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Ranked Mappable Criteria for Magmatic Units: Systematization of the Ossa-Morena Zone Rift-Related Alkaline Bodies

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Abstract: The Ossa-Morena Zone (SW Iberian Massif) hosts the largest set of Cambro–Ordovician alkaline magmatic plutons related to the Palaeozoic rifting of the northern Gondwana margin so far described. An organized framework for their classification at different scales is proposed through data-driven ranks based on their distinctive petrological features relative to other rift-related magmatic rocks found throughout western Europe. The classification method aims to enhance geological mapping at different scales, regional- and continental-scale correlations, and, as such, facilitate the petrogenetic interpretation of this magmatism. The hierarchical scheme, from highest to lowest rank, is as follows: rank-1 (supersuite) assembles rocks that have distinctive characteristics from other magmatic units emplaced in the same magmatic event; rank-2 (suite) categorizes the units based on their major textural features, indicating if the body is plutonic, sub-volcanic, or a strongly deformed magmatic-derived unit; rank-3 (subsuite) clusters according to their spatial arrangement (magmatic centres) or association to larger structures (e.g., shear zones or alignments); rank-4, the fundamental mapping unit, characterizes the lithotype (alkaline granite, alkaline gabbro, syenite, albitite, etc.) by considering higher ranks (alkalinity and textural aspects); rank-5 characterizes the geometry of individual plutons (with several intrusions) or swarms; rank-6 (smallest mappable unit) corresponds to each intrusion or individual body from a swarm. Although this classification scheme is currently presented solely for the Ossa-Morena Zone, the scheme can be easily extended to incorporate other co-magmatic alkaline bodies, such as those in the NW Iberian allochthonous units or other peri-Gondwanan zones or massifs, in order to facilitate regional correlations of the rift-related magmatism.

Keywords: lithodemic classification; alkaline magmatic rocks; Ossa-Morena Zone; Iberian Massif

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1. Introduction

The systematic hierarchization of lithodemic units is a key aspect of the geological mapping of intrusive, deformed, and metamorphosed rocks. The effective classification of such units facilitates the consistent and accurate interpretation of regional geological processes, providing a standardized framework for better comparisons and correlations of geological units at a global scale. In highly deformed terranes, establishing the nomenclature and relationships between intrusions of similar nature and related magmatic-derived tectono-metamorphic units contributes to the deepening of knowledge regarding tectonic events, magmatic processes, and regional metamorphism [1–4]. The implications of a well-defined hierarchized nomenclature in igneous provinces or belts go beyond the possibility of large-scale interpretations, as locally, it can contribute to delineating the spatial relationships between igneous bodies (centres, clusters, swarms, or alignments), as well as emphasizing the individual massifs and their internal architecture [2]. The thorough ranked classification enhances the knowledge of complex magmatic systems and, when significant, their tectono-metamorphic evolution from local-scale to province/terrane-scale, and therefore, it is useful for a range of applications, like paleogeographic reconstruction or mapping and the management of natural resources. Several broad classification methods have been proposed, ranked, compared, and reformulated to systematize the nature of the magmatic rocks associated with specific events, and they have been employed for different purposes [1,2,4–9]. These range from geological mapping and determining large-scale tectono-thermal events to regional assemblages of rocks with similar compositional features and economic significance.

In this work we present a hierarchical classification of the Cambro–Ordovician rift-related alkaline magmatic rocks of the Ossa-Morena Zone (OMZ, Figure 1; SW Iberia) using a ‘6-ranks’ method, partially following recommendations from the revised North American Stratigraphic Code (NASC), the British Geological Survey Rock Unit Classification System (BRUCS), and the Cooperative Lithodemic and Stratigraphic System (CLASS) [2–4,10]. The systematic grouping of such rocks provides, beyond the criteria for applications in geological mapping at different scales, the framework for further studies of alkaline magmatic systems, as it outlines the extent of relatable bodies and assists with correlations across analogous magmatic segments throughout the peri-Gondwanan terranes. We avoid inferences on the regional delineation of large igneous provinces and their volume or timespan, as well as metallogenic provinces. Our interpretation assumes that the alkaline rocks represent pulses from a larger tectono-magmatic event (the Palaeozoic rift of the Gondwana northern realm) and therefore are part of a large rift-related igneous province that includes other magmatic-derived units. The necessity of a complete classification of the OMZ alkaline bodies independent from the other OMZ rift-related magmatic rocks (e.g., tholeiitic mafic rocks or peraluminous granitoids [11–20]) is derived from the mappable lithological variations with implications in the petrogenesis and the potential ore-forming systems known to develop in such alkaline magmatic environments [6,21].

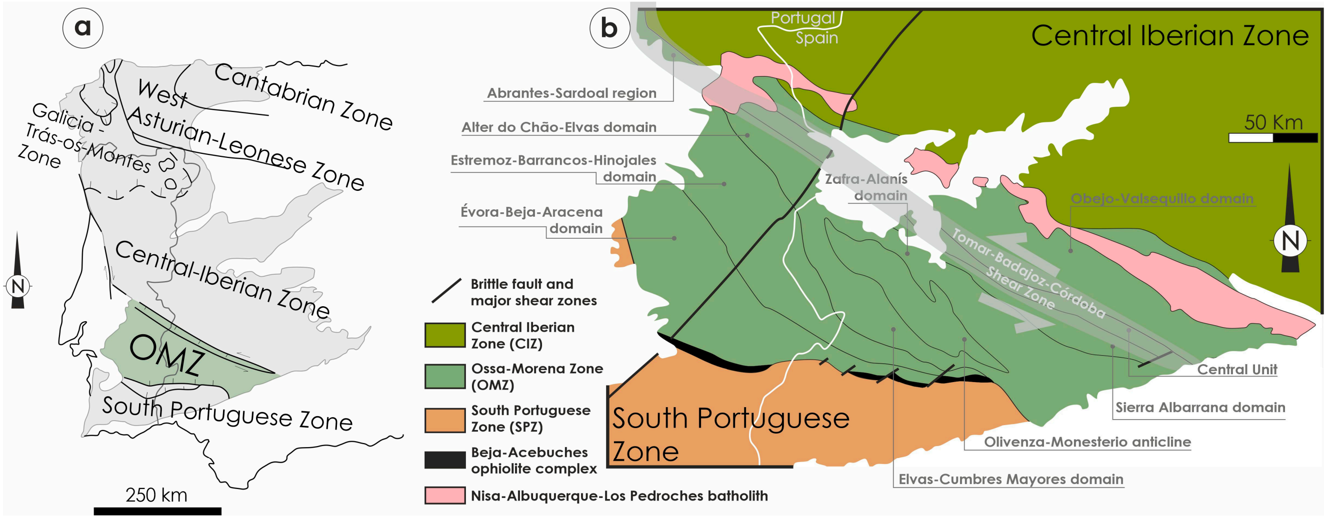

Figure 1. (**a**) Location of the Ossa-Morena Zone (OMZ) within the tectono-stratigraphic zonation of the Iberian Massif (adapted from [22,23]). (**b**) Major structural domains of the OMZ, adapted from [24,25], separated by the major shear zones from [24,26,27]. The grey area corresponds to the sinistral Tomar–Badajoz–Córdoba Shear Zone [28].

2. Geological Setting

The Iberian Massif comprises the geological units related to the final stages of the Cadomian Orogeny (late Ediacaran) and the subsequent Variscan Cycle, i.e., the Palaeozoic opening and closure of the Rheic oceanic basins, which culminates with the Laurussia–Gondwana continental collision that formed Pangea [29–34]. The Palaeozoic evolution of the Iberian Massif is characterized by the Cambro–Ordovician rifting [15,17,35], followed by the Ordovician–Lower Devonian passive margin [25,36], and finally the mid-Devonian–Carboniferous subduction and continental collision [29,32,37]. The processes related to the Variscan cycle imposed a tectono-stratigraphic zonation throughout the Iberian Massif [23], with different tectono-magmatic and metamorphic characteristics depending on the distance from the Rheic suture zone [38–49]. The OMZ corresponds to the outer zone of the Iberian segment of the Gondwana margin and is therefore characterized by distinctive sedimentation and magmatic patterns. This zone can be further compartmentalized by structural or tectono-stratigraphic domains [24,25,27] (Figure 1b), majorly composed of variably metamorphosed and deformed successions (e.g., [17,25,50–55]), as well as syn-orogenic sequences [56,57], thermal domes [47,58,59], and collision-related plutonism that persisted mainly during Carboniferous times [11,46,48,60–64].

All segments of the OMZ comprise key elements for understanding the influence of the Cadomian Orogeny and the subsequent rifting of northern Gondwana, which culminated with the opening of Rheic and related oceans [34]. Evidence for the reconstruction of the Cadomian orogen is well preserved in the Zafra–Alanís and Obejo–Valsequillo domains and to a lesser extent, in the Abrantes–Sardoal domain and in the Central Unit, the Tomar–Badajoz–Córdoba Shear Zone (TBCSZ) [28], as well as in the Olivenza–Monesterio Anticline. In these domains, remnants from oceanic-affinity units (developed in fore-arc and back-arc environments) [65–69] and from the major arc-building and arc-related volcanism [70–80] have been found.

The oldest sedimentary units are the Ediacaran Série Negra Group, deposited in the arc basins during the ca. 600–545 Ma interval [51,81]. The arc system ceased at ca. 541–534 Ma [70,82]. The regional rift-related lithostratigraphic Cambrian succession discordantly overlays the Série Negra Group and includes (from the bottom to the top): Lower Detrital (LD), Detrital Carbonate (DC), Upper Detrital (UD), and Main Rift (MR) sequences (e.g., [15,17,27,83]).

The coeval magmatic activity is widespread in the OMZ and is characterized by an early event of subalkaline felsic magmatism progressively followed by a subalkaline to mildly alkaline bimodal main rift event from ca. 539 to 500 Ma [11,13–18,20,58,59,84,85] and the later persisting subalkaline [54,86–90] and mildly alkaline to peralkaline bimodal magmatism from ca. 500 to 470 Ma [12,19,91–94]. Most of the rift-related magmatism in the Galicia-Trás-os-Montes and Central Iberian zones (GTMZ and CIZ) consists of subalkaline rocks, i.e., peraluminous granitoids and tholeiitic mafic rocks, emplaced during the late rift event (e.g., [83,87,95–97]). However, in specific segments of the GTMZ (in the lower allochthonous), the magmatism achieved alkaline and peralkaline composition and is also represented by alkaline granitoid orthogneisses [98–100] and alkaline metavolcanic rocks (e.g., [101–104]), which are prone to be correlated with the alkaline magmatism of the OMZ. In regions where these rocks are described, alkaline magmatism generally postdates subalkaline magmatism [91,98,99]; in contrast, in areas lacking evidence of alkaline rocks, the peraluminous character persists into later stages [95,96,105]. While the subalkaline magmatism is pervasive in the OMZ, sections with documented alkaline magmatic bodies emplaced during the later rift magmatic events are restricted to the central-north domains. This includes the Alter do Chão-Elvas domain (in Portugal), with a lithostratigraphic sequence that ramifies into the Elvas–Cumbres Mayores and the Zafra–Alanís branches, as well as the Olivenza–Monesterio Anticline (in Spain) and the Central Unit (Figures 2 and 3). In this work, thorough geological mapping was conducted to access the geometry, textures, and main mineralogical features of the alkaline magmatic rocks in Portugal and confronted with information from published works. Alkaline massifs from the Spanish side are well characterized in published maps and the literature, on which we based our ranked classification.

Besides Iberia, the Cambro–Ordovician rift-related magmatism is also found in other segments of the rifted margin of northern Gondwana, namely in the Armorican, Central, and Bohemian Massifs [106,107], consisting majorly of subalkaline (peraluminous or tholeiitic) magmatic bodies (e.g., [108–112]). Alkaline magmatism is reported to be very scarce and consists essentially of variably metamorphosed volcanic units, preferably located in the outer zones of the massifs or in allochthonous complexes [110,111,113,114]).

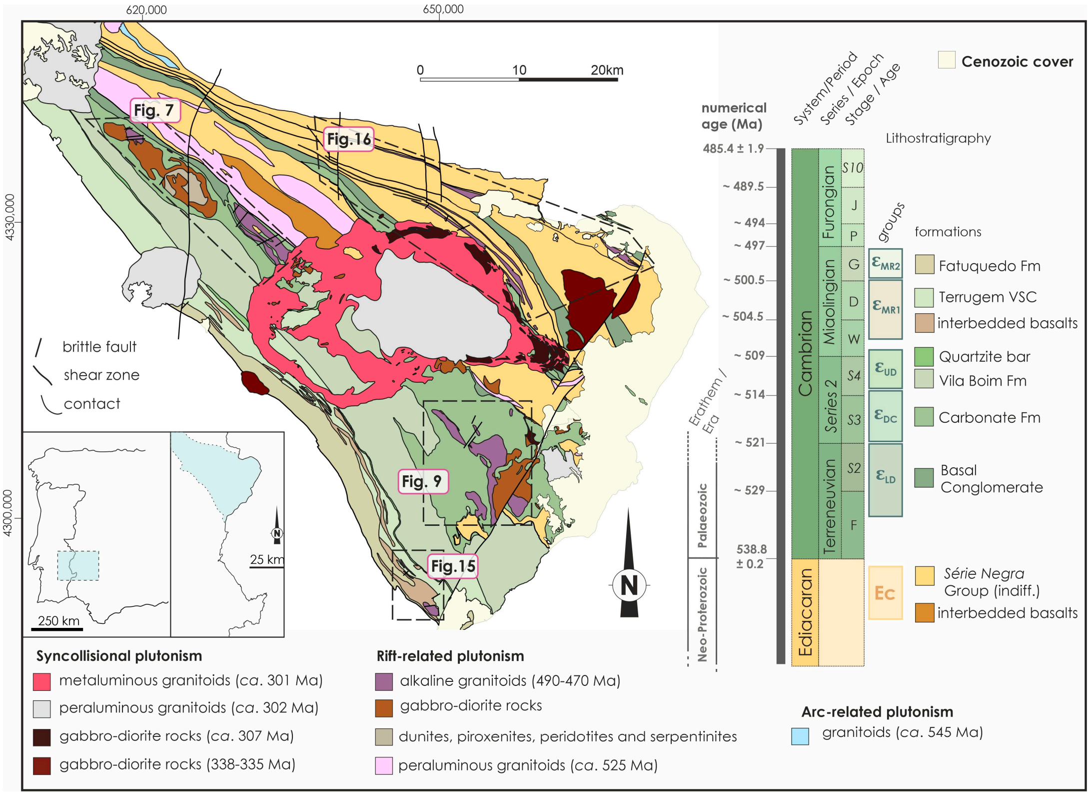

Figure 2. Location and geological map of the Portuguese side of the study area, including the Alter do Chão–Elvas domain and a segment of the central unit/Tomar–Badajoz–Córdoba Shear Zone, adapted from [115–121]. References regarding ages are found throughout the text.

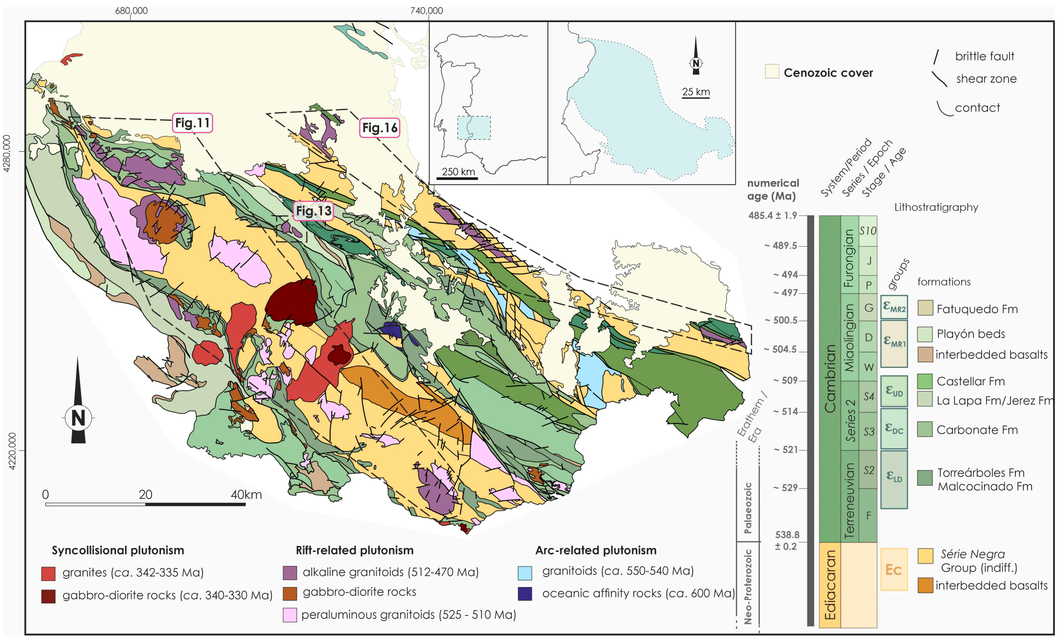

Figure 3. Location and geological map of the Spanish side of the area with rift-related alkaline magmatic bodies, with segments of the Elvas–Cumbres Mayores, Sierra Albarrana, and Zafra–Alanís domains, as well as part of the central unit/Tomar–Badajoz–Córdoba Shear Zone (Central Unit). Adapted from [122]. References regarding ages are found throughout the text.

3. The Classification Method and Nomenclature

A chain classification arrangement of the OMZ alkaline rocks is proposed following the recommendations of the ISG and the NASC [3,10], further complemented with some intermediate rank terminology by the BRUCS [1] and the CLASS [4]. A diagrammatic summary is presented in Figure 4. Like the classical lithodemic classification of the ISG and the NASC (e.g., [10]), the fundamental unit is the lithodeme, i.e., (rank 4), the most basic mappable element at ca. 1:50,000 scale (either a lithotype or an unmappable rock association). Two or more lithodemes with the same class can be part of a higher rank unit but if mixed with lithostratigraphic elements (like large country rock enclaves), the term 'complex' should be employed. The suite (rank 2) groups alkaline magmatic rocks with the same relatable properties, i.e., the same emplacement model (igneous) or deformed lithotypes. This distinguishes the 'intrusive' (plutonic bodies), 'subvolcanic' (hypabyssal stocks and dykes), and 'mylonite' (the high-strain alkaline orthogneisses) suites. The ensemble of all the suites (rank 2) is a supersuite, rank 1 in the hierarchy arrangement. The term 'assemblage' or 'superassemblage' is proposed for the high-ranked classification of tectono-metamorphic units in the BRUCS [2]; however, those terms are avoided for the metamorphosed high-strain alkaline orthogneisses. All these alkaline rocks are related to the same magmatic process, although they have experienced different tectono-metamorphic paths during the Variscan Orogeny. Instead, the higher-ranked classification of these units should infer their features before deformation/recrystallization due to their petrogenetic and geochemical similarities (also proposed by Maxeiner et al. [4]).

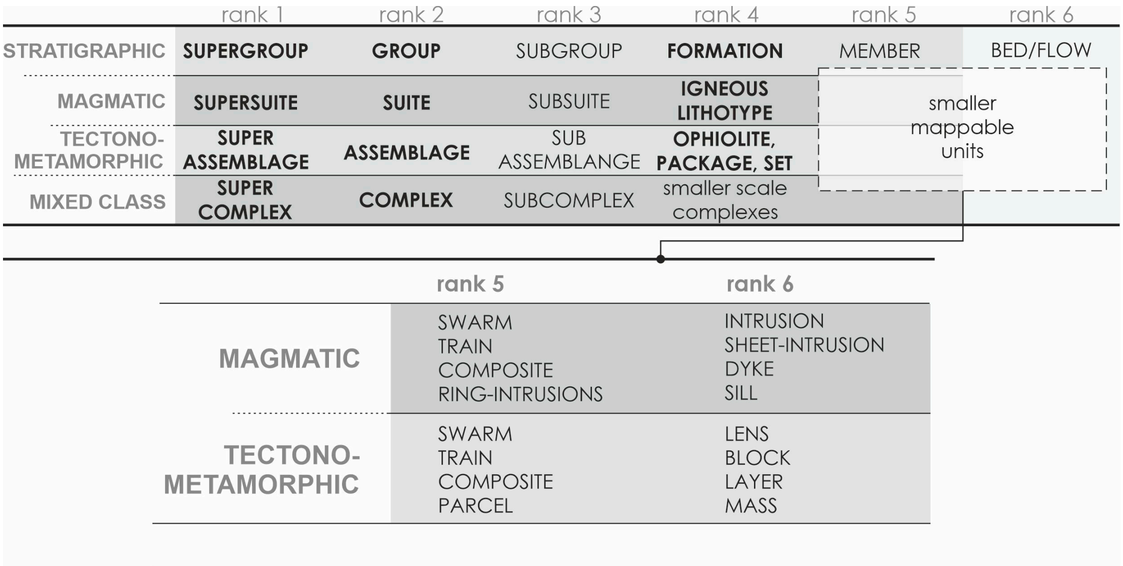

Figure 4. Classification systems for stratigraphic, morphogenetic, and mixed-class units, partially adapted from BRUCS [2], with only some examples of rank 5 and rank 6 classifications. the terms in bold are used at a larger scale (>1:50,000). Mixed class units include more than one genetic type and have lower ranks. Ranks 5 and 6 can be used for detailed mapping (<1:50,000) and to characterize individual massifs or swarms.

The region where the OMZ alkaline igneous bodies outcrop has been informally referred to as a province, known as 'Província Alcalina' (e.g., [123]), as it consists of a large region with magmatic rocks exhibiting similar petrographic and geochemical features. However, the term 'province' will not be used as a formal rank in this classification, as suggested by Gillespie et al. [2]. Likewise, unit terms usually employed in biostratigraphic and mineralogical categories, like 'zone' and 'facies', are also avoided [2,124].

Further categorization subdivides the suites. Rank 3 (subsuite) is a division of a parent suite [4] and gathers spatially associated bodies in 'clusters' (or 'centers' if disposed around a central point [2]). This may be useful for inferring magmatic centres or associating different massifs to a broader structure and can be significant in cartographic representation at more detailed scales.

Rank 4 (the lithodeme) is the fundamental mappable rank and is equivalent in importance to the "Formation" in the lithostratigraphic system. Here, we use the main igneous lithotype (e.g., granite, syenite, and albitite), considering the higher classification ranks (1 and 2) that reflect the time of emplacement and texture, to avoid a possible misleading overlapping with other alkaline magmatic rocks spawned in other events.

Ranks 5 and 6 define the association of smaller bodies or an individual massif, classifying them according to their morphological aspects and internal complexity. These ranks should only be used for detailed mapping (Figure 5). The smaller units are placed in rank 6 (simple intrusions or lenses), and if two or more similar rank 6 bodies have a spatial relationship or a mappable lithological complexity, they become part of a rank 5 unit. A magmatic body can be a 'pluton' (simple or composite) and can be further characterized if it displays a distinctive shape (such as 'ring-intrusion' if it shows an annular form or 'sheet-intrusion' if it has a tabular shape) [2]. The volcanic and hypabyssal structures are either dykes or sills, and (sub)rounded bodies can also be considered plutons. The mylonite bodies have tabular/lensoidal shapes and are referred to as 'lenses' to distinguish the tectono-metamorphic units from similarly shaped sheet-intrusions or dykes. The close associations of small simple bodies can be defined as 'swarms' if the outcrops are dispersed or as 'trains' if they display a linear disposition (morphological concepts from [2]).

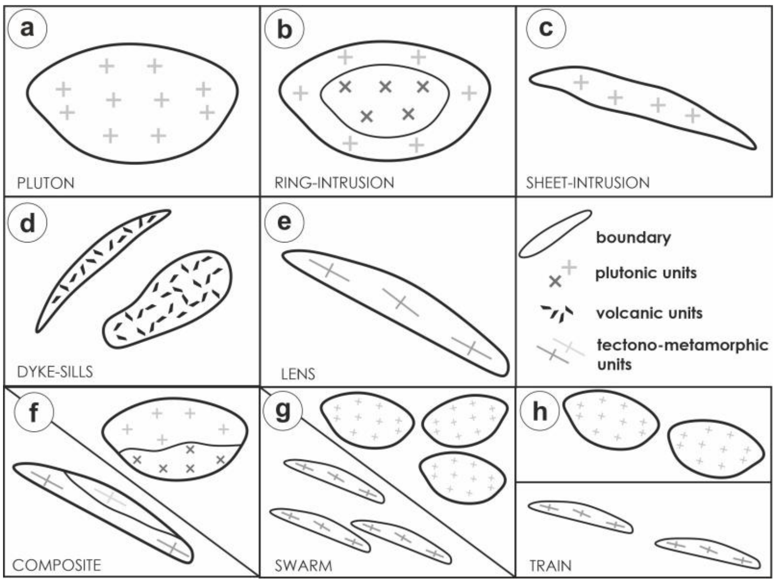

Figure 5. Schematic representation of the mappable morphological types and designation of groups with spatially associated bodies. (**a**) Circular or ovoidal simple pluton; (**b**) ring-intrusion, a unit comprising more than one related intrusion, with an inner body bounded by a ring-shaped distinct body; (**c**) sheet-intrusion, represented by a tabular plutonic body with two long parallel borders much larger than the lateral dimensions; (**d**) dyke (**left**) and sill (**right**), correspondently near vertical or near horizontal tabular volcanic bodies; (**e**) lensoidal body of orthogneiss (lens); (**f**) composite unit, embodied by two or more lithotypes (also referred to as 'parcel' if the tectono-metamorphic units are contiguous at outcrop); (**g**) swarm, a group of two or more related dispersed units; and (**h**) train, a group of two or more units in a linear disposition. Schemes were made following definitions for unit terms in the hierarchy of morphogenetic units, from [2].

4. The Rheic Rift-Related Alkaline Supersuite

The Rheic rift-related Alkaline Supersuite encompasses all the magmatic and high-strained bodies emplaced along the northern margin of Gondwana suitable to be classified as alkaline. Within the Iberian Massif, this occurred during several steps within the ca. 505–470 Ma timespan ([11,12,16,19,91]), and the largest ensemble of units is found on the OMZ (Figure 6). Magmatic bodies considered for the supersuite contain modal feldspathoids, alkali amphiboles, or pyroxenes and have higher $Na_2O + K_2O$ relative to CaO, even if they are geochemically classified as metaluminous [125–128]. The term 'peralkaline' is the geochemical term employed for rocks that show a molar ratio of $Na_2O + K_2O)/Al_2O_3 > 1$, while the term 'alkaline' is more broadly used (values for the peralkalinity index for the different massifs of the OMZ in Table 1). On this subject, the OMZ rift-related alkaline rocks are predominantly sodic (with the exceptions of some alkaline granitoids or orthogneisses), in opposition to other alkaline magmatic rocks in the region associated with collisional/post-collisional settings [60,70,129]. Regarding the mineralogical classification, all the rocks contained within this supersuite are considered miaskitic [130,131], as the only agpaitic phase described so far is aenigmatite in one intrusion, while the accessory minerals include zircon and titanite [123]. The term agpaitic was deceitfully employed to characterize some of the rocks in the supersuite as a synonym for peralkaline in previous works [123]. Agpaitic rocks are specifically defined by their unique mineral assemblages, with complex Zr- and Ti-bearing silicates, which are not necessarily present in all peralkaline rocks [130,131]. Volcanic rocks with alkaline signatures that are part of OMZ lithostratigraphic units, volcano–sedimentary complexes, or tectono-metamorphic assemblages will not be part of the supersuite. These are the Umbría-Pipeta, Playón, and Terrugem alkaline basalts [15,17,93]; the Tapadão, Peringote, Terço, and Fome weakly alkaline metarhyolites [93,123]; as well as the Ribeira de Odearce intermediate alkaline rocks [49] (in the Moura–Phyllonite Complex/Cubito–Moura unit from the Évora–Beja–Aracena domain). It is worth noting that previous works interpreted felsic volcanics in the Estremoz volcano–sedimentary complex (Estremoz–Barrancos–Hinojales domain), in the Vila Boim Formation (Alter do Chão–Elvas domain), and near Caia as alkaline rocks [118,123,132]; however, subsequent studies have demonstrated that these rocks are more accurately classified as subalkaline rhyolites emplaced in ca. 500 Ma [86,93,133].

In the Iberian Massif, lithostratigraphic classifications are usually applied to each tectono-stratigraphic zone, such as the Douro–Beiras Supergroup (Douro and Beiras groups) in the Central Iberian Zone [134], or the Culm/Baixo Alentejo Flysh Group in the South Portuguese Zone [135], among others, because these units resulted from independent tectono-sedimentary and paleogeographic evolution. Despite the supersuite being herein proposed at the "zone-scale", alkaline magmatic bodies emplaced in other zones during the Palaeozoic rift (like the ones from the lower allochthonous from the GTMZ or found elsewhere in the Variscides) are susceptible to be integrated [26,136]. Rift-related alkaline rocks from NW Iberia basal allochthonous have been previously characterized, also contrasting in composition from other subalkaline rocks emplaced during the same event [98–100]. It is also noteworthy to acknowledge the presence of alkaline volcanic rocks within metasedimentary sequences from units in the NW Iberia allochthonous complexes (e.g., [101–104]) and to a lesser extent in the northernmost CIZ [101].

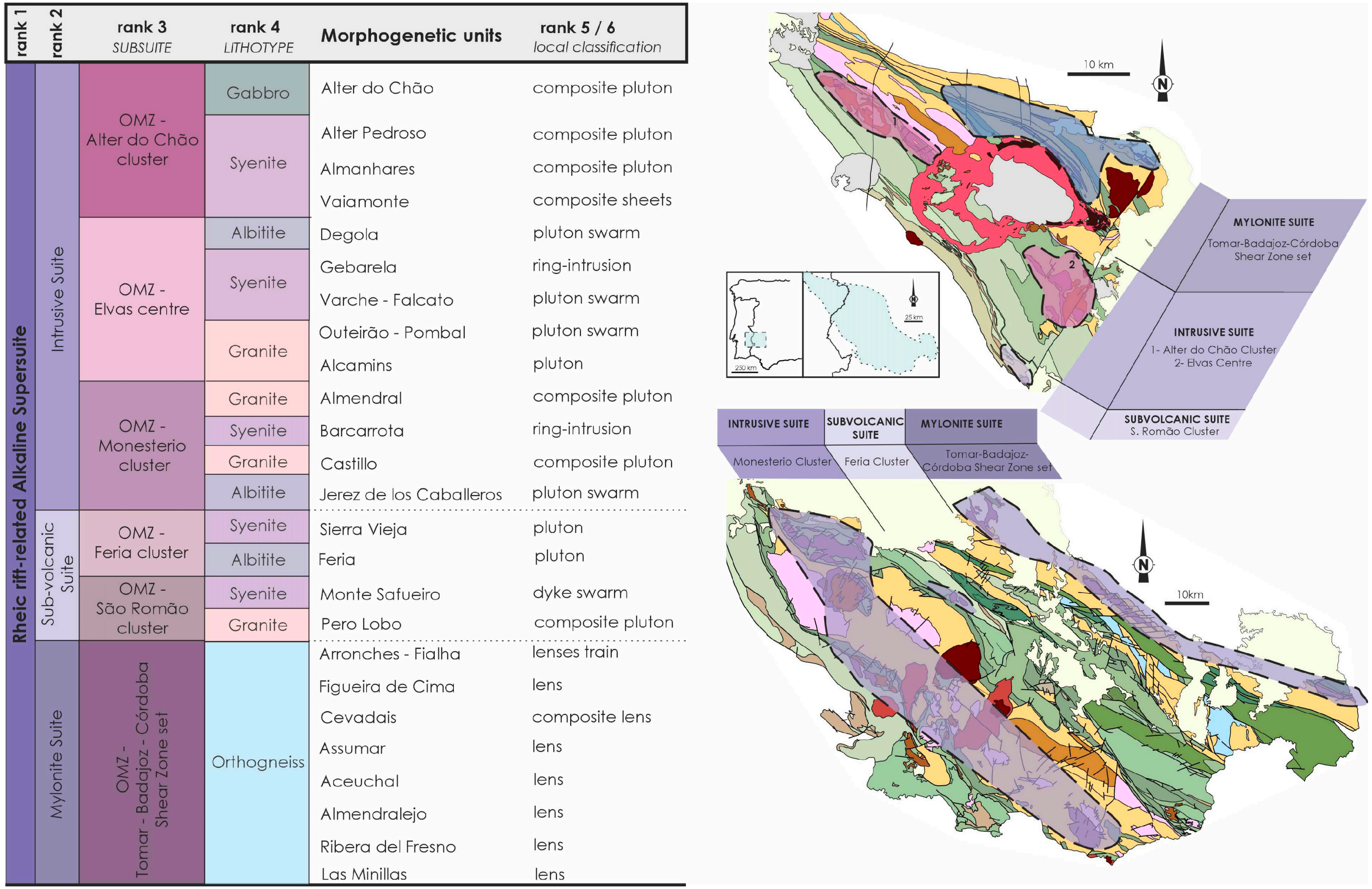

Figure 6. Ranked classification scheme for the alkaline magmatic bodies of the Ossa-Morena Zone, with the 6 ranks adapted and following the recommendations from [2,4,10], with locations of the suites and the clusters over the maps from Figures 2 and 3.

Along the northern Gondwana margin, rift-related alkaline magmatic rocks are very scarce when compared to the Iberian Massif, as they have only been identified as alkaline orthogneisses in the Cellier Unit of the South Armorican Domain (Armorican Massif [114]) and alkaline bimodal metavolcanic rocks in the Lower Gneiss Unit of the Central Massif [111] in the Maures Massif [113], as well as in the Fichtelgebirge and Kaczawa Complex from the West Sudetes (Saxo-Thuringian Zone, Bohemian Massif, e.g., [110]).

In the proposed scheme of the alkaline supersuite, three suites can be distinguished based on shared similarities regarding their magmatic and tectono-metamorphic textural features: (i) the intrusive suite, (ii) the sub-volcanic suite, and (iii) the mylonite suite. Further subdivisions provide additional information for understanding magmatic processes and structural alignments by assessing magmatic centres or the grouping of geochemically and structurally related bodies. In the OMZ, the units from the intrusive suite can be divided into the Alter do Chão, Elvas, and Monesterio clusters/centres and the sub-volcanic suite into the São Romão and Feria clusters. As the mylonite suite comprises a set of elongated orthogneiss bodies dispersed throughout a large high-strain sinistral shear zone (the Tomar–Badajoz–Córdoba Shear Zone), there is no justification to subdivide it into clusters.

Table 1. Range of the peralkalinity index (PI = molar $Na_2O + K_2O/Al_2O_3$ [125,126]) values of the felsic rocks from the OMZ part of the alkaline supersuite, from whole-rock geochemical data published in the literature. Peralkaline bodies achieve PI > 1.0.

Suite	Subsuite	Pluton/Swarm	Peralkalinity Index	References
Intrusive	OMZ—Alter do Chão cluster	Alter Pedroso	0.85–1.27	[123]
		Almanhares	0.94–1.08	[123]
		Vaiamonte	0.77–1.05	[123]
	OMZ—Elvas centre	Degola	0.91–0.93	[123,137]
		Gebarela	0.81–1.13	[123,137]
		Varche–Falcato	0.62–1.46	[123]
		Outeirão-Pombal	0.84–1.0	[123]
		Alcamins	0.92–1.0	[123]
	OMZ—Monesterio cluster	Almendral	0.81	[138]
		Barcarrota	0.57–1.13	[12,138]
		Castillo	0.75–0.91	[138–140]
		Jerez de los Caballeros	0.94–0.96	[141]
Sub-volcanic	OMZ—Feria cluster	Feria	0.79–0.93	[138,141,142]
		Sierra Vieja	0.98–1.34	[138,141,142]
	OMZ- São Romão cluster	Monte Safueiro	0.80–0.97	[93]
		Pero Lobo	0.48–0.89	[93]
Mylonite	OMZ—TBCSZ set	Arronches–Fialha	0.79–1.22	[123]
		Figueira de Cima	0.97–1.14	[123]
		Cevadais	0.91–1.11	[123]
		Assumar	0.77	[123]
		Aceuchal	0.83–1.00	[12]
		Almendralejo	0.97–1.02	[12]
		Ribera del Fresno	0.72–0.90	[12,143]
		Las Minillas	0.75–0.82	[12]

5. The Intrusive Suite

5.1. OMZ—Alter do Chão Cluster

The Alter do Chão Cluster is located between the Alter do Chão and the Vaiamonte (Monforte) villages and comprises three plutons, variably deformed and dispersed in a

NW-SE tectonic alignment (Figure 7a). From these, the Alter Pedroso composite pluton is distinguished by its exotic textural and mineralogical features (Figure 8a–d). The lithologic variability and distinct mineralogy of this pluton has been intensively described in classic petrology works [115,144–150] (particularly the Al-poor riebeckite, mentioned as "osannite" [145,148]), and the first sketch of a geological map was presented by Serralheiro [151], which was improved with current field works (Figure 7b). Two major intrusive units can be separated in the Alter Pedroso pluton (Figure 7b): at the NE, a unit composed of coarse-grained leucocratic syenites with rare riebeckite (Figure 8a), and at the SW, a unit characterized by mesocratic fine-grained syenites with aegirine and riebeckite phenocrysts (classically referred to as "lusitanite" [146], Figure 8b), or banded riebeckite syenites. The SW mesocratic syenite unit often shows pegmatoid varieties (Figure 8c), which range from hololeucocratic (albite-dominant) rocks to tabular melanocratic bodies essentially composed of riebeckite megacrystals (anciently referred to as "osannite-hornblendite" [145] and after as "pedrosite" [115], Figure 8d). Geochronological studies determined zircon U/Pb emplacement ages of 482 ± 16 Ma [92] for this pluton. Towards the NE, small sinistral shear zones are commonly found (Figure 7b), culminating with the development of gneissic textures in the northernmost limit of the body.

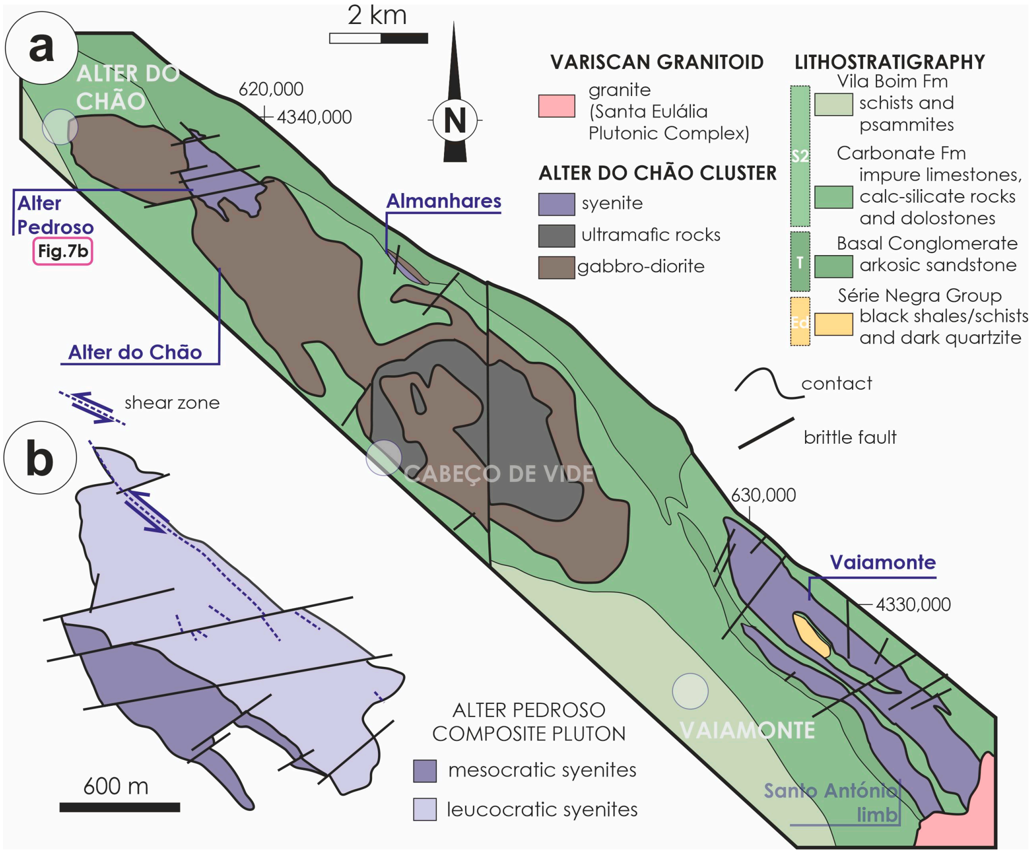

Figure 7. (**a**) Regional lithological map of the elongated Alter do Chão cluster (rank 3 unit), partially adapted from [149]. The southwestern body of Vaiamonte (separated by a stripe of rocks from the Carbonate Fm) is the Santo António limb. (**b**) Detailed geological map of the major different units of the Alter Pedroso composite pluton (rank 5 unit), with the two distinct syenite intrusions (rank 6 units).

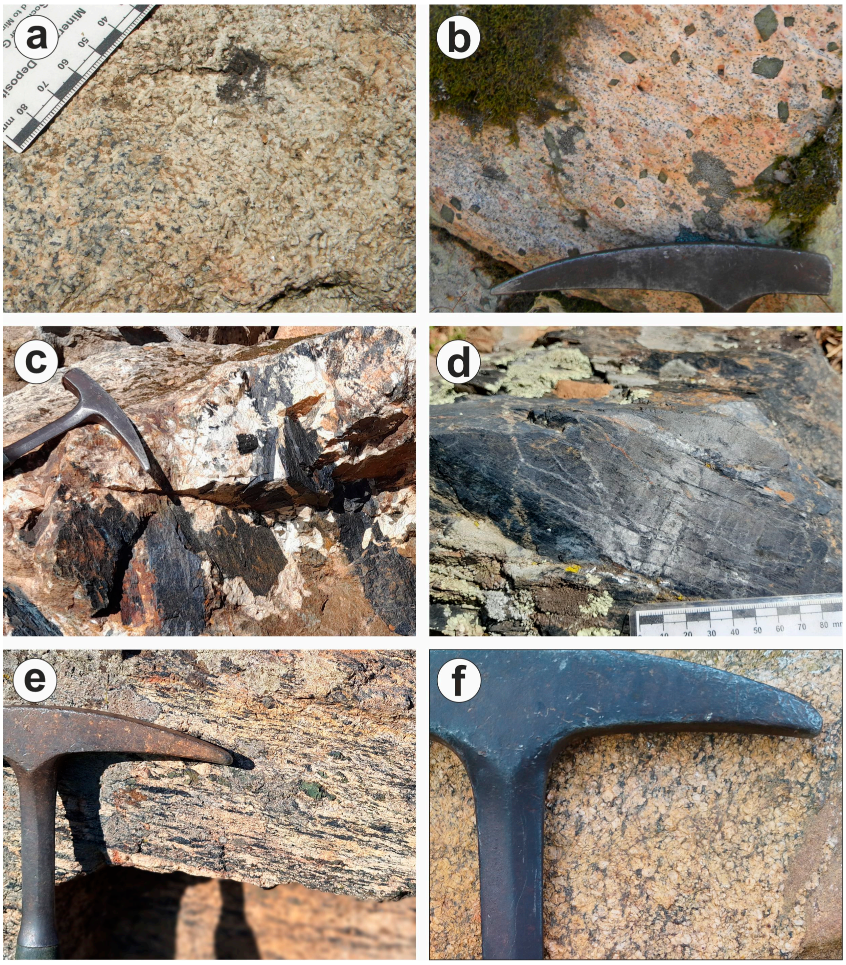

Figure 8. Representative textural aspects of rocks from the Alter do Chão Cluster. Rocks from the intrusions of the Alter Pedroso pluton: (**a**) Leucocratic syenite. (**b**) Mesocratic aegirine-bearing syenite ("lusitanite" [146]). (**c**) Pematoid syenite with riebeckite megacrystals. (**d**) A pegmatoid rock solely composed of riebeckite ("pedrosite" [115]). Sheared intrusions from the Vaiamonte sheet-complex: (**e**) strongly foliated mesocratic syenite and (**f**) weakly foliated leucocratic syenite.

In Almanhares (to the east), a very narrow nepheline syenite occurs contiguous to a small metamafic body. This is the only known occurrence of a nepheline syenite in the Alter do Chão–Elvas Domain and in the equivalent Spanish parts; another point of distinction of this body is the presence of sodalite associated with nepheline and taramite amphibole [123].

To the southeast, the Vaiamonte body consists of folded sheet-like intrusions mixed with large portions of Ediacaran–Cambrian country rocks, following the NW-SE regional trend. The southwest tabular intrusion (referred to as "Santo António" [123,149]) is a weakly deformed leuco-mesocratic syenite interpreted to be the limb of a large syncline structure, according to new geological mapping surveys. To the north, the observed structure shows a transition from a synform to an antiform, overlaid by rocks from the Series 2 Carbonate Formation. The antiform part of the body is composed of variably deformed intrusions that range from hololeucocratic to mesocratic syenites or quartz syenites and rare sheared pegmatoid syenites (Figure 8e,f). The core of the antiform is characterized by a succession of siliciclastic and metavolcanic rocks, similar to the Ediacaran–Terreneuvian successions.

An elongated mostly mafic segmented pluton outcrops between the Alter do Chão and Cabeço de Vide villages. It is composed of weakly alkaline kaersutite gabbros (average $Na_2O + K_2O$ = 2.07%, up to 3.33% [123,152]), diorites, and ultramafic rocks (pyroxenites, dunites, and peridotites, commonly serpentinized). The presence of kaersutite supports this mafic body in the Alkaline Supersuite [126]. The geochronology studies of the gabbros yielded very poorly constrained K/Ar ages of ca 501–432 Ma [153], which nonetheless fall within the emplacement time range of the alkaline rocks. Field observations conclude that the Alter Pedroso pluton intrudes the gabbro, as also inferred by Teixeira et al. [149].

5.2. OMZ—Elvas Centre

In the Elvas region, the alkaline and peralkaline plutonic bodies are majorly restricted to the Series 2 Carbonate Formation, intruding rocks from this succession, and they are also spatially associated with tholeiitic gabbro–diorite rocks [123] (Figure 9a). Alkaline rocks from this group also show distinctive textural features (Figure 10). Within this cluster, the southernmost Alcamins body, a NW-SE elongated monotonous hedembergite-bearing granite (Figure 10a) [119], is the only one that contacts not only rocks from the Carbonate Formation but also from the basal Cambrian succession of the Ediacaran Série Negra Group outcropping in the Torre de Cabedal structure [115,119,154].

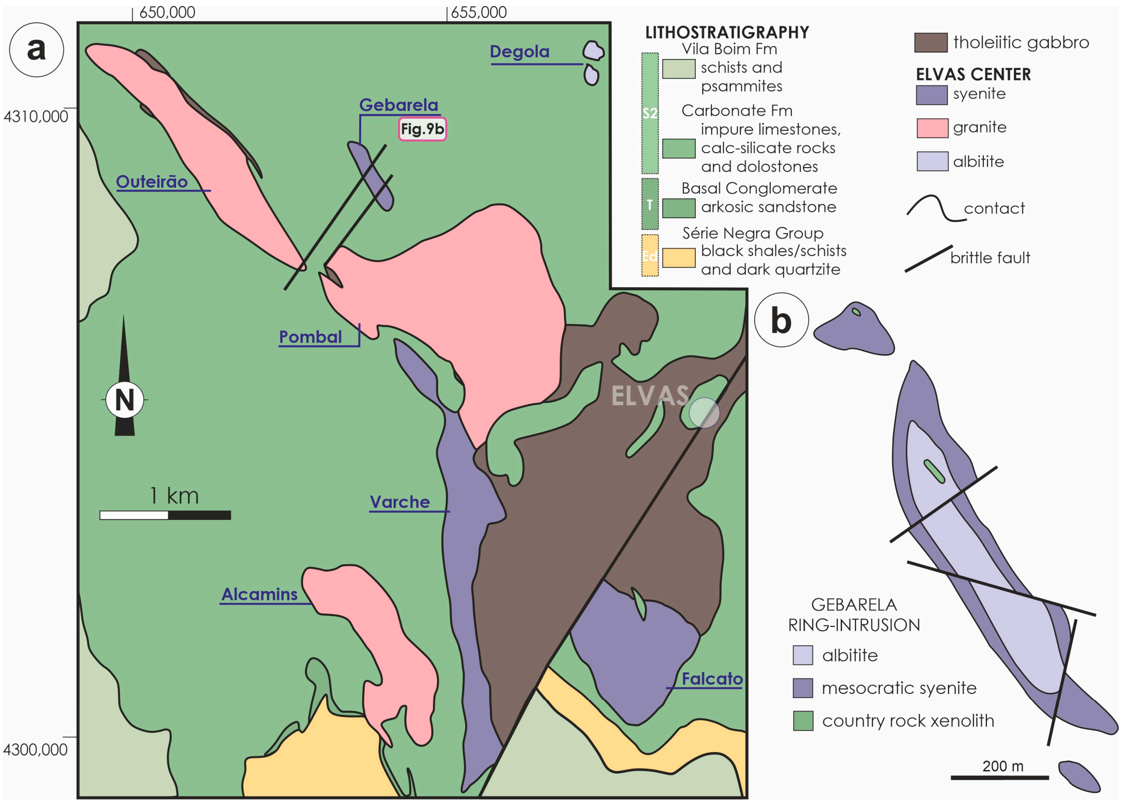

Figure 9. (**a**) Regional lithological map of the Elvas Centre (rank 3 unit, adapted from [119,149]), with the tabular and sub-circular/ovoidal plutonic alkaline bodies distributed asymmetrically in a central point and stretched following a NW-SE trend. The large fault separating Varche and Falcato intrusions corresponds to the Messejana fault (mentioned in the text). (**b**) Detailed geological map of the concentric zonation of the Gebarela ring intrusion (a slightly similar zonation has previously been proposed in [137]). In this region, the pluton swarms and the ring intrusion are classified at rank 5, while the individual plutons and each unit from the Gebarela body are rank 6.

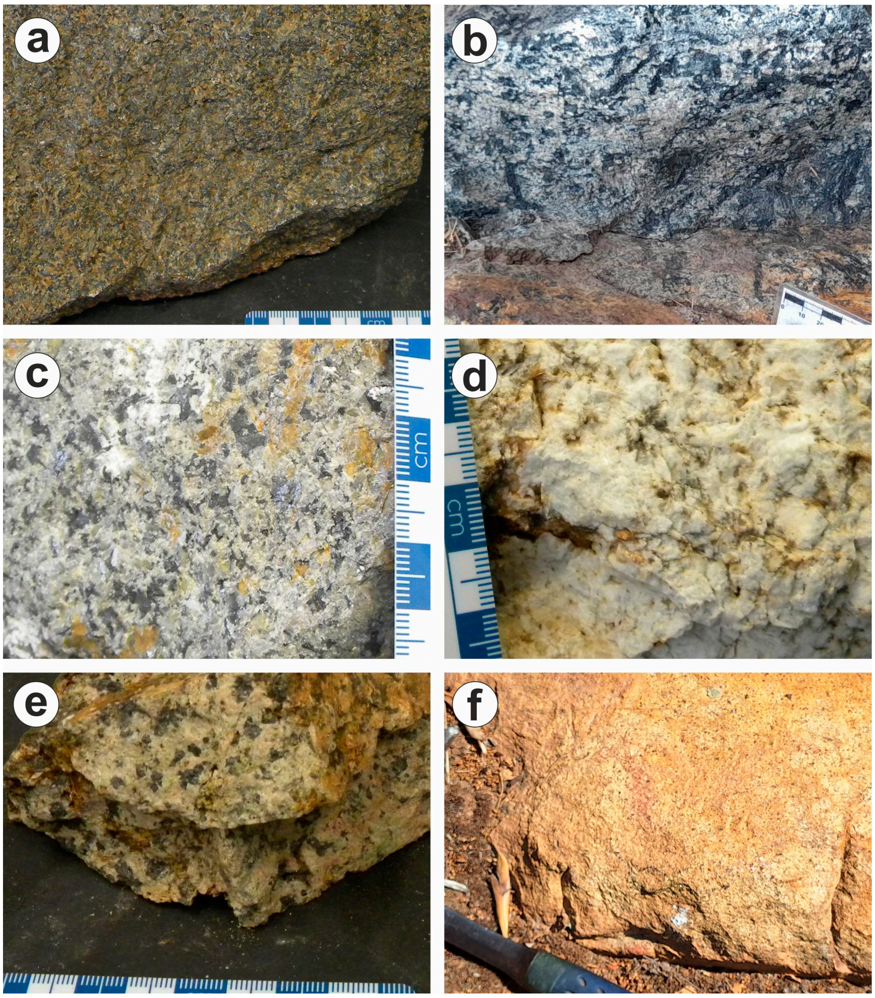

Figure 10. Macroscopic features of rocks from the Elvas Centre: (**a**) Hedembergite-bearing granitoid from Alcamins, (**b**) Mesocratic syenite from Varche, (**c**) Mesocratic syenite from Falcato, (**d**) Albitite from the inner Gebarela core, (**e**) Mesocratic syenite from the Gebarela ring intrusion, (**f**) Perthosite from the Degola-folded pluton.

The outcrops of the Varche and Falcato pluton also occur in the south of the gabbro, intruding the carbonate succession. Rocks from this pluton correspond to distinct types of mesocratic syenites (Figure 10b,c) and are characterized by high peralkalinity index values (PI up to 1.46) and the presence of aenigmatite (though scarce) [123]. Both Varche and Falcato are considered the same pluton that was dismembered by the late-Variscan NE-SW left-lateral Messejana fault [149]. Geochronological data determined a crystallization age of 490 $\pm$ 4 Ma for these rocks [91]. Contiguous to the Varche–Falcato outcrops (at the west), the elongated bodies of Pombal and Outeirão are alkaline leucocratic granites (e.g., [123]) that are also separated by a NE-SW discontinuity and likewise classified as a pluton swarm; the Outeirão segment also comprises associated marginal mafic rocks [119].

The Gebarela composite body (NE from the Outeirão-Pombal pluton swarm) consists of a small tabular and concentrically zoned peralkaline pluton (Figure 9b) [123], composed of albitite rocks in the inner domain (Figure 10d) and an external ring of mesocratic garnet-bearing syenites (Figure 10e). Recent geological mapping surveys (Figure 9b) confirm the lithological zoning proposed by Pinto Coelho et al. [137]. Despite a few small outcrops of country rock xenoliths within the inner albitite unit, these do not represent a significant part of the body, and therefore, the appropriate designation should be 'ring-intrusion'.

Finally, in the northernmost part, two very small subcircular perthosite bodies (a variety of albitite, Figure 10f) crop out in Degola, with a N-S alignment (Degola-Taipas, [119]), representing the two limbs of a folded pluton (according to new field mapping surveys).

5.3. OMZ—Monesterio Cluster

This cluster encompasses the alkaline plutonic rocks that are spatially associated with the Olivenza–Monesterio Anticline (Figure 11a). These include not only the bodies located within the core of the anticline (Barcarrota and Castillo) but also those emplaced along its northeastern and southwestern limbs, corresponding to the Zafra–Alanís and Elvas–Cumbres Mayores domains (Figure 1) [24,25]. These bodies do not generally have well-marked elongated shape when compared to the Alter do Chão–Elvas domain (Figures 7a and 9a), which show the result of deformation processes associated with the subduction and collisional phases of the Variscan Orogeny during Devonian–Carboniferous times.

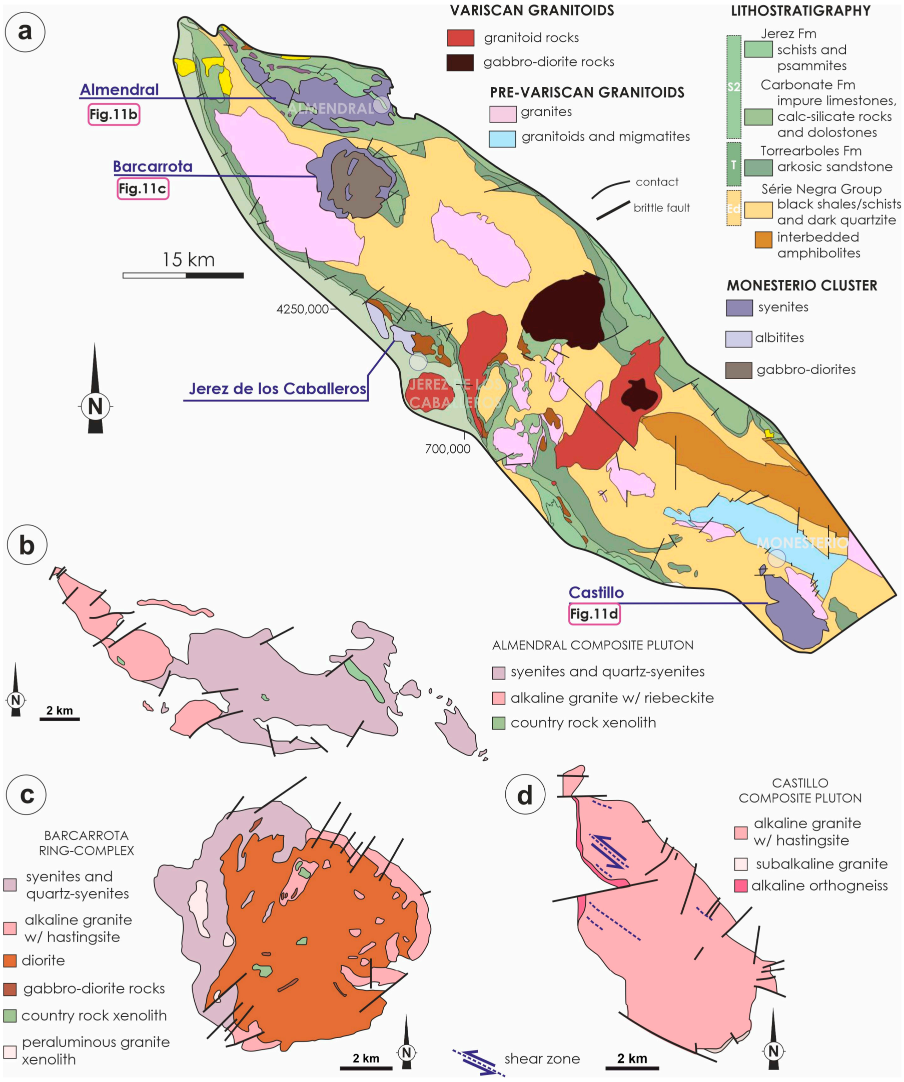

Figure 11. (**a**) Regional lithological map of the Monesterio cluster (rank 3), adapted from [122,155–158]. (**b**) Detailed map of the Almendral composite pluton, comprising syenite/quartzsyenite and granite intrusions, from [159]. (**c**) The Barcarrota ring complex, composed of syenites and quartz syenites and alkaline granite ring intrusions, around the central mafic body [160,161]. (**d**) Zonation of the Castillo composite pluton, with subalkaline granites to the southeast, the main alkaline granite body, and the orthogneiss northwest rim, from [162].

In the northeast limb, the Almendral body is represented by a composite WNW-ESE slightly elongated pluton that majorly intrudes carbonate formation [158]. This pluton is composed of alkaline granites and syenites/quartz syenites, characterized by the presence of sodic amphiboles [158,159], as well as minor roof pendants with carbonate rocks [163]. The detailed map (Figure 11b; [159]) shows that the alkaline granites are majorly restricted to the western side of the pluton whereas syenites of variable grain size crop outs within the central and eastern parts. Radiometric K-Ar dating of the syenites of Almendral yielded ages of 450 ± 12 and 481 ± 10 Ma [164], with the latter being considered the closest age to crystallization by comparison to the other alkaline plutonic bodies intruding the Carbonate Formation (e.g., [91]). Small outcrops of small-grained syenites still occur between Olivenza and Valverde de Leganés [138], assumed as part of the Almendral body.

In the southern limb of the Olivenza–Monesterio Anticline (near the municipality of Jerez de los Caballeros), a swarm of albitites intrudes the Carbonate Formation and the Upper Detrital succession. These albitites (Figure 12a) are spatially associated with tholeiitic gabbros but are interpreted to have been emplaced at a later stage [94]. The relative timing of emplacement suggests that the gabbros postdate the late Series 2 Miaolingian volcanics, while the albitites postdate the gabbros. However, no radiometric data for these albitites are currently available to confirm the crystallization ages.

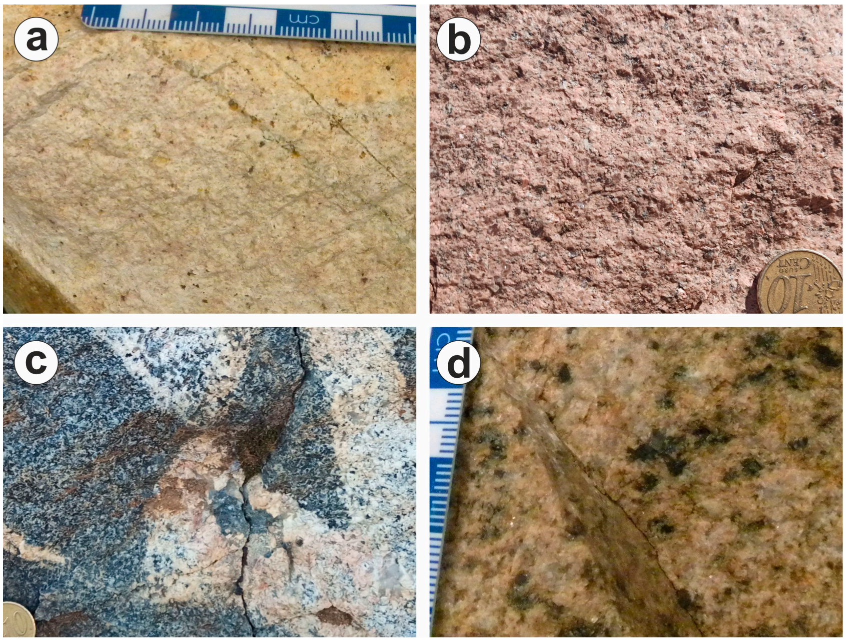

Figure 12. Macroscopic aspects of the rocks from the Monesterio cluster: (**a**) albitite from the Jerez de los Caballeros swarm. (**b**) Leucocratic quartz syenites and (**c**) gabbro–diorite rocks from the Barcarrota ring complex. (**d**) Hastingsite-bearing granite from the Castillo pluton.

Two large plutons occur in the core of the Olivenza–Monesterio Anticline. The Barcarrota pluton (Figures 11c and 12b,c) is a subrounded composite pluton characterized by syenite and granite ring intrusions around a major alkaline gabbro–diorite core, enveloping large portions of country rock xenoliths (carbonate roof pendants and portions of the Táliga peraluminous granite) [160,161,164]. It intrudes the metassedimentary rocks of the Série Negra Group, as well as a part of the Cambrian succession and the Táliga granite. The alkaline character of the different intrusions (PI reaching 0.96, Table 1) has been previously reported [160]. The geochemical data suggest a genetic relationship between the different lithotypes of this pluton, from the mafic-intermediate terms to the more evolved felsic rocks [160]. The internal magmatic structure and distinct large country rock xenoliths suggest that the Barcarrota pluton should be considered as a 'ring-complex'. Geochronology studies determined the emplacement ages of this body of around 502 Ma (U/Pb methods yielded ca. 501 Ma for the granites and ca. 503 Ma for the diorite core [12], K/Ar methods yielded 505 ± 5 Ma and Rb/Sr calculated isochron yielded 508 ± 1.4 Ma [165]). The Castillo composite pluton intrudes rocks from the Série Negra Group and the Culebrín peraluminous granite, located near Monesterio (Figure 11d). In addition to a very narrow southern margin that comprises a subalkaline granite, the Castillo central rocks consist of hastingsite-bearing alkaline granites that are variably deformed (Figure 8d) [11,139,162]. The intensity of shear deformation increases towards the northwestern part, where orthogneisses are found [139,162] (Figure 11d). The radiometric data yielded crystallization ages of 502 ± 8 Ma for the Castillo composite pluton [11].

6. The Sub-Volcanic Suite

The OMZ part of the Sub-Volcanic Suite is composed of shallow-level intrusions of alkaline rocks, primarily restricted to late Series 2 Miaolingian successions of the southernmost Alter do Chão Elvas domain (in Portugal) and of the Zafra–Alanís domain, located in the northern limb of the Olivenza–Monesterio Anticline (in Spain).

6.1. OMZ—Feria Cluster

The Feria Cluster includes small hypabyssal bodies intruding the Carbonate, Vallehondo, and Playón formations during the Cambrian (Figure 13).

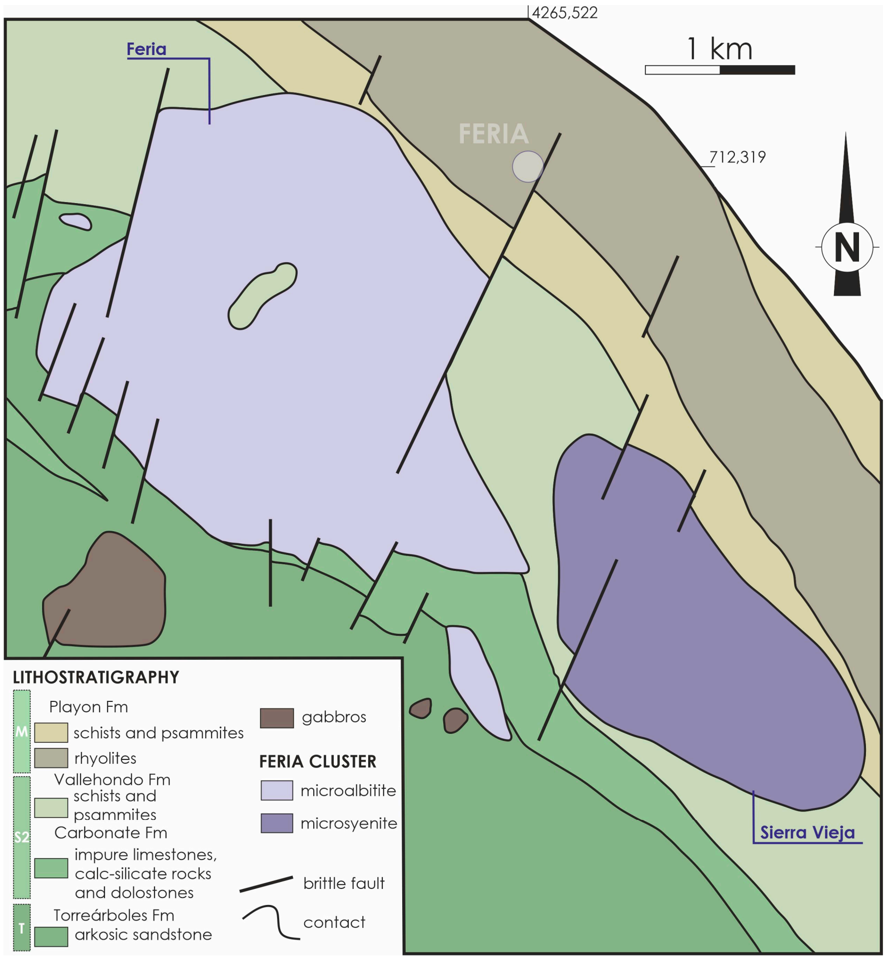

Figure 13. Lithological map of the Feria cluster, showing the Feria albitites and the Sierra Vieja hypabyssal syenite body, from [142].

Southwest of the municipality of Feria, at least three fine-grained albitite and microsyenite bodies outcrop were found (Figure 14a), intersecting all rocks from the Cambrian succession [141,142,156]. Zircon U-Pb studies determined crystallization ages of 514 ± 3 Ma [16], which is not consistent with the age of some intruded lithostratigraphic rocks (lower Miaolingian). To the southeast, the Sierra Vieja body is a homogenous alkaline granitoid stock hosting sodic pyroxene and amphibole phenocrysts within a fine-grained (<2 mm) quartz–feldspathic groundmass (Figure 14b) and is thus considered a hypabyssal pluton (though in the literature, it is often named granite, e.g., [16,90]). It exhibits peralkaline geochemical values (PI up to 1.28, Table 1) and yields zircon crystallization ages of 517.6 ± 4 Ma [16], which is not compatible with the age of the intruded late Series 2 Miaolingian country rocks [94,142]. Also, Sánchez-García et al. [16] reported that the analyzed samples only contained angular zircon fragments with patchy irregular zonation, weak luminescence, and a high degree of lead loss. This pluton should at least yield ages from the uppermost Series 2, or most likely Miaolingian.

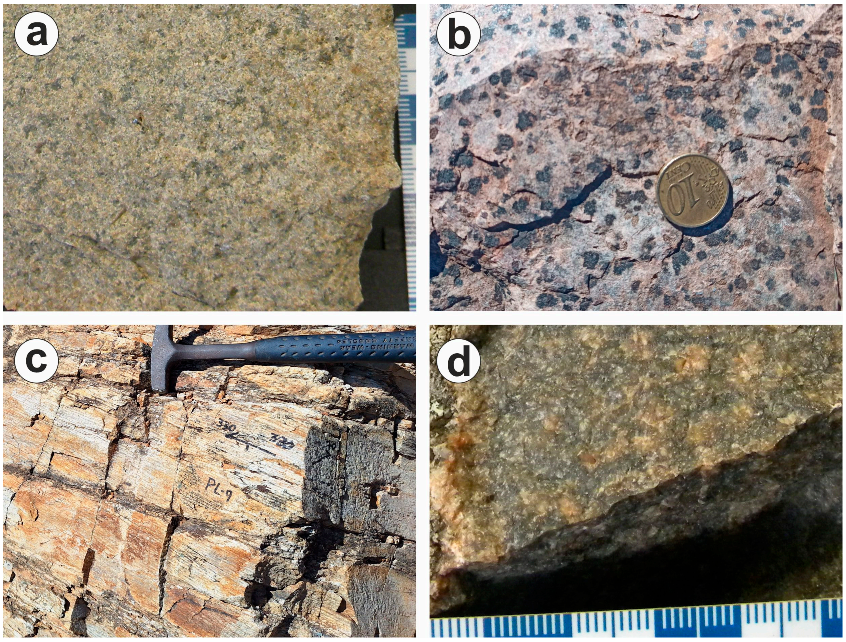

Figure 14. Rocks from the Sub-Volcanic Suite: (**a**) macroscopic features of the Feria and (**b**) the Sierra Vieja rocks. Rocks from the Pero Lobo pluton: (**c**) sheared microgranite from the southwestern intrusion and (**d**) quartz syenite from the northwestern intrusion.

6.2. OMZ—São Romão Cluster

The São Romão Cluster (Figure 15a) is located in the vicinity of São Romão and is composed of alkaline subvolcanic bodies that intrude Miaolingian successions, including the alkaline mafic rocks from the Terrugem volcano–sedimentary complex (Terrugem VSC) [93,166]. There are no geochronological data for the rocks of this cluster, but based on biostratigraphic constraints regarding the lateral equivalents of the intruded Terrugem VSC (i.e., the Playón Formation; [54]), upper Miaolingian ages (late Drumian–Guzhangian) are inferred. The Monte Safueiro volcanics consist of scattered melanocratic trachytic and microsyenitic dykes outcropping at the top of the Miaolingian successions [93,119,166], arranged as a dyke swarm. The Pero Lobo Massif is a composite body with two granitoid units: a microgranite with a similar texture to the Monte Safueiro dykes and dark quartz-syenites (Figure 14d), which are possibly considered intrusive [93]. Structurally, the Pero Lobo body is sheared (mostly in their southernmost domains; Figures 14c and 15b), showing an ellipsoidal shape and highlighting a primary horizontal stratiform layering with the microgranite at the top and the quartz-syenites at the bottom (Figure 15b).

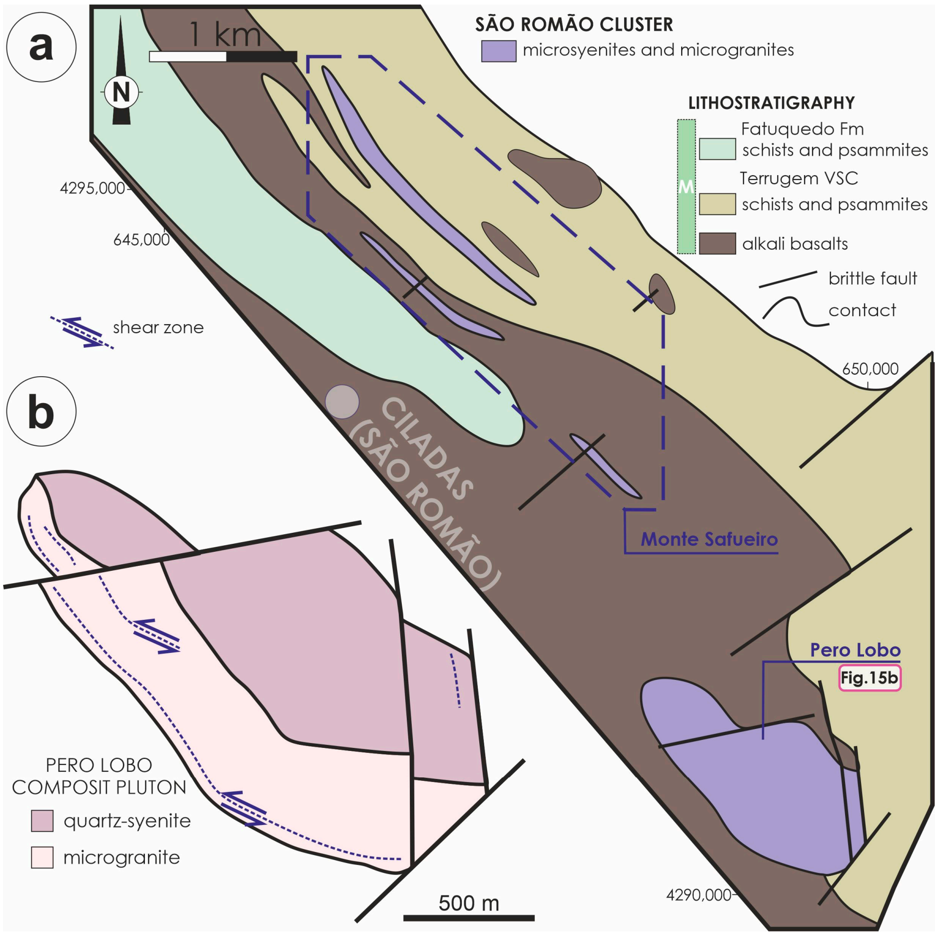

Figure 15. (**a**) Geological map of the region of the rank 5 Monte Safueiro trachytic/microsyenite dyke swarm and the Pero Lobo body (São Romão Cluster, Sub-volcanic Suite), intruding the Miaolingian succession, adapted from [119,120]. (**b**) Lithological map of the Pero Lobo petrographic zoning (alkali microgranite and quartz syenite). Each individual "unnamed" dyke from the Monte Safueiro swarm and intrusion type from the Pero Lobo body is a rank 6 unit.

7. The Mylonite Suite

OMZ—Tomar–Badajoz–Córdoba Set

The TBCSZ is a major tectonic structure in the Iberian Massif developed during the Variscan Orogeny, and it consists of a large high-strain sinistral shear zone with intense ductile deformation, showing transcurrent tectonics under distinct metamorphic grades [24,28,167–169]. The lithological units are characterized by dominant left-lateral kinematics with strain partitioning, showing intense tectonic foliation and lineation, in which the lithological contacts serve as zones of weakness and are reactivated as shear zones.

Along the Tomar–Badajoz–Córdoba Shear Zone, an alignment of alkaline and peralkaline orthogneisses crops out as lensoidal bodies with different sizes from the region of Assumar (Arronches) to Granja de Torrehermosa (Azuaga) (Figure 16a,b). All orthogneiss lenses follow the regional WNW-ESE to NW-SE trend. The fact that these rocks experienced high-strain deformation and metamorphic recrystallization makes them tectono-metamorphic units; however, we propose a grouping based on the magmatic nature of the protolith. In Assumar, a very narrow lensoidal body (Figure 16c) of a reddish hastingsite-bearing sheared granite (with discrete augen tendencies, Figure 17a) intrudes Cambrian carbonates, e.g., [123]. This is the only body from this set that intrudes the Cambrian units, and it is the one with the lowest PI (ca. 0.77, Table 1).

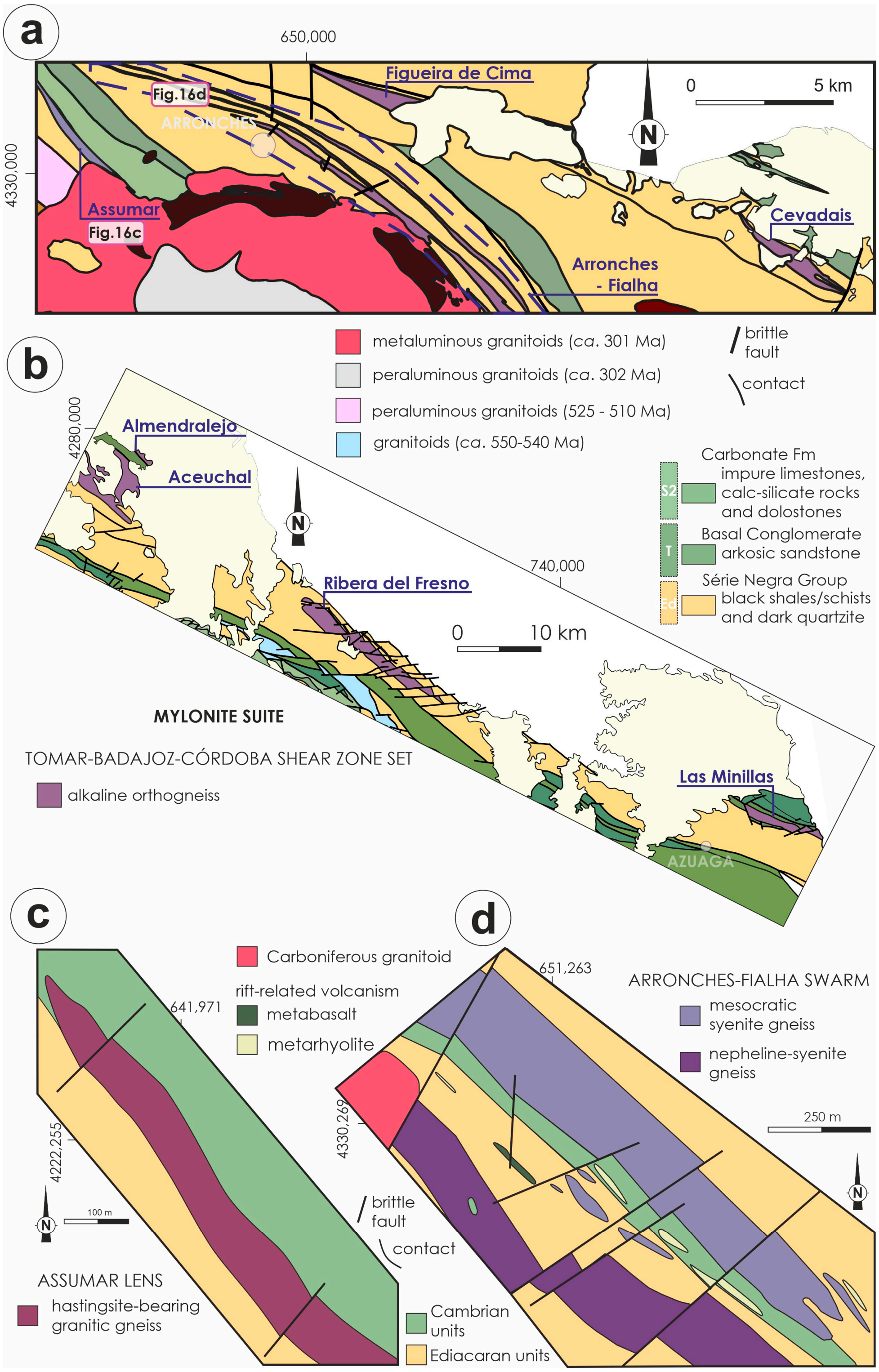

Figure 16. Localization of the bodies from the Mylonite Suite within the Central Unit in (**a**) the Portuguese segment and (**b**) the Spanish segment. Lithological maps of different alkaline orthogneisses: (**c**) the lens of Assumar and (**d**) lens from the Arronches–Fialha swarm.

Slightly to the east, disperse alkaline orthogneisses from the Arronches–Fialha swarm (Figure 16d) crop out intruding Ediacaran rocks. The lithotypes vary from nepheline syenites to hastingsite-bearing granites [123,137,149] (Figure 17b) and have a wide range of PI values (from 0.79 to 1.22, Table 1). The textural features found in the different bodies (with S and S-L fabrics) can be ascribed to different primary textural and mineralogical properties that presumably underwent different conditions of tectono-metamorphic recrystallization [137,170]. One of the lenses from the Arronches–Fialha swarm yielded protolith U/Pb ages of ca. 470 ± 3 Ma [91]. North of this swarm, the Figueira de Cima mesocratic syenite gneiss (initially described by [115]), with katophorite and richterite amphiboles [123], occurs as an elongated WNW-ESE lens.

The Cevadais composite lens (Ouguela region, Campo Maior) comprises two contiguous sheared syenite bodies that are interpreted as a folded structure [90]. A structural map has been presented by Pereira et al. [167]. Two different strongly sheared facies have been described in this body [123,149,171,172], corresponding to riebeckite- and aegirine-bearing syenite gneiss with S-L or L-dominant fabrics (regionally named "cevadaisite" [115,149], Figure 17c), as well as a narrow sodalite-bearing nepheline syenite lens (classically referred to as "ouguelite" [171]), with no riebeckite [149]. The Cevadais syenite yielded crystallization ages of 479 ± 3 [91].

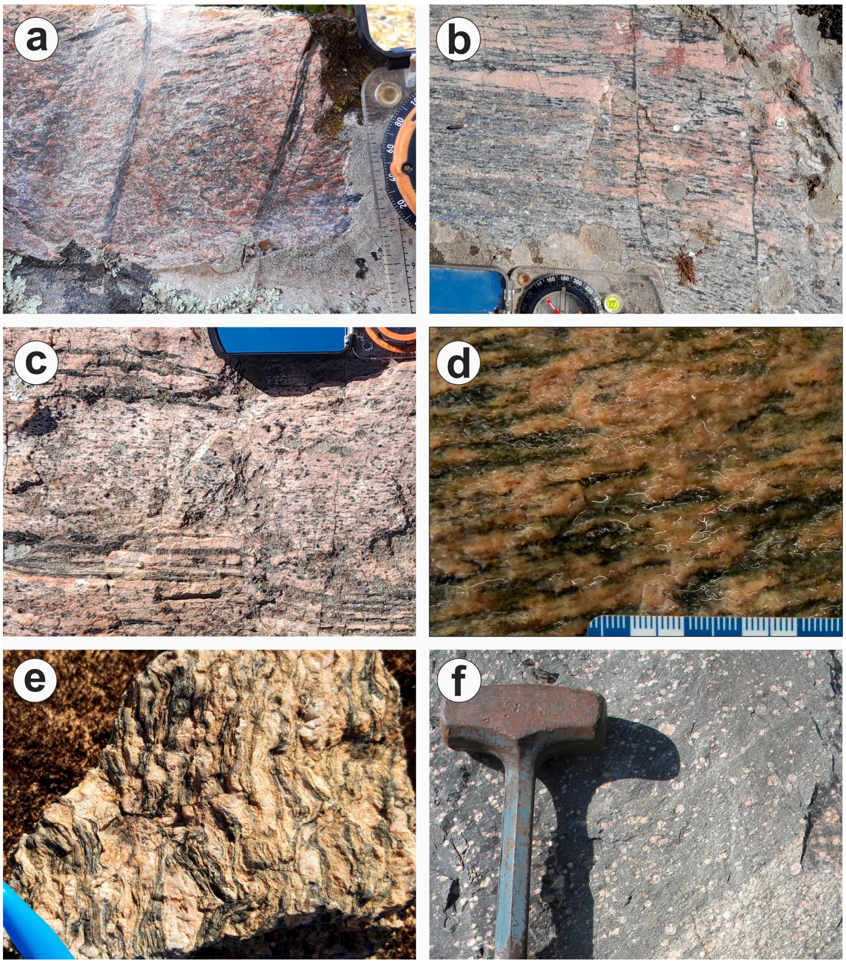

Figure 17. Distinct fabrics from the lensoidal body characteristics of the Mylonite Suite: (**a**) hastingsite-bearing granitic gneiss, (**b**) nepheline-syenite gneiss from the Arronches–Fialha swarm (Fialha area), (**c**) Riebeckite- and aegirine-bearing syenite gneiss from Cevadais ("cevadaisite" [115,171]), (**d**) Almendralejo hastingsite-bearing syenite gneiss, (**e**) granitic gneiss from Ribera del Fresno, and (**f**) granitic gneiss from Las Minillas.

In Almendralejo (near Badajoz, Spain), two parallel lenses crop out, both with S-L fabric and following the NW-SE regional trend partially covered by Cenozoic sediments. The southwest Aceuchal lens is a reddish hastingsite-bearing granitic gneiss (with scarce riebeckite) emplaced in ca. 477 Ma [12]. The Almendralejo body (Figure 17d) is described as riebeckite-bearing aegirine–augite orthogneiss, practically contemporaneous with the Aceuchal body, yielding zircon U/Pb ages of ca. 475 Ma [12].

The Ribera del Fresno lens is a coarse-grained granitic augen gneiss (Figure 17e) with a mildly alkaline composition (PI up to 0.90, Table 1, previously referred to as "subaluminous" [143]). Geochronological studies on the protolith yielded zircon U/Pb ages of 476 ± 7 Ma [19]. The Las Minillas lens is located to the southeast of Ribera del Fresno (Azuaga) and consists of a variably foliated mesocratic augen gneiss (Figure 17f) with a granitic composition. This body is compositionally subalkaline (with mild PI values of 0.75–0.82, Table 1), and no alkali minerals have yet been described in its assemblage [12]; however, the resemblances with the more documented Ribera del Fresno body suggest that they could have similar genetic evolution and protolith compositions. Previous geochronological studies yielded very poorly constrained ages (556 +159/−67 Ma [12]), but posteriorly determined crystallization ages of ca. 474 Ma (Schafer, in [173]).

8. Final Remarks

The classification method presented herein is a ranked system that was applied to the alkaline magmatic rocks of the OMZ (SW Iberia), designed to improve geological mapping across scales and strengthen regional and continental correlations. Likewise, the clear delineation of the extent of the supersuite is also prone to allow for inferences on the rift-related alkaline magmatism, areas with more concentrated magmatic activity and described as high-strained bodies. Ranks 1 to 4 should be useful for geological mapping and classifying rocks for regional geological studies, while ranks 5 and 6 are more dedicated for detail mapping. The location of the suites may provide clues for the paleogeography and configuration of the Cambrian crust and magmatic activity on the OMZ, posteriorly parallelized to the regional northwest–southeast trend related with the Variscan Orogeny.

It is noticeable that the sub-volcanic suite (Feria and S. Romão clusters) is inserted in the upper levels, within mostly Miaolingian country rocks, while the rest of the bodies (intrusive and mylonite suites) are emplaced within the Ediacaran–Cambrian Series 2 sequences. The plutons in the core of the Olivenza–Monesterio Anticline yielded the oldest ages, while the rocks from the mylonite suite are the most recent. The alkaline orthogneisses from the mylonite suite exhibit the youngest crystallization ages. The clusters highlight specific associations of co-magmatic plutons that may infer ancient magmatic centres (as in the case of Elvas) or encompass high-strain bodies in large shear zones.

All bodies could be mapped at a scale >1:50,000 according to the representative lithotypes (rank 4). The smaller rank classes (ranks 5 and 6) provide information on the internal architecture or lithofacies of each pluton or specific rock dispositions. Overall features (mineralogical and geochemical) show that the degree of alkalinity of rocks from the supersuite in all the domains increases from the southeast to the northwest and varies with the age and size of each pluton. The nepheline syenites (even if deformed) and albitites consist of smaller plutons, while syenites and syenite gneisses show a moderate size, and the quartz syenites, granites, and gabbro–diorites show the largest volume. Despite this work providing a regional-scale overview on the Cambro–Ordovician OMZ alkaline rocks, the Rheic-related alkaline bodies from the other northern Gondwana regions—from the Iberian GTMZ to the Armorican, Central, and Bohemian Massifs—could be integrated in this ranked classification scheme for the alkaline magmatic bodies to better constrain the rift-related alkaline magmatism at the North Gondwana margin terrane scale.

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