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Ollo de Sapo Cambro-Ordovician volcanics from the Central Iberian basement—A multiphase evolution

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Abstract

The Cambro-Ordovician rhyodacitic to dacitic volcanics from the Central Iberian basement, currently known as Ollo de Sapo (toads eye), have been reported as a specific group of felsic porphyritic rocks with blue quartz and large phenocrysts of K-feldspar, in a partly vitreous or fine-grained matrix. Interpreted to form Cambro-Ordovician volcanic domes, they are accompanied by tuffs, ignimbrites and products of reworking in a near-surface environment. The coarse- to fine-grained rocks exhibit rather large K-feldspar phenocrysts, plagioclase and rounded blue quartz, representing former corroded phenocrysts. Their colouration indicates unmixing of TiO_2 at around 900°C during cooling from relatively high crystallisation temperatures, indicating their origin at hot lower crustal conditions. We propose at least a two-step evolution (1) starting around 495 Ma in the lower crust of a collapsing cordillera, generating a phenocryst-rich mush and adiabatic melting of the lower crustal protolith to produce the spectacular Ollo de Sapo porphyrites, before (2) magma ascent and crustal extension leading to a different thermal regime around 483 Ma.

1 | INTRODUCTION

The initially recognised "*Iberian Porphyroid Formation*" by Lotze (1945, 1956) had the more popular name Ollo de Sapo (toads eye), given by Hernández Sampelayo (1922) for Early Palaeozoic augengneisses. Such rocks were identified in the Central Iberian Basement by Parga Pondal, Matte, and Capdevila (1964) among a large variety of Ordovician augengneisses and metamorphic rocks, and despite their striking aspect with blue quartz phenocrysts have not yet been fully understood. In the search of more detailed information on their evolution, and inspired by the recent discussions on present-day volcanic areas (e.g., Cooper, 2017; Putirka, 2017), we reinterpret the Ollo de Sapo Early Palaeozoic felsic volcanics that contained very large K-feldspar phenocrysts (up to 10 cm) and rounded, conspicuously blue quartz prior to their deformation.

Located principally in the so-called "Dominio del Ollo de Sapo" (González Lodeiro, Díez-Montes, & Martínez Catalán, 2004), they occur across about 600 km within their Cambro-Ordovician host rocks (Figure 1). Pérez-Estaún and Bea (2004) presented a first review, and García-Arias, Díez-Montes, Villaseca, and Blanco-Quintero (2017) reviewed new insights. The corresponding areas were initially chosen and studied by Lotze's students (Plogmann, 1973; Riemer, 1963; Schäfer, 1969; consult: von Raumer, 2008) at a time when geology was entirely based on fieldwork. In this paper, we reconsider the formation of the Ollo de Sapo porphyrites, introducing some hitherto poorly appreciated original texts from this area.

2 | GEOLOGY AND PALAEOTECTONIC SETTING

Following Martínez Catalán et al. (2009), the Cambro-Ordovician Ollo de Sapo volcanic and volcaniclastic series were emplaced along the northern margin of Gondwana among Cadomian crustal elements of the Iberian basement and their corresponding contemporaneous sediments. Being part of the European Variscan orogen, the related

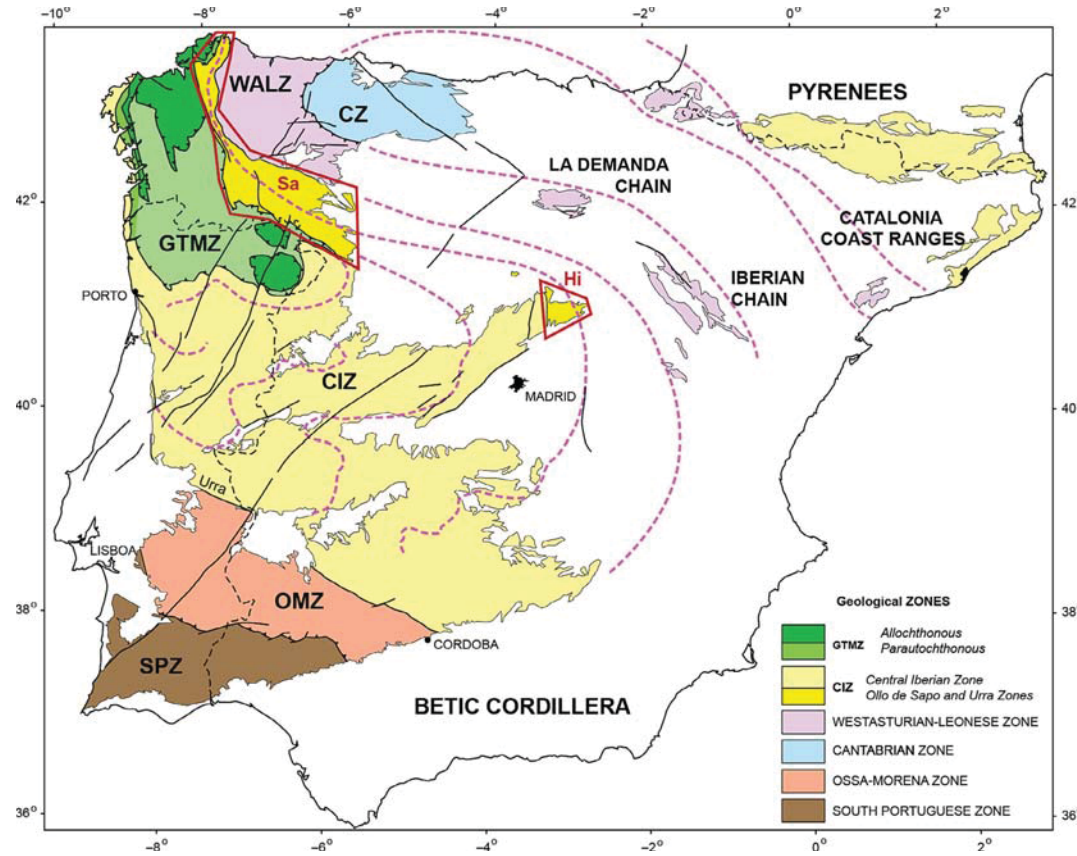

FIGURE 1 Iberian Basement areas modified after Martínez Catalán, 2012 with distribution of the Ordovician Ollo de Sapo Porphyroids, including the Urra Zone and the Ollo de Sapo Zone (OSZ, red boxes), including the Hiendelaencina (Hi) and Sanabria (Sa) areas. CIZ: Central Iberian Zone, Cz: Cantabrian Zone, GTMZ: Galicia-Tras os Montes Zone, OMZ: Ossa Morena Zone, OSZ: Ollo de Sapo Zone, SPZ: South Portuguese Zone, WALZ: West-Asturian-Leonese Zone. Red hatched lines: contours of late Variscan oroclinal bending (Martínez Catalán, 2012)

Variscan nappe stacking and high-grade metamorphic overprint reached partial melting conditions (Alcock, Martínez Catalán, Arenas, & Díez Montes, 2009; Ballèvre et al., 2014), and the last major transformations coincided with the Late Variscan large-scale oroclinal bending of the Iberian domain (Martínez Catalán, 2012), strongly transforming the original contours and framework of the Cambro-Ordovician volcanic sequence. The latter was dated by lithostratigraphic means and through U–Pb age data as Late Cambrian to Ordovician (495–480 Ma), and consists of distinct rather short-lived magmatic events (Bea, Montero, González Lodeiro, & Talavera, 2007; Bea et al., 2010; Díez Montes, 2007; Gutiérrez-Alonso et al., 2007; Montero, Bea, González-Lodeiro, Talavera, & Whitehouse, 2007; Montero, Talavera, Bea, Lodeiro, & Whitehouse, 2009), inferring different stages of emplacement. In the framework of the opening of the Rheic Ocean (Nance et al., 2010; Stampfli, Hochard, Vérard, Wilhem, & von Raumer, 2013), the corresponding plate-tectonic setting of the peri-Gondwanan region defines the European Variscan blocks, which comprise basement areas like the Central Iberian domain (Arenas, Martínez Catalán, Abati, & Sánchez-Martinez, 2007) and the Ossa Morena basement (Sánchez-García, Quesada, Bellido, Dunning, & González del Tánago, 2008), and represent relics of a former Ediacaran–Cambrian active margin with its accreted exotic terranes.

Subsidence patterns for both regions (von Raumer & Stampfli, 2008; their figure 4) and the plate-tectonic model (Stampfli et al., 2013) suggest that the two domains were part of different sectors of the Gondwana margin. As the Rheic Ocean opened in its more western part around 490 Ma, represented by the Ossa Morena, the region began to form the southern passive/transform margin of the Rheic Ocean. Eastward, the Central Iberian basement remained under an Ordovician basin-and-range regime generated by the collapsing cordillera, after a supposedly rather thick lower crust, before the Rheic Ocean opened. This region was the site of major phases of extension or compression reflecting the variable buoyancy of the incoming subducting oceanic plate.

Accretion of an intraoceanic arc (Figure 2) and local obduction of a back-arc (von Raumer, Stampfli, Arenas, & Sánchez Martínez, 2015; their figure 3) created compressional phases in the mid-Ordovician, followed by renewed extension after subduction resumed. Ensuing slab roll-back eventually induced the rapid opening of the Rheic ocean in the late Ordovician accompanied by the detachment of the Hunic terrane.

3 | OLLO DE SAPO—GEOLOGICAL AND PETROGRAPHICAL OBSERVATIONS

Within this geological framework, the Ollo de Sapo felsic porphyrites were emplaced in the Lower Ordovician "Capas de Montes" in which Riemer (1963, 1966) documented a sedimentary contact. The corresponding sedimentary pile (Figure 3), renamed the Ollo de Sapo Formation (González Lodeiro et al., 2004) with an estimated thickness of 2,000–4,500 m, is mostly composed of coarse-grained subvolcanic lithologies. Among the strongly folded Variscan structures, the Puebla de Sanabria and Hiendelaencina areas have been identified as loci of the most important outcrop areas:

- Schäfer's (1969) original descriptions from the Hiendelaencina area identified microgranular to coarse-grained low-grade felsic porphyrites characterised by a serial growth of K-feldspar phenocrysts from very large (10 cm) to 1 cm size, accompanied by tiny droplet-like blue quartz (former corroded phenocrysts), and plagioclase of up to about 1 cm, hosted in a fine-grained groundmass. He possibly observed flow structures rather than metamorphic deformation (Figure 4) in an assemblage of rhyolithic ignimbrites, with their cogenetic volcanic products, as well as postintrusion conglomerates containing abundant grains of blue quartz.
- Plogmann (1973) described in his doctoral thesis in the Sanabria area two distinct units (I, II) of coarse-grained augengneiss, the latter forming a large tongue-shaped body accompanied by lateral derivative volcanics and shale units. The coarse-grained former porphyrites display a foliated matrix with large phenocrystals of K-feldspar (4–8 cm) and up to 1-cm-size bluish rounded quartz crystals. Generally, abrupt boundaries to other lithologies were observed, where shaly to sandy layers contain small phenocryst-bearing tuff intercalations. Microscopic observations of the widely distributed augengneiss confirm the volcanic origin, with a clear porphyric texture defining distinct generations of phenocrysts in a fine-grained matrix. Quartz and plagioclase phenocrysts have undergone magmatic corrosion (tubular corrosion channels), and plagioclase appears with a glomerophyric overgrowth. K-feldspar phenocrysts display chemical growth zones (not analysed) with contemporaneous inclusion of plagioclase of first generation parallel to the growth zones.

In addition, Navidad's (1978) observations from Hiendelaencina and Sanabria show strong and abrupt changes between microgranular and coarse-grained porphyrites. Her observed broken quartz probably represent porphyroclasts.

Díez Montes (2007) identified the rather homogeneous intrusive pile of rhyodacitic to dacitic volcanics to subvolcanic rocks from Sanabria as two volcanic dome clusters of about 40 km in diameter before their Variscan deformation. He illustrates rather large crystals and patches of irregular blue quartz among idiomorphic K-feldspar phenocrysts, locally with rapakivi-type overgrowths (Figure 5a,b).

According to Díez Montes (2007), the flanks of the eastern dome were covered by coarse-grained tuffs with porphyroclasts of quartz, plagioclase and K-feldspar in a fine-grained matrix. Intercalated lithic-rich sandstones, locally with graded bedding, indicate depositional periods during volcanic quietness in a near-surface environment. Welded ignimbrites and epiclastic units from reworking loose pyroclastic materials testify to explosive stages with ash falls and their reworking products. More massive rhyolites are proposed to represent conduits for the ignimbrite eruptions.

4 | PETROLOGICAL INFORMATION FROM PHENOCRYSTS

Schäfer (1969), Plogmann (1973) and Navidad (1978) considered the blue quartz as an essential petrological feature, and both Schäfer (1969) and Navidad (1978) early on discussed the possibility of nano-size TiO_2 inclusions causing the blue colour.

4.1 | Temperature estimates

Based on Müller, van den Kerkhof, Behr, Kronz, and Koch-Müller (2009), von Raumer, Bussy, Schaltegger, Schulz, and Stampfli (2013) suggested that the blue cathodo-luminescence of quartz and, by implication, the Ollo de Sapo quartz phenocrysts indicate high TiO2 contents, suggesting their crystallisation at high temperatures. Seifert et al. (2011) finally confirmed in their study on other blue-quartz-bearing granitoid rocks that the blue colour of quartz phenocrysts resulted from oriented exsolution of minor TiO_2-crystallites in the quartz host that caused "Rayleigh scattering". Based on Ti-in-quartz thermometry, these authors estimated primary growth temperatures from core to rim of about 900–700°C in blue quartz phenocrysts. Given the similarities of the blue quartz of the Ollo de Sapo with the samples studied by Seifert et al. (2011), we assume similar temperatures. Values given by Bea et al. (2007) for related Iberian orthogneisses (820°–890°C), although not in identical rock units, confirm at least comparable temperatures in the country rocks of the region.

Díez Montes (2007) collected further observations on the Ollo de Sapo quartz crystals and put forward the following essential information:

- embayments in corroded blue quartz phenocrysts were filled by a fine-grained uncoloured matrix, possibly altered matrix glass.
- a second colourless generation of smaller quartz phenocrysts with a euherdral habitus, whose shape appears locally completely moulded to a matrix, accompany probably former tuffs.

We deduce that the first generation of quartz phenocrysts of the Ollo de Sapo Ordovician porphyrites formed at high temperatures of around 900°C before cooling to a lower temperature, which resulted in unmixing of TiO_2.

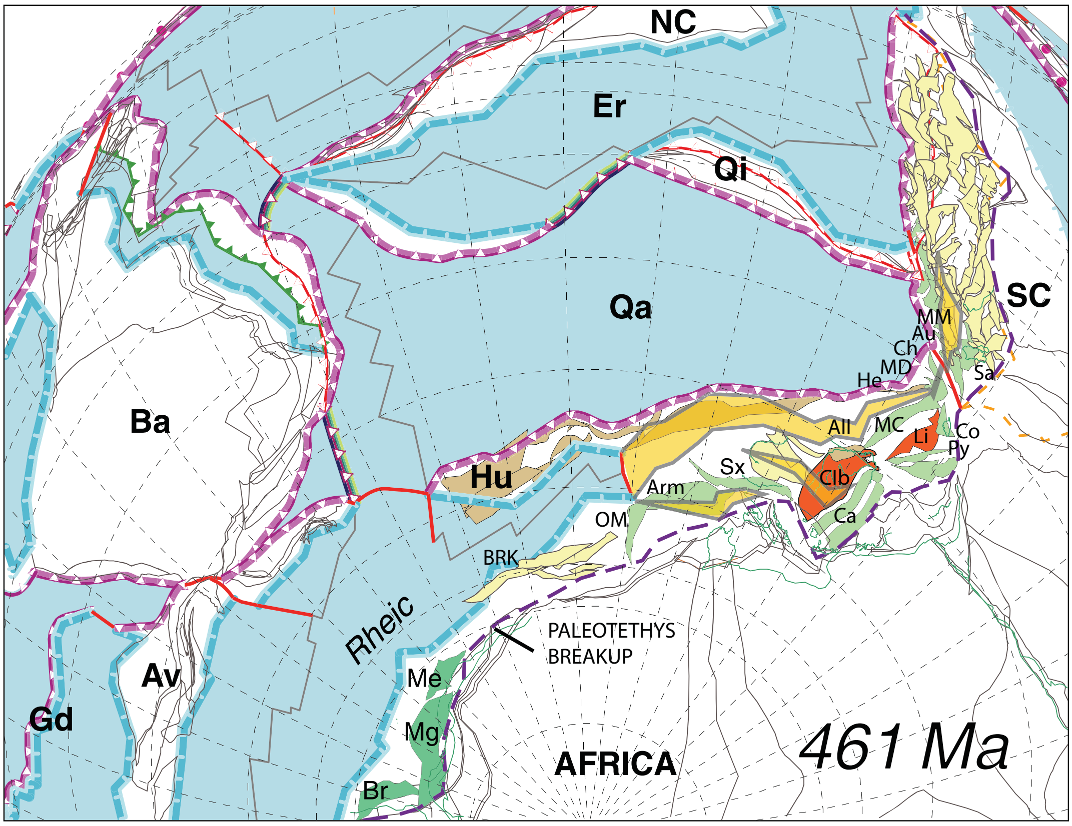

FIGURE 2 Plate-tectonic reconstruction after Stampfli, von Raumer, and Wilhem (2011) at 461 Ma, showing the location of the Iberian basement areas along the Gondwana margin in their undeformed lower Palaeozoic distribution, and adjacent geological framework including Cadomian and Chinese basement domains. Considering Stampfli et al. (2013, their figure 1), the general displacement between different geological units during Ordovician times cannot be neglected, the Cambro-Ordovician volcanics in question being consequently connected and an entire part of this intracontinental evolution. The Rheic Ocean, with its western branch (470 Ma) and, in orange, its future eastern branch as zones of rifting, is indicated. The location of the Central Iberian basement (CIb), brick coloured, is indicated by its detrital zircons (Bea et al., 2010), contributing directly to the peri-Gondwana palaeogeography (comp. Meinhold, Morton, & Avigad, 2013). If unfolded, the Ollo de Sapo volcanics in Figure 1 stretch at least 600 km and could be related towards the east (Li) with Cambro-Ordovician volcanics observed from Vendée to Mouthoumet (Pouclet et al., 2016), identifying a general Late Cambrian European rifting period of a specific sector of the Gondwana active margin. The general evolution may correspond to the sections presented in von Raumer et al. (2015, their figure 4). *Explanation*: Major continents: Av: Avalonia, Ba: Baltica, Gd: Ganderia, NC: North China, Qa: Qaidam Ocean, Qi: Qinling, SC: South China, Er: Erlaping. Brick coloured—CIb: Central Iberian basement, Li (Central Massif, from Vendée to Mouthoumet); Light brown—HU: Hunic units (Karakum, Kunlun East, Pamir-Jinsha, Turan); Light Green—Gondwanan Variscan units: All Iberian allochthonous; Arm: Armorica, Ca: West Cantabrian-Leonese zone, Co: Corsica, MC: French Central Massif, northern part; Li (from Vendée to Mouthoumet), OM: Ossa Morena; Py: Pyrenees; Sa: Sardinia; Sx: Saxothuringian; former (light green) Gondwanan Variscan units: Au: Austroalpine, Ch: Chamrousse, He external massifs, MD: Moldanubian - Tepla–Barrandian, MM: Montagne Noire, Maures, Tanneron, From the West-Gondwana margin: Dark green – Br: Brunswick, Mg: Meguma; Me: Moroccan Meseta. Yellow: BRK: Betics, Rif, Kabylies. Purple hatched line: Palaeotethys breakup

Considering feldspar phenocrysts, Plogmann (1973) and Díez Montes (2007) described rapakivi-type overgrowth of K-feldspar phenocrysts (e.g., Figure 5a), representing, after Eklund and Shebanov (1999), a major break and disequilibrium after magma mixing during feldspar growth in the temperature range 900–700°C.

4.2 | Pressure estimate

The related pressure conditions for the blue quartz are difficult to constrain, but, following von Raumer et al. (2013), the initial stage of crystallisation of the quartz before cooling and exsolution supposedly occurred at lower crustal levels at high temperatures. At the time of the Cadomian orogeny, the Central Iberian basement was still underlain by a thick crust, which would indicate the possibility of high pressure formation for the quartz phenocrysts, before the whole crust was put under crustal extension.

However, the Q–Ab–Or data for the granitoid orthogneisses (Montero, Talavera, & Bea, 2017; their figure 4b) plot clearly between the 5 and 2 kbar cotectic lines, suggesting that these melts, emplaced at around 480 Ma, equilibrated after their ascent to higher crustal levels.

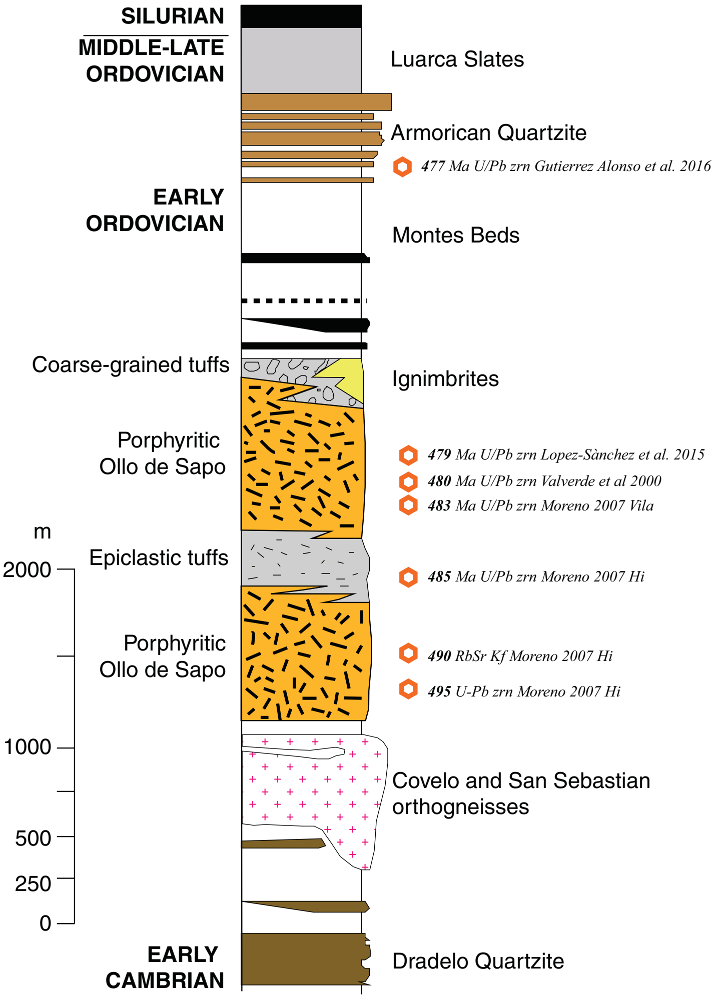

FIGURE 3 Lithostratigraphic characteristics of the Ollo de Sapo type volcanics from the Puebla de Sanabria locality (Sa). The stratigraphic column (comp. García-Arias et al., 2017), modified after Díez Montes et al. (2010), is ultimately from Martínez García and Plogmann (1981) and Plogmann (1973). Orange polygons: references of radiometric age data are not located at the appropriate position in the stratigraphic column. The Covelo- and San Sebastian orthogneiss bodies represent a slightly different total rock composition, representing the so-called “younger” granitoids in the entire Central Iberian Zone (Díez Montes, oral comm)

5 | A CONCEPTUAL MODEL

Summarising Díez Montes (2007), the Ollo de Sapo volcanics formed two phenocryst-rich subvolcanic domes that were emplaced into, and separated by, contemporaneous metapelites and sandstones and cooled under a volcanic and volcaniclastic shield. Díez Montes, Martínez Catalán, and Bellido Mulas (2010) also suggested that the volcanic and subvolcanic rocks may have built up several near-surface edifices along a tectonic structure. The mega-K-feldspar phenocrysts and large blue quartz crystals of the Ollo de Sapo porphyrites initially formed early (about 495 Ma) at depth and later were corroded with corrosion embayments filled by a micro-crystalline matrix.

The abundance, size and long residence history during cooling are reminiscent of models of magma chambers below a caldera, as discussed by Cooper (2017, figure 3d) for the Yellowstone Caldera. If the analogy is applicable, then the Ordovician Ollo de Sapo volcanics (comp. Díez Montes, 2007) may also have formed a crystal mush that was reactivated after cooling by recharging magmas in relatively short time intervals. However, the high temperature indicates early crystallisation of phenocrysts at lower crustal levels, implying a large distance of ascent towards endogeneous growth at near-surface conditions (Díez Montes et al., 2010). In order to reconcile the early high-T formation, shallow emplacement and slow cooling (and TiO_2-exsolution), we envisage a transcrustal silicic magma system (Sparks & Cashman, 2017) in accordance with “possibly there was an extended history of magmatism in the upper crust spanning perhaps a few millions of years that may reflect an initial crystallisation followed by storage at low temperatures—perhaps subsolidus—which would allow the exsolution to happen, but any particular population of crystals may only have been held at high temperatures in a liquid-dominated magma body for only a few hundreds or thousands of years”—“such a model would certainly fit with what we are observing from feldspar and zircon dating.” (Cooper, written message, related to Cooper, 2017; figure 3c).

It is well understood that Cooper's (2017) residence times of mush and melts of 100–300 ka (Cooper, 2017; figure 3b) are typical for single batches of evolved, shallow silicic magma systems, and these cannot be compared to the Ordovician time-scales discussed above. These span 20 Ma from when magmatism was initiated at lower crustal levels in Ordovician times over a time period from 495 to 483 Ma (Montero et al., 2007, 2009) to the emplacement at the Hiendelaencina and Villadepera sites (480 Ma to 474 Ma). However, early intrusions and the magma batch represented by the older units of the Ollo de Sapo intrusive and

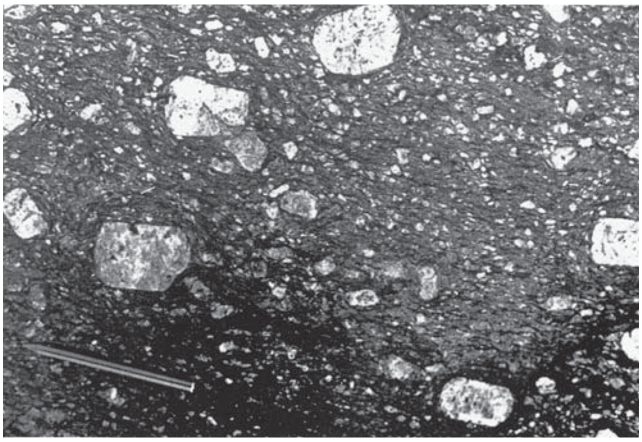

FIGURE 4 Aspect of Ollo de Sapo type porphyrites at surface from the Hiendelaencina locality (reproduction of a unique remaining photodocumentation): original figure 17 from Schäfer (1969), blue quartz not recognisable. Serial-sized K-feldspar phenocrysts, the largest are surrounded by a clear flow structure expressing the high viscosity of the magmatic matrix (pencil indicates original magmatic flow direction)

extrusive suite could have formed as a near-solidus crystal mush and melt system in a thick collapsing Ordovician cordillera as a result of a “transcrustal magmatic mush system”. Subsequently, these magmatic systems where strongly affected by widespread (basin-and-range type) crustal extension that generated further melting at higher crustal levels during the Ordovician. Zircons extracted from the phenocrysts yielded a U–Pb age of 485 ± 6 Ma and a Pb–Pb age of 483 ± 3 Ma, which could indicate a multistage and protracted magma reservoir.

In this conceptual model, the observed range of ages clearly indicate a multistage magmatic evolution with distinct different magmatic pulses, possibly generating and emplacing silicic magmas at distinct crustal levels. The initial stage of lower crustal melting and generation of the porphyrites then corresponds to a lower crustal hot zone (Annen, Blundy, & Sparks, 2006), i.e., a lower crustal crystal mush-like system (Figure 6). Magmas that separated from this zone ascended and were emplaced as porphyrites beneath an evolving caldera and represent a subsequent stage, being influenced by the viscosity of the magmas and the thickness of the crust. The younger generation of granitoids since 480 Ma then is strongly influenced by the following stage of crustal extension. This younger stage (480 Ma to 474 Ma) is also expressed at the Hiendelaencina site by contemporaneous volcanic events at the surface, which appear correlated in the more northern-located West-Asturian-Leonese domain with contemporaneous extensive acidic ash falls (Gutiérrez-Alonso, Gutiérrez-Marco, Fernández-Suárez, Bernárdez, & Corfú, 2016; Gutiérrez-Alonso et al., 2007). During this late phase, Ollo de Sapo type 480 Ma minor porphyritic subvolcanic magmatic bodies with tiny blue quartz phenocrysts appear in the Albera massif (Eastern Pyrenées) (Marina Navidad, written communication).

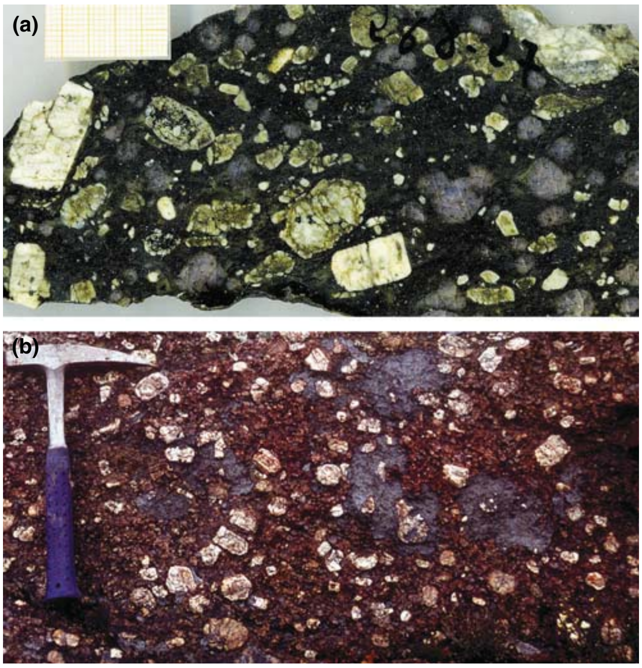

FIGURE 5 Aspect of Ollo de Sapo type porphyrites from the Sanabria Region. (a) Coarse-grained porphyrite Ollo de Sapo type with large K-feldspars, plagioclase and blue quartz. Road from Mombuey to Fresno de la Carballeda, 1 km from Mombuey (coord UTM, WGS84, 719.925, 4.655.127), original picture 286-27, courtesy Díez Montes (Salamanca). (b) Irregular-shaped large blue quartz clusters and K-feldspar phenocrysts from road Mombuey to Manzanal de la Infantes, km 4. Coord: UTM, WGS84; 717.795, 4.658. 432. Such irregularly shaped blue quartz may suggest the presence of pre-magmatic relics from the wall-rock, such as quartz of conglomeratic origin, or even of quartz veins resisting melting, and predating their transformation into blue quartz. The faint mm-sized dark patches are probably restitic bi-rich clusters. (Original picture 1-30, courtesy of Díez Montes (Salamanca)

6 | PLATE-TECTONIC CONSIDERATION AND CONCLUSIONS

Bea et al. (2007) and Díez Montes (2007) interpreted the volcanic activity of the Ollo de Sapo as related to rifting. We follow this model for the subvolcanic Ollo de Sapo porphyroids in the framework of a basin-and-range collapse of the peri-Gondwana cordillera. After 480 Ma, the crustal extension would have evolved into an intracordilleran rifted (volcanic arc?) situation—perhaps even causing the formation of Ordovician anatectic melts. The late Ordovician ash falls in the West-Asturian-Leonese domain (Gutiérrez-Alonso et al., 2016) would indicate the continuation of Ordovician volcanic activity, probably, as proposed by von Raumer et al. (2015, their figure 3), accompanying a possible slab detachment and ensuing general collapse of the cordillera at that time, which led to the final opening of the Rheic Ocean in the Central Iberian sector of the Gondwana margin.

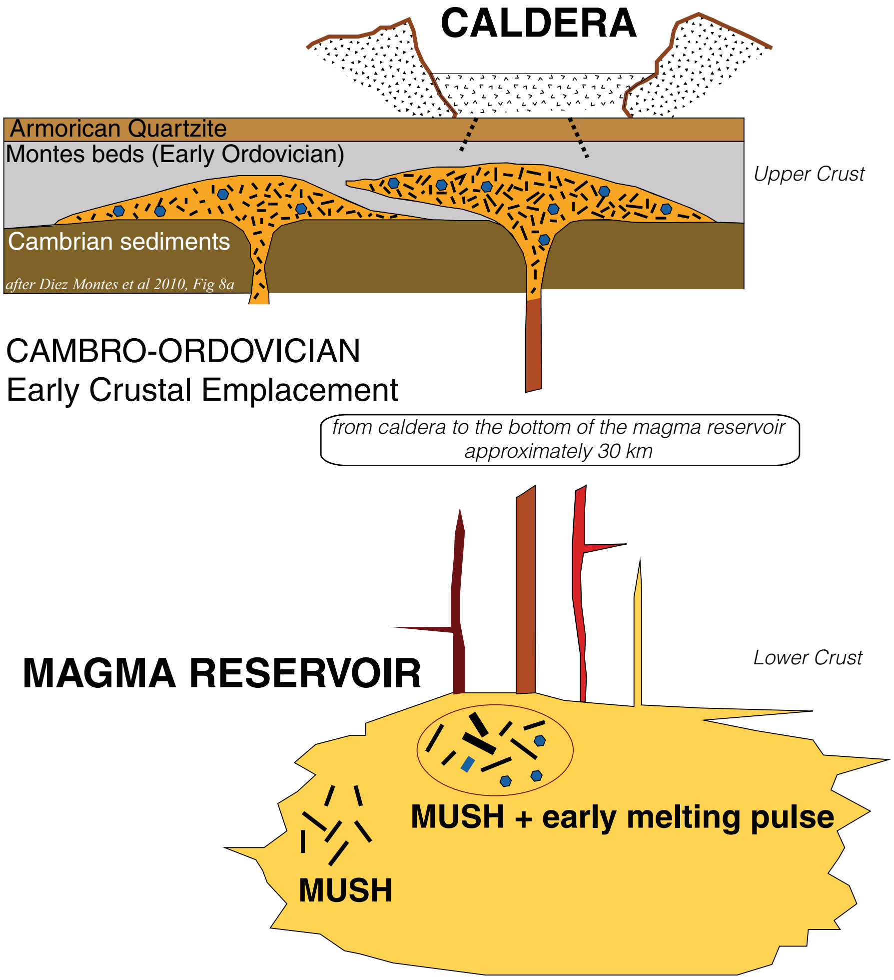

FIGURE 6 Central Iberian Cambro-Ordovician volcanics reconstituted in their proposed genetic framework modified after Díez Montes et al. (2010, their figure 8a, early stage of dome), and models inspired after Cooper (2017) and Sparks and Cashman (2017). Interpretation of the Ollo de Sapo porphyritic facies (purely schematic pattern) as a possible early subsolidus version of phenocrysts formed at lower crustal levels and emplacement as domes with blue quartz and K-feldspar (around 495 Ma, Montero et al., 2007) before subsequent melts emplaced around 485 Ma and younger magmatic pulses arrived

Additional melting during crustal extension would have produced the younger granitoids <480 Ma, but formation of intermediate stages of volcanic to subvolcanic composition at distinct places cannot be excluded. Field differences between the Hiendelaencina and Sanabria sites could indicate crystallisation at different crustal levels.

It should be added that rocks comparable to those discussed above would normally remain unique, as their near-mush preservation would not survive anatectic melting.

Among the great number of known Ordovician felsic rock assemblages from the European Variscides, few examples containing blue quartz are known (von Raumer et al., 2013), but the existence of extremely large K-feldspar phenocrysts themselves would not justify identifying such rocks automatically as Ollo de Sapo type, which would lead to a confusing terminology. Data have to be completed for a better recognition of the role of early K-feldspars and blue quartz as phenocrysts, and U–Pb ages that can be directly related to the formation of the high-TiO_2 (blue) quartz may help in differentiating the early high-T deep crustal history from the later shallow crustal evolution after extension. Finally, it seems obvious that along the thousands of kilometres of the Gondwana active margin different plate-tectonic scenarios existed in Cambro-Ordovician times, some corresponding to the geological settings discussed above.

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