegmatites from the Seixoso-Vieiros (GTOMZ) and the Queiriga and Gonçalo (CIZ) fields at  $301 \pm 3$  Ma (Fig. 13). These results and field observations clearly show the absence of relationship between this event and emplacement of the late-to post-D3 biotite  $\pm$  cordierite-bearing granite suite. The rare-element pegmatites of the Fregeneda-Almendra field have been dated at about 300 Ma by  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  dating on micas (Roda *et al.*, 2009; Vieira, 2010). Emplacement of these bodies could be related to the event at  $301 \pm 3$  Ma highlighted by our study. Emplacement of this rare-element pegmatite was contemporaneous with a second peak of emplacement of granitoids at about 299 Ma (Fig. 13).

The age  $304 \pm 9$  Ma obtained for the Formigoso pegmatite from the Arga-Minho field is difficult to associate to either of the two events because the uncertainty is too large (Fig. 13). The Arga-Minho field is bordered to the east by the Vigo-Régua shear zone (Fig. 12), as is the Seixoso-Vieiros field. One possibility is that this fault played a role in the emplacement of the two pegmatites fields. If such is the case, the two fields could be contemporaneous, with emplacement of the pegmatites of the Arga-Minho field occurring during the third event at  $301 \pm 3$  Ma. On the other hand, the presence of early-D3 granodiorite-granite suites emplaced along the Vigo-Régua shear zone shows that this structure was active during the first stage of the D3 event (Pamplona *et al.*, 2006). The rare-element Arga-Minho pegmatites could therefore also be related to the  $310 \pm 5$  Ma event.

Granitoids from northwestern Iberia generally have asymmetric, elongate shapes parallel to the main structural features of the belt (Fig. 1). Some of them, for example the early D3 granodiorite-granite suite, show strong spatial relationships with major shear zones. In comparison, contemporaneous pegmatite fields dated during this study appear to be distributed following the two geotectonic domains of the inner part of the Iberian Variscan massif, the GTOMZ and the CIZ. Emplacement ages of rare-element pegmatites decrease toward the outer part of the belt, with younger ages in the CIZ (Fig. 12). This agrees with the documented propagation of deformation, metamorphism and magmatism in the different geotectonic zones as proposed by Dallmeyer *et al.* (1997). However, additional geochronological and structural studies are needed to confirm this observation.

As mentioned previously, granitoids are widespread within the Variscan Iberian massif. In the CIZ and in particular during the D3 event, large-scale emplacement of peraluminous bodies occurred over almost 30 Ma (Fig. 12).

Given our results, it is surprising that emplacement of rare-element pegmatites or granites does not appear to be related to one specific event of granite emplacement; on the contrary, it

was widespread over time. Moreover, no specific type of “parent” peraluminous granite has been identified in the Variscan Iberian massif, although some similarities do exist in terms of chemical and mineralogical composition between rare-element pegmatites of different ages, for example between the rare-element pegmatites of the Barroso-Alvão field (about 310 Ma) and those of the Fregeneda-Almendra field (about 295–300 Ma, Roda *et al.*, 2009). In the CIZ, Roda-Robles *et al.* (2018) proposed that lithium-rich pegmatites are related to two micas peraluminous leucogranites in its northern part and to P-rich highly peraluminous granites in its southern part on the basis of spatial and geochemical relationships.

In addition, in the French Massif Central and the South Brittany Variscan domain, where peraluminous granites with ages equivalent to those of peraluminous granites from the GTOMZ and CIZ are also widespread, rare-element pegmatites are essentially absent, with only one field known in the Mont d’Ambazac (Limousin, France, Raimbault, 1998). The situation is completely different in the Iberian massif where several very important fields of rare-element pegmatites are known.

High-temperature, medium- to low-pressure metamorphism (HT-MP) documented in the Iberian massif occurred from about 360 to 340 Ma during the D2 phase and from 332 to 325 Ma during the D3 phase (Montero *et al.*, 2004; Bea *et al.*, 2009 and references therein). The Argemela granite was emplaced at the end of the second event. The two rare-element pegmatite emplacement events are not related to any documented HT-MP metamorphic event. The situation is different in the Moldanubian domain of the Variscan belt (Eastern Europe), where rare-element pegmatites are contemporaneous with HT-MP metamorphic events, during the main orogenic activity of this part of the Variscan belt (Melleton *et al.*, 2012). However, the contemporaneity of rare element magmatic events in Iberia and in the French Massif central is remarkable. Indeed, dating of several rare elements pegmatites and granites lead to similar middle to late Pennsylvanian ages (Cheilletz *et al.*, 1992; Melleton *et al.*, 2015; Marcoux *et al.*, 2021).

### Implications for rare-element melts generation

Several studies (Marignac and Cuney, 1999; Cuney *et al.*, 2002; Cuney and Barbey, 2014) argued that rare-element granite and pegmatite emplacement events in the French Massif Central, dated at  $308 \pm 2$  Ma (Cheilletz *et al.*, 1992), are coeval with HP-HT metamorphism of the lower crust. This metamorphism would result in devolatilization of the lower crust, producing fluids enriched in F, Li and other rare elements. These fluids would induce a low degree of partial melting of an unknown protolith of the middle crust. The produced melts would then be collected and channelled along vertical structures in the crust.

A number of observations favour a middle- to upper-crust source origin for the rare-element melts of the Iberian Massif:

-The existence of at least three distinct rare-element magmatic events in the Iberian Massif, in particular two events separated by almost 30 Ma in the CIZ. Our dataset strongly argues against the involvement of lower crustal processes, because devolatilization of the lower crust can be considered as

an irreversible, secular event occurring during a relative short time span. Moreover, [Fernández-Suárez \*et al.\* \(2006\)](#) dated lower crustal granulite xenoliths from the Spanish Central system by U-Pb on zircon and concluded that the Iberian lower crust recorded HT metamorphic conditions only between 310 Ma and 280 Ma during the Variscan orogeny. Some rare-element pegmatites and granites dated in our study predate this metamorphic event ([Fig. 12](#)) and thus cannot have been generated by the mechanisms proposed by [Marignac and Cuney \(1999\)](#) and [Cuney \*et al.\* \(2002\)](#).

-In the Iberian Massif, rare-element pegmatites and granite suites were emplaced under similar spatial and temporal conditions. Because of their strong crustal affinities, the leucogranite suites are considered the best candidates for the generation of LCT-type pegmatites (review in [Černý \*et al.\*, 2005](#), and [London, 2008](#)). [Neiva and Ramos \(2010\)](#) reached the same conclusion for the rare-element pegmatites of the Seixo Amarelo-Gonçalo field. [Castro \*et al.\* \(1999\)](#) suggested that sources of peraluminous leucogranites could be gneiss and greywackes. Their experimental work also highlighted that the amount of melt needed to generate the large outcropping plutons would be produced at low pressure, during decompression. This suggests that potential sources of the rare-element-enriched melts, such as peraluminous two-mica granites, would more likely be located in the upper to middle crust. In Central and Northern Portugal, recent studies argued for mid-crustal metasedimentary sources for the two micas leucogranite ([Carvalho \*et al.\*, 2012](#); [Costa \*et al.\*, 2014](#)). On the other hand, our dataset does not allow us to recognize the genetic relationships between rare-element pegmatites and granodiorite-granite suites or two-mica peraluminous granite suites. Both types of granitic magma were emplaced over a short period and mainly simultaneously, indicating that metaigneous and metasedimentary sources melted contemporaneously.

The existence of at least three different rare-element events between 330 and 300 Ma in the Iberian Variscan Massif strongly argues against any genetic relationships between lower crustal processes and the origin of rare-element melts. Additional geochemical and geochronological investigations of migmatites and high-grade formations of the GTOMZ and the CIZ are needed to study this hypothesis. In particular, investigations of melt inclusions in peritectic minerals from a metasedimentary protolith that underwent a very low degree of melting could provide important constraints on the chemistry of the first melts generated ([Bartoli \*et al.\*, 2013](#)). New experimental petrology studies are also required to definitely eliminate ([Černý \*et al.\*, 2005](#); [London, 2008](#)) or confirm this hypothesis. On the other hand, the scarcity of rare-element granites and pegmatites and their location in restricted geographic areas of an orogenic belt strongly suggest that particular pre-enriched fertile sources are a prerequisite for the generation of rare-element melts. The role of deformation in the segregation, migration and emplacement of rare-element-enriched melts is also of first importance to understand the generation of these magmas. Several recent studies highlighted the role of deformation structures in the emplacement of rare-element pegmatites ([Demartis \*et al.\*, 2011](#); [Deveaud \*et al.\*, 2013](#)). As discussed earlier, because of the apparent spatial relationships of several rare-element pegmatite fields in the

Iberian Variscan belt, structural studies dedicated to these fields could provide additional constraints on the mechanisms that gave rise to rare-element melts.

### U-Pb dating of columbite-group minerals to date Li-, Be-, Sn-, W-, Ta-, Nb- or REE-bearing ore deposits

Establishing geochronological constraints is a key feature to understand the genesis of most ore and mineral deposits. However, in many cases, this can prove very difficult because of the particular nature of some mineral assemblages. Previous geochronological studies based on U-Pb dating of CGM demonstrated the validity of the method used to date emplacement of pegmatite from the Paleoproterozoic to the Cretaceous ([Romer and Wright, 1992](#); [Romer and Smeds, 1994, 1996, 1997](#); [Romer and Lehmann, 1995](#); [Glodny \*et al.\*, 1998](#); [Melcher \*et al.\*, 2008](#); [Melleton \*et al.\*, 2012](#); [Deng \*et al.\*, 2013](#); [Che \*et al.\*, 2015, 2019](#); [Van Lichtervelde \*et al.\*, 2017](#); [Zhou \*et al.\*, 2016](#); [Legros \*et al.\*, 2019](#); [Feng \*et al.\*, 2020](#); [Garate-Olave \*et al.\*, 2020](#)). Moreover, assimilation of common Pb and loss of radiogenic Pb seem to occur more rarely in CGM than in zircon ([Melleton \*et al.\*, 2012](#)). During our study, we dated several grains of columbite-(Mn), columbite-(Fe), tantalite-(Mn) and tantalite-(Fe). Our results did not reveal any differences in the behaviour of the U-Pb system in the four minerals of the columbite group, and we were able to use these minerals to date the emplacement of several distinct ore bodies. This is in agreement with observation of other studies dedicated to columbite-group minerals dating ([Che \*et al.\*, 2019](#); [Feng \*et al.\*, 2020](#)). Moreover, metamictization processes do not seem to affect U-Pb isotopic systematics in CGM ([Feng \*et al.\*, 2020](#)).

Because columbite-group minerals occur in a wide range of ore deposits related to peraluminous magmatism (rare-element pegmatites and granites, [Linnen \*et al.\*, 2012](#); Sn-W deposits, [Lerouge \*et al.\*, 2007](#)) and also in some REE- and Nb-bearing carbonatites ([Melcher \*et al.\*, 2008](#)), they appear to provide useful and powerful geochronological constraints on the formation of these ore deposits. Nevertheless, age uncertainties need to be strongly reduced in order to decipher chronological relationships in geological settings with long-lived magmatic activities, such as the Variscan orogeny.

## Conclusions

In situ U-Pb dating by LA-SF-ICP-MS of columbite-group minerals from Iberian rare-element granites and pegmatites provides new constraints on the generation of rare-element melts during the Variscan orogeny. Three events have been recognized. The Argemela granite, in the Central Iberian Zone (CIZ), with an age of  $326 \pm 3$  Ma, provides some of the oldest evidence of magmatic activity in this part of the Variscan belt. Rare-element pegmatites of the LCT family from the Galicia-Trás-os-Montes Zone (GTOMZ), which gave an average age of  $310 \pm 5$  Ma, contemporaneous with the early syn-D3 granodiorite-granite suite or the syn-D3 leucogranite suite, represent the second event. The third event corresponds to the emplacement of rare-element pegmatites of the LCT family in the CIZ and in the southern GTOMZ at about  $301 \pm 3$  Ma,

which corresponds to the end of late- to post-D3 granitic suites emplacement.

Contemporaneous fields of rare-element pegmatites are arranged in belts similar to those formed by granitoid suites. Pegmatites fields from both the GTOMZ and the CIZ reveal a southward younging trend of emplacement ages, which matches the propagation of deformation, metamorphism and magmatism in the different geotectonic zones.

The existence of three different rare-element events in the Iberian Massif argues against the involvement of lower crustal HP-HT metamorphism in the generation of rare-element melts as the emplacement of rare-element pegmatites does not appear to have been coeval with documented HT-MP metamorphism. Possible sources of rare-element-enriched melts are more likely located in the middle to upper crust, as are the major components of granitic magmatism.

The reproducibility of analyses of U and Pb isotopes observed during this study is a good argument to consider that columbite-group minerals are good candidates to perform geochronological study of ore deposits related to peraluminous magmatism and some REE- and Nb-bearing deposits.

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## Supplementary material

**Table S1.** LA-ICP-MS U-Pb isotope data for columbite and tantalite from rare-element pegmatites and granites from the Galicia-Trás-os-Montes Zone.

**Table S2.** LA-ICP-MS U-Pb isotope data for columbite and tantalite from rare-element pegmatites and granites from the Central Iberian Zone.

**Table S3.** Chemical compositions of dated CGM grains measured by EPMA.

The Supplementary Material is available at <http://www.bsgf.fr/10.1051/bsgf/2022004/olm>.

## References

Ábalos B, Carreras J, Druguet E, *et al.* 2002. Variscan and Pre-Variscan Tectonics. In: Gibbons W, Moreno MT, eds. *The Geology of Spain*. Geological Society of London, pp. 155–183.

- Almeida A, Martins HC, Noronha F. 2002. Hercynian acid magmatism and related mineralizations in Northern Portugal. *Gondwana Research* 5: 423–434.
- Antunes IMHR, Silva MMVG, Corfu F. 2008. Geochemistry of S-type granitic rocks from the reversely zoned Castelo Branco pluton (Central Portugal). *Lithos* 103: 445–465.
- Antunes IMHR, Neiva AMR, Ramos JMF, Silva PB, Silva MMVG, Corfu F. 2013. Petrogenetic links between lepidolite-subtype aplite-pegmatite, aplite veins and associated granites at Segura (central Portugal). *Chemie Der Erdre-Geochemistry* 73: 323–341.
- Azevedo MR, Nolan J. 1998. Hercynian late-post-tectonic granitic rocks from the Fornos de Algodres area (northern Central Portugal). *Lithos* 44: 1–20.
- Ballouard C, Elburg MA, Tappe S, Reinke C, Ueckermann H, Doggart S. 2020. Magmatic-hydrothermal evolution of rare metal pegmatites from the Mesoproterozoic Orange River pegmatite belt (Namaqualand, South Africa). *Ore Geology Reviews* 116: 103252. <https://doi.org/10.1016/j.oregeorev.2019.103252>
- Bartoli O, Cesare B, Poli S, Bodnar RJ, Acosta-Vigil A, Frezzotti ML, *et al.* 2013. Recovering the composition of melt and the fluid regime at the onset of crustal anatexis and S-type granite formation. *Geology* 41: 115–118.
- Bea F, Montero P, González-Lodeiro F, *et al.* 2006. Zircon thermometry and U-Pb ion-microprobe dating of the gabbros and associated migmatites of the Variscan Toledo Anatectic Complex, Central Iberia. *Journal of the Geological Society* 163: 847–855.
- Bea F, Montero P, González-Lodeiro F, Talavera C. 2007. Zircon inheritance reveals exceptionally fast crustal magma generation processes in Central Iberia during the Cambro-Ordovician. *Journal of Petrology* 48: 2327–2339.
- Bea F, Pesquera A, Montero P, Torres-Ruiz J, Gil-Crespo PP. 2009. Tourmaline 40Ar/39Ar chronology of tourmaline-rich rocks from Central Iberia dates the main Variscan deformation phases. *Geologica Acta* 7: 399–412.
- Beetsma JJ. 1995. *The late Proterozoic/Paleozoic and Hercynian crustal evolution of the Iberian Massif, N. Portugal*. PhD Thesis, Vrije Universiteit Amsterdam, pp. 223.
- Carracedo M, Paquette JL, Alonso Olazabal A, *et al.* 2009. U-Pb dating of granodiorite and granite units of the Los Pedroches batholith. Implications for geodynamic models of the southern Central Iberian Zone (Iberian Massif). *International Journal of Earth Sciences* 98: 1609–1624.
- Carvalho PCS, Neiva AMR, Silva MMVG, Corfu F. 2012. A unique sequential melting mechanism for the generation of anatectic granitic rocks from the Penafiel area, northern Portugal. *Lithos* 155: 110–124. <https://doi.org/10.1016/j.lithos.2012.08.019>
- Castro A, Corretgé LG, De La Rosa J, *et al.* 2002. Palaeozoic magmatism. In: Gibbons W, Moreno MT, eds. *The Geology of Spain*. Geological Society of London, pp. 117–153.
- Castro A, Patiño Douce AE, Corretgé LG, De La Rosa JD, El-Biad M, El-Hmidi H. 1999. Origin of peraluminous granites and granodiorites, Iberian massif, Spain: an experimental test of granite petrogenesis. *Contribution to Mineralogy and Petrology* 135: 255–276.
- Černý P. 1982. Petrogenesis of granitic pegmatites. In: Černý P, ed. *Granitic pegmatites in Science and Industry*, Mineralogist Association of Canada, Short Course Handbook 8: 405–461.
- Černý P. 1989. Characteristics of Pegmatite deposits of Tantalum. In: Möller P, Černý P, Saupé F, eds. *Lanthanides, Tantalum and Niobium*. Springer, Berlin, Heidelberg, pp. 195–239.

- Černý P, Ercit ST. 2005. The classification of granitic pegmatites revisited. *Canadian Mineralogist* 43: 2005–2026.
- Černý P, Ercit TS, Smeds S-A, Groat LA, Chapman R. 2007. Zirconium and hafnium in minerals of the columbite and wodginite groups from granitic pegmatites. *Can. Mineral.* 45: 185–202. <https://doi.org/10.2113/gscanmin.45.2.185>
- Cerny P, Ercit TS, Wise MA. 1992. The tantalite-tapiolite gap; natural assemblages versus experimental data. *Can. Mineral.* 30: 587–596.
- Černý P, Blevin PL, Cuney M, London D. 2005. Granite-related ore deposits. *Economic Geology* (100th anniversary): 337–370.
- Charoy B, Lothe F, Dusausoy Y, Noronha F. 1992. The crystal chemistry of spodumene in some granitic aplite-pegmatite from Northern Portugal. *Canadian Mineralogist* 30: 639–651.
- Charoy B, Noronha F. 1991. The Argemela granite-porphyrty (Central Portugal): the subvolcanic expression of a high-fluorine, rare-element pegmatite magma. In: Pagel & Leroy, eds. *Source, Transport and deposition of metals*. Balkema, Rotterdam, pp. 741–744.
- Charoy B, Noronha F. 1996. Multistage growth of a rare-element, volatile-rich microgranite at Argemela (Portugal). *Journal of Petrology* 37: 73–94.
- Charoy B, Noronha F, Lima AMC. 2001. Spodumene-Petalite-Eucryptite: mutual relationships and alteration style in pegmatite-aplite dykes from Northern Portugal. *Canadian Mineralogist* 39: 729–746.
- Che X-D, Wang R-C, Wu F-Y, *et al.* 2019. Episodic Nb–Ta mineralisation in South China: Constraints from in situ LA–ICP–MS columbite-tantalite U–Pb dating. *Ore Geology Reviews* 105: 71–85. <https://doi.org/10.1016/j.oregeorev.2018.11.023>
- Che X-D, Wu F-Y, Wang R-C, *et al.* 2015. In situ U–Pb isotopic dating of columbite-tantalite by LA-ICP-MS. *Ore Geology Reviews* 65: 979–989. <https://doi.org/10.1016/j.oregeorev.2014.07.008>
- Cheilletz A, Archibald DA, Cuney M, Charoy B. 1992. 40Ar/39Ar age of topaze-lepidolite leucogranite of Beauvoir and of sodolithic pegmatites of Chédeville (North French Massif Central). Petrologic and geodynamic meaning. *Comptes Rendus Académie des Sciences, Paris*, 315: 329–336.
- Christiansen EH, Sheridan MF, Burt DM. 1986. The geology and geochemistry of Cenozoic topaz rhyolites from the Western United States. *Geological Society of America Special Paper* 205: 82.
- Coleman DS, Gray W, Glazner AF. 2004. Rethinking the emplacement and evolution of zoned plutons: Geochronologic evidence for incremental assembly of the Tuolumne Intrusive Suite, California. *Geology* 32: 433–436.
- Correia Neves JM. 1964. Genese des zonar gebauten beryllpegmatits von Venturinha (Viseu, Portugal) in geochemischer sicht. *Beiträge zur Mineralogie und Petrographie* 10: 357–373.
- Costa MM, Neiva AMR, Azevedo MR, Corfu F. 2014. Distinct sources for syntectonic Variscan granitoids: Insights from the Aguiar da Beira region, Central Portugal. *Lithos* 196–197: 83–98. <https://doi.org/10.1016/j.lithos.2014.02.023>
- Cotelo Neiva JM. 1944. Tin and wolfram Portuguese deposits. *Comunicações dos Serviços Geológicos de Portugal*, XXV, pp. 251. (In Portuguese).
- Cotelo Neiva JM. 1992. The pegmatite deposit of Vieiros (Amarante) with cassiterite, columbotantalite and Li-bearing minerals. Unpubl. *Report written for the mining company Nortenha, S.A.R.L, Minas de Vieiros, Amarante, Portugal*, pp. 63.
- Cuney M, Alexandrov P, Le Carlier De Veslud, *et al.* 2002. The timing of W-Sn rare-metal mineral deposit formation in the Western Variscan chain in their orogenic setting: the case of the Limousin area (Massif Central, France). In: Blundell DJ, Neubauer F, Von Quadt A, eds. *The timing and location of major ore deposits in an evolving orogen*. Geological Society of London Special Publication 204: 213–228.
- Cuney M, Barbey P. 2014. Uranium, rare-metals, and granulite-facies metamorphism. *Geosciences Frontiers* 5: 729–745.
- Cuney M, Marignac C, Weisbrod A. 1992. The Beauvoir topaz-lepidolite-albite granite (Massif Central, France): a highly specialized granite with disseminated Sn-Li-Ta-Nb-Be mineralisation of magmatic origin. *Economic Geology* 87: 1766–1794.
- Dallmeyer RD, Martinez Catalan JR, Arenas R, *et al.* 1997. Diachronous Variscan tectonothermal activity in the NW Iberian Massif: Evidence from 40Ar/39Ar dating of regional fabrics. *Tectonophysics* 277: 307–337.
- Demartis M, Pinotti LP, Coniglio JE, *et al.* 2011. Ascent and emplacement of pegmatitic melts in a major reverse shear zone (Sierras de Córdoba, Argentina). *Journal of Structural Geology* 33: 1334–1346.
- Deng XD, Li JW, Zhao XF, *et al.* 2013. U-Pb isotope and trace element analysis of columbite-(Mn) and zircon by laser ablation ICP-MS: Implications for geochronology of pegmatite and associated ore deposits. *Chemical Geology*. <https://doi.org/10.1016/j.chemgeo.2013.02.014>
- Deveaud S, Gumiaux C, Gloaguen E, Branquet Y. 2013. Spatial statistical analysis applied to rare-elements LCT-type pegmatite fields: an original approach to constrain faults-pegmatites-granites relationships. *Journal of GEOsciences* 58: 163–182.
- Deveaud S, Millot R, Villaros A. 2015. The genesis of LCT-type granitic pegmatites, as illustrated by lithium isotopes in micas. *Chemical Geology* 411: 97–111. <https://doi.org/10.1016/j.chemgeo.2015.06.029>
- Dias G, Leterrier J, Mendes A, Simões PP, Bertrand JM. 1998. U-Pb zircon and monazite geochronology of post-collisional Hercynian granitoids from the Central Iberian Zone (Northern Portugal). *Lithos* 45: 349–369.
- Dias G, Simões PP, Ferreira N, Leterrier J. 2002. Mantle and crustal sources in the genesis of late-Hercynian Granitoids (NW Portugal): Geochemical and Sr-Nd isotopic constraints. *Gondwana Research* 5: 287–305.
- Diaz-Alvarado J, Castro A, Fernandez C, Moreno-Ventas I. 2011. Assessing bulk assimilation in cordierite-bearing granitoids from the Central System Batholith, Spain: Experimental, geochemical and geochronological constraints. *Journal of Petrology* 52: 223–256.
- Ercit TS. 1994. The geochemistry and crystal chemistry of columbite-group minerals from granitic pegmatites, southwestern Grenville Province, Canadian Shield. *Can. Mineral.* 32: 421–438.
- Farias P, Gallastegui G, Lodeiro FG, *et al.* 1987. Insights on the lithostratigraphy and structure of the Central Galicia. *IX Reunión de Geología do Oeste Peninsular*. Publicação do Museu e Laboratório Mineralógico e Geológico da Faculdade de Ciências, Universidade do Porto, Program Abstr.1, pp. 411–431. (in Portuguese).
- Farinha J, Lima A. 2000. Study of the Lithium rich aplite pegmatite bodies from the Barroso-Alvão região, Northern Portugal. *Estudos, Notas e Trabalhos* 42: 48 (in Portuguese).
- Feng Y, Liang T, Linnen R, *et al.* 2020. LA-ICP-MS dating of high-uranium columbite from no. 1 pegmatite at Dakalasu, the Chinese Altay orogen: Assessing effect of metamictization on age concordance. *Lithos* 362–363: 105461. <https://doi.org/10.1016/j.lithos.2020.105461>
- Fernández-Suárez J, Arenas R, Jeffries TE, Whitehouse MJ, Villaseca C. 2006. A U-Pb study of zircons from a Lower Crustal Granulite Xenolith of the Spanish Central System: A record of Iberian lithospheric evolution from the Neoproterozoic to the Triassic. *Journal of Geology* 114: 471–483.

- Fernández-Suárez J, Dunning G.R, Jenner G.A, Gutiérrez-Alonso G. 2000. Variscan collisional magmatism and deformation in NW Iberia: Constraints from U-Pb geochronology of granitoids. *Journal of the Geological Society* 157: 565–576.
- Ferreira N, Iglesias M, Noronha F, Pereira E, Ribeiro A, Ribeiro ML. 1987. Granitoids from the Central Iberian Zone and their geodynamical setting. In: *Geología de los Granitoides y Rocas Asociadas del Macizo* (Bea F, *et al.*, eds.), pp. 37–51 (in Spanish).
- Frei D, Gerdes A. 2009. Precise and accurate in situ U-Pb dating of zircon with high sample throughput by automated LA-SF-ICP-MS. *Chemical Geology* 261: 261–270.
- Fuertes-Fuente M. 1996. *The pegmatites from the area of Lalín-Forcarei (Galicia) and their mineralizations of rare-elements*. PhD Thesis, Oviedo University, Oviedo, Spain, pp. 283. (in Spanish).
- Fuertes-Fuente M, Martín-Izard A. 1998. The Forcarei Sur rare-element granitic pegmatite field and associated mineralization, Galicia, Spain. *Canadian Mineralogist* 36: 303–325.
- Fuertes-Fuente M, Martín-Izard A, Boiron MC, Mangas J. 2000. Fluid evolution of rare-element and muscovite granitic pegmatites from central Galicia, NW Spain. *Mineralium Deposita* 35: 332–345.
- Garate-Olave I, Roda-Robles E, Gil-Crespo P-P, Pesquera A, Errandonea-Martín J. 2020. The Tres Arroyos granitic Aplite-Pegmatite field (Central Iberian Zone, Spain): Petrogenetic constraints from evolution of Nb-Ta-Sn oxides, whole-rock geochemistry and U-Pb geochronology. *Minerals* 10: 1008. <https://doi.org/10.3390/min10111008>
- García Iglesias J, Loredó Pérez J, Martín Izard A. 1991. Mineralogy, geochemistry and thermometry of late hydrothermal veins within the Vilatuxe spodumene-bearing pegmatites, Pontevedra, NW Spain. In Pagel & Leroy, eds. *Source, transport and deposition of metals*. Balkema, Rotterdam, pp. 173–176.
- García Moreno O, Corretgé LG. 2007. Processes of assimilation in the genesis of cordierite leucogranites from the Iberian Massif: A short review. *Canadian Mineralogist* 45: 71–85.
- Gerdes A, Zeh A. 2006. Combined U-Pb and Hf isotope LA-(MC)-ICP-MS analyses of detrital zircons: comparison with SHRIMP and new constraints for the provenance and age of an Armorican metasediment in Central Germany. *Earth and Planetary Sciences Letters* 249: 47–61.
- Gloaguen E. 2006. *Constraints from an integrated study on relationships between granites and veins mineralization (Au and Sn-W) in a late-orogenic context (Variscan belt, Central Galicia, Spain)*. PhD thesis, Orleans University, pp. 493. (in French).
- Gloaguen E, Branquet Y, Chauvet A, Bouchot V, Barbanson L, Vignerresse JL. 2014. Tracing the magmatic/hydrothermal transition in regional low-strain zones: The role of magma dynamics in strain localization at pluton roof, implications for intrusion-related gold deposits. *Journal of Structural Geology* 58: 108–121.
- Glodny J, Grauert B, Fiala J, Vejnar Z, Krohe A. 1998. Metapegmatites in the western Bohemian massif: ages of crystallisation and metamorphic overprint, as constrained by U-Pb zircon, monazite, garnet, columbite and Rb-Sr muscovite data. *Geologische Rundschau* 87: 124–134.
- Glover AS, Rorgers WZ, Barton JE. 2012. Granitic Pegmatites: Storehouses of industrial minerals. *Elements* 8: 269–273.
- Gomes CL. 1995. Discrimination of the spectre of resources related to the evolution of granites of the field of Arga-Minho (North of Portugal). *Estudos, Notas e Trabalhos, I.G.M.* 37: 59–86. (in Portuguese).
- Gomes CL, Nunes JEL. 1990. The paragenes corresponding to Li-mineralization of field of aplo-pegmatite of Arga-Minho (North Portugal). *Memórias e Notícias, Publ. Mus. Lab. Mineral. Geol. University of Coimbra* 109: 131–166. (in Portuguese).
- Gutiérrez-Alonso G, Fernández-Suárez J, Jeffries T, *et al.* 2011. Diachronous post-orogenic magmatism within a developing orocline in Iberia, European Variscides. *Tectonics* 30: 1–17.
- Helal B, Bilal E, Pereir E. 1993. Nigerite in rare-element pegmatites and associated granites of Seixoso área (Northern Portugal). In: Fenoll Hach-Ali, Torres- Ruiz, Gervilla, eds. *Current research in geology applied to ore deposits*, pp. 253–257.
- Henzen BJ. 1967. Mineralogy and petrography of some tin-lithium and beryllium bearing albite pegmatites near Doade, Galicia (Orense). *Leidse Geol. Meded.* 36: 249–259.
- Julivert M, Fontboté JM, Ribeiro A, Conde L. 1974. *Mapa Tectónico de la Península Ibérica y Baleares. Escala 1: 1 000 000*. Madrid: Instituto Geológico y Minero de España, Memoria Explicativa, pp. 113 (in Spanish).
- Kontak DJ, Creaser RA, Heaman LM, Archibald DA. 2005. U-Pb tantalite, Re-Os molybdenite, and <sup>40</sup>Ar/<sup>39</sup>Ar muscovite dating of the Brazil Lake pegmatite, Nova Scotia: a possible shear-zone related origin for an LCT-type pegmatite. *Atlantic Geology* 41: 17–29.
- Konzett J, Hauzenberger C, Ludwig T, Stalder R. 2018a. Anatectic granitic pegmatites from the Eastern Alps: a case of variable rare metal enrichment during high-grade regional metamorphism. II: Pegmatite staurolite as an indicator of anatectic pegmatite parent melt formation – a field and experimental study. *The Canadian Mineralogist* 56: 603–624. <https://doi.org/10.3749/canmin.1800011>
- Konzett J, Schneider T, Nedyalkova L, *et al.* 2018b. Anatectic granitic pegmatites from the Eastern Alps: A case of variable rare-metal enrichment during high-grade regional metamorphism – I: Mineral assemblages, geochemical characteristics, and emplacement ages. *The Canadian Mineralogist* 56: 555–602. <https://doi.org/10.3749/canmin.1800008>
- Légros H, Mercadier J, Villeneuve J, *et al.* 2019. U-Pb isotopic dating of columbite-tantalite minerals: Development of reference materials and in situ applications by ion microprobe. *Chemical Geology* 512: 69–84. <https://doi.org/10.1016/j.chemgeo.2019.03.001>
- Lerouge C, Deschamps Y, Piantone P, Gilles C, Breton J. 2007. Metal-carrier accessory minerals associated with W ± Sn mineralization, La Châtaigneraie tungsten ore district, Massif Central, France. *Canadian Mineralogist* 45: 875–889.
- Lima A. 2000. *Structure, mineralogy and genesis of the spodumene-rich aplite pegmatite bodies from Barroso-Alvão, Northern Portugal*. PhD Thesis, Univ. Porto, Portugal and INPL, Nancy, France, pp. 270. (in Portuguese).
- Lima A, Rodrigues R, Guede A, Novák M. 2009. The rare elements-rich granite of Seixoso area (Outeiro mine, Northern Portugal). Preliminary results. *Estudios Geológicos* 19: 182–187.
- Lima SF, Corfu F, Neiva AMR, Ramos JMF. 2012. Dissecting complex magmatic processes: an in depth U-Pb study of the Pavia Pluton, Ossa-Morena Zone, Portugal. *Journal of Petrology* 53: 1887–1911.
- Lima SM, Neiva AMR, Ramos JMF, Cuesta A. 2014. Long-lived magmatic systems and implications on the recognition of granite-pegmatite genetic relations: Characterization of the Pavia granitic pegmatites (Ossa-Morena Zone, Portugal). *Chemie der erde* 74: 625–639.
- Linnen RL, Cuney M. 2005. Granite-related rare-element deposits and experimental constraints on Ta-Nb-W-Sn-Zr-Hf mineralization. In: Linnen RL, Samson IM, eds. *Rare-element geochemistry and mineral deposits*. Geological Association Canada Short Course Notes 17: 45–68.
- Linnen RL, Van Lichtervelde M, Černý P. 2012. Granitic pegmatites as Sources of Strategic Metals. *Elements* 8: 275–280.

- London D. 2008. Pegmatites. *Canadian Mineralogist Special Publications* 10: 347.
- London D. 2018. Ore-forming processes within granitic pegmatites. *Ore Geology Reviews* 101: 349–383. <https://doi.org/10.1016/j.oregeorev.2018.04.020>
- Ludwig K. 2003. *Isoplot/Ex version 3: a Geochronological toolkit for Microsoft Excel*. Geochronology Center, Berkeley.
- Lv Z-H, Chen J, Zhang H, Tang Y. 2021a. Petrogenesis of Neoproterozoic rare metal granite-pegmatite suite in Jiangnan Orogen and its implications for rare metal mineralization of peraluminous rock in South China. *Ore Geology Reviews* 128: 103923. <https://doi.org/10.1016/j.oregeorev.2020.103923>
- Lv Z-H, Zhang H, Tang Y. 2021b. Anatexis origin of rare metal/earth pegmatites: Evidences from the Permian pegmatites in the Chinese Altai. *Lithos* 380–381: 105865. <https://doi.org/10.1016/j.lithos.2020.105865>
- Maijer C. 1965. Geological investigations in the Amarante region (Northern Portugal) with special reference to the mineralogy of the cassiterite-bearing albite pegmatites. Grafisch Centrum, Deltro.
- Manning DAC, Hill PI. 1990. The petrogenetic and metallogenic significance of topaz granite from the southwest England ore field. *Geological Society of America Special Paper* 246: 51–69.
- Marcoux E, Barré B, Pichavant M, Poujol M. 2021. Âge et genèse de la coupole granitique à métaux rares (Sn, Li, Nb-Ta, W) de Montebrais (Creuse, Massif central français). BSGF – Earth Sciences *Bulletin* 192: 16. <http://doi.org/10.1051/bsgf/2020042>
- Marignac C, Cuney M. 1999. Ore deposits of the French Massif Central: insight into the metallogenesis of the Variscan collision belt. *Mineralium Deposita* 34: 472–504.
- Martín-Izard A, Fuertes-Fuentes M, Cepedal A, *et al.* 2000. The Rio Narcea gold belt intrusions: geology, petrology, geochemistry and timing. *Journal of Geochemical Exploration* 71: 103–117.
- Martín-Izard A, Reguilón R, Palero F. 1992. Las mineralizaciones litíferas del oeste de Salamanca y Zamora. *Estudios Geológicos* 48: 19–30.
- Martínez Catalán JR, Schulmann K, Ghienne J-F. 2021. The Mid-Variscan Allochthon: Keys from correlation, partial retrodeformation and plate-tectonic reconstruction to unlock the geometry of a non-cylindrical belt. *Earth-Science Reviews* 220: 103700.
- Martins T. 2009. *Multidisciplinary study of pegmatites and associated Li and Sn-Nb-Ta mineralisation from the Barroso-Alvão region*. PhD thesis, University of Porto, Portugal, pp. 196.
- Martins T, Lima A. 2011. Pegmatites from Barroso-Alvão, Northern Portugal: anatomy, mineralogy and mineral geochemistry. *Cader-nos Lab. Xeolóxico de Laxe, Coruña* 36: 177–206.
- Martins T, Lima A, Simmons WB, Falster A, Noronha F. 2011. Geochemical fractionation of Nb–Ta oxides in li-bearing pegmatites from the Barroso–Alvão pegmatite field, northern Portugal. *The Canadian Mineralogist* 49: 777–791.
- Martins HCB, Sant’Ovaia H, Noronha F. 2009. Genesis and emplacement of felsic Variscan plutons within a deep crustal lineation, the Penacova-Régua-Verín fault: An integrated geophysics and geochemical study (NW Iberian Peninsula). *Lithos* 111: 142–155.
- Martins HCB, Sant’Ovaia H, Noronha F. 2013. Late-Variscan emplacement and genesis of the Vieira do Minho composite pluton, Central Iberian Zone: Constraints from U-Pb zircon geochronology, AMS data and Sr-Nd-O isotope geochemistry. *Lithos* 162–163: 221–235.
- Matte P. 1986. *The Variscan belt among the circum-Atlantic Paleozoic belts, model of evolution and position of the main crustal blocks during Permian and Carboniferous*. Bulletin de la Société Géologique de France II: 9–24. (in French).
- Matte P. 1991. Accretionary history and crustal evolution of the Variscan belt in Western Europe. *Tectonophysics* 196: 309–339.
- Melcher F, Sitnikova MA, Graupner T, Martin N, Oberthür T, Henjes-Kunst F, *et al.* 2008. Fingerprinting of conflict minerals: columbite-tantalite (“coltan”) ores. *SGA News* 23: 1–14.
- Melleton J, Gloaguen E, Frei D. 2015. Rare-elements (Li-Be-Ta-SnNb) magmatism in the European Variscan Belt – A review. Mineral resources in a sustainable world. In: *13th SGA Biennial Meeting 2015 Proceedings*, Vol. 2, pp. 807–810.
- Melleton J, Gloaguen E, Frei D, Novák M, Breiter K. 2012. How are the emplacement of rare-element pegmatites, regional metamorphism and magmatism interrelated in the Moldanubian domain of the Variscan Bohemian massif, Czech Republic? *The Canadian Mineralogist* 50: 1751–1773.
- Michaud JA-S, Gumiaux C, Pichavant M, Gloaguen E, Marcoux E. 2020. From magmatic to hydrothermal Sn-Li-(Nb-Ta-W) mineralization: The Argemela area (central Portugal). *Ore Geology Reviews* 116: 103215. <https://doi.org/10.1016/j.oregeorev.2019.103215>
- Michaud JA-S, Pichavant M. 2020. Magmatic fractionation and the magmatic-hydrothermal transition in rare metal granites: Evidence from Argemela (Central Portugal). *Geochimica et Cosmochimica Acta* 289: 130–157. <https://doi.org/10.1016/j.gca.2020.08.022>
- Michel J, Baumgartner L, Putlitz B, Schaltegger U, Ovtcharova M. 2008. Incremental growth of the Patagonian Torres del Paine laccolith over 90 k.y. *Geology* 36: 459–462.
- Miller FK, Morton DM. 1980. Potassium-argon geochronology of the eastern Transverse Ranges and southern Mojave Desert, southern California. USGS Professional Paper 1152. <https://doi.org/10.3133/pp1152>
- Montero P, Bea F, Zinger TF, Scarrow JH, Molina JF, Whitehouse M. 2004. 55 million years of continuous anatexis in Central Iberia: single-zircon dating of the Peña Negra Complex. *Journal of the Geological Society* 161: 255–263.
- Müller A, Romer RL, Pedersen R-B. 2017. The Sveconorwegian Pegmatite Province – Thousands of pegmatites without parental granites. *Canadian Mineralogist* 55: 283–315.
- Nasdala L, Hofmeister W, Norberg N, *et al.* 2008. Zircon M257—a homogeneous natural reference material for the ion microprobe U-Pb analysis of zircon. *Geostandards and Geoanalytical Research* 32: 247–265.
- Neiva AMR. 1975. Geochemistry of coexisting aplites and pegmatites and of their minerals from Central Northern Portugal. *Chemical Geology* 16: 153–177.
- Neiva AMR. 1977. Geochemistry of the pegmatites and their minerals from central northern Portugal. *Anais da Faculdade de Ciências do Porto, LX*, pp. 1–28.
- Neiva AMR, Gomes CL, Silva PB, Gomes MEP, dos Santos ACT. 2019. Geochemistry of granitic aplite-pegmatite dykes and sills and their minerals from the Gravanho-Gouveia area in Central Portugal. *Geochemistry* 79: 221–234.
- Neiva AMR, Ramos JMF. 2010. Geochemistry of granitic aplite-pegmatite sills and petrogenetic links with granites, Guarda-Belmonte área, central Portugal. *European Journal of Mineralogy* 22: 837–854.
- Neiva AMR, Gomes MEP, Ramos JMF, Silva PB. 2008. Geochemistry of granitic aplite-pegmatite sills and their minerals from Arcozelo da Serra area (Gouveia, central Portugal). *European Journal Mineralogy* 20: 465–485.

- Neiva AMR, Silva PB, Corfu F, Ramos JMF. 2011. Sequential melting and fractional crystallization: Granites from Guarda-Sabugal area, central Portugal. *Chemie der Erdre-Geochemistry* 71: 227–245.
- Neiva AMR, Williams IS, Lima SM, Teixeira RJS. 2012. U-Pb and <sup>39</sup>Ar-<sup>40</sup>Ar data constraining the ages of the sources, emplacement and recrystallization/cooling events from late- to post-D3 Variscan granites of the Gouveia area, central Portugal. *Lithos* 153: 72–83.
- Neiva AMR, Williams IS, Ramos JMF, Gomes MEP, Silva MMVG, Antunes IMHR. 2009. Geochemical and isotopic constraints on the petrogenesis of Early Ordovician granodiorite and Variscan two-micas granite from the Gouveia area, Central Portugal. *Lithos* 111: 186–202.
- Noronha F. 1987. Occurrence of pegmatite bodies with spodumene in the Dornelas geological map. Unpublished Portuguese Geological Survey Internal report. (in Portuguese).
- Noronha F, Ramos JMF, Rebelo J, Ribeiro A, Ribeiro ML. 1981. Test of correlation of the phases of Hercynian deformation in the NW of the Iberian Peninsula. *Leid. Geol. Meded.* 52: 87–91.
- Novák M, Tomáš K, Gadas P. 2013. Geological position, mineral assemblages and contamination of granitic pegmatites in the Moldanubian Zone, Czech Republic; examples from the Vlastějovice region. *Journal of Geosciences* 58: 21–47. <http://doi.org/10.3190/jgeosci.132>
- Nunes JEL, Gomes CL. 1994. The crystal chemistry of spodumene in some granitic aplite-pegmatite bodies of Northern Portugal: A comparative review: Discussion. *The Canadian Mineralogist* 32: 223–226.
- Ordóñez-Casado B. 1998. *Geochronological studies of the Pre-Mesozoic basement of the Iberian Massif: the Ossa-Morena Zone and the Allochthonous Complexes within the Central Iberian Zone.* PhD dissertation, ETH, Switzerland 12940, 235 p.
- Orejama D, Villaseca C, Valverde-Vaquero P, Belousova EA, Armstrong RA. 2012. U-Pb geochronology and zircon composition of late Variscan S- and I-type granitoids from the Spanish Central System batholith. *International Journal of Earth Sciences* 101: 1789–1815.
- Pagés Valcarlos JL. 1998. The pegmato-aplitic field of Doade (Ourense, Spain) and associated Sn and Ta mineralizations. *Cadernos Lab. Xeolóxico de Laxe, Coruña*, 23, 27–41. (in Spanish).
- Pamplona J, Gutiérrez-Alonso G, Ribeiro A. 2006. Superposition of shear zones during orogenic development: an example from the NW Variscan Belt (Viana do Castelo, NW Portugal). *J. Struct. Geol.* 28: 1327–1337.
- Parfenoff A, Pomerol C, Tourenq J. 1970. Les minéraux en grains. *Méthodes d'étude et détermination.* Masson et Cie, 575 pp.
- Parga Pondal I, Martínez Cardoso G. 1948. Die Lithium-pegmatite von Lalín, Prov. Pontevedra, Galizien. *Schweizerische Mineralogische und Petrographische Mitteilungen* 28: 324–334. (In German).
- Pereira MF, Silva JB, Drost K, Chichorro M, Apraiz A. 2010. Relative timing of transcurrent displacements in northern Gondwana: U-Pb laser ablation ICP-MS zircon and monazite geochronology of gneisses and sheared granites from the western Iberian Massif (Portugal). *Gondwana Research* 17: 461–481. <https://doi.org/10.1016/j.gr.2009.08.006>
- Pouchou JL, Pichoir F. 1984. A new model for quantitative X-ray-microanalysis: Application to the analysis of homogeneous samples. *Rech. Aerosp.* 167–192.
- Puga M, Leal Gomes C, Vide R. 2003. Mode of occurrence and testing of industrial application of petalite from the deposit of the pegmatite of Queiriga – Sátão (Viseu). Resumos, IV Congresso Ibérico de Geoquímica, Coimbra, pp. 196–198. (in Portuguese).
- Raimbault L. 1998. Composition of complex lepidolite-type granitic pegmatites and of constituent columbite-tantalite, Chêdeville, Massif Central, France. *The Canadian Mineralogist* 36: 563–583.
- Ramos JMF. 1998. Rare metals mineralization from the Seixo Amarelo – Gonçalo field. *Contributions for their knowledge.* PhD Thesis, University of Lisbon, vol. 1 and 2, pp. 659 (in Portuguese).
- Ramos JMF. 2007. Seixo Amarelo-Gonçalo rare-element aplite-pegmatite field. In: *Pegmatites: the State of the Art. Internacional Symposium.* Field Trip Guide Book, Memórias No.9, Universidade do Porto-Faculdade de Ciências, Departamento de Geología, pp. 73–87.
- Roda E. 1993. *Characteristics, distribution and petrogenesis of the pegmatites from La Fregeneda (Salamanca, Spain).* Ph.D thesis, University del Pais Vasco, Spain, pp. 200 (in Spanish).
- Roda E, Pesquera A, Velasco F, Fontan F. 1999. The granitic pegmatites of the Fregeneda área (Salamanca, Spain): characteristics and petrogenesis. *Mineralogical Magazine* 63: 535–558.
- Roda E, Vieira R, Lima A, Pesquera-Pérez A. 2009. Petrogenetic links between granites and pegmatites in the Almendra-Fregeneda area (Salamanca, Spain and Guarda, Portugal): New insights from <sup>40</sup>Ar/<sup>39</sup>Ar dating in micas. *Estudios Geológicos* 19: 305–310.
- Roda-Robles E, Pesquera A, Gil-Crespo PP, Vieira R, Lima A, Garate-Olave I, *et al.* 2016. Geology and mineralogy of Li mineralization in the Central Iberian Zone (Spain and Portugal). *Mineralogical Magazine* 80: 103–126. <https://doi.org/10.1180/minmag.2016.080.049>
- Roda-Robles E, Villaseca C, Pesquera A, Gil-Crespo PP, Vieira R, Lima A, *et al.* 2018. Petrogenetic relationships between Variscan granitoids and Li-(F-P)-rich aplite-pegmatites in the Central Iberian Zone: Geological and geochemical constraints and implications for other regions from the European Variscides. *Ore Geology Reviews* 95: 408–430.
- Romer RL, Lehmann B. 1995. U-Pb columbite age of Neoproterozoic Ta-Nb mineralization in Burundi. *Economic Geology* 90: 2303–2309.
- Romer RL, Smeds SA. 1994. Implications of U-Pb ages of columbite-tantalites from granitic pegmatites for the Palaeoproterozoic accretion of 1.90–1.85 Ga magmatic arcs to the Baltic Shield. *Precambrian Research* 67: 141–158.
- Romer RL, Smeds SA. 1996. U-Pb columbite ages of pegmatites from Sveconorwegian terranes in southwestern Sweden. *Precambrian Research* 76: 15–30.
- Romer RL, Smeds SA. 1997. U-Pb columbite chronology of post-kinematic Palaeoproterozoic pegmatites in Sweden. *Precambrian Research* 82: 85–99.
- Romer RL, Wright JE. 1992. U-Pb dating of columbites: A geochronological tool to date magmatism and ore deposits. *Geochimica and Cosmochimica Acta* 56: 2137–2142.
- Ruiz C, Fernandez-Leyva C, Locutura J. 2008. Geochemistry, geochronology and mineralisation potential of the granites in the Central Iberian Zone: The Jalama batholith. *Chemie der Erde-Geochemistry* 68: 413–429.
- Shaw RA, Goodenough KM, Roberts NMW, Horstwood MSA, Chenery SR, Gunn AG. 2016. Petrogenesis of rare-metal pegmatites in high-grade metamorphic terranes: A case study from the Lewisian Gneiss Complex of northwest Scotland. *Precambrian Research* 281: 338–362. <https://doi.org/10.1016/j.precamres.2016.06.008>
- Silva D, Lima A, Gloaguen E, Gumiaux C, Noronha F, Deveaud S. 2018. Chapter 3 – Spatial geostatistical analysis applied to the Barroso-Alvão rare-elements pegmatite field (Northern Portugal).

- In: Teodoro AC, ed. *Frontiers in Information Systems, GIS an overview of applications*, Bentham Science Publishers, Sharjah, UAE, 1: 67–101.
- Simmons B, Shail RK, Andersen JCØ. 2016. The petrogenesis of the Early Permian Variscan granites of the Cornubian Batholith: Lower plate post-collisional peraluminous magmatism in the Rhenohercynian Zone of SW England. *Lithos* 260: 76–94. <https://doi.org/10.1016/j.lithos.2016.05.010>
- Simmons W, Falster A, Webber K, Roda-Robles E, Boudreaux AP, Grassi LR, Freeman G. 2016. Bulk composition of Mt. Mica Pegmatite, Maine, USA: Implications For the origin of an LCT type pegmatite by Anatexis. *The Canadian Mineralogist* 54: 1053–1070. <https://doi.org/10.3749/canmin.1600017>
- Sláma J, Košler J, Condon DJ, *et al.* 2008. Plešovice zircon – A new natural reference material for U-Pb and Hf isotopic microanalysis. *Chemical Geology* 249: 1–35.
- Solá AR, Williams IS, Neiva AMR, Ribeiro ML. 2009. U-Th-Pb SHRIMP ages and oxygen isotope composition of zircon from two contrasting late Variscan granitoids, Nias-Albuquerque batholith, SW Iberian Massif: Petrologic and regional implications. *Lithos* 111: 156–167.
- Teixeira RJS, Neiva AMR, Silva PB, Gomes MEP, Andersen T, Ramos JMF. 2011. Combined U-Pb geochronology and Lu-Hf isotope systematics by LAM-ICPMS of zircons from granites and sedimentary rocks of Carrazeda de Ansiães and Sabugal areas, Portugal, to constrain granite sources. *Lithos* 125: 321–334.
- Teixeira RJS, Neiva AMR, Gomes MEP, Corfu F, Cuesta A, Croudace IW. 2012. The role of fractional crystallization in the genesis of early syn-D3, tin-mineralized Variscan two-mica granites from the Carrazeda de Ansiães area, northern Portugal. *Lithos* 153: 177–191.
- Valle Aguado B, Azevedo M.R, Schaltegger U, Martínez Catalán J.R, Nolan J. 2005. U-Pb zircon and monazite geochronology of Variscan magmatism related to syn-convergence extension in Central Northern Portugal. *Lithos* 82: 169–184.
- Valverde-Vaquero P, Cuesta Fernández A, Gallastegui G, Suárez O, Corretgé LG, Dunning GR. 1999. U-Pb dating of Late Variscan magmatism in the Cantabrian Zone (Northern Spain). EUG X meeting, 28th March–1st April, 1999, Strasbourg (France), pp. 101.
- Van Lichtervelde M, Grand’Homme A, de Saint-Blanquat M, *et al.* 2017. U-Pb geochronology on zircon and columbite-group minerals of the Cap de Creus pegmatites, NE Spain. *Mineralogy and Petrology* 111: 1–21.
- Vieira R. 2010. Aplite-pegmatite bodies with rare-elements from Almendra (V.N. de Foz-Côa) & Barca D’Alva (Figueira de Castelo Rodrigo). *Fregeneda-Almendra apatite-pegmatite field*. Ph.D thesis, University of Porto, Portugal, pp. 1–275 (in Portuguese).
- Von Knorring O, Vidal Romani JR. 1981. On the mineralogy of the O Casteliño spodumene pegmatite near Lalín, Galicia, Spain. *Cuad Lab Xeol Laxe* 2: 259–262.
- Webber KL, Simmons WB, Falster AU, Hanson SL. 2019. Anatectic pegmatites of the Oxford County pegmatite field, Maine, USA. *The Canadian Mineralogist* 57: 811–815. <https://doi.org/10.3749/canmin.AB00028>
- Yan Q-H, Qiu Z-W, Wang H, *et al.* 2018. Age of the Dahongliutan rare metal pegmatite deposit, West Kunlun, Xinjiang (NW China): Constraints from LA-ICP-MS U-Pb dating of columbite-(Fe) and cassiterite. *Ore Geology Reviews* 100: 561–573. <https://doi.org/10.1016/j.oregeorev.2016.11.010>
- Ypma PJM. 1966. Structural petrology of an area near Santiago de Compostela (NW Spain). *Leidse Geol Medred* 45: 1–71.
- Zeck HP, Wingate MT, Pooley G. 2007. Ion microprobe U-Pb zircon geochronology of a late tectonic granitic-gabbroic rock complex within the Hercynian Iberian belt. *Geological Magazine* 144: 157–177.
- Zhou Q, Qin K, Tang D, Wang C, Sakyi PA. 2016. LA-ICP-MS U-Pb zircon, columbite-tantalite and <sup>40</sup>Ar–<sup>39</sup>Ar muscovite age constraints for the rare-element pegmatite dykes in the Altai orogenic belt, NW China. *Geological Magazine* 155: 707–728. <https://doi.org/10.1017/S0016756816001096>

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