Geology of the contact area between the Internal and External Nappe Zone of the Sardinian Variscan Belt (Italy): new insights on the complex polyphase deformation occurring in the hinterland-foreland transition zone of collisional belts

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ABSTRACT
This study aims to decipher the structural evolution of a sector of the Nappe Zone in the Sardinian Variscan Belt. We investigated the Barbagia Thrust between the Meana Sardo Unit (belonging to the External Nappe Zone) in the footwall and the Barbagia Unit (belonging to the Internal Nappe Zone) in the hanging wall. Combining the geological survey with meso- and microstructural analysis, we realized a 1:10,000 scale geological map highlighting the polyphasic evolution developed under low-grade metamorphic conditions during the Variscan orogeny. Both units preserve (i) an early phase generally observed far from the tectonic contact and mainly in the Meana Sardo Unit (D1), (ii) a syn-nappe ductile deformation linked to the Barbagia Thrust activity and a top-to-the S-SW sense of shear (D2) and (iii) a large-scale nappe refolding (D3). A late extensional stage (D4), with the development of collapse folds, marks the end of the orogenic cycle.

1. Introduction
In collisional belts, the gradual transition from tectonic units occurring in the metamorphic core of the belt to those deformed at higher structural levels and progressively incorporated in the orogenic wedge is identified as the hinterland-foreland transition zone, forming a fold-and-thrust belt (Larson et al., 2010; Montomoli et al., 2018; Schneider et al., 2014; Thigpen et al., 2010). Generally, these orogenic sectors are characterized by large-scale nappe stacks with different generations of superimposed folds and cleavages that complicate the understanding of the structural architecture (Ghosh et al., 2020; Montomoli et al., 2018; Sarkarinejad & Ghanbarian, 2014; Thigpen et al., 2010, 2013). Nappe boundaries are often marked by the presence of regional-scale contractional (thrust-sense) ductile shear zones that accommodate large displacements and control the growth of orogenic wedges (Ghosh et al., 2020; Grasemann et al., 1999; Ring & Brandon, 1999; Thigpen et al., 2010). Several difficulties in unravelling the tectono-metamorphic evolution of the hinterland-foreland transition zone arise from the overprinting of post-nappe stacking deformation that modifies the original attitude of pre- and syn-nappe stacking elements (e.g. secondary foliations, tectonic contacts, folds vergence). Untangling the geological complexity derived from the geological survey and outcrop observation requires microstructural analysis (e.g. Carosi et al., 2016; Caso et al., 2021; Papeschi et al., 2020).

The Variscan Belt in Sardinia represents an excellent site where it is possible to investigate the tectonic mechanisms active during the evolution of collisional-type orogenesis during the Paleozoic, as this area has not been strongly reworked by the later Alpine orogenic cycle (Carmignani et al., 1994, 2001). The Sardinian hinterland-foreland transition zone has been subdivided into External and Internal Nappe Zone (Carmignani et al., 1994, 2001). The Barbagia Thrust (BT; Carosi & Malfatti, 1995; Carosi & Pertusati, 1990; Montomoli et al., 2018; Petroccia et al., 2022), a thrust-sense movement, regional ductile to brittle shear zone (Carosi et al., 2002, 2004; Carosi & Malfatti, 1995; Conti et al., 1998, 1999, 2001), marks the boundary between both nappes. It plays a critical role during the nappe stacking and the exhumation of the crustal units. At the end of the compressive deformation, the complete nappe pile and relative tectonic contacts have been refolded by post-nappe stacking regional-scale antiforms and synforms that complicate the structural architecture. Whereas the setting of different portions of the hinterland of the Sardinian belt...
has been well investigated by several authors (Carosi et al., 2020, 2022; Carosi & Palmeri, 2002; Casini et al., 2010, 2015; Cruciani et al., 2015), few studies have addressed the understanding of the structural architecture of the low-grade Nappe Zone (Carmignani et al., 1994; Conti et al., 1999, 2001; Funedda, 2009; Montomoli et al., 2018; Petroccia et al., 2022). In this work, we present a new 1:10,000 scale geological map (Main Map), supported by unpublished meso- and microstructural data. The excellent exposures of both rocks and structures make this sector of the Sardinian Belt a fundamental area to unravel the complex polyphasic history that occurred during the Variscan pre-, syn- and post-nappe stacking deformation.

2. Geological setting

The Sardinian Paleozoic basement is a segment of the Southern European Variscan belt (Matte, 2001). The metamorphic grade increases from very low-grade on the southwestern side of the island up to medium- and high-grade in the northern sector. In particular, the belt is classically described as a collisional-type chain (Carmignani et al., 1994, 2001, 2016; Cruciani et al., 2015 for a critical review) consisting of (Figure 1(a)): (i) the External Zone or foreland, (ii) the Nappe Zone or hinterland-foreland transition zone and (iii) the Axial Zone or the hinterland of the belt.

The Nappe Zone has been classically subdivided into External (central to southern Sardinia) and Internal (northern to central Sardinia) Nappe Zone (Figure 1(a)). The lithostratigraphic succession is similar in both nappes: Lower Cambrian to Ordovician metasandstone, phyllite and quartzite (Carmignani et al., 1994; Cocco et al., 2018; Cocco & Funedda, 2019; Pertusati et al., 2002), Middle Ordovician metaconglomerate and metavolcanic rocks (Oggiano et al., 2010), Upper Ordovician meta-arkose and metasiltstone, Silurian–Lower Devonian black shale, phyllite, and marble, Middle–Upper Devonian marble, and Lower Carboniferous synorogenic flysch (Conti et al., 2001). The main difference between Internal and External nappes is the lack or the paucity of Ordovician metavolcanic rocks and Devonian limestones in the Internal Nappe Zone sequence (Carmignani et al., 1994, 2001).

Meana Sardo, Gerrei, Rio Gruppa, Castello Medusa and Sarrabus units belonging to the External Nappe Zone (Figure 1(b); Carmignani et al., 1994; Carosi et al., 1991; Cocco & Funedda, 2011, 2012; Funedda et al., 2011, 2015) are mainly deformed under syn-tectonic regional greenschist-facies metamorphism (Carmignani et al., 1994; Carosi et al., 1991, 2010; Cocco et al., 2018; Franceschelli et al., 1992). The only exception is the Monte Grighini Unit, where amphibolite-facies conditions have been detected (Cruciani et al., 2016; Musumeci, 1991). Two main metamorphic complexes constitute the Internal Nappe Zone: the Low-Grade Metamorphic Complex (LGMC; Barbagia, Goceano, and southern Nurra units; Carmignani et al., 1994; Montomoli, 2003) in greenschist-facies and the Middle Grade Metamorphic Complex (MGMC; Baronie, Anglona, and northern Nurra units; Carmignani et al., 1982, 1994, 2001) reaching amphibolite-facies conditions. The Barbagia Thrust (BT; Carosi & Malfatti, 1995; Carosi & Pertusati, 1990; Montomoli et al., 2018; Petroccia et al., 2022) is a regional-scale ductile to brittle shear zone that extends from central to southeastern Sardinia for more than 50 km along strike and marks the boundary between the Internal and the External Nappe zones.

Meso- and microstructural observations from different authors (Carmignani et al., 1982, 1994; Carmignani & Pertusati, 1977; Carosi et al., 2004; Carosi & Pertusati, 1990; Conti et al., 1998; Conti & Patta, 1998; Dessau et al., 1982), point to a complex polyphase evolution. Four deformation phases have been detected and described in both Internal and External Nappe Zone (Carosi et al., 2002, 2004; Conti et al., 1998, 2001). D1 and D2 are related to continental collision and shortening, responsible for nappe emplacement, followed by later D3 and D4 phases. The D1 tectonic event is generally associated with the development of F1 pluridecametric S-SW-verging folds, better preserved in the External Nappe Zone (Carosi, 2004; Carosi et al., 2002, 2004; Carosi & Malfatti, 1995; Conti et al., 1998, 1999). Approaching the BT, F1 folds become much tighter and their wavelength decreases (Carosi et al., 2004). The D1 phase was progressively obliterated by the D2 event developed during the main nappe emplacement stage and linked to the BT activity (Montomoli et al., 2018 and references therein). A S2 mylonitic foliation with kinematic indicators pointing to a top-to-the S-SW sense of shear is recognizable. The BT is characterized by ductile to brittle deformation, highlighted by cataclastic deformation overprinting mylonite (Carosi et al., 1991; Carosi & Malfatti, 1995). Greenschist facies deformation is highlighted by syn-tectonic recrystallization of muscovite, quartz, albite and chlorite. After nappe-stacking deformation linked to D1 and D2 phases, the D3 phase is responsible for regional-scale antiforms and synforms (Flumendosa Antiform, Barbagia Synform and Gennargentu Antiform; Carmignani et al., 1994; Conti et al., 1999; Figure 1(a) and (b)). The entire nappe pile, the BT, older foliations and folds (Figure 1(b)) were refolded by these kilometre-scale upright folds. The end of the orogenic activity is characterized by the extensional collapse of the belt (D4 phase), associated with open folds, brittle-ductile shear zones and by the emplacement...
Figure 1. (a) Tectonic sketch map of the Sardinia Island (modified after Carosi et al., 2020; Montomoli et al., 2018). (b) Schematic geological cross-section (A-A') along the Nappe Zone (modified after Carmignani et al., 1994; Conti et al., 1999, 2001).
of the Sardo-Corso batholith at ~320-280 Ma (Casini et al., 2012; Del Moro et al., 1975). The crystalline basement is unconformably covered by Upper Carboniferous and Permian sequences, followed by Mesozoic carbonates (Costamagna & Barca, 2004) and by a volcano-sedimentary succession emplaced during the Oligo-Miocene time (Funedda et al., 2011).

The study area, located in the Barbagia region in the southwestern sector of the Lago Alto del Flumendosa (Figure 1(a)), is represented by the structurally upper Barbagia Unit (BU, Internal Nappe Zone) overthrust on the Meana Sardo Unit (MSU, External Nappe Zone). We focused on a key area of the hinterland-foreland transition zone where the contact between the Internal and External nappes is marked by a well-exposed mylonitic zone. The BT and all previous structural elements (e.g. F2 folds, S2 foliation) were subsequently refolded by an upright kilometre-scale antiform, the Gennargentu Antiform. The study area is located in its southern limb (Figure 1(a)), where previous F2 folds change their attitude and F2 axial planes dip towards the S-SW and not to the hinterland or N-NE (Carosi et al., 2004; Montomoli et al., 2018).

3. Methods

The study area is located in the southwestern sector of the Lago Alto del Flumendosa, in central Sardinia, and covers an area of ~20 km². New 10 m contour lines have been obtained using the DTM TINITALY/01 (Tarquini et al., 2007) with 10 m-cell size m grid resolution, integrated into a WGS 84, UTM 32N GIS spatial database to derive a Hillshade map. The geological map (see Main Map) has been realized at 1:10,000 scale. To better document the distribution of the metamorphic basement, we do not report quaternary deposits in the resulting map. The mapping workflow includes (i) mapping of both lithologies and structures; (ii) measurement of structural elements: (S) for syn-metamorphic surfaces or axial plane foliation; (A) for fold axes; (L) for object lineations; (F) for folds; and (D) for the deformation phases; and (iii) microstructural analysis on oriented thin sections, cut parallel to the object lineation and perpendicular to the main foliation (approximating the XZ plane of the finite strain ellipsoid). A numerical progression in the description of deformation phases, besides the primary bedding S0, has been used (e.g. S1, S2). All the collected structural elements have been plotted in equal-area stereo diagrams in the lower hemisphere. Mineral abbreviations are after Whitney and Evans (2010) except for white mica, Wm. Foliations, kinematic indicators and mylonites have been classified according to Passchier and Trouw (2005). Quartz microstructures, indicative of dynamic recrystallization, are defined according to Piazolo and Passchier (2002), Stipp et al. (2002) and Law (2014). Mylonite has been classified considering the percentage of the matrix compared to porphyroclasts, varying from 50-90% for mylonitic rocks to more than 90% for ultramylonite.

4. Lithostratigraphy

The Barbagia Unit succession (also known as ‘Postgo- ländian’; Vai & Cocozza, 1974) has been mapped as a single metasedimentary formation (Filladi Grigie del Gennargentu Fm., Fg; Main Map). It is constituted by quartzitic and micaceous metasandstone alternating with metasiltstone and quartzite interbedded with grey phyllite. Sometimes, close to the BT, a thin and not mappable layer of porphyroids has been recognized (Main Map). The protolith age was referred from Cambrian to Ordovician (Carmignani et al., 1994; Pertusati et al., 2002). Meana Sardo Unit begins with a basal siliciclastic succession (Arenarie di Sola- nas-San Vito Fm., Sv; Barca et al., 1988; Calvino, 1959; Main Map), dated from Middle Cambrian to Lower Ordovician (Di Milia & Toniorgi, 1993). It is made by alternating fine- to coarse-grained metasandstone, grey-green metasiltstone, and meta-argillite, with thickness varying from cm- to m-scale. The succession continues with volcanic rocks belonging to the Monte Santa Vittoria Fm. (Ms; Carmignani et al., 2001; Main Map). This formation includes three lithostratigraphic units that were previously informally defined by Min- zoni (1975), including the Manixeddu, Monte Corte Cerbos, and Serra Tonnai formations (Carosi et al., 2004). It is mainly represented by metaconglomerate, metavolcanoclase, grey-green metarhyolite, green metabasalt and dacitic metagimbrite. The age of the protolith is ~460 Ma (Middle-Late Ordovician) based on radiometric analyses (Pavanetto et al., 2012), confirming previous stratigraphic ages (Carmignani et al., 1994). A change from volcanic to siliciclastic rocks is testified by the presence of Upper Ordovician terrigenous formation (Orroledu Fm., Or; Loi, 1993; Loi & Dabard, 1997; Main Map). It consists of metarkose, metagraywacke and phyllite with quartz–sericite–chlorite matrix. These metasediments locally contain interbedded basic to intermediate metaepiclastite. The youngest lithological unit is made by black graphitic shales with interbedded limestone layers (Scisti a Graptoliti Fm., Sg; Main Map) that are Silurian to Early Devonian in age (Barca & Jäger, 1989; Corradini et al., 1998; Gnoli, 1993). The post-Variscan magmatic rocks are made by northwest-trending rhyolitic to rhyodacitic aplitic dykes (α; Upper Carboniferous-Permian; Carmignani et al., 2001). They contain phenocrysts of quartz, feldspar, and plagioclase, as well as aggregates of biotite crystals within a fine-grained groundmass. The Triassic-Jurassic rocks are recognizable in the Perda et Liana inselberg. They are characterized by dolostone,
which is typically massive and structureless, alternating shale and dolomitic limestone, quartzitic sandstone and conglomerate (Triassic-Jurassic Genna Selole and Dorgali Fm., C; Costamagna & Barca, 2004).

5. Structural analysis

Based on overprinting criteria and structures observed from meso- to microscale, we defined four ductile deformation phases heterogeneously distributed in both units. The original bedding ($S_0$; Figure 2(a)) is only recognizable as a compositional alternation or dismembered lens-shaped fragments in sectors where a strong lithological contrast, e.g. quartz layers within a metasandstone matrix, is present. Due to the strong transposition related to the D$_2$ phase in the investigated area, it is nearly impossible to identify fold systems associated with the D$_1$ phase. The D$_1$ structural elements are well recognizable, mainly in the MSU far from the BT. S$_1$ foliation can be identified in the hinge zone of the F$_2$ folds or as meso- (Figure 2) and vary from gently inclined to isoclinal; Figure 2(e)) and range from gently inclined to isoclinal, overturned to recumbent folds, and developing at micro- to map-scale. The interlimb angles of F$_2$ folds range from 60° to 120° (close to sub-iso-clinal; Figure 2(e)) and vary from gently inclined to recumbent. F$_2$ folds generally show rounded and thickened hinges with stretched limbs (class 2 of Ramsay, 1967), which can be classified as B5 according to Hudleston (1973). F$_2$ folds show an S$_2$ foliation parallel or sub-parallel to the relative fold axial planes, and it generally represents the main foliation at the outcrop-scale. The strike of the S$_2$ foliation is quite constant, ranging from E-W to NW-SE with scattered values (Figure 2(d)). A$_2$ fold axes show a main E-W trend gently plunging toward both E and W, with quite scattered values (Figure 2(e)). A N-S or NE-SW trend of the L$_2$ object lineation on the S$_2$ foliation is recognizable. The F$_2$ fold axes are nearly perpendicular to the L$_2$.

In the MSU metavolcanic rocks, the principal anisotropy is a continuous and pervasive S$_2$ foliation. In the metapelitic and metasandstone, the S$_2$ can be generally classified as a gradational to discrete spaced crenulation cleavage. Far from the tectonic contact, the S$_2$ is mainly associated with pressure solution and reorientation of pre-existing tabular grains (Figure 2(c)). Moving toward the BT, the S$_2$ becomes a mylonitic continuous foliation (Figure 2(d)) associated with the blastesis of white mica + chlorite. The D$_3$ phase is characterized by meso- to macroscopic scale, E-W trending F$_3$ folds that overprint and reorient all previous structural elements (Figure 2(f,g)). A$_3$ fold axes (Figure 2(f)) generally trend parallel to the A$_2$ ones and perpendicular to the L$_2$ object lineation. The F$_3$ structures are gentle to open S-SE verging upright to steeply inclined parallel or asymmetric folds with centimetric (Figure 2(f)) to plurimetric long wavelength. Locally, kink type folds occur. In the F$_3$ hinge zones and only in less competent rocks, the S$_3$ axial-plane foliation is represented by a spaced, disjunctive cleavage. No metamorphic mineral assemblage related to this phase has been observed, whereas the main deformation mechanism is pressure solution and reorientation of pre-existing grains. D$_3$ folds affect all previous structural elements, determining the variation of the axial plane dipping of the F$_3$ folds. The studied sector is indeed located in the southern limb of one of these regional-scale folds (i.e. Gennargentu Antiform), where F$_3$ folds display S-SW dip of the axial plane and not toward the N-NE as well explained by previous knowledge (Corsi et al., 2004; Montomoli et al., 2018). Thus, all F$_2$ folds display a S-SW vergence, but they are antithetic synforms and synclinal antiforms (see the Main Map). The last D$_4$ phase is associated with gentle to open folds, with sub-horizontal axes and axial planes (Figure 2(h)). Locally, some minor-scale kink-folds occur. No axial plane and metamorphic mineral assemblage related to the D$_4$ phase has been observed. A late brittle deformation with N-S striking faults has been recognized.

6. The Barbagia Thrust

In the mapped area, the BT is characterized by a h-m thick mylonitic zone. The BT-related structures (D$_2$) overprint both metasedimentary and metavolcanic or metavolcanoclastic rocks of the MSU and metasandstone, metasiltstone, and metapsammite of the BU. In both units, a variation in structural style moving toward the BT across the deformation gradient is recognizable. The intensity of deformation increases toward the BT, where folds become tighter and lineation more pervasive; contemporaneously, the spacing between foliation domains decreases. Approaching the high-strain zone, the mylonitic foliation obliterates the previous D$_3$ structures, thus they are rarely detectable. Kinematic indicators, including C-C’-S fabric and asymmetric porphyroclasts of quartz or feldspar indicating a general top-to-the S-SW normal sense of shear with local variation to SE have been recognized (Figure 3(a)).
Figure 2. Outcrop and microscale view of the main structural features. The structural equal-area projections (lower hemisphere) of the $S_2$ poles and $L_2$ (d), $A_2$ (e), $A_3$ (f) and $A_4$ (h) axes are shown. (a) Microscopic evidence of $S_2$ gradational crenulation cleavage. $S_0$ bedding and $S_1$ foliation, parallel to $S_0$, are also present. (b, c) $S_2$ spaced foliation at both meso- and microscale (XPL: crossed-polarized light). In the thin section, $S_1$ is marked by Wm + Chl. (d) Fine continuous $S_2$ foliation is defined by Wm + Chl (XPL). (e) $F_2$ fold, deforming the $S_0$/$S_1$ foliation in metasedimentary rocks belonging to the BU. (f,g) $F_3$ folds, deforming the $S_2$ foliation in metasedimentary rocks belonging to the MSU. No clear $S_3$ axial-plane foliation in the $F_3$ hinge zone is recognizable. (h) Late open folds ($F_4$) with sub-horizontal axes and axial planes deforming $S_2$ spaced foliation.
Sheared metavolcanic rocks belonging to MSU are characterized by a progressive grain-size reduction and a transition from mylonite to ultramylonite along a deformation gradient towards the centre of the shear zone (Figure 3(b)). The foliation wraps around rotated plagioclase and feldspar porphyroclasts. Feldspar shows undulose extinction and rare flame perthite. In ultramylonite, quartz recrystallization mechanism could not be detected due to its extremely small grain size and phase-mixing with mica.

In metasedimentary rocks from both nappes, the intensity of deformation increases going toward the BT. The spacing between foliation domains decreases, and at the same time, the foliation varies from a spaced/disjunctive cleavage to a continuous cleavage (Figure 3(c)). The mylonitic foliation is defined by elongated quartz grains and phyllosilicate-rich levels. Phyllosilicate layers are dominated by chlorite + white mica. In the farthest samples from the BT, quartz shows a strong undulose extinction, deformation bands, small new-grains and rare brittle deformation features. These structures indicate that the bulging mechanism (BLG) is the main dynamic deformation mechanism (Law, 2014; Stipp et al., 2002). However, quartz often shows elongated sub-grains with new quartz grains of smaller size surrounding larger grains, generating a bimodal grain size, indicating the presence of subgrain rotation recrystallization (SGR) mechanism.

7. Final remarks

The new geological map at 1:10.000 scale is the most detailed, currently available representation of the geo-structural setting of this sector of the Nappe Zone in the Sardinian Variscan Belt. Two juxtaposed units have been distinguished: the lower one represented by the Meana Sardo Unit and the upper

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**Figure 3.** (a) Mesoscopic kinematic indicators of mylonites belonging to the Barbagia Thrust indicating a top-to-the S-SW sense of shear. (b,c) Structural variation going toward the Barbagia Thrust in both units. (b) variation from mylonites (on the left) to ultramylonites (on the right) in metavolcanic rocks belonging to the MSU. (c) Progressive variation of the foliation from spaced cleavage to a continuous cleavage moving toward the BT in metasedimentary rocks.
one testified by the Barbagia Unit. The contact in between, the Barbagia Thrust (Carosi & Malfatti, 1995; Carosi & Pertusati, 1990; Montomoli et al., 2018; Petroccia et al., 2022), is marked by a pluri-m-thick mylonitic zone affecting both units. Detailed mapping, coupled with multi-scale structural observations, allowed the definition of a polyphase evolution (Figure 4), consisting of three ductile deformation phases developed under a contractional tectonic regime and the fourth one under extensional conditions. The D1 tectonic phase is associated with greenschists-facies paragenesis. In the study area, these structures were obliterated during the D2 phase and, therefore, it is not possible to constrain with precision their kinematics and geometry. According to Carosi et al. (2004), the D1 phase can be related to the early stage of collision. The prominent deformation phase (D2) is responsible for the development of the main foliation (Figure 5(a)), pervasive at all scales (S2). It becomes more mylonitic moving toward the BT and displays several kinematic indicators with a main top-to-the S-SW normal sense of shear (Figure 5(a)). Indeed, we detected an increase in the strain gradient moving from the structurally higher parts of the BU and from the structurally lower parts of the MSU toward the BT high-strain zone. The S2 foliation is marked by greenschists-facies mineral assemblage (Wm + Chl). Both BLG and SGR mechanism has been detected (Law, 2014; Stipp et al., 2002). The presence of MSU and BU highly sheared rocks deformed under non-coaxial mylonitic conditions (Figure 5(b)) and the emplacing of the MSU and BU with a topto-the S-SW normal sense of shear during the N-S shortening agree with previous investigations (e.g. Carosi et al., 2004; Conti et al., 2001; Montomoli et al., 2018). The D2 phase is linked to the syn-nappe stacking and exhumation of the BU (Montomoli et al., 2018). After the crustal thickening and the nappe-stacking evolution, all the previous structural elements are widely deformed by weakly asymmetric to upright D3 folds (Figure 5(a)). Folds show nearly-vertical axial planes, and therefore no clear transport direction can be associated with this event. However, if we admit that the shortening direction had to be perpendicular to the axial planes and to the trend of fold axes, D3 phase had a similar shortening direction to the D2. Restoring the original pre-Gennargentu Antiform attitude of the D2 fold structures detected in the investigated area, F2 show a SW-S verging anticlinal antiforms and synclinal synforms highlighting a top-to-the S-SW sense of transport. This also agrees with the S-SW sense of shear and the fold polarity detected within the Monte Santa Vittoria area, in the southern limb of the Barbagia Synform (Carosi et al., 2004; Montomoli et al., 2018). Thus, the presence of the BT mylonitic zone in the different sectors of the Barbagia Synform, with the same structural and kinematic features and the similar shortening direction

Figure 4. Synoptic reconstruction of the field and microstructural investigations of the deformation history of the BU and MSU.
between the D$_2$ and D$_3$ phase, confirms the post-nappe stacking folded structure. This architecture, in agreement with the model of Conti et al. (1999) and Carmignani et al. (1994), emphasizes the presence of large-scale structures acquired in a contractional setting during the late deformation stage of crustal thickening and not during the late orogenic extension. Also, the lack of metamorphic mineral growth during the D$_3$, is consistent with the coupling of BU with MSU under greenschist-facies conditions (D$_1$ and D$_2$) and a subsequent antiformal stacking during the regional horizontal shortening under upper-crustal conditions (D$_3$). During the orogenic extensional phase (D$_4$), folds with sub-horizontal axial planes (F$_4$) are recognizable. This geometry suggests the gravitational collapse of the thickened orogen. Different authors (Carmignani et al., 1994; Conti et al., 1999, 2001) highlighted the presence of low- to high-angle normal faults in correspondence of the antiforms limbs displaying an opposite sense of shear and leading to tectonic unroofing of the antiformal hinge zones. However, in the investigated area, no clear BT-parallel extensional structures overprinting BT-related mylonite have been observed.

As a whole, the polyphase history recorded in this sector of the Nappe Zone in Sardinia, summarized in this study, highlights the complex tectonic history that occurred during the evolution of an orogenic wedge. In particular, this area records a pre-, syn- to post-nappe stacking evolution developed under contractional conditions and a late-extensional deformation. We also point out the importance of the BT in the architecture of the Sardinian belt, representing a major tectonic boundary characterized by a well-developed non-coaxial deformation and separating two different sectors of the Sardinian orogenic wedge system.

**Software**

The map has been drawn using QGis 3.16 Hannover, and its final assemblage has been realized with Adobe Illustrator® CC 2018. Structural data have been plotted with the software Stereonet© 10.

**Geolocation information**

The study area is located in the southwestern sector of the Lago Alto del Flumendosa (Sardinia, Italy).
area is placed between 4417800–1532400 and 4421400–1538400; coordinate system: WGS 1984 / UTM Zone 32 N.

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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 and its supplementary materials.

**Disclosure statement**

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