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The unique Cambro-Ordovician silicic large igneous province of NW Gondwana: Catastrophic melting of a thinned crust

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A B S T R A C T

Cambro–Ordovician silicic magmatism in the Central Iberian Zone of the Iberian Massif (Ollo de Sapo Formation, OSF) constitutes a voluminous and geochemically atypical magmatic event that formed preceding the breakup of the northern margin of Gondwana. To date, and due to uncommon geochemical signatures, such as a high Fe, Mg content compared to anatectic melts and the departing from the calc-alkaline trends, the origin of such magmatic event is not fully understood. Herein, we report a data-analysis of geochemistry linking magmas and source compositions. The analysis of the combined data from multiple studies ascribes the geochemistry of the OSF rocks to a combination of extensive melting of Ediacaran metasiliciclastic rocks and a Ca-rich component. It is hypothesized that fluids released by crystallization of mafic magmas contributed to partial melting of a thick metasedimentary pile represented by Ediacaran siliciclastic rocks. Such melting event gave rise to a mobile nebulite or *migma*, which was able to extrude and form the super-eruption or "flare-up" that characterizes Cambro-Ordovician silicic magmatism at the Gondwana margin. Fast, catastrophic crustal melting with large-scale restite entrainment, triggered by the influx of mafic magma-derived fluids, are considered the main cause of the unique features of this Cambro-Ordovician atypical silicic large igneous province of Gondwana.

1. Introduction

The Cambro–Ordovician magmatic rocks, known as the Ollo de Sapo Formation (OSF) in the Iberian Massif, form thick piles (up to 2 km in Sanabria) of volcanic, subvolcanic and plutonic successions, along hundreds of km of lineaments, in the Central-Iberian Zone (Díez-Montes et al., 2010; Fernandez et al., 2008; Montero et al., 2009). They represent correlatives of numerous small outcrops of magmatic rocks distributed along the European Variscan belt (García-Arias et al., 2018 for review) and equivalent formations in the Famatina magmatic belt in South America (Nance, 2010; Nance et al., 2010). Thus, a global-scale episode of voluminous silicic magmatism, with the category of a large igneous province (LIP), was developed at the Gondwana supercontinent margin along a short period of 30 My from ca. 500 to 470 Ma (e.g., Díaz-Alvarado et al., 2016; Montero et al., 2007; Rubio-Ordóñez et al., 2012).

Whole-rock geochemistry of this Cambro-Ordovician magmatic event reveals unique features that have not been encountered so far in the geological record, and whose causes remain unknown. Here we present a reinterpretation of petrological features and data-analysis using geochemical and experimental databases to shed light on the origin of magmas and the confluent phenomena that were determinant for its unique magmatic compositions. The interest is two-fold: (1) determination of mechanisms of magma generation will help to constrain the tectonic setting with consequences on plate reconstructions of the Gondwana supercontinent; and (2) assessment of crustal recycling versus new crust addition can be better understood through the analysis of such silicic large igneous provinces, in which, voluminous magmatism was concentrated over a short time period. This study is focused on the Cambro–Ordovician magmatism of the Central-Iberian Zone representing the basement of Gondwana and preceding the breakup of northern margin of the Gondwana supercontinent, where large

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geochemical and geochronological data sets have been produced along the last years from the OSF (Bea et al., 2007; Díaz-Alvarado et al., 2016; Díez Montes et al., 2010; Gutiérrez-Alonso et al., 2016; Montero et al., 2007; Montero et al., 2017), preceding the breakup of northern margin of the Gondwana supercontinent.

Although an extensional tectonic setting is well documented on regional structures and sedimentation in the inner zones of the Iberian Massif (e.g., Martínez Catalán et al., 2004) during Cambro–Ordovician times, coeval magmatic rocks of the OSF do not have the typical geochemical features of rift-related A-type (metaluminous to peralkaline) granitic rocks (Bonin, 2007). By contrast, they have arc-like geochemical signatures for trace elements, and collisional S-type fingerprints (peraluminous) for major elements. Such atypical geochemical features remain unexplained, leading to considerable debate and confusion regarding tectonic interpretations (see Álvaro et al., 2020; García-Arias et al., 2018 for review). The aim of this study is to decipher the processes generating the atypical geochemistry of these Cambro-Ordovician magmas. Although varied tectonic-petrologic scenarios have been proposed, all of them agree in excluding a collisional setting. The lack of contractional structures and regional Barrovian metamorphism of Cambro-Ordovician age is not in favor of crustal thickening in an orogenic belt. Lithosphere extension is the most plausible scenario (Díez Montes et al., 2010; Martínez Catalán et al., 2004), with the Cambro-Ordovician silicic magmatism of the Central Iberian Zone being interpreted as resulting from extensive melting of Ediacaran siliciclastic crustal sources under the thermal influence of mantle-derived mafic magmas (Bea et al., 2007; Castro et al., 2020). Such Ediacaran crustal source is supported by the anomalously large content of inherited zircon (more than 70%) with ages in the range ca. 590–615 Ma and $\delta^{18}O$ values around 6.5‰, in contrast with higher values of $\delta^{18}O \approx 10‰$ for Cambro–Ordovician igneous zircons of ca. 485 Ma (Bea et al., 2007; Montero et al., 2017). Paradoxically, neither melting of Ediacaran metasiliciclastic rocks nor melting of a mafic lower crust can generate the unique features of the OSF. Our study reveals the participation of three components, namely anatectic peraluminous melts (S-type), Ca-rich fluids derived from mafic magmas and pelitic restites, in the generation of crystal-rich *migma* batches. We demonstrate that a pelitic source exclusively cannot produce the magmas even if restite entrainment is fully operative. An extra component (mafic) is needed and is identified as a relevant contributor to the magma sources, whose uniqueness resides on accelerated melting conditions caused by fast extension, heating from the underlying mantle and water released from invading wet mafic magmas. This analysis reveals how heterogeneous and discontinuous the processes of crustal reworking along the evolution of continents can be.

2. Petrography, geochemistry and work hypothesis

Detailed descriptions of the Cambro–Ordovician silicic magmatism from the Central Iberian Zone (Fig. 1) revealed an unequivocal volcanic provenance of many of the rocks forming the Ollo de Sapo Formation (Díez Montes et al., 2010), whose original textural and field characterization was mostly obliterated by the Variscan deformation and metamorphism. Volcanic domes and volcanoclastic layers alternate with sub-volcanic and plutonic facies in a thick succession that may reach 2 km in some areas of NW Spain. These gneissic rocks are characterized by a mesocratic groundmass enclosing the characteristic megacrysts of K-feldspar (up to 15 cm length; Fig. 2) and plagioclase.

Despite textural and grain size heterogeneities, bulk rock compositions are classified as dacites and rhyolites, mostly concentrated at about 69 wt% SiO_2 (Fig. 3A). They are peraluminous, with ASI [alumina saturation index = molar $Al_2O_3/(Na_2O + K_2O + CaO)$] values clustered close to 1.4 (Fig. 3B), and typically magnesian (Fig. 3C) with Fe# ≈ 0.7 [Fe#=wt% $FeO^T/(FeO^T + MgO)$; T denoting total Fe as FeO] and Mg# [molar MgO/(MgO + FeO)] close to 0.4 on average for $SiO_2 \approx 70$ wt% (Fig. 3C). The values overlap the field of I-type granites (Castro, 2020), while other geochemical features, like the high ASI values, points to S-type granites. The uncertain type classification of the OSF is the consequence of the atypical chemistry of these "granitic-like" rocks.

On the basis of the marked peraluminosity and the high fraction of inherited Ediacaran zircon grains, the OSF rocks are inferred to be anatectic magmas from the underlying Ediacaran metapelites and metagreywackes of the Schist-Greywacke Complex (SGC) (Bea et al., 2007; Talavera et al., 2013; Talavera et al., 2012).

Due to being richer in Fe + Mg + Ti (maficity) compared with the systematic leucocratic composition of S-type anatectic melts (Castro et al., 1999; Patiño Douce and Johnston, 1991; Vielzeuf and Holloway, 1988), the OSF magmas may represent, in principle, a *migma* (melt + restite or nebulite) system in which, ferromagnesian phases responsible for the high maficity have been entrained and transported in suspension in the way up from the anatectic source. The values of Mg# for both systems remain almost constant at 0.4 being slightly higher for the OSF than the SGC on average, with independence of the silica content (Fig. 3D), (OSF and SGC). This supports that no fractionation occurred during restite entrainment as the bulk mafic restite was transferred to the *migma*. Although restite entrainment is described as a common phenomenon in anatectic granites (Clemens, 2003; Clemens and Stevens, 2012; Garcia-Arias and Stevens, 2017), it is not sufficient to account for the composition of the OSF rocks. While restite entrainment may increase the maficity (Fe + Mg + Ti) of the melt + restite migma, this process cannot explain the enrichment in Ca and alkalis of the OSF (Fig. 4A). Because of the anomalous low-Ca content of Iberian Ediacaran metagreywackes, compared to other greywackes (Taylor and McLennan, 1985), restite entrainment is not enough to account for the OSF composition. Consequently, the work hypothesis in this study is that both, water and extra components are added to the system from a water-rich mafic magma supplying the required elements (Ca, Na and K).

3. Discussion

Projection on the Or-An-Opx plane (see Appendix A) and the Eskola's ACF diagram provides a comprehensive analysis of the end-members involved (Fig. 4). The OSF rocks plot below the restite-melt mixing line (Fig. 4B, C) linking Ediacaran SGC metasediments and the anatectic experimental melts from literature (see Appendix A). The same is observed using anatectic granites instead of experimental melts (Fig. 4D, E). Although the presence of restitic minerals (e. g., Bt aggregates) is a characteristic feature of the OSF (García-Arias et al., 2018), a close-system process such as *restite unmixing* cannot be the only one involved to account for the chemistry of the OSF magmatism. It is common that pelitic migmatites use to contain little veins of Ca-rich leucosomes (trondhjemites): However, Ca-enrichment is appreciated on the overall composition of the in the OSF rocks, not restricted to veins. Because the necessary additional component is supplying mainly Ca and alkalis (Ca according to the ACF projection), it is hypothesized that such components come from a magma of dioritic composition. For further geochemical modelling, we use a monzodioritic composition average (Table 1; purple dot in Fig. 4), taken from a global database compiled by Gómez-Frutos (unpublished work).

It is noteworthy the similarity of OSF rocks with the Ediacaran SGC metasiliciclastic rocks, in terms of trace elements, whose petrological and geochemical data suggest provenance from a recycled orogen (Ugidos et al., 1997). Both display similar REE patterns

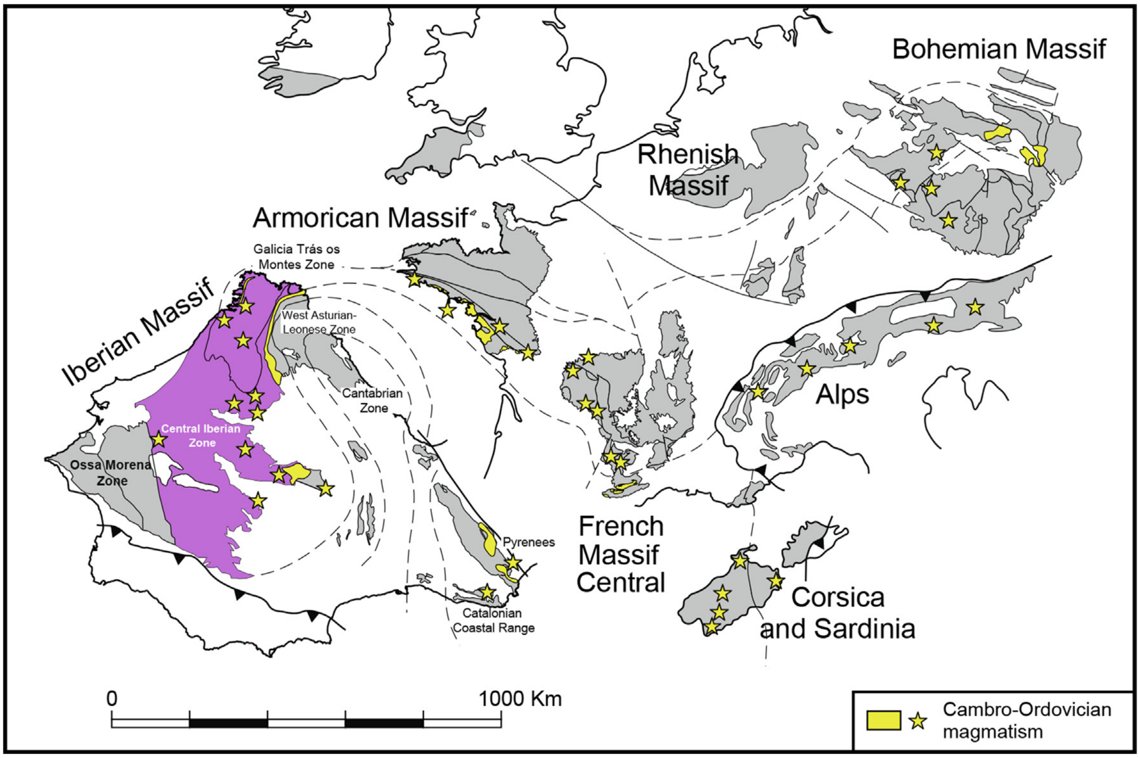

Fig. 1. Location of Cambro-Ordovician atypical silicic rocks in the Iberia Massif and correlatives in the Western European Variscides. Large outcrops of the Ollo de Sapo Formation are in yellow and small outcrops of Cambro-Ordovician magmatic rocks are marked with stars (after compilation of (García-Arias et al., 2018). The Central Iberian Zone is highlighted in purple.

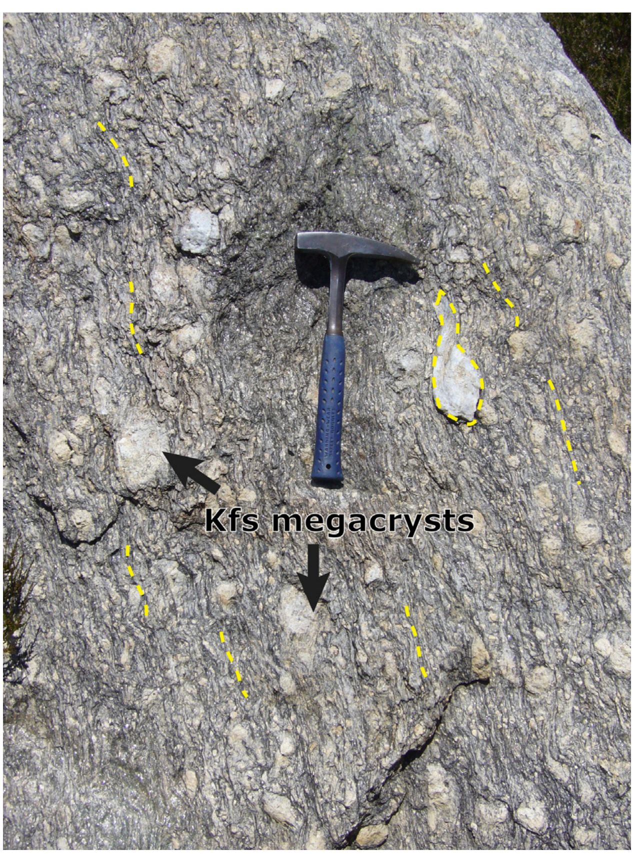

Fig. 2. Photograph of ignimbritic facies of the Ollo de Sapo gneiss showing the Kfs megacrysts and foliation.

(Castro et al., 2009); Fig. 5D) and both plot onto the fields of volcanic-arc granites (VAG) and/or *syn*-collisional granites (Syn-COLG) of the Pearce's (Pearce et al., 1984) discriminating diagrams (Fig. 5). SGC metapelites and metagreywackes derived from igneous source rocks with upper continental crustal affinity, suggests a depositional setting influenced by an active Cadomian magmatic arc (Fuenlabrada et al., 2016; Pereira et al., 2012; Talavera et al., 2015). The OSF rocks record the geochemical signatures of the metasedimentary source represented by the Ediacaran SGC rocks.

3.1. Origin of magmas: A case of three-component mixing

The available geochemical and petrological data support that the Cambro-Ordovician OSF rocks derived from a hybrid mobile *migma* (nebulite) system composed of component 1- an anatectic liquid, component 2- restitic minerals, and component 3- a mafic component of monzodioritic affinity. Component 2 was entrained from the refractory minerals and peritectic phases, as a process of either bulk restite entrainment or selective restite entrainment (García-Arias, 2018), of the SGC metasedimentary source. Restite entrainment of pure anatectic systems involving only metasedimentary rocks will define compositional trends parallel to the melt-restite mixing line (Fig. 4), which is not the case for the OSF. Because the partial melts from metasedimentary sources have typically values of Mg# lower than the source (Clemens and Stevens, 2012), an extra component is necessary to maintain the OSF values close to those of the SGC. Hybridization during melting with a high-Mg component may account for the observed similarities in Mg# between rocks of the OSF rocks and SGC metapelites and metagreywackes (Fig. 3D). At the same time, this process also compensates the depletion in FeO of the OSF rocks.

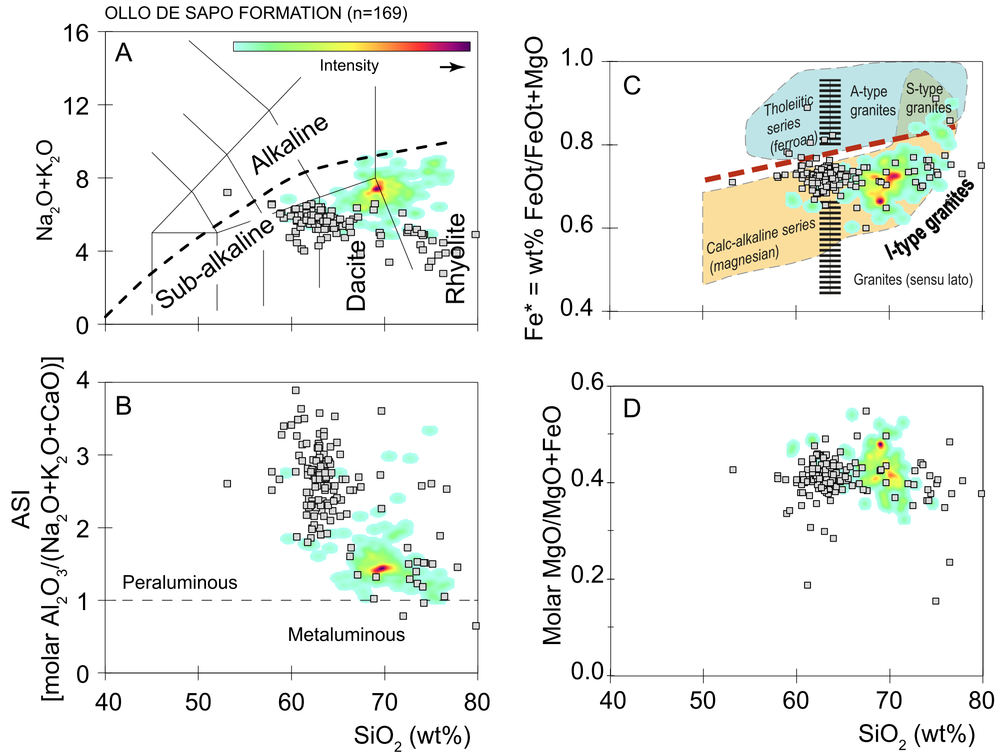

Fig. 3. Geochemical diagrams showing major element relations of the Cambro-Ordovician Ollo de Sapo Formation (OSF) rocks compared with the Ediacaran SGC metasedimentary rocks (grey squares). They plot in the field of dacites of the TAS (total alkalis vs silica) diagram (A) with silica contents relatively lower than rhyolites. Most of the OSF rocks are strongly peraluminous (B) and plot paradoxically in the field of magnesian (calc-alkaline) series according to Miyashiro's discrimination line (C). The molar MgO/MgO + FeO ratio (D) remains almost constant in both formations (OSF and SGC). Data sources: OSF rocks, compilation in García-Arias et al. (2018) and data from Montero et al. (2017); SGC metasedimentary rocks, compilation in Fernandez et al. (2008). Kernel density estimates were computed using a generic function density in R. Smoothing bandwidth for kernel estimates is scaled to the standard deviation of the Gaussian smoothing. The number of equally spaced points, at which the density is estimated, is 512. Intensity color bar is included in A.

While the presence of an important restite component (component 2) in the chemistry of the OSF rocks is better understood in the light of major element relations (Fig. 4), which is strongly supported by the abundant inherited zircons of Ediacaran age (ca. 590–615 Ma; Montero et al., 2017; Bea et al., 2007), the nature and origin of the mafic component (component 3), however, remain uncertain. In principle, a stacking of mafic igneous rocks interspersed with the SGC metasedimentary rocks, or an injection of mafic magmas at the time of melting, are plausible scenarios. Mafic rocks are scarce in the outcropping sections of SGC, whose lowermost base is unknown. Although it is clear from the diagrams of Fig. 4 that OSF rocks are out of the arc magmatic trend, the composition of the mafic component may be close to diorites of calc-alkaline affinity.

Another possibility, which is compatible with the former one, is that metasomatic fluids derived from a wet mafic magma that may have invaded a composite source formed by metasiliciclastic rocks and mafic igneous rocks in alternating layers. Some monzodiorites of Cambro-Ordovician age have been described in the Central Iberian Zone (Carrascal and Oledo pluton; Antunes et al., 2009; Neiva et al., 2009; Solá, 2007; Solá et al., 2008). Wet monzodiorites have been alleged as the trigger of water fluxed melting (Castro, 2020; López et al., 2005). An example of crustal metasomatism, involving a water-rich dioritic magma, is reported in the Sanabria appinitic complex (Castro et al., 2003). Furthermore, pegmatites associated to K-rich magmas (monzodiorites) are rich in Pl and Amp or Amp and Kfs (shonkinites).

In order to explore the composition of the fluid derived from a monzodioritic magma, we modelled the averaged monzodioritic composition (Table1) by Rhyolite-MELTS code (Ghiorso and Gualda, 2015) with an initial water content of 3 wt% at 5 kbar. We considered the composition of the residual melt (Table1) at water saturation (≈10.5 wt%) and plotted such melt composition (yellow star) together with the monzodioritic magma in Fig. 4. The three components define an area (black triangle in Fig. 4), within which the bulk of the OSF rocks are comprised.

Another outstanding feature of the OSF rocks is an enrichment in Ba (Fig. 5), with concentrations up to 2694 ppm and an average value of 758 ppm, above the Ba values of the SGC and S-type leucogranites. Considering neither the composition of SCG nor their resulting experimental melts have such Ba concentrations, and external supplier of Ba becomes necessary (Fig. 5C). With the aim to know the composition in trace elements of the saturated melt, we assume that all Ba is partitioned to the saturated melt. We use the Cr_2O_3 content from the modelled composition with MELTS (yellow star in Fig. 5C). In this case, the invading magma seems to be closer to the water-saturated melt (yellow star) than the monzodioritic magma (Fig. 5C). Therefore, it is inferred that fluids from typically Ba and Sr-rich monzodioritic magmas (Fowler and Rollinson, 2012) must be responsible for bringing a significant amount of Ba to the system. Since monzodioritic magmatism is likely derived from a metasomatized mantle, differences in the exact nature of the metasomatism and geochemistry of the lithospheric mantle below the margins of Gondwana are expected (Murphy et al., 2008) (Fig. 6). Whatever the nature of this variability, it seems plausible that a water-rich mafic component with monzodioritic affinity may explain the outstanding geochemical features of the Cambro-Ordovician OSF rocks.

We interpret that the peculiar composition of the OSF rocks is only possible if anomalously high contents of restitic minerals

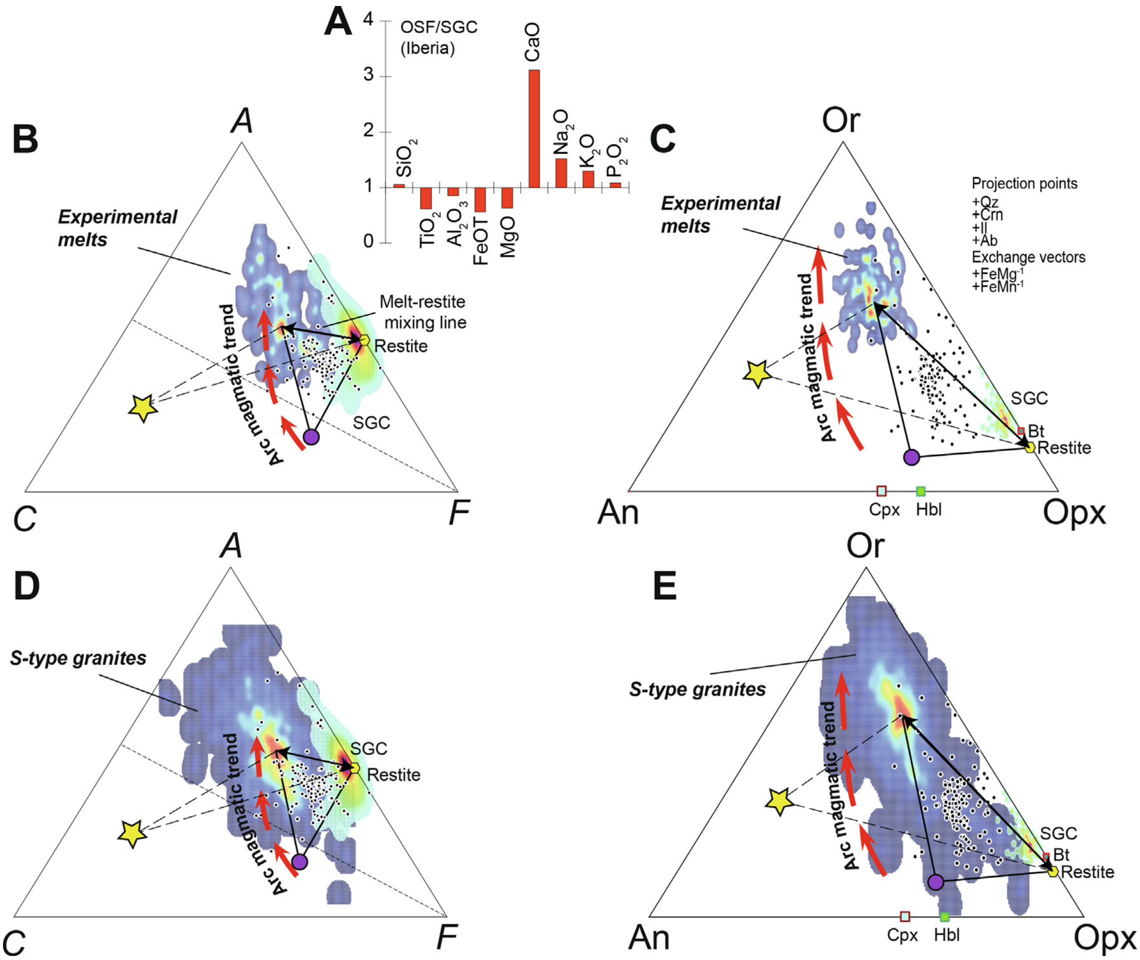

Fig. 4. (A) Histogram showing relative depletion/enrichment of major elements in the Cambro-Ordovician OSF rocks compared to the Ediacaran SGC metasedimentary rocks, denoting the need for addition of an extra calc-alkaline component rich in Ca, Na and K. (B, C) Eskola's ACF and An-Or-Opx diagram showing compositional space relations of OSF rocks (black dots) and potential end members involved, namely the Ediacaran SGC metasedimentary rocks and anatectic experimental melts. (D, E) Same projections of B and C showing the comparison with S-type granites. OSF rocks plot onto a region delimited by a triangle traced from the kernel maxima of SGC metasedimentary rocks and anatectic melts/granites, and the global average of the monzodiorites (purple dot) or their water-saturated melt (large star), outside of the melt–restite mixing line. OSF rocks also plot outside the experimental main cotectic array of the calc-alkaline batholiths (Castro, 2021). ACF plot according to the classical Eskola's diagram (*A* = molar Al_2O_3-Na_2O-K_2O; *C* = CaO; *F* = FeOT + MgO + MnO). Projection of the space An–Or–Opx according to Appendix A. Data sources for SGC metasedimentary rocks from compilation in Fernandez et al. (2008); experimental melts and S-type granites are given in the Appendix A. Mineral abbreviations after (Whitney and Evans, 2010). Kernel conditions as in Fig. 2.

Table 1
Composition (wt% and ppm) of the modelled compositions.

	Average monzodioritic composition	Saturated liquid from the monzodiorite
SiO_2	56.86	69.78
TiO_2	0.96	0.08
Al_2O_3	15.03	14.15
FeO	6.23	0.69
MnO	0.12	0.57
MgO	5.51	0.10
CaO	5.72	4.28
Na_2O	3.31	3.76
K_2O	3.26	4.51
P_2O_5	0.50	2.08
Total	97.5	100
H_2O	3.00	10.7
Ba (ppm)	1549	1549
Cr (ppm)	242.3	11.20

from the Ediacaran SGC metasedimentary source are incorporated (component 2), together with the addition of Ca-rich fluids (component 3) giving rise to a mobile *migma*. That is, melts were not efficiently extracted from the source as normally happens in anatectic domains with the segregation of S-type peraluminous leucogranites (Brown et al., 1995). A plausible explanation is that melt batches occurred in a short period of time making the partially molten zone mechanically unstable and buoyant as a whole (Fig. 6). Estimations based on zircon solubility (Bea et al., 2007) yield values between 10^3 and 10^4 years for duration of OSF melting. These fast time estimations are shorter than the calculated time for crustal melting by heat conduction from a hotter invading magma (Koyaguchi and Kaneko, 1999; Koyaguchi and Kaneko, 2000). A cause for a short-time, catastrophic melting can be the addition of water by vein infiltration into the magmatic zone. Water dissolved in a mantle-derived wet magma (e.g., a monzodiorite) may be released when the melt reaches saturation during crystallization (second boiling) and transferred by vein migration almost instantly, decreasing the solidus of the metasedimentary source and leading to catastrophic melting and mechanical instability of a *migma* that contain restites, granitic melt and components from the invading fluid. Some conceptual problems of this model refer to the water diffusion being slower than thermal diffusion (Weinberg and Hasalová, 2015), and its inability to efficiently extract the melt after the water-fluxed melting (Pistone et al., 2017). However, the melt fraction and mobility would increase

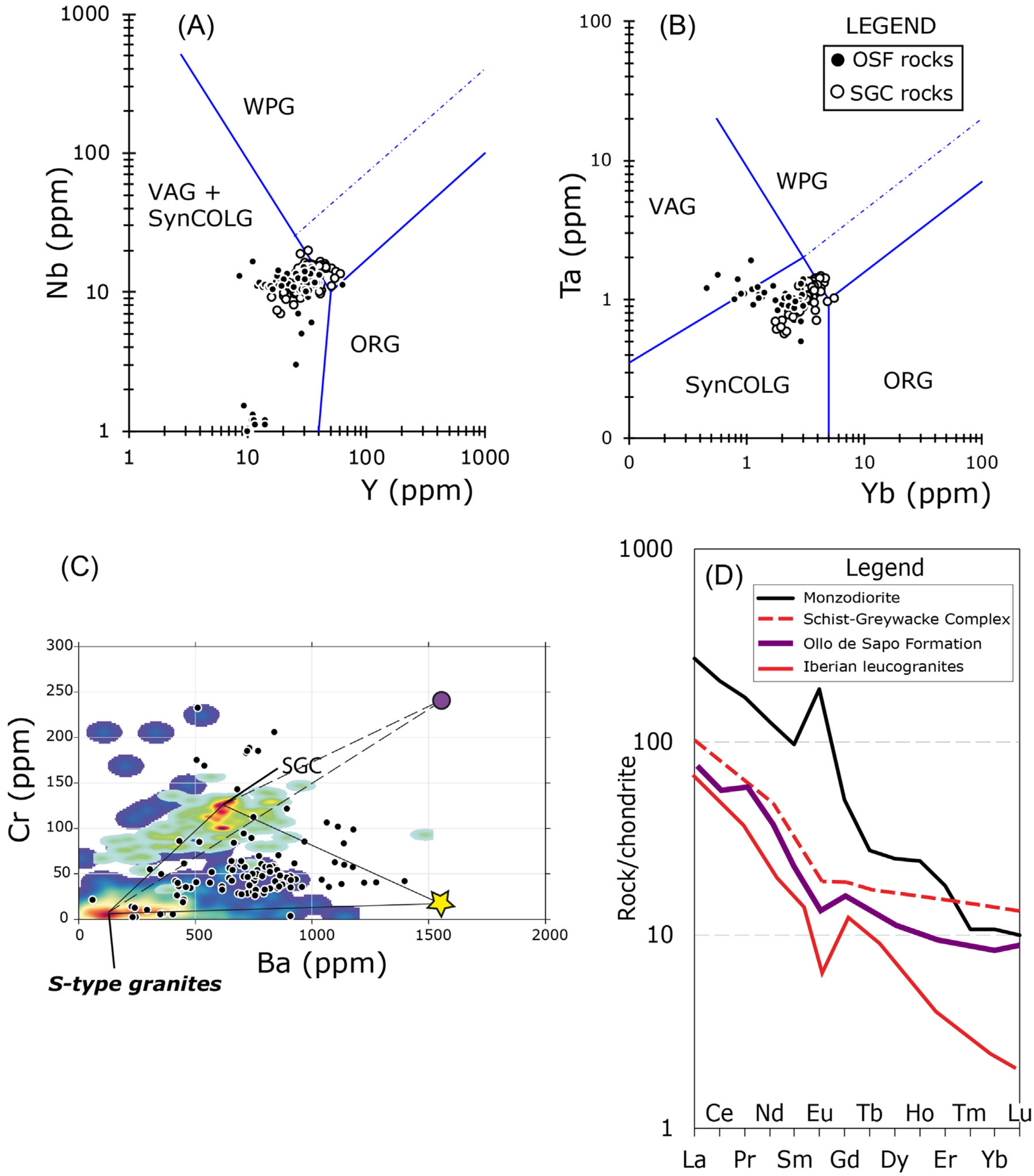

Fig. 5. (A and B) Pearce's diagram discriminating between Volcanic Arc Granites and Syn-Collisional Granites. (C) Ba-Cr kernel density plots for the three components system proposed and the Cambro-Ordovician OSF rocks. The average value of the global composition of monzodiorites and their saturated melt are represented by the puprple dot and yellow star, respectively. (D) REE diagram modified from Castro et al. (2009) showing also the monzodiorite average composition.

rapidly with the mafic component injecting through multiple veins, in agreement with observed field relations of partially molten igneous rocks by water infiltration (Weinberg and Hasalová, 2015; and references herein). This mechanism would considerably increase the melting surface, making water-fluxed melting much faster than heat conduction.

Melt fractions of the *migma* system must be high (30–50 vol% melt), to overcome the rheological threshold (Vigneresse et al., 1996) and to allow magma ascend and eventually erupt to the surface. High melt fractions can be achieved in case of a water-rich mafic magma invading the anatectic area at the time of melting. The large effect on melt productivity by water addition in pelites has been documented in experiments. For instance, up to 40 vol% liquid can be formed in pelites with addition of only 2 wt% water at 6 kbar and 775 °C (Patiño Douce and Harris, 1998). Moreover, melting under the influx of a water-rich fluid accounts for the absence of peritectic minerals after biotite breakdown in pelites, indicating temperatures below ca. 800 °C (Vielzeuf and Holloway, 1988).

Isotopic fingerprints indicate that OSF rocks comes from a source linking the SGC to a more primitive (at 470 Ma) but crustal-enriched endmember (Fig. 7). The implication is that the mafic component, needed to account for major element chemistry, is more primitive than the Ediacaran SGC metasedimentary rocks. This is compatible with an enriched mantle source that was fluxed by an old (Precambrian?) crustal isotopic reservoir. The metasomatizing magmas have a marked crustal signature, with high values of Sr initial ratios, possibly inherited from a subducted crustal protolith. An enriched mantle is the characteristic source of monzodioritic magmas (Fowler and Rollinson, 2012; Lobach-Zhuchenko

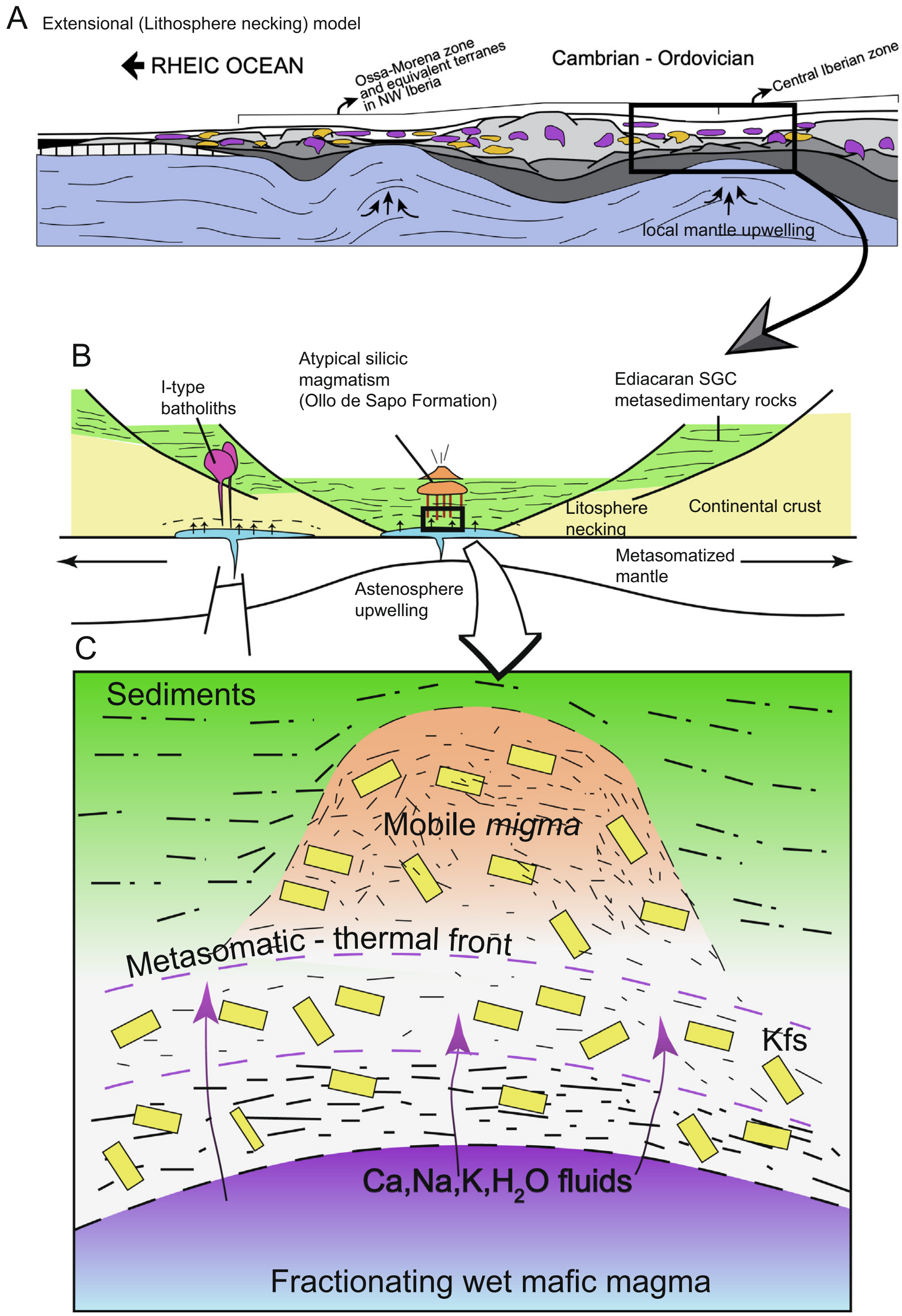

Fig. 6. (A) Model for lithospheric extension of the Central Iberian Zone during the evolution of Gondwana passive margin (adapted from Díez-Fernández et al. (2015). Schematic cartoon (B) showing a plausible tectonic scenario for the generation of atypical silicic magmas during Cambro-Ordovician lithospheric extension in the Iberian Massif and stages preceding Gondwana margin breakup. In narrow bands, where the Ediacaran SGC metasedimentary rocks were close to the crust-mantle boundary and lower mafic crust was absent, fluids from a metasomatized mantle magmas interact directly with sedimentary rocks causing a *mobile migma* or hybrid nebulite (C) that accounts for geochemical and textural features of the atypical Cambro-Ordovician OSF silicic magmas. A metasomatic front is generated allowing the most mobile elements, like K, to generate the large Kfs crystals. In places where lower mafic crust is present, the same process may produce calc-alkaline batholiths.

et al., 2008), supporting the hypothesis of monzodiorites as the carrier of water-rich fluids and mafic components to the source of the OSF. This process accounts for fast melting and hybridization with Ca, Na, Mg, K, Ba-rich fluids derived from the mafic magma. The consequence is the generation of catastrophic *migma* batches forming OSF rocks. The water-bearing mafic magma is bound to contain isotopic signatures older than Ediacaran SGC metasedimentary rocks, which is possible if a Cadomian or older tectonic event (including possible subduction) was responsible for metasomatizing the mantle source of the Cambro-Ordovician mafic magmas (Murphy et al., 2008).

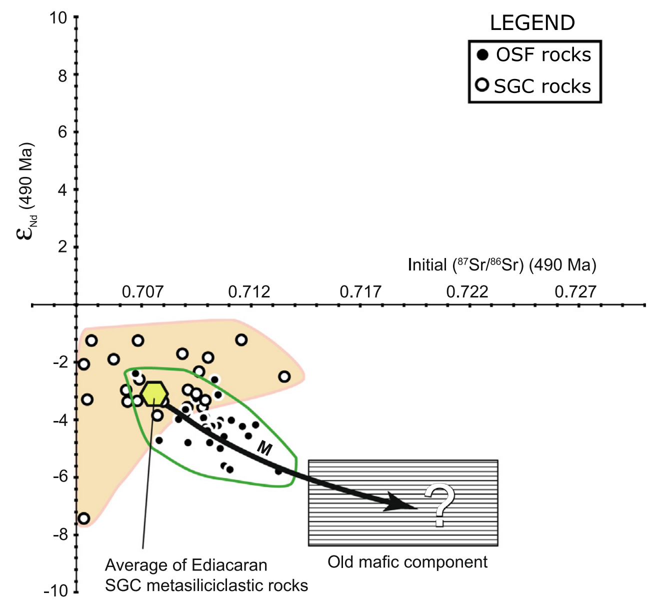

Fig. 7. Sr–Nd initial isotopic ratio diagram plotting rocks of the Cambro-Ordovician OSF compared with the Ediacaran SGC metasedimentary rocks as the most plausible source of the Cambro-Ordovician magmas. Data are normalized to the age of magmatism of the OSF rocks (ca. 490 Ma). OSF rocks are more evolved compared with the SGC metasedimentary rocks. As inferred from major element relations, the added mafic component (along the line labeled M) must be isotopically older than the Ediacaran metapelites and metagreywackes.

This is our favored hypothesis because mafic magmas supply the necessary water and heat to make possible the crustal melting. The alternative scenario is melting of a metasediment-diorite composite crustal source. The thermal input necessary to reach the melting of such composite source is not registered in the Cambro-Ordovician geological record.

3.2. Tectonic implications

Contrary to what is found in other regions of the Western European Variscan belt, of which Sardinia (Cocco et al., 2018) and the Alps (Franz and Romer, 2007; Zurbriggen, 2015) are remarkable examples, contractional deformation and Barrovian metamorphism associated with crustal thickening during Cambro-Ordovician times is not recognized in the Iberian Massif. Although there are arguments to postulate the existence of a subduction zone on the Gondwana margin in Cambro-Ordovician times (Cocco and Funedda, 2019), we must be very cautious when trying to extend it to the Iberian Massif.

Field relations show that Cambro-Ordovician sedimentation and volcanism was associated with extensional tectonics in the Central-Iberian (Castro et al., 2020; Dias da Silva et al., 2016; Díez-Montes et al., 2010), Ossa-Morena (Díez-Fernández et al., 2015), and Cantabrian (Gutiérrez-Alonso et al., 2016) zones. The local recognition of a Lower Ordovician (Tremadocian-Floian) unconformity (i.e., Toledanic unconformity) between the Ediacaran SGC metasedimentary rocks and the overlying Cambro-Ordovician OSF rocks and/or Ordovician siliciclastic platform sequence (Amorican Quartzite, Gutiérrez-Marco et al., 2002) supports this hypothesis. The recent findings of: (1) strongly sheared low-pressure high-grade SGC metamorphic rocks associated with the emplacement of Ordovician granodiorite-tonalite plutons of the Beiras-Extremadura batholith in the Central Iberian Zone (Castro et al., 2020; Rubio-Ordóñez et al., 2012) that partly coincide with the timing of (2) mantle-derived alkaline and peralkaline rocks with involvement of some crustal contamination (Díez-Fernández et al., 2015) and crustal-derived granitic rocks associated with low-pressure migmatites from the Ossa Morena Zone (Solís-Alulima et al., 2020) are strong arguments in favor of this extensional tectonics model for the Gondwana margin. Another argument also in favor of this major crustal extension are the subsidence patterns of Cambro-Ordovician basins from the Central Iberian, Ossa-Morena, Cantabrian and West Asturian-Leonese zones (Raumer and Stampfli, 2008). A divergent (extensional) tectonic setting, dominating during the Cambro-Ordovician the evolution of the Iberian passive margin, was also recently proposed to account for the petrogenetic processes related to the generation of granodiorites and tonalites from the Beiras-Extremadura batholith (Castro et al., 2020). These atypical calc-alkaline igneous rocks were probably generated through the crustal recycling of the pre-extensional Cadomian subduction related arc triggered by heating transfer and water inputs at the lower crust by hydrated mafic magmas ascending from an underlying metasomatized mantle. The generation of the OSF magma can be framed in the same model. The arrival of a water-bearing mafic magma to the anatectic zone triggered extensive and catastrophic partial melting of the thick metasedimentary pile represented by Ediacaran SGC metasedimentary sequence, giving rise to a mobile nebulite or *migma* (Fig. 6), which was able to extrude and form super-eruptions or "flare-up" events giving rise to a felsic LIP. The Cambro-Ordovician tectonic evolution of the Iberian Massif may be compared to a magma-rich passive margin preceding the Gondwana margin breakup, which probably reactivated pre-existing Cadomian structures. The extended or hyper-extended continental margin was characterized by the development of large throughs and voluminous magmatic input consisting predominantly of silicic rocks emplaced on and atop the thinned lithosphere, coevally to final plate rupture and the onset of the Rheic Ocean. Compositional variations of Cambro-Ordovician magmatism in the Iberian Massif can be understood as the direct result of the cessation of the Cadomian arc activity followed by extension in the formerly overriding plate (Díez-Fernández et al., 2015). The increased heat flow and related voluminous magmatic and anatectic events giving rise to the formation of the Cambro-Ordovician intracontinental rift basins in the Gondwana margin were originated by the arising of a slab-window formed by ridge-subduction underneath the Cadomian orogen (Linnemann et al., 2008). This, in turn, may have caused a switch from active to transform margin setting during the Cambrian (Linnemann et al., 2008). Other model advanced to explain these events considers the development of a protracted convergent setting that has extended over time from Cambrian to Ordovician (Díez Fernández et al., 2012; Fernandez et al., 2008). This tectonic model explains the expanded rifting of the Gondwana margin as a back-arc basin that may have promoted drifting of *peri*-Gondwanan terranes after the inception of to the Rheic Ocean. The coexistence of crustal- and mantle-derived magma sources implied the thermal support from the underlying upwelling mantle impinging on the mechanical boundary layer of overlying lithosphere. Under these circumstances, magmatic underplating was probably favored in the lithosphere necking domain, marking the transition between the hyperextended continental crust and the normal thick crust (Chenin et al., 2018; Sutra et al., 2013). The thermal regime could also be enhanced by the presence of a mantle plume (Pufahl et al., 2020).

4. Conclusions

The obtained results of the data-analysis of geochemical data linking magmas and source compositions support that the atypical Cambro-Ordovician OSF silicic magmatic rocks generated by extensive melting of Ediacaran SGC metasedimentary rocks, fluxed by hydrous mafic magmas. The Cambro-Ordovician OSF rocks resulted from crystallization near the surface, and as volcanic ejecta, of a *migma* system formed by a mixture of three main components, namely an anatectic granitic melt (component 1), restitic minerals (component 2) and cafemic components (Ca, Mg and Fe) derived from a water-rich magma (component 3). A fluid-bearing magma, supplying water and calc-alkaline components, arrived to the anatectic zone triggered extensive and catastrophic partial melting of the thick metasedimentary pile of Ediacaran metapelite and metagreywacke sequence. Later, a mobile nebulite or *migma* generated, being able to extrude and form the super-eruption or "flare-up" that characterizes the *peri*-Gondwanan Cambro-Ordovician felsic large igneous province.

CRediT authorship contribution statement

Carmen Rodríguez: Formal analysis, Conceptualization, Data curation, Writing – original draft. **Antonio Castro:** Supervision, Conceptualization, Writing – original draft, Project administration, Funding acquisition, Writing – review & editing. **Daniel Gómez-Frutos:** Formal analysis, Writing – original draft, Data curation. **Gabriel Gutiérrez-Alonso:** Supervision, Conceptualization, Project administration, Funding acquisition, Writing – review & editing. **M. Francisco Pereira:** Conceptualization, Writing – original draft, Writing – review & editing. **Carlos Fernández:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gr.2022.01.011.

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