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SCIENCE

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Lithotectonic units of the Cabeço de Vide Massif (Ossa-Morena Zone, SW Iberian Massif): a bedrock map to decipher superimposed orogenies

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ABSTRACT
This study provides a new cartographic framework for a geologically complex region in the SW Iberian Massif (central-east Portugal). We have redefined lithological ensembles and clarified structural relationships between rock types (unconformities and faults). This has led to re-interpreting some lithological contacts in the Cabeço de Vide Massif. In this work, we have also mapped new structures, such as folds and shear zones. The resulting map provides an updated interpretation of the region's subsurface structure and tectonic history based on rock type recognition and structural data. These findings significantly enhance our understanding of the Variscan and Cadomian orogenies in the Ossa-Morena Zone.

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Highlights

- The study redefines lithotectonic units in the Cabeço de Vide Massif with a new cartographic framework.
- New shear zones and folds are identified, improving understanding of bedrock deformation phases.
- Cartographic patterns clarify lithotype relationships and tectonic events.

1. Introduction

Studying complex geological regions requires detailed mapping and structural analysis to interpret their tectonic history and evolution accurately. In response to this, lithotectonic units emerge. These units are defined based on structural, deformational, and metamorphic criteria shared by a group of rocks. They also consider these rocks' mutual relationships, origin, and geological evolution. This classification applies regardless of whether the rocks are sedimentary, igneous, or metamorphic. In this context, the Cabeço de Vide Massif (Ossa-Morena Zone, SW Iberian Massif) has been the subject of numerous geological studies; however, gaps remain in understanding the structural framework and relationships between the multiple lithologies exposed in the area. Previous works provided valuable insights, yet specific lithological contacts and structural features, such as folds and shear zones, went unnoticed or were not fully delineated and understood.

Cartographic patterns help identify the crosscutting relationships between lithotectonic units (faults, intrusions, or unconformities) and their superimposition. Establishing the spatial and temporal distribution of structures based on the bedrock map is crucial to ascribe the development of these structures to a given deformation phase within an orogenic cycle. Any older geological record may be obscured by more recent geological processes, making the distinction of the first challenging. So, older structures can be recognised appropriately if younger (superimposed) structures are recognised first. Field observations are the primary source for identifying superimposed geological events. But sometimes geological maps can help solve this issue, too. This study highlights the significance of maps and the information they provide in identifying relationships between lithotectonic units and their current geometry (i.e. structure).

This paper aims to fill these gaps by presenting a new cartographic framework that integrates a novel grouping of lithological ensembles (lithotectonic units), structural data, and a geological cross-section in the Cabeço de Vide Massif (central-east Portugal).

The geological mapping that has been published for this region was published more than fifty years ago

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(Gonçalves & Fernandes, 1973), which is why it is essential to update it. The lithotectonic units have been redefined based on rock type, lithostratigraphy, structural position, metamorphic imprint, age (if available), and primary cross-cutting relationships (e.g. igneous intrusion, unconformity, etc.). This new grouping applied to the bedrock, combined with new structural data, offers a comprehensive view of the tectonothermal evolution of the study area, providing a wealth of new information to the geological community. Our results set the basis for distinguishing the record related to the two most prominent geological events the Ossa-Morena Zone has experienced, namely the Cadomian and Variscan orogenies.

2. Geological setting

The Iberian Massif represents the southernmost segment of the Variscan Orogen in Europe (Figure 1a), which was formed as a result of the collision between Gondwana, Laurussia, and other pericontinental terranes during the Devonian and Carboniferous periods (Díez Fernández et al., 2016; Martínez Catalán et al., 2009; Matte, 2001). Most of the Iberian Massif originally belonged to the Gondwana megacontinent, which fragmented into peripheral terranes during the early Paleozoic. These terranes were later reattached to their parent continent as far-traveled tectonic nappes during the Variscan Orogeny (Chantraine et al., 2001; D'Lemos et al., 1990; Eguíluz et al., 2000; Linnemann et al., 2008; Nance et al., 1991; Pereira et al., 2007).

The early tectonothermal evolution of these peripheral terranes is intricately linked to the subduction of oceanic crust beneath Gondwana, resulting in the formation of a continental arc system during the Neoproterozoic-Cambrian period and whose record is broadly related to the Avalonian-Cadomian Orogeny (Andonaegui et al., 2016; Díez Fernández et al., 2019, 2022; Linnemann et al., 2008; Quesada, 1990). This orogen, dated between ca. 600 and 525 Ma (Bandrés et al., 2004; Díez Fernández et al., 2017; Fuenlabrada et al., 2012, 2016; Henriques et al., 2015; Pereira et al., 2023), was characterised by subduction, which led to arc-related magmatism and the creation of marginal basins (Arenas et al., 2018, 2022, 2024a, 2024b; Quesada, 1990; Rojo-Pérez et al., 2022). The dynamics of the Cadomian Orogeny involved alternating periods of contractional and extensional deformation (Bandrés et al., 2002; Blatrix & Burg, 1981; Díez Fernández et al., 2019; Eguíluz et al., 2000; Expósito et al., 2003; Moreno-Martín et al., 2023, 2025; Simancas et al., 2004), followed by a rifting process and the opening of the Rheic Ocean during the early Paleozoic (Nance et al., 2010).

In the southwest of the Iberian Massif, the Ossa-Morena Zone (Figure 1) contains a record of the Cadomian Orogeny (Chichorro et al., 2008; Eguíluz et al., 2000; Expósito et al., 2003; Pereira et al., 2008, 2012; Quesada, 1990). In the Ossa-Morena Zone's Cabeço de Vide Massif (Figure 2), ultramafic and mafic rocks (serpentinites, metagabbros and amphibolites) are recognised. This assemblage of magmatic rocks, which has traditionally been linked to a Cambrian-Ordovician continental rifting event (Oliveira et al., 1991), may represent relics of an older obducted oceanic crust, as has been inferred in other sectors of the SW Iberian Massif (Arenas et al., 2018; Díez Fernández et al., 2019, 2022; Moreno-Martín et al., 2025). Metagabbros surround the Cabeço de Vide serpentinised ultramafic rocks, and both occur within a vast exposure of marbles. These serpentinites and marbles are crosscut by gabbroic dykes (Gonçalves, 1971; Gonçalves & Fernandes, 1973). In turn, other mafic rocks (amphibolites) occur within phyllites and black quartzites of the Ediacaran Serie Negra Gp. (Carvalhosa, 1965; Eguíluz, 1988).

3. Methods

The geological map of Cabeço de Vide Massif was performed at the 1:20,000 scale, utilising ArcGIS 10.8 in a Surface Pro 3 tablet assisted by GPS and GIS technologies (Orux-maps GP-like mobile app; https://www.oruxmaps.com). Digital topography maps were obtained from Registo Nacional de Dados Geográficos (https://snig.dgterritorio.gov.pt) and were used as the base for annotation (meso- and microstructural observations) and tracing of contacts. The orientation of structural data (geological planes and lines) was obtained using an analogical compass (model Brunton Axis Transits). The geological map incorporates previous surveys such as those by Gonçalves (1971) and Mata and Munhá (1990). In our map, original cartographic data have been integrated with (structural and geochemical) data from Gonçalves and Fernandes (1973), Gonçalves et al. (1975), Ribeiro da Costa (1985), Lopes (2004) and Díez Fernández et al. (2015). The Main Map's new contacts and structural data (Figure 2) have been obtained using the projection transverse Mercator and the Coordinate System ED 1950 UTM Zone 29N spatial database.

Figure 2 includes the Main Map (Figure 2a), a lithostratigraphic column with the inferred geological unconformities (Figure 2b), and a geological cross-section (Figure 2c) interpreting the region's subsurface structure. A numerical progression has been used to describe the deformation phases for each orogenic cycle (C- Cadomian; V- Variscan) and related structural elements (e.g. D_C, D_{V1}, S_C, S_{V1}).

4. Lithostratigraphy of the study area

Previous studies described the lithologies of the Cabeço de Vide Massif (Díez Fernández et al., 2015; Gonçalves, 1971; Gonçalves et al., 1975; Gonçalves &

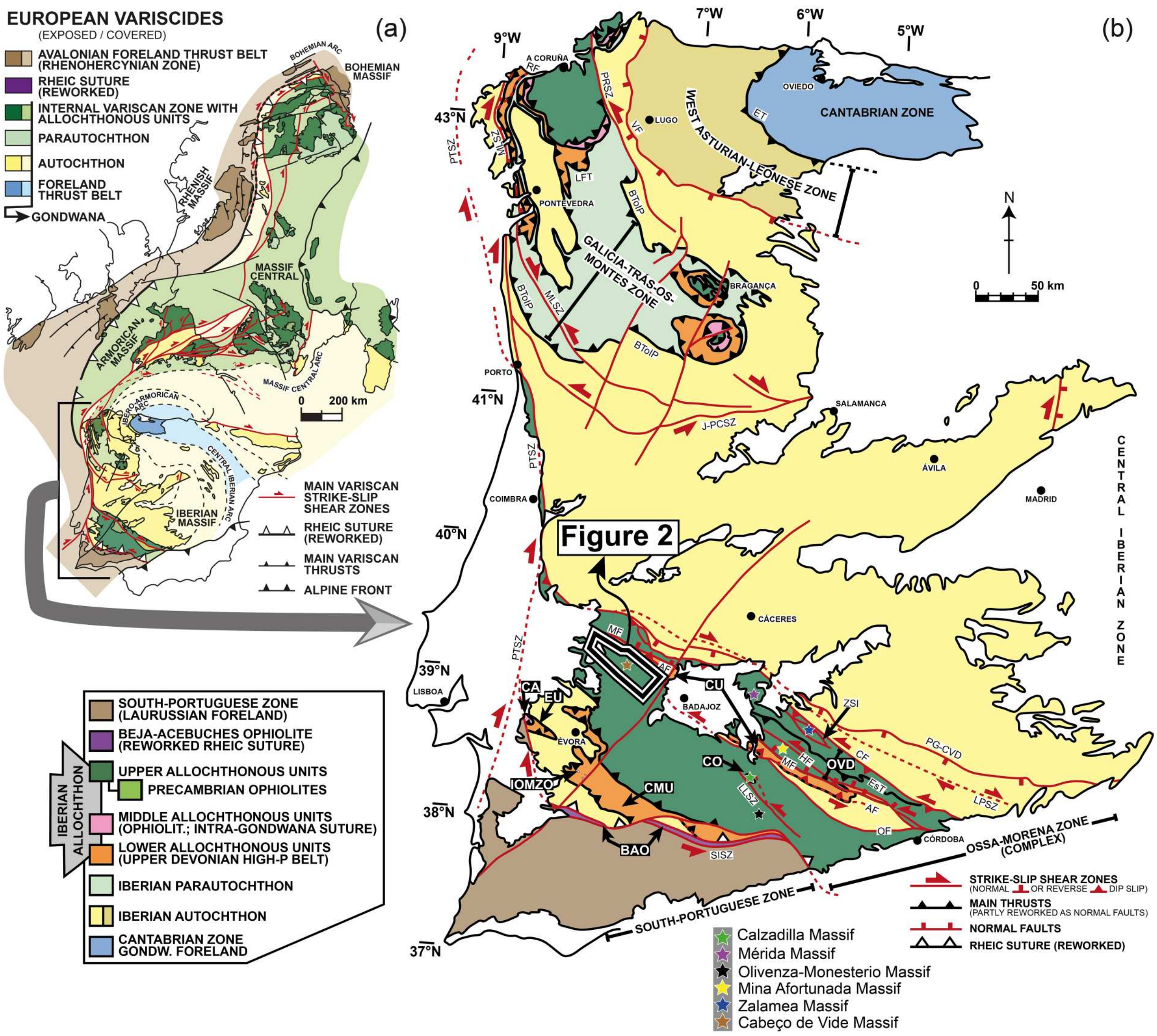

Figure 1. (a) Map of the Variscan Orogen indicating the primary terranes implicated in the orogeny. (b) Geological map of the Iberian Massif (Díez Fernández & Arenas, 2015). Abbreviations: AF – Azuaga Fault; BToIP – Basal Thrust of the Iberian Parautochthon; BAO – Beja–Acebuches Ophiolite; CA – Carvalhal Amphibolites; CF – Canaleja Fault; CMU – Cubito–Moura Unit; CO – Calzadilla Ophiolite; CU – Central Unit; EsT – Espiel Thrust; EU – Escoural Unit; ET – Espina Thrust; HF – Hornachos Fault; IOMZO – Internal Ossa-Morena Zone Ophiolites; J–PCSZ – Juzbado-Penalva do Castelo Shear Zone; LFT – Lalín-Forcarei Thrust; LPSZ – Los Pedroches Shear Zone; LLSZ – Llanos Shear Zone; MLSZ – Malpica–Lamego Shear Zone; MF – Matachel Fault; OF – Onza Fault; OVD – Obejo–Valsequillo Domain; PG–CVD – Puente Génave–Castelo de Vide Detachment; PRSZ – Palas de Rei Shear Zone; PTSZ – Porto–Tomar Shear Zone; RF – Riás Fault; SISZ – South Iberian Shear Zone; VF – Viveiro Fault; ZSI – Zalamea de la Serena Imbricates. The Cadomian massifs that emerge in SW Iberian Massif are marked with coloured stars.

Fernandes, 1973; Mata & Munhá, 1990; Ribeiro da Costa, 1985), even from a geochemical perspective (Lopes, 2004). With some modifications, considering our new geological map and structural data (fabrics, unconformities, faults and folds affecting the different rock assemblages and not previously identified) and lithostratigraphic groupings (based on a tectonometamorphic criteria), we rely on these descriptions and our observations to establish a new grouping into lithotectonic units.

4.1. Cabeço de Vide serpentinites

This unit comprises metamorphosed ultramafic and minor mafic rocks. The ultramafic rocks are mostly serpentinised dunites, with minor pyroxenites and hornblendites, exhibiting variable degrees of serpentinisation (Gonçalves, 1971; Ribeiro da Costa, 1985; Ribeiro da Costa & Barriga, 2022; Figure 3a). Some of these ultramafic rocks show cumulate textures (Ribeiro da Costa, 1985). Serpentinites result from the almost complete replacement of olivine and pyroxene to a lesser extent (Ribeiro da Costa, 1985). The Cabeço de Vide serpentinites comprise serpentine and minor olivine, clinopyroxene, oxides, and chlorite, oriented to define a penetrative and intense foliation (S_C) (Figure 3a). The dominant serpentine phase is chrysotile (Ribeiro da Costa, 1985) and minor antigorite (Gonçalves & Fernandes, 1973). The observed mineral alterations include scapolitization, amphibolitization, and serpentinisation (Canilho, 1973). In this unit, the mafic component

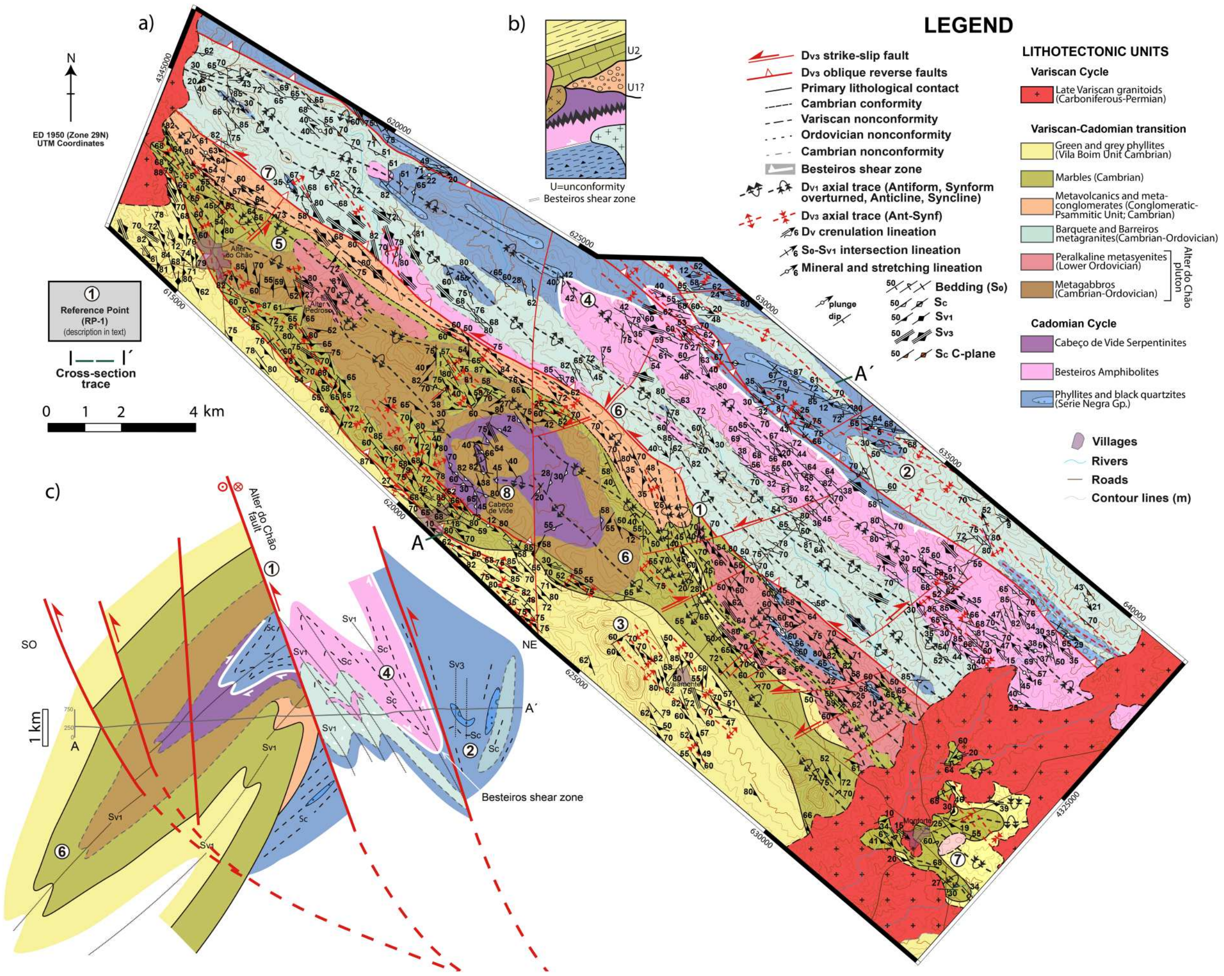

Figure 2. (a) Geological map with the planar and linear structures of the Cabeço de Vide Massif. (b) Lithostratigraphic column, including the Cadomian inferred shear zone and the main Cambrian unconformities. The white jagged line represents the contact between amphibolites and serpentinites, which we cannot observe on the map because it is on top of the topography. (c) Geological cross-section.

is represented by decimeter-scale patches of fine-grained (meta)gabbro. The Cabeço de Vide serpentinites are much more strongly deformed than the surrounding marbles and Alter do Chão metagabbros. The marbles (Cambrian Series 2 in age; see section 4.1.5) rest unconformably on top of the serpentinites, and the boundaries of the Alter do Chão metagabbros (Cambro-Ordovician in age; see section 4.1.8) cut the trace of the main foliation in the serpentinites (e.g., NE of Cabeço de Vide; Figure 2). Collectively, these observations suggest a minimum Early Cambrian age for the emplacement of the serpentinites.

4.2. Besteiros amphibolites

This unit consists of amphibolites with a foliation (S_C) defined by the preferred orientation of green, blue, and brown amphibole, plagioclase, minerals of the epidote group, and minor quartz, sphene, chlorite, and opaque minerals (Figure 3b). Amphibole has been dated using the $^{40}Ar/^{38}Ar$ isotopic method, yielding ages of 501 ± 25 Ma, 480 ± 25 Ma, and 432 ± 8 Ma (Lopes et al., 1993). The current contact of this unit with the surrounding Ediacaran metasedimentary rocks of the Serie Negra Gp. (see below) is defined by a band of mylonites, and both units are intruded by the Barreiros pluton dated at 525 ± 1 Ma (U-Pb on zircon, Sánchez-García et al., 2013).

4.3. Serie Negra Group

This unit comprises grey phyllites-schists with intercalations of meta-arkoses (dominant at the lower part of the series), minor calc-silicate rocks, and black quartzites, which can reach several km in lateral continuity (Alía, 1963; Carvalhosa, 1965; Vegas, 1968; Figure 3c, d). The phyllites-schists show a penetrative foliation (S_C) defined by quartz, biotite, muscovite, minor chlorite, fine-grained plagioclase, opaque minerals, and rare epidote-group minerals (Gonçalves & Fernandes, 1973). The meta-arkoses are quartz-feldspathic rocks with a foliation (S_C) composed of quartz, microcline, plagioclase, muscovite, and, to a lesser extent, biotite, opaque minerals, zircon, apatite, and sphene (Gonçalves & Fernandes, 1973). In the Serie Negra Group, three foliations exist, S_C is the

Figure 3. (a) Main S_C foliation in Cabeço de Vide serpentinites crosscut by later near-vertical fractures filled with mafic igneous rocks. (b) Compositional tectonic banding (main S_C foliation) in Besteiros amphibolites. Top right: microscope photo of the Besteiros amphibolites near the contact with the Serie Negra Gp. and affected by the Besteiros shear zone. (c) Alternation of black quartzites and phyllites defining the primary bedding (S_0) in the Serie Negra Gp and S_C subparallel to the bedding. Note the growth of (grey) cordierite porphyroblasts in the lighter metapelitic layers, suggesting local thermal metamorphism. Top right: microscope photo of the Serie Negra Gp. phyllites near the contact with the Besteiros amphibolites and affected by the Besteiros shear zone. (d) D_{V1} tight folds affecting S_0 and main S_C foliation in Serie Negra Gp. (e) Main S_{V1} foliation in conglomerates from the Conglomeratic-Psamitic Unit. Note elongated clasts, some of which are of metagranitoids, metavolcanics rocks or black quartzites. (f) D_{V3} and D_{V1} folds affecting the bedding in marbles. (g) D_{V1} fold in marbles with an axial plane foliation (S_{V1}). (h) Bedding (S_0) and S_{V1} foliation in metapelites and meta-sandstones from Vila Boim Unit. Note the slight obliqueness between bedding and foliation. (i) Cambrian nonconformity (yellow dashed line) defined by the intrusion of metagranitoids into the Serie Negra Gp. (note orientation of bedding). (j) Poorly foliated Cambrian metagranitoids with fine-medium grain size. (k) Poorly foliated Alter do Chão metagabbros.

main foliation and S_{V1} and S_{V3} are poorly developed crenulation cleavage defined by existing minerals.

The age of the sedimentary protoliths of the Serie Negra Gp. ranges between ca. 590–540 Ma (Linnemann et al., 2008; Schäfer et al., 1993), but the sections containing abundant metabasites, such as the case in this section (Montemolín Fm.), can have a maximum depositional age of ca. 602 Ma (Rojo-Pérez et al., 2022). New geochronological data indicate that the maximum age of the series is 620 Ma (Rojo-Pérez et al., 2025). The metasedimentary rocks of the Serie Negra Gp. are intruded by the Barquete pluton, dated at 526 ± 4 Ma (U-Pb on zircon; Pereira et al., 2011).

4.4. Conglomeratic-Psammitic Unit

This unit contains metaconglomerates, meta-arkoses, and metavolcanics. The metaconglomerates tend to be at the base of this unit. They comprise elongated clasts of varying sizes (3–12 cm), sourced from igneous rocks and the Ediacaran metamorphic basement on which they should rest unconformably. Clasts are made of quartzite, schist, meta-arkose, black quartzite (identical to that from the Serie Negra Gp.) and volcanic rocks (Gonçalves, 1969; Figure 3e). The inferred matrix has an argillaceous-sericitic composition (currently white mica and chlorite). The meta-arkoses dominate the upper part of the unit. The metavolcanics are intercalated with the metaconglomerates and meta-arkoses, and they have mostly felsic composition (rhyolites, trachytes), consisting of K-feldspar (orthoclase and perthite), plagioclase (albite), quartz, biotite, muscovite, epidote, and chlorite (Gonçalves et al., 1975; Mata & Munhá, 1990). This unit also includes minor mafic (tholeiites) rocks, which were attributed to fractional crystallisation processes during the Cambrian by Mata and Munhá (1990). All rocks of this unit exhibit a foliation defined by the preferred orientation of their mineralogy. Its main foliation (S_{V1}) is defined by the preferred orientation of minerals such as quartz, plagioclase, feldspar, biotite, muscovite, epidote, chlorite and opaque minerals, depending on the rock protolith.

In the lack of a precise age, this unit represents a potentially Cambrian volcanic-sedimentary sequence resting unconformably over the Ediacaran metamorphic basement (Gonçalves, 1969, 1971; Lopes, 2003; Rojo-Pérez et al., 2024; Teixeira & Gonçalves, 1967; Vegas, 1970), from which the clasts of metamorphic rocks (notably the black quartzites) were extracted.

4.5. Marbles

The marbles are mainly composed of recrystallised calcite and dolomite in varying proportions. These metamorphic rocks exhibit a compositional banding probably derived from their protolith (bedding). Still, the recrystallised grains are aligned to define a main foliation (S_{V1}; defined by calcite and dolomite) that is also observed in the surrounding lithologies (Figure 3f,g), suggesting that bedding may have been transposed. The marbles are locally intercalated with phyllites-slates that occur as centimetre- to metre-thick layers. This unit is affected by thermal metamorphism in the surroundings of the Permo-Carboniferous granitoids and around the Alter do Chão metagabbros (Roseiro et al., 2025). The metamorphic aureoles affecting these marbles developed feldspar, muscovite, minerals of the epidote group, chlorite, hornblende, diopside, biotite, chalcopyrite, and pyrite (Gonçalves & Fernandes, 1973; Seco Andrade, 2022). A few lenses of metabasite (metadiabase) can also be observed within the marbles. The protolith age of the marbles is considered Cambrian (Series 2) because, in other regions of the Ossa-Morena Zone, similar carbonate rocks unconformably overlie the Ediacaran Serie Negra Gp. and are overlain conformably by a siliciclastic sequence with Cambrian fossils (Gonçalves, 1971; Goncalves & Fernandes, 1973). In the Elvas region, 50 km southeast of Cabeço de Vide, these marbles are intruded by alkaline plutonic rocks dated at 490 ± 4 Ma (U-Pb on zircon; Díez Fernández et al., 2015).

4.6. Vila Boim Unit

It consists of a volcano-sedimentary series composed of metasandstones (greywackes), phyllites-slates and minor metaconglomerates (flysch deposits), and metavolcanic rocks. Green phyllites-slates and metagreywackes are intercalated at the base, green phyllites-slates dominate the upper part, and (peralkaline) metavolcanics occur at the top (Gonçalves & Fernandes, 1973; Figure 3 h). Some metaconglomerate beds can be found at an intermediate level within the series. The phyllites-slates show a penetrative foliation (S_{V1}) defined by the preferred orientation of quartz, plagioclase, sericite, muscovite, and ferromagnesian minerals. The metaconglomerates comprise quartz clasts of varying sizes within a quartz and sericite matrix. These rocks contain fauna (e.g., trilobites) from the Cambrian (Delgado, 1904; Goncalves & Fernandes, 1973; Teixeira, 1952).

4.7. Cambrian metagranitoids

This unit consists of two plutons (Barreiros granite-tonalites and Barquete peraluminous granites, Pereira et al., 2011) composed of coarse- to medium-grained alkaline metagranites, peraluminous biotite metagranites, metagranodiorites and weakly metaluminous metatonalites (Pereira et al., 2011; Sánchez-García et al., 2013) (Figure 3i and j). Both plutons intruded the Ediacaran Serie Negra Gp. The Barreiros pluton crosscuts the Besteiros amphibolites and generates contact metamorphism in the phyllites of the Serie Negra Gp. (Figure 3c). The mineralogy of the metagranitic bodies is oriented. The main foliation (S_C) is defined by quartz, alkali feldspar (microcline, perthite), albite, oligoclase, biotite, muscovite, and chlorite, which are common to most of them. Amphibolites and black quartzites from the Serie Negra Gp. occur as enclaves (Gonçalves & Fernandes, 1973; Pereira et al., 2011), some of which have a mapable size (Figure 2a).

The protolith age of Barreiros and Barquete granitic rocks is Cambrian (518 ± 45 Ma, U-Pb on zircon, De Oliveira et al., 2002, p. 525 ± 1 Ma, U-Pb on zircon, Sánchez-García et al., 2013; and 526 ± 4 Ma, U-Pb, Pereira et al., 2011).

4.8. Alter do Chão metagabbros

This unit is made of olivine-anorthositic and amphibole-bearing metagabbros (Figure 3k). The Alter do Chão metagabbros are primarily composed of plagioclase, clinopyroxene, olivine, brown and blue-green hornblende, biotite, chlorite, and oxides, with mesocumulate textures (Ribeiro da Costa, 1985), all of which are poorly oriented to define a Variscan foliation. Two types of metagabbros can be distinguished based on their geochemistry (tholeiitic and alkaline; Canilho, 1973; Lopes, 2004; Ribeiro da Costa, 1985). In the Cabeço de Vide Massif, the contact of this unit with the marbles is parallel to an aureole of thermal metamorphism that also extends into the Vila Boim Unit (Gonçalves, 1971; Roseiro et al., 2025; Seco Andrade, 2022). Dykes of metagabbro crosscut the Cabeço de Vide serpentinites (Gonçalves, 1971; Gonçalves & Fernandes, 1973) and their main foliation (Figure 2 and Figure 3a). The main foliation observed in the serpentinites is much more penetrative, intense, and oriented differently (Figure 3a) than the planar fabric and boundaries observed in the metagabbros (Figure 3k). K-Ar ages obtained from amphibole concentrates of metagabbros suggest an emplacement age at ca. 480–500 Ma (Lopes et al., 1993).

4.9. Alter do Chão (per)alkaline metasyenites

This unit contains metaigneous rocks of alkaline to peralkaline composition, primarily syenites rich in sodium feldspar and riebeckite. These rocks include K-feldspar, plagioclase (albite), riebeckite, minor quartz, biotite, muscovite, oxides, allanite, and zircon. This mineral assemblage shows a preferred orientation and defines a Variscan foliation parallel to the surrounding rocks. The boundaries of the Alter do Chão (per)alkaline metasyenites cut across the boundaries of the Serie Negra Gp., Vila Boim, and Marbles units, as well as the boundary of the Alter do Chão metagabbros. The protolith age of these (per)alkaline magmatic rocks is Cambrian-Ordovician (482 ± 16 Ma, U-Pb on zircon, Lancelot & Allegret, 1982, p. 490 ± 4 Ma and 470 ± 3 Ma, U-Pb on zircon, Díez Fernández et al., 2015).

4.10. Late Variscan granitoids

Late Variscan granitoids consist of two batholiths of considerable size, only parts of which crop out in the mapped area to the NW (Nisa-Albuquerque batholith) and SE (Santa Eulália-Monforte batholith). Although both are of late Variscan age (Permo-Carboniferous), their mineralogy and geochemistry differ. Relative to the Variscan deformation, these granitoids are post-tectonic, showing only subtle crystal orientation (K-feldspar ± biotite) related to magmatic flow.

The Nisa-Albuquerque batholith is composed of monzogranites and leucogranites with U-Pb zircon ages that range between ca. 305 and 309 Ma (González-Menéndez, 2002; Solá et al., 2009). Its mineral assemblage consists of quartz, K-feldspar, plagioclase, biotite, and cordierite altered to pinite. Other phases, such as muscovite, tourmaline, and andalusite, are common. Accessories include apatite, ilmenite ± rutile, monazite, zircon and xenotime. The geochemistry of these granites is strongly peraluminous and P-rich with low CaO and $FeO_t + MgO + TiO_2$ contents (González-Menéndez, 2002; Solá et al., 2009). Small granodioritic-tonalitic stocks are also recognisable.

The Santa Eulalia-Monforte batholith is formed by pinkish leucogranites and monzogranites, and small mafic stocks (gabbros, diorites, tonalites and granodiorites) with U-Pb zircon ages ranging between ca. 297–307 Ma (Cruz et al., 2022; González-Menéndez et al., 2006; Pereira et al., 2017). The granite mineral assemblage consists of quartz, K-feldspar, biotite ± plagioclase ± amphibole. Allanite and zircon are the most abundant accessories. Other phases include unidentified oxides and secondary minerals. They are weakly peraluminous to metaluminous and P-poor, with low to moderate CaO and $FeO_t + MgO + TiO_2$ contents. Another important granitic unit, not present on the current map, occurs in the core of the batholith (Cruz et al., 2022; González-Menéndez et al., 2006; Pereira et al., 2017). It includes kilometre-sized xenoliths of Ediacaran amphibolites and Cambrian phyllites and marbles.

5. Structural framework

The main structures will be introduced in reverse chronological order. The intrusion of late Variscan plutonic rocks represents the latest major magmatic event in the region's geological evolution. These Permo-Carboniferous granites cut the youngest fabrics and structures identified in the region, which are upright, open folds, and left-lateral strike-slip faults with reverse slip that affect all of the other lithologies in the area as well as previous structures and fabrics. These faults developed during the third phase of Variscan regional deformation (D_{V3}). The most prominent D_{V3} structures are the Alter do Chao fault (RP-1; Figure 2a) and D_{V3} folds affecting the Cadomian structures and basement (RP-2; Figure 2a) as well as previous Variscan structures (e.g. D_{V1} folds and S_{V1} foliation; RP-3; Figure 2a). The Alter do Chao fault (RP-1; Figure 2a) is a reverse, oblique strike-slip shear zone with left-lateral movement.

The second phase of Variscan deformation (D_{V2}) is not represented in the Alter do Chão-Cabeço de Vide Massif. However, in other sectors of the Ossa-Morena Zone, D_{V2} includes the development of a flat-lying foliation (S_{V2}) that transposes former structures (e.g. D_{V1}) and is related to Variscan extensional tectonics after a period of crustal thickening (Díaz Azpiroz et al., 2002; González del Tánago, 1995; Martín Parra et al., 2006; Pereira et al., 2007, 2009, 2011).

S_{V1} is the first and main foliation observed in the Cambrian metasedimentary and metavolcanic rocks and the Cambrian-Ordovician meta-igneous rocks. S_{V1} was formed during the first phase of Variscan regional deformation (D_{V1}) and is the second foliation found in the phyllites of the Serie Negra Gp., Besteiros amphibolites, and Cambrian meta-granitoids (namely, the Barquete and Barreiros plutons), north of the Alter do Chão fault. S_{V1} is the axial plane foliation to overturned folds that affect the bedding of Cambrian metasedimentary rocks, the primary lithological contacts of the Cambrian-Ordovician igneous rocks and the S_C foliation (RP-4; Figure 2a). Except for the late Variscan granitoids, the curved trace of the contacts observed within the Serie Negra Gp. (RP-2; Figure 2a) and in the Paleozoic rocks (RP-1, 4, 5, 6 and 7; Figure 2a) correspond to hinge zones of Variscan folds (see fold traces in Figure 2). According to the mineral assemblages that define the foliations, the metamorphism associated with the Variscan deformation is low grade, usually within the chlorite zone but locally reaching the biotite zone.

S_C is the main foliation observed in the Serie Negra Gp., the Cabeço de Vide serpentinites, Besteiros Amphibolites, and the Cambrian metagranitoids. This foliation does not occur in the rest of the lithologies of the region, which are as old as Early Cambrian and rest unconformably on top of them or intrude them. In the rocks bearing the S_C fabric, we can observe up to two superimposed crenulation cleavages; one shallowly-dipping in origin (S_{V1}) and another one near-vertical in origin (S_{V3}). The youngest rocks bearing the S_C fabric correspond to the Barreiros and Barquete plutons. S_C is associated with asymmetric microstructures such as C-C´-S fabrics and sigma objects, which attest to the development of a broad ductile shear zone. The mylonites along the mechanical contact between the Besteiros amphibolites and the meta-sedimentary rocks of the Serie Negra Gp. (Besteiros Shear Zone) are cut by the Cambrian plutons (RP-4; Figure 2a). Accordingly, the Besteiros Shear Zone and accompanying deformation (i.e. S_C sensu lato) are considered as formed during the Cadomian cycle. According to the mineral assemblages observed in the main foliation, the metamorphism associated with S_C is usually low to medium grade (biotite zone for the metapelites and epidote amphibolite facies for the metabasites).

The Alter do Chão pluton (Alter do Chão (per)alkaline metasyenites and Alter do Chão metagrabbros) shows intrusive contacts with the marbles (metamorphic aureole and local skarn) and the Cabeço de Vide serpentinites (RP-8; Figure 2a). The Cabeço de Vide serpentinites and their S_C foliation are affected by D_{V1} overturned folds, just like the rocks that conform to the Alter do Chão pluton. The Alter do Chão pluton's intrusive contact suggests that the exhumation of the serpentinites predates the intrusion of the metagabbros and (per)alkaline metasyenites.

6. Discussion

A field-based study of the Cabeço de Vide Massif has resulted in a novel cartographic representation and recognition of newly identified rock ensembles and structures, thus offering insights into their tectonothermal evolution. The relationships between these ensembles, whether sedimentary, intrusive, or mechanical, have been clarified, and the new definition of lithotectonic units has been established and updated. We have considered the continental or oceanic affinity of the rock ensembles and the Cadomian and Variscan structures that affect them.

The new structural data have allowed the identification of new structures, such as Cadomian shear zones and Variscan overturned and upright folds, which went unnoticed in previous studies but have been described in nearby areas (Apalategui et al., 1990; Chacón, 1979; Chacón et al., 1983; Díez Fernández et al., 2019; Expósito et al., 2003; Moreira et al., 2014; Moreno-Martín et al., 2025). The newly acquired cartographic and structural data enable the reconstruction of the subsurface structure, as illustrated in Figure 2c. With the structural data in this new map, the geological relationships exposed over the territory can be projected down the surface and over the current topography. For instance, the contact between the Serie Negra Gp. and the Besteiros amphibolites is mechanical (not primary), as evidenced by a shear zone between the two units (Figure 3b and c).

In the Cabeço de Vide Massif, two main geodynamic cycles can be interpreted based on a collective analysis of the lithotectonic units' features. In the meta-conglomerates of the Conglomeratic-Psammitic Unit, the occurrence of metamorphic pebbles extracted from the Serie Negra Gp. suggests that this unit and the overlying marbles rest unconformably over Serie Negra Gp. and accompanying metaigneous rocks (e.g. amphibolites). The siliciclastic succession that includes these metaconglomerates is the oldest unit that lacks S_C foliation. In any other older unit, S_C foliation pre-dates the first Variscan foliation (S_{V1}). This observation suggests that a significant change in the geodynamics of the region (i.e. transition from the Cadomian to the Variscan cycle) should have occurred between the formation of the Cambrian series containing the siliciclastic (e.g. conglomerates) and carbonated sedimentary rocks and the intrusion of the Cambrian-Ordovician (per)alkaline syenites and gabbros (Alter do Chão pluton). The (per)alkaline metasyenites and metagabbros of Alter do Chão are consistent with a post-Cadomian rifting event, which began around ~520-500 Ma (Díez Fernández et al., 2015; Quesada, 2006; Sarrionandia et al., 2012; Sánchez-García et al., 2008, 2010). This rifting event would mark the onset of the Variscan cycle in the region.

The (older) Cadomian cycle would include (i) the sedimentation of the Serie Negra Gp. and the formation of the protoliths of the Besteiros amphibolites, (ii) the development of the ductile shear zone juxtaposing the aforementioned units, (iii) the early exhumation of the Cabeço de Vide serpentinites, (iv) the intrusion of Early Cambrian granitoids and (v) the deformation and metamorphism of the Early Cambrian granitoids and its host rocks (Serie Negra Gp. and Besteiros amphibolites) in a broad ductile shear zone (development of S_C).

Evidence of any contraction-related structure before the D_{V1} Variscan folds is missing in the Cambrian-Ordovician rocks. However, the Ordovician igneous rocks that intruded in that time frame (e.g. Alter do Chão pluton) suggest severe lithosphere extension (i.e. strong mantle input; Díez Fernández et al., 2015). Interestingly, the exhumation of a piece of upper mantle (Cabeço de Vide serpentinites) before the sedimentation of carbonated rocks is a process observed in several Cadomian suture zones recently described in SW Iberia (e.g. Arenas et al., 2018; Díez Fernández et al., 2019, 2022; Moreno-Martín et al., 2025). The recognition of this sequence of events paves the way for further investigations regarding the mechanisms involved in the exhumation of that piece of upper mantle in the region and its possible link to the development and subsequent evolution of a suture zone. Finally, the D_{V1} and D_{V3} structures and the Carboniferous-Permian magmatism would represent the region's culmination of the Variscan cycle.

7. Conclusions

This study presents a new cartographic framework with an innovative grouping of lithological assemblages, structural measurements, and a geological cross-section. These data contribute to a better understanding of the area's geological history and structure. The new lithotectonic units defined for the Cabeço de Vide Massif, the structural data, and their subsurface projection offer an updated perspective on the tectonothermal evolution of this region of the Ossa-Morena Zone (SW Iberian Massif), especially in terms of discrimination of major geodynamic cycles (Cadomian vs. Variscan).

Software

The map was drawn using ArcMap software (v. 10.8) and Adobe Illustrator® CC 2020.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Data availability statement

The authors confirm that the data supporting the findings of this study are freely available within the article.

Geological information

The study area comprises the Cabeço de Vide Massif (south-central Portugal). It is between 615500 and 4346600 and 635200 and 4320600 m. The Coordinate System is ED 1950 / UTM Zone 29 N, with UTM Coordinates.

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