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South Variscan terrane accretion: Sardinian constraints on the intra-Alpine Variscides

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Abstract

Structural data are presented that show that the Sardinian Variscides form the boundary of the Variscan intra-Alpine terrane, thrust onto a Gondwana foreland. This model replaces the currently held hypothesis that the south Armorican suture zone continues into the Sardinian Variscides. The orogenic activity propagated toward the foreland in two distinct waves: (1) thrusting, burial and Barrovian type metamorphism that reached the internal orogen in Late Devonian times and lasted in the external orogen until Early Carboniferous times. Transpressional strain partitioning is suggested by frontal thrusting in the external orogen and lateral displacement in the internal orogen. (2) Normal faulting, exhumation and local Buchan type metamorphism were superimposed on the internal orogen probably since Early Carboniferous times and reached the external orogen contemporaneously with the Late Carboniferous emplacement of voluminous granitic intrusions. Extensional doming and lateral displacement indicate a transtensional regime. The sense of orogen-parallel displacement during both stages was left-lateral on inward dipping movement planes and right-lateral on outward dipping movement planes. The resulting left-lateral displacement between the intra-Alpine terrane and the Gondwana foreland is due to the bending of the Variscan belt, during which the Sardinian segment underwent a bookshelf type movement within an overall right-lateral displacement regime.

Keywords: Sardinia; Variscan Orogeny; Suture zone; Transpression; Transtension; Oroclinal bending

1. Introduction

The Variscan Orogen resulted from the late Paleozoic collision of the high-latitude-derived Gondwanan terranes with the low-latitude terranes of Laurussia (Fig. 1). Paleogeographical reconstructions of this period support a longitudinal drift with right-lateral displacement between both domains in the order of 6000 km (Shelley and Bossière, 2000). Paleomagnetic data indicate significant clockwise vertical-axis rotations of the intervening terranes (Edel, 2001). The Variscan Orogen covers large parts of Europe and is represented by the Avalonian, Armorican and intra-Alpine terrane assemblages (Fig. 2). Their basement consolidated at the Neoproterozoic Gondwana margin during the Avalonian–Cadomian Orogeny (Nance and Murphy, 1994). Avalonia originated from Grenvillian basement of about 1.3–1.0 Ga, and was therefore situated closer to Laurentia than Armorica, which recycled ancient West African crust of about 2–3 Ga (Murphy et al., 2004). The intra-Alpine terrane is thought to be a segment of this Neoproterozoic belt, located east of Armorica on the North African boundary of Gondwana (Von Raumer, 1998).

In early Paleozoic times, Avalonia left Gondwana and collided with Laurentia and Baltica to accomplish the Laurussian terrane assemblage (Caledonian orogeny in Fig. 3). At the same time, Armorica was subjected to a passive margin evolution and rifting within the peri-Gondwanan realm, while the intra-Alpine terrane was still exposed to active margin tectonics (Frisch and Neubauer, 1989; Von Raumer et al., 2002). A mid-Devonian orogenic event coincides with the migration of non-marine fish and flora across the Rheic Ocean (McKerrow et al., 2000). It is preceded by Eo-Variscan high-pressure metamorphism and succeeded by the ultimate closure of the Rheic seaway in Carboniferous times. The post-collisional igneous activity is commonly associated with Buchan type metamorphism and right-lateral wrenching. The orogenic signature of the widespread late Variscan magmatism in the intra-Alpine terrane was probably caused by an active margin (Finger and Steyrer, 1990), facing the Paleotethys Ocean at the SE Variscan flank (Fig. 1).

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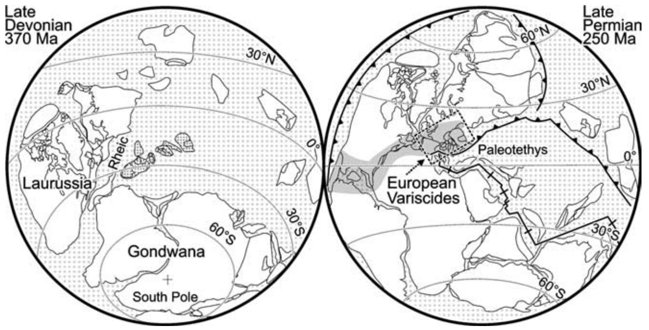

Fig. 1. Paleogeographic reconstructions (after Torsvik and Cocks, 2004; © 2004, with permission from the Geological Society, London), illustrating the right-lateral displacement between Laurussia and Gondwana during Variscan times.

Single- and multiple-suture models have been proposed for the Variscan Orogen in Europe. Biostratigraphic data only support the closure of the Rheic Ocean (Robardet, 2003). Other closed oceans, for example south of the Armorican terrane, are mainly inferred from intercalations of eclogitic and oceanic rocks, thrust over foredeep deposits (Matte, 2001). According to Stampfli et al. (2002), the Paleotethys occupied not only the southeastern, but also the southern vicinity of the European Variscides until early Triassic suturing with Gondwana.

The south European part of the Variscan Orogen became considerably obscured by the superimposed Alpine Orogen. This has made the correlation of the dismembered Sardinian section with other parts of the Variscan belt difficult and highly controversial. On the one hand, the Sardinian section is interpreted as continuation of the south Armorican suture zone (Cappelli et al., 1992). On the other hand, it is inferred to be part of the intra-Alpine area (Matte, 1991), whose entity as suspect terrane is suggested by the mid-Ordovician active margin record (Fig. 3), the presence of recycled basement of Grenvillian age, detected in the Calabria–Peloritan section (Trombetta et al., 2004), as well as by the occurrence of Late Ordovician Baltic taxa in the fold-and-thrust belt of the Sardinian Variscides (Loi and Dabard, 1997). Thus, the intra-Alpine terrane may have become right-laterally displaced from a previously closer vicinity to Baltica to its present position with respect to Armorica during the late Variscan Orogeny (Matte, 2001; Stampfli et al., 2002).

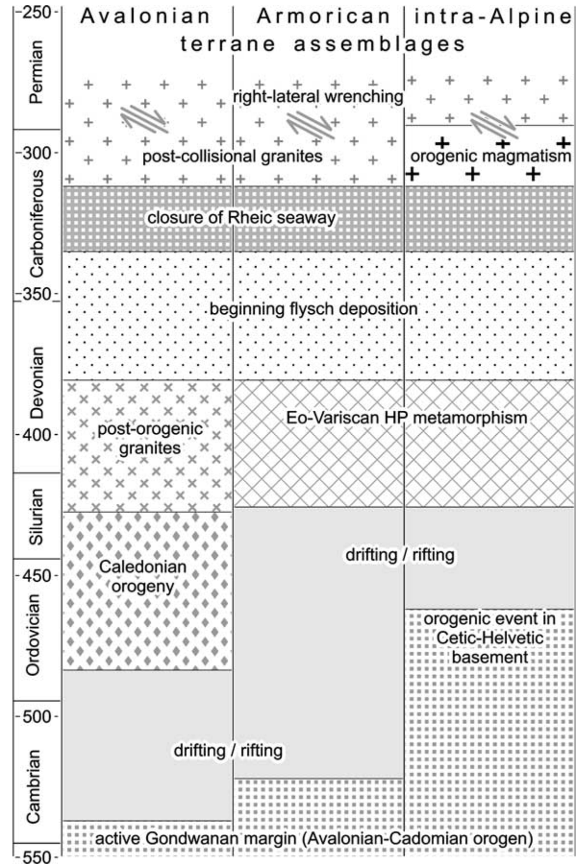

Fig. 3. Schematic tectonostratigraphy of the principal terranes in the European Variscides (modified after Frisch and Neubauer, 1989; Matte, 1991; Von Raumer, 1998; Winchester et al., 2002).

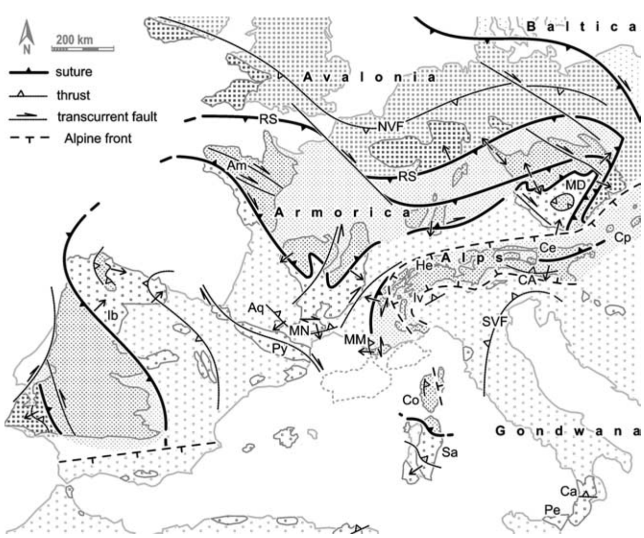

Fig. 2. The principal terranes and sutures in the European Variscides (modified after Cappelli et al., 1992; Matte, 2001; Winchester et al., 2002). The probable Permian positions of Corsica and Sardinia are shown in dotted outline between the European mainland and their present day positions. Am—Armorican massif; Aq—Aquitaine; CA—Carnic Alps; Ca—Calabria; Ce—Cetic basement; Co—Corsica; Cp—Carpathians; He—Helvetic basement; Ib—Iberia; Iv—Ivrea zone, MD—Moldanubian zone; MM—Maures Massif; MN—Montagne Noire; NVF—north Variscan front; Pe—Peloritan; Py—Pyrenees; RS—Rheic suture; Sa—Sardinia; SVF—south Variscan front.

The aim of this study is to determine whether the Sardinian Variscides represent the continuation of the south Armorican suture zone, or instead have their origin within the intra-Alpine terrane assemblage. We critically re-examine the deformation history of the proposed suture zone in NE Sardinia (Cappelli et al., 1992), and correlate it with the metamorphic evolution and radiometric age record. The Alpine reorientation is estimated to reconstruct the pre-Alpine geometry and enable correlations with neighbouring areas. Contrary to Cappelli et al. (1992), our data indicate that there is neither a suture zone in NE Sardinia nor a structural correlation with the south Armorican section.

Instead, we argue that the Sardinian Variscides formed part of the intra-Alpine terrane assemblage, originally located east of Armorica.

1.1. Geological setting

The Variscan basement of Sardinia is exposed in Tertiary rift escarpments and transected by transfer faults (e.g. the Nuoro fault in Fig. 4). The Tertiary overprint and/or reorientation of the Variscan basement occurred in two stages (Helbing et al., in press): (1) counterclockwise rotation of the whole Corsica–Sardinian section into its present-day position (Fig. 2), and (2) curvature of the east Sardinian margin (Fig. 4) due to the detachment of the Calabria–Peloritan section. The differential rotation of the latter stage is marked by post-Variscan dykes, suggesting clockwise and counterclockwise rotations in NE and SE Sardinia, respectively (Fig. 4). Before the Alpine detachment, the Corsica–Sardinian section was connected on the one side with the Variscan belt that is exposed in the Maures Massif and which continues farther in the external massifs of the Western Alps (Westphal et al., 1976; Matte, 1991). On the other side, it was joined to the Calabria–Peloritan section, which was in turn linked to the South Alpine Ivrea section (Schenk, 1981; Handy et al., 1999).

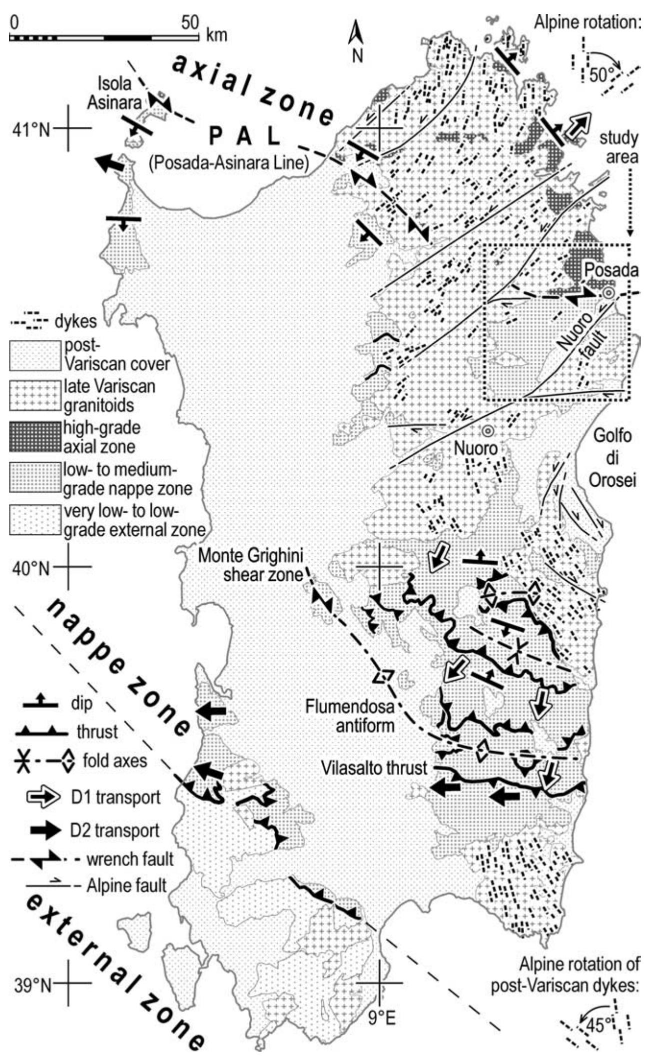

Fig. 4. Structural zoning of the Sardinian Variscides (modified after Arthaud and Sauniac, 1981; Elter et al., 1999; Conti et al., 2001; Carosi and Oggiano, 2002; Helbing et al., in press). The curvature of the Variscan basement at the east coast due to Tertiary transcurrent faulting is illustrated by the rotated post-Variscan dykes. The dotted outline in NE Sardinia indicates the position of the study area, which is shown in more detail in Fig. 5.

The Variscan basement of Sardinia extends from a foreland in the SW (external zone), through a fold-and-thrust belt in the middle (nappe zone), to an axial zone in the NE (Arthaud and Sauniac, 1981). The contrasting early Paleozoic tectonostratigraphies of the foreland and internal zones (nappe zone and axial zone) correlate with the Ibero–Aquitaine and Alpine domain, respectively (Helbing and Tiepolo, 2005).

Relics of eclogite and granulite facies metamorphism in dispersed amphibolite intercalations of the axial zone are interpreted to have an Early Devonian age of circa 415 Ma (U–Pb zircon; Palmeri et al., 2004). Contemporaneously deposited sediments in the nappe zone constitute a subsiding passive margin sequence (Carmignani et al., 1994). Wildflysch deposition commenced in Late Devonian times (post-Early Famennian) and culminated in Early Carboniferous times (Visean; Barca, 1991).

The oldest cooling ages and the onset of post-collisional magmatism show a foreland-directed younging in the Corsica–Sardinian section (Matte, 1991). For example, the Barrovian peak metamorphism in Corsica is constrained by Mid-Devonian ages (Ar–Ar amphibole; Maluski, 1977), shifting to Early Carboniferous ages of about 350 Ma in Sardinia (Ar–Ar amphibole; Del Moro et al., 1991). The first intrusions of the Corsica–Sardinian batholith give Early Carboniferous ages of circa 345 Ma in Corsica (U–Pb zircon; Paquette et al., 2003) and Late Carboniferous ages of circa 310 Ma in Sardinia (Rb–Sr whole rock; Del Moro et al., 1975). The Barrovian metamorphism was followed by a Buchan type metamorphism that locally led to anatexis, defined in Sardinia by Late Carboniferous ages of circa 300 Ma (Rb–Sr whole rock; Macera et al., 1989).

Different models have been proposed for the structural relation between the internal and external parts of the orogen. The nappe zone records first southward, then westward directed thrusting, eventually followed by kilometre-scale open folding that dominates the orogenic trend (Conti et al., 2001). Retrogressive right-lateral wrenching operated contemporaneously with the granitic intrusions (Elter et al., 1990; Musumeci, 1992). Cappelli et al. (1992) proposed that the axial zone was thrust over the nappe zone toward the foreland. However, an early transport in the opposite direction is recorded in the axial zone of the NE Sardinian Golfo di Aranci area (Elter and Ghezzo, 1995). Its deeper crustal level in comparison with the nappe zone is inferred to be the result of exhumation during extensional doming (Elter et al., 1999). The Monte Grighini complex (Musumeci, 1992) in the core of the Flumendosa antiform and the laterally attached

Stephano–Permian molasse basin (Barca et al., 1995) have also been interpreted as expressions of post-collisional extension. In contrast, the formation of the Flumendosa antiform is related by Conti et al. (2001) to ongoing crustal shortening. This study presents new structural data from the NE Sardinian transition between nappe zone and axial zone to elucidate the contentiously interpreted relation between both parts of the orogen.

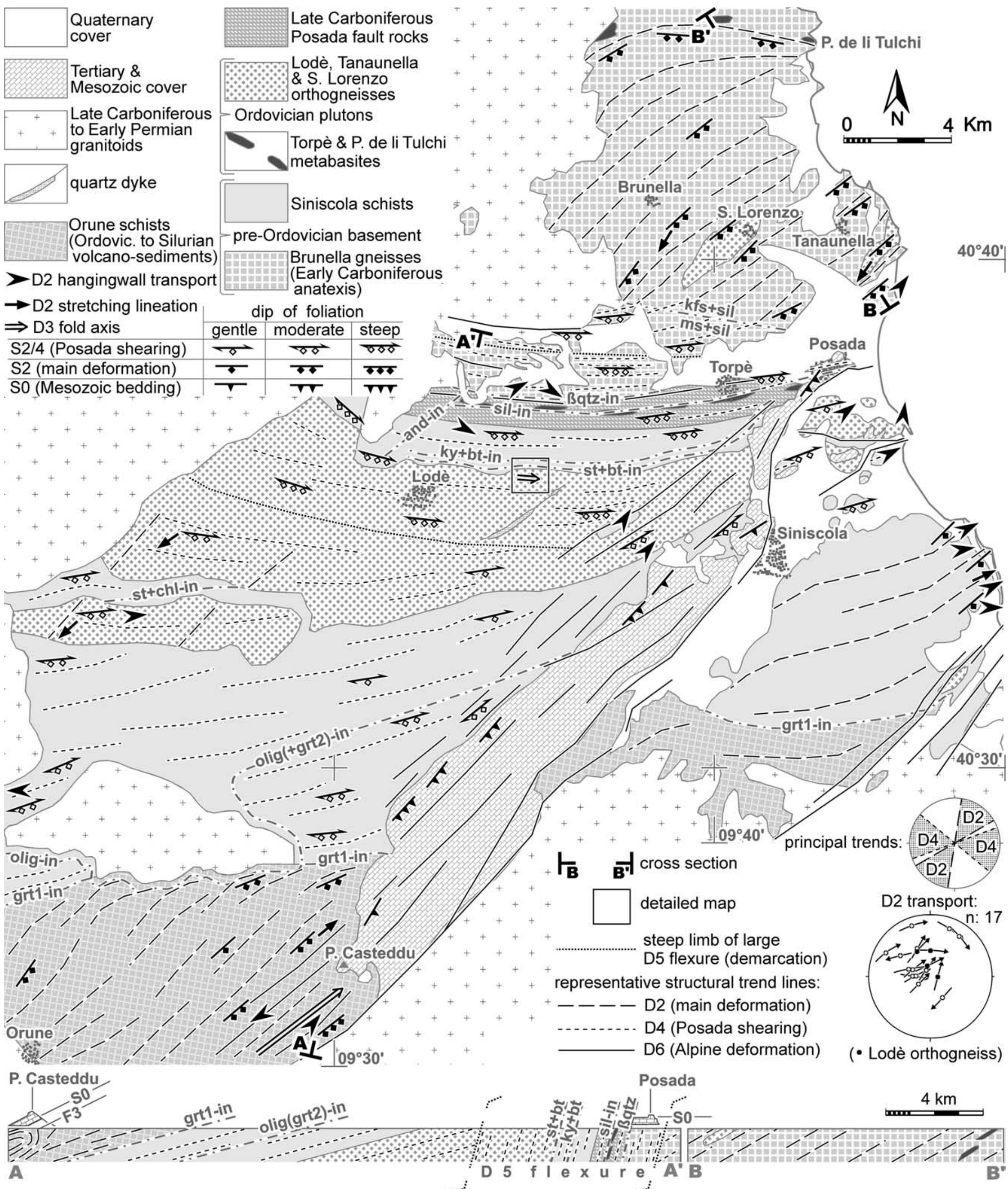

Fig. 5. Structural map (geological base map modified after Barca et al. (1996)) and cross-sections of the NE Sardinian study area (see Fig. 4). Abbreviations of the metamorphic minerals are used throughout this paper after Kretz (1983) in addition to olig for oligoclase. The post-Variscan cover beds of Punta Casteddu and Posada are projected on cross-section A–A′. S2/4 is used to describe a composite layering dominated by S2 and S4. Plane, lineation and direction of the D2 hanging wall transport are shown in equal area, lower hemisphere, stereographic projection after Hoeppener (1955). The outline of the detailed map refers to the section shown in Fig. 11.

1.2. Suture hypothesis

A suture zone, which is generally defined by a belt of mélange, blueschist and/or ophiolite, as well as by distinct geological histories of the sutured plates (Howell et al., 1985), is assumed by Cappelli et al. (1992) to run from south Armorica to north Sardinia. The Sardinian axial zone and nappe zone thus represent the Armorica-derived upper plate and the Gondwana-derived lower plate, respectively. The intervening Posada–Asinara line (PAL) is proposed to delineate the suture, along which the axial zone was eventually thrust over the nappe zone. Subduction of oceanic lithosphere is inferred from amphibolites of MORB origin, interpreted as remnants of an oceanic mélange. An originally inverted metamorphic sequence in the PAL-hosting sequence is believed to be reversed in the overturned limb of a large back fold and eventually overprinted by wrenching.

Major aspects of the suture hypothesis are unconfirmed. For example, the suture hypothesis is put in doubt by the fact that the geological histories of the rocks on either side of the PAL correlate well (Helbing and Tiepolo, 2005), which is inconsistent with the hypothesis that the two sides of the PAL constitute different terranes. Furthermore, the geochemistry of the amphibolites is partly so ambiguous that these rocks could equally well be continental rift basalts (Ricci and Sabatini, 1978), instead of rocks of MORB origin. Finally, post-peak metamorphic cooling began at about the same time on each side of the PAL (Ferrara et al., 1978; Del Moro et al., 1991). This observation is inconsistent with an inverted metamorphic sequence, which would imply a contact effect in the lower plate with simultaneous cooling in the overriding plate. This study critically reexamines the north-over-south lying sequence, metamorphic inversion, back folding, and the supposed oceanic mélange, to show that the suture hypothesis should be rejected.

2. Structure

The overall structural and metamorphic appearance of the NE Sardinian study area is that of a fault-bounded gneiss dome enveloped by a schistose mantle (Fig. 5). Gently plunging fold axes and southward dipping foliations prevail. Low-grade metapelites and metapsammites, interlayered with porphyroids, greenschists, and graphitic schists occur in the south. This sequence, which is referred to as Orune schists, overlies an amphibolite- and orthogneiss-hosting pre-Variscan basement. The basement includes the metapelitic Siniscola schists and the migmatitic Brunella gneisses. The transition between medium-grade Siniscola schists and high-grade Brunella gneisses is defined by the Posada shear zone. The metamorphic rocks are overlain by Mesozoic to Tertiary calcareous rocks along the Alpine Nuoro fault (Fig. 4). Five individual deformation events and three stages of porphyroblast growth can be distinguished that predate the Alpine overprint (Table 1). The earliest deformational and porphyroblastic fabrics (D1 and M1 in Table 1) remain from a pre-Variscan cover–basement

Table 1
Short characterization of deformational events (D1–D6) and porphyroblast generations (M1–M3)

pre-Variscan (Helbing and Tiepolo, 2005):	
D1	Local remnants of continuous cleavage
	Quartz veins coplanar with S1 in phyllosilicate-rich layers
	S1 inclusion trails in first porphyroblast generation
M1	*Garnet, chloritoid (Siniscola schists)*
	Precursor of fibrolite–quartz nodules (Brunella gneisses)
	Post-D1/pre-D2
Variscan:	
D2	NE–SW trend, metamorphic peak fabrics
	Most dominant and pervasive in all metamorphic rocks
	Isoclinal intrafolial folds homoaxial with stretching lineation
M2	*Post-D2/syn-D3 plagioclase (Orune schists)*
	Syn-D2/pre-D3 plagioclase, staurolite, ky (Siniscola schists)
	Syn-D2 to syn-D4 sillimanite (Brunella gneisses)
D3	Well cylindrical D3 folds of originally recumbent attitude
	Hock-shaped refolding pattern (F3 is homoaxial with F2)
	Most prominent in Orune schists, northern Lodè orthogneiss
D4	Non-coaxial, E–W trend, focused in Posada shear zone
	Northern wallrocks: medium-grade retrogression
	Southern wallrocks: low-grade retrogression (C′-type shear bands)
D5	Local, upright refolding and steep crenulation cleavage
	Steep belt, in which the Posada fault rocks crop out
	Homoaxial with D4 stretching lineation
M3	*Post-D5 andalusite (contact aureole of granitoids)*
post-Variscan:	
D6	Brittle deformation of pre-Mesozoic to Tertiary rocks
	Tilted sedimentary bedding in post-Variscan cover
	Focused in the Alpine Nuoro fault and subordinate branches

assemblage (see Helbing and Tiepolo, 2005). The subsequent structural and metamorphic events are described below, while orientation data are shown in Fig. 6 and summarized in Table 2.

2.1. D2 (main deformation)

A continuous D2 cleavage, superimposed on intrafolial folds, forms the most pervasive fabric in the study area. A fold-axis–parallel stretching lineation is defined by aligned quartz grains and additionally by the alignment of phenocrysts in the meta-igneous rocks and the first porphyroblast generation in the pre-Variscan basement. The D2 structures are least affected by subsequent deformational overprints in the Orune schists and Brunella gneisses, where they trend NE–SW (zones 1 and 7 in Fig. 6). The D2 stretching lineation is also preserved with similar trend in parts of the southwestern Lodè orthogneiss (zone 3 in Fig. 6). D2 folds are absent in the meta-igneous rocks, probably due to insufficient primary anisotropy.

D2 reflects the rising peak-metamorphic conditions from low-grade in the south to high-grade in the north. For example, the temperature for incipient feldspar recrystallization (~500 °C; Voll, 1976) was not exceeded in the Orune schists, where feldspar phenocrysts in meta-igneous rocks underwent brittle deformation. In the Lodè orthogneiss, K-feldspar augen marginally recrystallized. High-grade indicators, such as lobate quartz–feldspar grain boundaries (Gower and Simpson, 1992) and high-quartz-derived chess board subgrain patterns

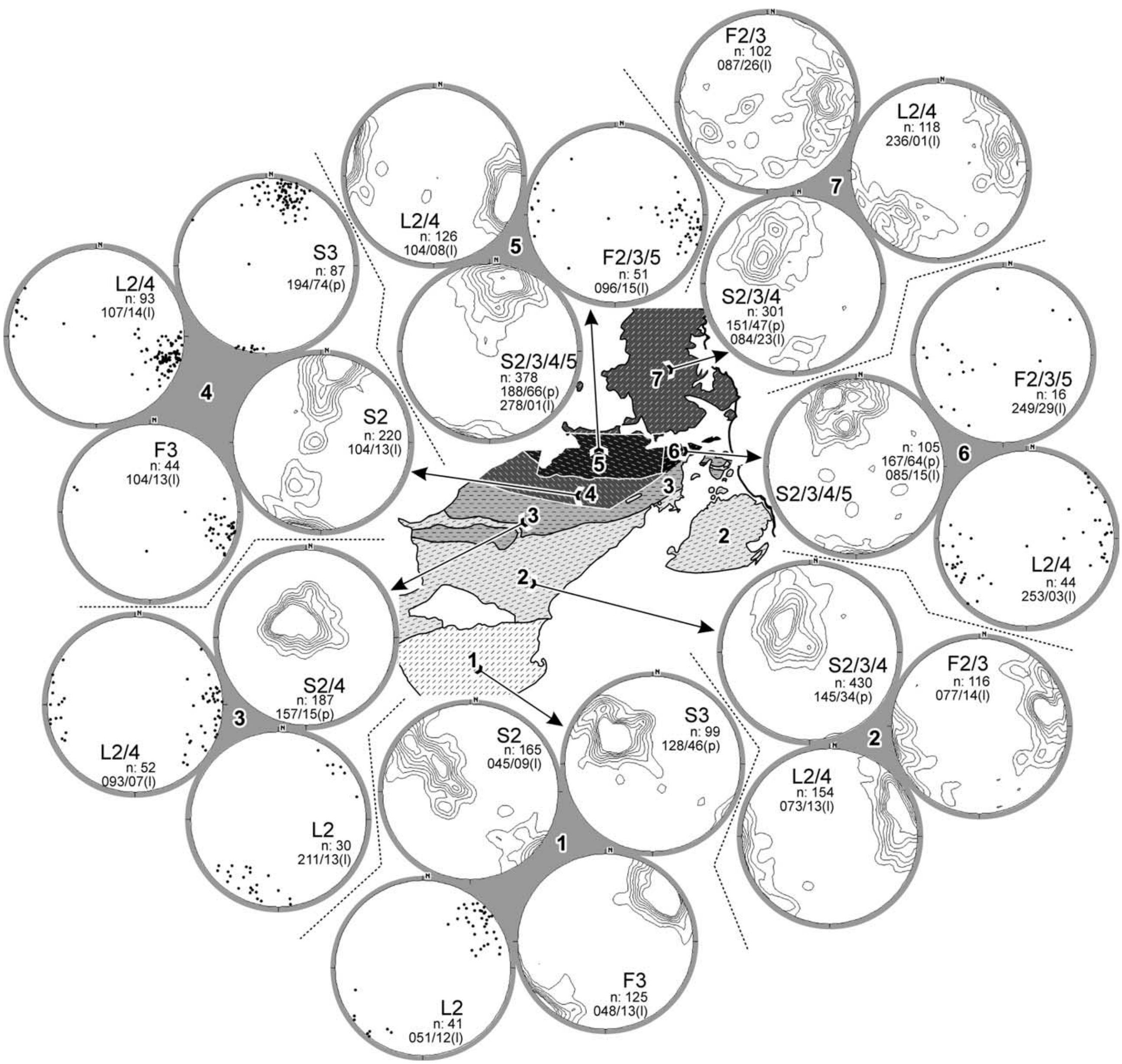

Fig. 6. Structural zones of the NE Sardinian study area (Fig. 5) with corresponding orientation of foliations, fold axes, and stretching lineations, stereographically projected on equal area lower hemispheres. Up to seven contour levels with intervals of 1.0 multiples of random distribution are counted by cosine powered weighting function (Adam, 1989). The poles of the best fit girdles and/or weighted averages are calculated after Woodcock (1977). Data interpretation is outlined in Table 2 and in detail explained in the text.

(Kruhl, 1996), are common in the Brunella gneisses and a stromatic layering with structures of high complexity remains in the migmatites.

A non-coaxial shear component is locally preserved, mainly as an asymmetric lattice preferred orientation in quartz. The lattice preferred orientation patterns confirm the northward increasing temperatures during D2 (Fig. 7a). In places of the Lodè orthogneiss, C-type shear band cleavages (terminology after Passchier and Trouw, 1996) and K-feldspar phenocrysts with σ-clast morphology and/or asymmetric myrmekites also indicate the D2 shear sense. The reorientation of the shear sense indicators by the subsequent D3 refolding has been constrained in the Orune schists (Fig. 7b). Taking the absence of the D3 folds in the southern and eastern Lodè orthogneiss into account (see Section 2.3), the shear sense indicators delineate a D2 stretching lineation-parallel hanging wall transport to the NE (Figs. 5 and 6).

2.2. M2 (peak-metamorphic porphyroblast growth)

The distribution of metamorphic zones suggests a progressive and prograde metamorphic evolution (Fig. 8). The southward decreasing grade is inferred to reflect a normal metamorphic sequence, based on the prevailing southern dip in conjunction with the stratigraphically higher level represented by the pre-Variscan cover in the south.

Table 2
Explanation of the stereo plot data and structural zoning in the study area (Fig. 6)

Zone 1 (western Orune schists):
Alpine-reactivated NE–SW trend, reoriented (tilted) dip
Cylindrical D3 folds homoaxial with D2 stretching lineation
Well developed F3 axial plane cleavage
Zone 2 (Siniscola schists south of the Lodè orthogneiss):
Appearance of D4 shear bands (C′-type): composite layering
E–W trend in the west (see Fig. 5)
Reorientation at Nuoro fault: E–W into NE–SW trend, tilting
Zone 3 (southern and eastern Lodè orthogneiss):
NE–SW-trending D2 stretching lineation in the west (Fig. 5)
Gently dipping S2/4 (layering of S2 and D4 shear bands)
Reorientation at Nuoro fault: E–W into NE–SW trend, tilting
Zone 4 (northern and northwestern Lodè orthogneiss):
Steepened dip in large D5 flexure
Reappearance of cylindrical F3 and S3 in the north
F3 homoaxial with D2 stretching lineation
Zone 5 (western Posada fault rocks with adjacent Siniscola schists and Brunella gneisses):
Steep dip related to the large D5 flexure
Composite fabrics of D2–D5
Dominant WNW–ESE trend
Zone 6 (eastern Posada fault rocks with adjacent Siniscola schists and Brunella gneisses):
Steep dip related to the large D5 flexure
Dispersed cluster due to Alpine overprint
Reorientation at Nuoro fault: WNW–ESE into NNE–SSW trend
Zone 7 (Brunella gneisses north of D5 flexure):
More dispersed than other zones, partly because of anatexis
Reappearance of NE–SW trend

Peak-metamorphic porphyroblast growth is observed to be syn- to post-kinematic with respect to D2 (Fig. 9). Fibrous sillimanite in the Brunella gneisses is associated with peak-metamorphic and retrograde fabrics (see Section 2.4). This continued growth under retrograde conditions might be explained by post-anatectic hydrogen metasomatism (Wintsch, 1975; Vernon, 1979). In the Orune schists, the relative timing of the plagioclase porphyroblasts is post-D2 to syn-D3, thus slightly later than in the Siniscola schists. This delay is inferred to be an expression of the longer duration until the necessary metamorphic conditions for the plagioclase porphyroblast growth reached the most external segment of the studied sequence.

The abundant growth of plagioclase at the expense of white mica in the Orune and Siniscola schists is a common phenomenon under decompressional metamorphic conditions (Jamieson and O'Beirne-Ryan, 1991). Indeed, such conditions are confirmed by the decompressional muscovite dehydration melting in the Brunella gneisses (Helbing, 2003). The decompressional plagioclase growth is associated with progressive albite replacement by oligoclase and prograde myrmekite formation along the oligoclase-in isograd. In agreement with thermo-barometric data (e.g. Ricci, 1992), this decompression is inferred to have taken place when temperatures were still rising or reached their peak.

2.3. D3 (refolding)

D3 involved the refolding of the main fabric. The axes of the similar D3 folds are parallel to the D2 stretching lineation and to the D2 fold axes, forming hook-shaped refolding patterns. A D3 axial plane cleavage is commonly associated. The refolding affected the study area in varying intensity. D3 folds are very prominent in the Orune schists (zone 1 in Figs. 6

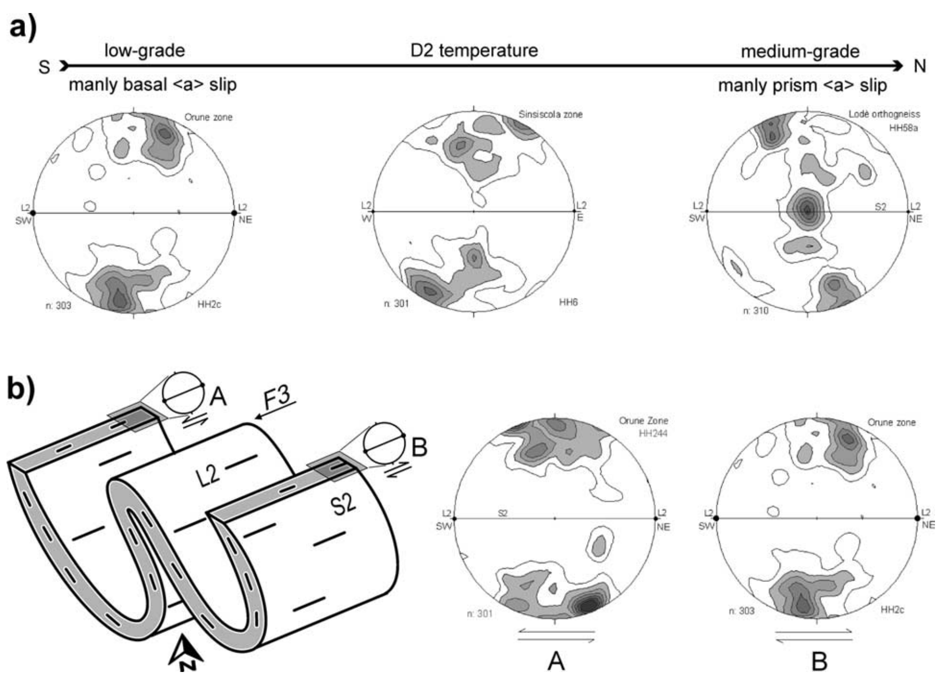

Fig. 7. Lattice preferred orientation of D2 quartz fabrics (c-axes are projected and contoured as in Fig. 6). (a) The change from mainly basal ⟨a⟩ slip in the Orune schists to prevailingly prism ⟨a⟩ slip in the Lodè orthogneiss reflects the northward increasing D2 temperatures (Passchier and Trouw, 1996, and references therein). (b) The relation of D2 shear sense and D3 refolding is shown.

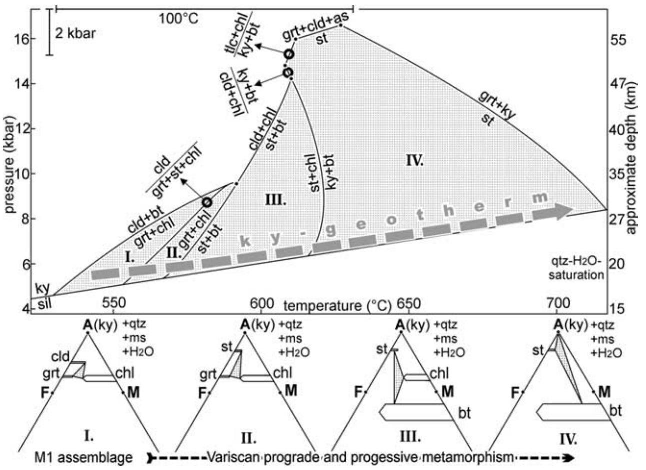

Fig. 8. Mineral assemblages of the Siniscola schists are shown in AFM projections and corresponding P–T grid after Spear and Cheney (1989).

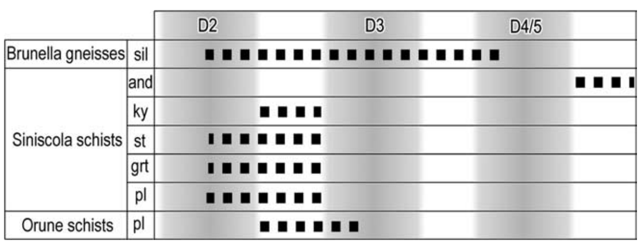

Fig. 9. Relative timing of porphyroblast growth and deformation (M2–M3 and D2–D5, see Table 1).

and 10), where the overturned and normal limbs of a kilometric first order fold are deduced (Fig. 5) from the changing S- and Z-shapes of subordinate folds and the spatial relation between axial plane cleavage and refolded foliation. The refolding becomes less prominent in the Siniscola schists, disappears in the southern and eastern Lodè orthogneiss (zone 3 in Fig. 6) and eventually reappears at the northern orthogneiss margin (zone 4 in Fig. 6), where it intensifies towards the contact with the Siniscola schists (Fig. 11).

The D3 strain localization appears to be controlled by the limiting supply of hydrous fluids under retrograde metamorphic conditions. Hydrous fluids produced by still ongoing dehydrational plagioclase growth (Fig. 9) may have facilitated D3, but only in the Orune schists. The intensifying D3 folds in the northern Lodè orthogneiss might reflect a hydrous fluid supply through the pathway provided by the contact with the Siniscola schists. Associated replacement of feldspar by muscovite and fold tightening are attributed to retrogression and volume loss by pressure solution due to the localized supply of these hydrous fluids. The general absence of larger D3 folds north of the Orune schists is consistent with the unfolded outline of the isograds on larger map scale (Fig. 5).

2.4. D4 (Posada shearing)

Non-coaxial D4 shearing is associated with retrograde alteration and a clockwise reorientation of the D2 trend into a Posada shear zone-parallel trend (Fig. 5). D4 caused variably transposed fabrics. In the southern Siniscola schists, the appearance of C′-type shear bands are the first indications of D4, which intensify towards the Posada shear zone. The shear bands indicate a hanging wall transport to western directions or, if the composite D4 foliation has a steep attitude, a right-lateral displacement. Comminution of the metamorphic porphyroblasts in conjunction with sericitization, saussuritization and chloritization led to the transformation of the medium-grade Siniscola schists into low-grade fault rocks, such as mylonites, cataclasites and, eventually, phyllonites in the most advanced stage of retrogressive deformation (Fig. 12).

In contrast to the southern wallrocks of the Posada shear zone, shear bands are uncommon in the Brunella gneisses, which underwent medium-grade retrogression, characterized by the appearance of retrograde muscovite, the stability of sillimanite, and the recrystallization of feldspar. This retrogression coincides with the sillimanite + muscovite zone (Fig. 5). The Brunella gneisses and the Torpè metabasites developed a strongly pronounced layering of quartzofeldspathic domains that alternate with mica and/or amphibole domains, respectively. The content of clasts, boudins and enclaves rises towards the shear zone. Their alignment and the one of fibrous sillimanite contribute to the D4 stretching lineation. The Torpè metabasites resisted the final low-grade retrogressive deformation that overprinted part of the Brunella gneiss-derived fault rocks.

2.5. D5 (doming)

A large flexure is outlined by the D2–D4 composite layering that first turns from a gentle and/or moderate dip to a steep dip in

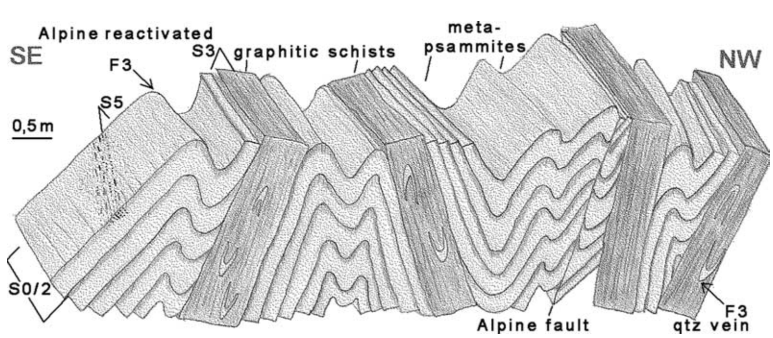

Fig. 10. Drawing of D3 folds in the Orune schists. The incompetent graphitic schists have accommodated Alpine reorientation by frictional slip along the D3 cleavage planes, passively rotating the competent metapsammites.

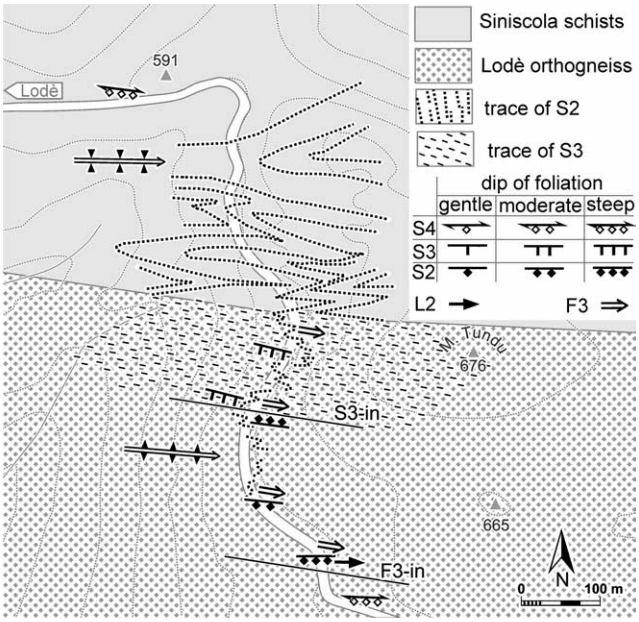

Fig. 11. Detailed map indicated in Fig. 5, illustrating the intensifying D3 refolding by progressive tightening and/or appearance of D3 folds and axial plane cleavage towards the contact of Lodè orthogneiss and Siniscola schists. The D3 folds in the Siniscola schists are redrawn from aerial photographs.

the Lodè orthogneiss and returns to a moderate dip again in the Brunella gneisses (Fig. 5). Besides the large flexure, a crenulation cleavage developed without corresponding folds in the Orune schists (S5 in Fig. 10). Towards the north, buckle folds locally formed. Parallelism of D5 structures with the displacement direction in the Posada shear zone and the position of the Posada shear zone in the steep limb of the large flexure both delineate a transtensional configuration, which is inferred to have accommodated doming of the axial zone by simultaneous flexuring and lateral shearing. This implies that D4 and D5 are expressions of the same exhumation process and that the Posada shear zone initially had a lower inclination. The flexure geometry suggests that the vertical displacement during doming corresponds to at least the 7-km-width of the steep limb. When the doming ceased, the studied sequence was already exhumed up to shallow crustal levels, as indicated by the andalusite in the contact aureole of the late Variscan granitoids (Fig. 9). This contact metamorphism constitutes the third metamorphic event (M3).

2.6. D6 (Alpine deformation)

The D6 Alpine deformation along the Nuoro fault and subordinate branches reactivated the D2 trend and deflected the D4 trend (Fig. 5). Resulting changes in strike contribute to girdle distributions of the orientation data (Fig. 6). D6 progressed from the Nuoro fault into the entire study area along a network of widespread minor brittle faults. Schistose domains accommodated the Alpine reorientation by frictional slip along the cleavage planes (Fig. 10). The tilting component of the Alpine deformation can be estimated from the inclination of the bedding in the Mesozoic to Tertiary cover (Fig. 5). The orientation of this bedding implies for the pre-Mesozoic orientation of the Variscan structures: (1) a gentle southern inclination of the D3 folds and of the composite D4 layering outside the D5 flexure, and (2) an upright to steeply southward dipping attitude of the D5 structures.

3. Discussion

Our investigations reveal a high-grade gneiss dome (axial zone) bounded by a retrogressive shear zone (PAL) and mantled by medium- to low-grade schists (nappe zone), thus confirming the overall dome structure proposed by Elter et al. (1999). The stratigraphical, structural and petrological data rule out a north-over-south lying sequence with an inverted metamorphic gradient, as postulated in the suture hypothesis of Cappelli et al. (1992). The orientation, scale and morphology of the D3 refolding also rule out that the studied sequence as a whole is overturned by a large back fold. It has been further shown that the Posada fault rocks evolved from the wall rocks by deformation under retrograde conditions. There is no evidence for the occurrence of an oceanic mélange.

The suture hypothesis of Cappelli et al. (1992) cannot be upheld with the structural data presented here. As mentioned before, the ambiguous geochemistry of the amphibolite intercalations is insufficient to distinguish a MORB or intra-continental rift basalt origin. The similar pre-Variscan history and contemporaneous Variscan peak metamorphism on either side of the PAL are further evidence in contradiction of the suture hypothesis. The continuous Mid-Devonian to Early Permian evolution of the Corsica–Sardinian section precludes an interruption by a suture zone. Nevertheless, suturing could have occurred before this period, where the foreland directed younging begins, which is more internally than the section under consideration here. The Early Devonian relics of eclogite and granulite facies (Palmeri et al., 2004) in the dispersed amphibolite intercalations of the axial zone may derive from this initial event. The contemporaneous passive margin environment in Sardinia (Carmignani et al., 1994) indicates a distant origin of these eclogitic relics.

The Sardinian example shows, in agreement with Shelley and Bossière (2002), that an overthrust foreland together with intercalations of oceanic and/or eclogitic rocks is not enough to locate a closed ocean. Considering the enormous transcurrent displacements during the Variscan Orogeny (Fig. 1), the intercalations could very well be dismembered and shuffled laterally into the Sardinian section. To prove the existence of a closed ocean, the igneous and sedimentary record of a corresponding active margin needs to be identified, which is not the case in Sardinia.

3.1. Tectono-metamorphic evolution

Prograde stage: The main deformation event (D2) is superimposed on earlier metamorphic fabrics (D1, M1 in Table 1) of a pre-Variscan cover–basement assemblage (Helbing and Tiepolo, 2005). The origin of the progressive and prograde M2 metamorphic sequence (Fig. 8) is explained by syn-collisional thrusting and burial during the Variscan

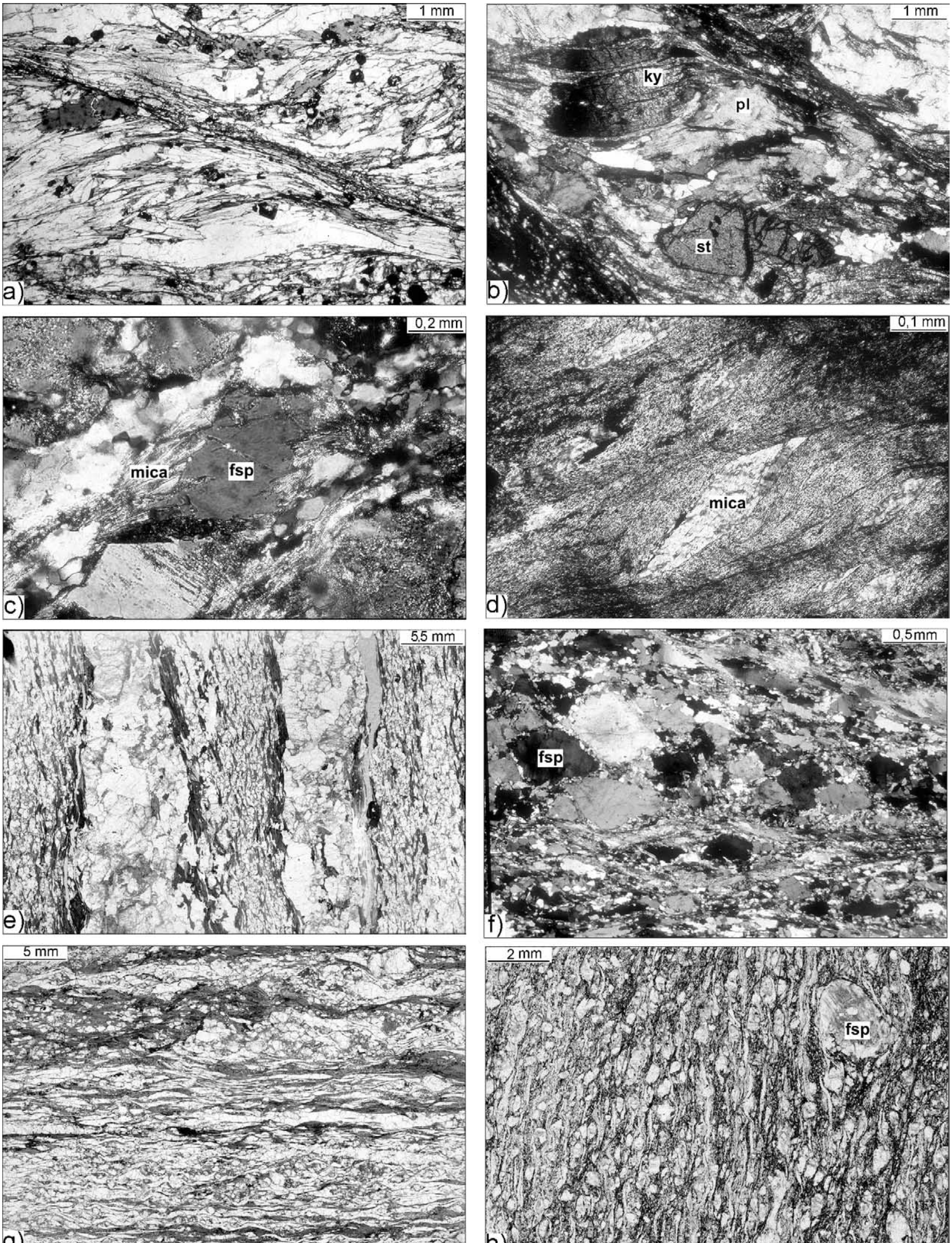

Fig. 12. Photomicrograph series of wall-to-fault-rock transformation (hanging wall (a)–(d); footwall (e)–(h)). (a) composite S2/4 of main foliation and shear band, Siniscola schist, plane-polarized light, (b) comminution of M2 porphyroblasts, progressing from shear bands into microlithon, Siniscola schist, crossed polars, (c) retrogressive replacement of feldspar by mica, Posada fault rock, crossed polars, (d) phyllonite with mica fish in quartz–chlorite–sericite groundmass, Posada fault rock, crossed polars, (e) leucosome with biotite selvages, Brunella gneiss, plane-polarized light, (f) former feldspar porphyroblast divided by conjugating fracture sets into lozenges that are mantled by smaller recrystallized feldspar, Posada fault rock, crossed polars, (g) mylonitizised gneiss, Posada fault rock, plane-polarized light, (h) protomylonite, Posada fault rock, plane-polarized light.

Orogeny. Decompressional melting in the axial zone and decompressional plagioclase growth in the nappe zone of the study area are related to the beginning of post-collisional exhumation. Given the syn-kinematic character of these features, D2 is associated with the compressional to decompressional prograde regional metamorphism recorded in the study area.

The prograde evolution is post-dated by the first Early Carboniferous cooling ages (Ferrara et al., 1978; Del Moro et al., 1991). The retarded porphyroblast growth and the ongoing folding (D3 refolding) in the external part of the studied sequence are consistent with the foreland-directed younging of orogenic events, as noticed by Matte (1991). Major pre-Carboniferous exhumation and erosion are confirmed by the Late Devonian onset of wildflysch deposition in southern Sardinia (Barca, 1991). While thrusting and flysch deposition culminated in southern Sardinia, advanced post-collisional thinning of the previously thickened crust is recorded by the shallow intrusion level of Early Carboniferous granitoids in north Corsica (andalusite–biotite contact aureole; Ferré and Leake, 2001). Apparently, the foreland-migrating front of crustal shortening was followed by a front of crustal extension.

The abundance of high-quartz relics in the axial zone may reflect a late rise of the geothermal gradient, which is supported by the late Carboniferous Buchan type metamorphism observed elsewhere in the Sardinian Variscides (Macera et al., 1989; Del Moro et al., 1991). Geothermobarometric data from the axial zone in the study area confirm such a late rise in the geothermal gradient (Helbing, 2003, and references therein).

Retrograde stage: Posada shearing (D4) was initiated when the schist–gneiss transition zone underwent medium- to low-grade retrogression. The rheological contrast between viscous flow in the footwall gneisses and semi-frictional flow in the highly anisotropic hanging wall schists probably enhanced the detachment along the intervening Posada shear zone. The medium-grade retrogressive deformation of the footwall is manifested in the development of the muscovite + sillimanite zone (Fig. 5).

During the shearing, the temperature difference between footwall gneisses and hanging wall schists was overcome (see Section 2.4). D4 shearing and D5 doming are thus referred to cooling and further exhumation into upper crustal levels. This is consistent with the development of the andalusite-bearing contact aureole during the subsequent intrusion of the Late Carboniferous granitoids. Ar–Ar muscovite ages that are younging from 340 Ma (Early Carboniferous) in the hanging wall schists to 300 Ma (Late Carboniferous) in the footwall gneisses (Di Vincenzo et al., 2004), confirm true crustal extension (Wheeler and Butler, 1994) accommodated by the Posada shearing and the associated doming. These ages display the distinct cooling histories of the hanging wall and footwall, and date two distinct retrogression and/or cooling events. The first one is recorded by the muscovite in the hanging wall and postdates the Middle to Late Devonian regional metamorphism of Barrovian type, whereas the second one is recorded by the muscovite in the footwall and postdates the Late Carboniferous metamorphism of Buchan type.

3.2. Structural correlation with the external orogen

As mentioned before, the Alpine reorientation of the Variscan basement in Sardinia comprises a counterclockwise rotation of the whole Corsica–Sardinian section into its present-day position (Fig. 2), followed by the curvature of the east Sardinian margin. The differential rotation of the latter stage is marked by post-Variscan dykes (Fig. 4). Undoing the 50° clockwise rotation of NE Sardinia during the latter stage, in order to enable the structural correlation with the other parts of the Sardinian Variscides, changes the present-day high-angle D2 trend with respect to the foreland-facing thrust front into a pre-Alpine D2 trend at low-angle to the foreland-facing thrust front, whereas the D4 trend, presently at low-angle to the foreland-facing thrust front, gives a pre-Alpine D4 trend at high-angle to this front (Fig. 13).

The currently NE-directed D2 hanging wall transport in the study area agrees with the early displacement determined by Elter and Ghezzo (1995) in the NE Sardinian Golfo di Aranci area. Taking the abovementioned reorientation into account, the non-coaxial D2 shear component suggests a pre-Alpine hanging wall transport approximately in the northwestern direction and/or a left-lateral displacement between internal orogen and foreland (Fig. 14). Such an approximately orogen-parallel trend is common in internal zones of orogenic belts and traditionally explained by transpression (Harland, 1971). Frontal thrusting in the external orogen and lateral displacements in the internal orogen (Fig. 14) are thus interpreted as transpressional strain partitioning.

The contrasting deformation in these supra- and infrastructural levels is, for example, illustrated by the orientation of the fold axes with respect to the stretching lineation, changing from perpendicular in the external orogen (Conti et al., 2001) to parallel in the internal orogen (Fig. 6). Moreover, the structural style changes most obviously at the greenschist to amphibolite facies transition as the large recumbent fold nappes, which are typical of the nappe zone, are absent in the axial zone (cross-section in Fig. 5).

The aforementioned change from crustal shortening to subsequent crustal extension (Section 3.1) is well-known in subduction rollback settings (Durand et al., 1999). However, further research is needed to prove whether this change represents rollback or foreland-propagating extensional collapse. Thinning of the lower lithosphere below the back arc

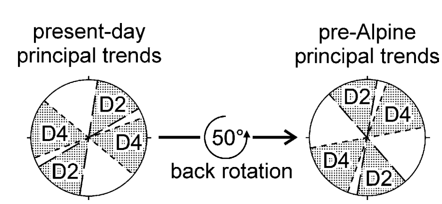

Fig. 13. Stereo plots of the Variscan basement trends in NE Sardinia in present-day orientation (Fig. 5) and in pre-Alpine orientation, restored according to the rotation of the post-Variscan dykes, as shown in Fig. 4.

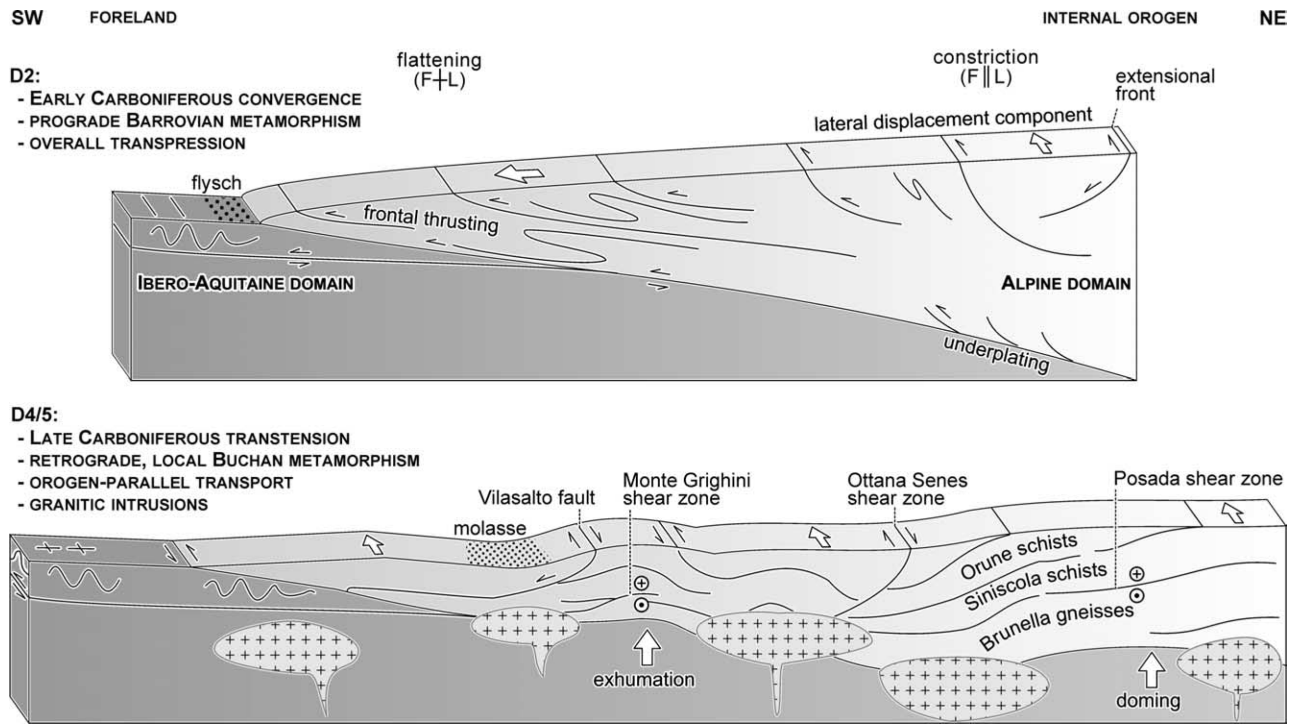

Fig. 14. Sketch of the two principal orogenic stages in the Sardinian Variscides. Note the opposite sense of lateral displacement on outward and inward dipping movement planes.

and/or internal orogen would increase the potential energy with respect to the fold-and-thrust belt (Platt and England, 1994). This is likely to drive crustal extension in the back arc and/or internal orogen, compensated by shortening in the foreland-overriding fold-and-thrust belt (Fleitout and Froidevaux, 1982). Lithospheric thinning below the back arc and/or internal orogen, with or without rollback, could explain the formation of the Corsica–Sardinian batholith in a Paleotethys subduction setting at the SE Variscan flank, as proposed by Finger and Steyrer (1990).

The pre-Alpine high-angle trend of the PAL with respect to the foreland-facing thrust front in SW Sardinia is a phenomenon restricted to NE Sardinia, because the Variscan basement to the west of the study area was not subjected to the differential rotation marked by the post-Variscan dykes in E Sardinia (Helbing et al., in press). The original along-strike curvature of the PAL further highlights the periclinal structure of the internal orogen. It results from D5 doming of the axial zone and associated steepening of the initially less inclined PAL. Taking the orogen-parallel trend of the PAL west of the study area into account (Fig. 4), which represents a much longer segment than the one in the study area, the displacement in the PAL is inferred to have a western, mostly orogen-parallel trend, although considerable lateral variations might locally occur. This displacement is principally consistent with the west directed nappe emplacement in southern Sardinia (Figs. 4 and 13; Conti et al., 2001). As previously noticed, the extensional doming of the axial zone, associated with lateral shearing, forms a transtensional configuration (Section 2.5). In contrast to Conti et al. (2001), who relate the formation of the Flumendosa antiform and related folds to orogen-perpendicular shortening, we explain these orogen-parallel-trending folds with bulk constriction that results from transtension (Dewey, 2002).

Summarizing the correlation between the internal and external orogens (Fig. 14), the Sardinian Variscides underwent transpression followed by transtension. The hanging wall transport of both stages was roughly westward directed (present day coordinates), ranging from perpendicular to parallel to the orogenic belt. The transcurrent displacement component was left-lateral on inward dipping movement planes and right-lateral on outward dipping movement planes. In this way, the Posada shear zone was initiated as a gently inclined detachment zone that was subsequently exposed by the transtensional exhumation of the axial zone in an outward dip, displaying right-lateral displacement. The resulting sense of displacement between internal orogen and foreland is left-lateral.

3.3. Correlation with neighbouring Variscan massifs

The significance of the structural and kinematic data becomes evident if one considers the possible continuation of the Sardinian Variscides into other exposed Variscan massifs, which were dismembered during the Alpine Orogeny.

The Freinet Fault in the Maures Massif is a retrograde normal fault that juxtaposes staurolite–kyanite schists of the external orogen against sillimanite gneisses of the internal orogen (Crevola and Pupin, 1994). It accommodated WNW directed extension within a Late Carboniferous time span of circa 320–300 Ma (Ar–Ar muscovite and biotite;

Morillon et al., 2000). Timing, kinematics, and orogenic setting of the Freinet Fault thus agree with the PAL.

The preceding deformation in the internal Maures Massif reflects a left-lateral displacement with respect to the external orogen and/or a hanging wall transport to the NNW (Morillon et al., 2000), which is consistent with the internal Sardinian Variscides. Syn-kinematic anatexis under low-pressure conditions is inferred to have an Early Carboniferous age of about 330 Ma in the internal Maures Massif (U–Pb zircon and monazite; Morillon et al., 2000, and references therein).

Transcurrent displacement in conjunction with north and west directed hanging wall transport has also been reported from the Variscan basement in the external massifs of the Western Alps (Fernandez et al., 2002), consistent with the northern vergence at the northern boundary of the intra-Alpine terrane (Neubauer and Handler, 2000).

The Val Colla shear zone in the South Alpine Ivrea section is retrograde and extensional, detaching greenschist and amphibolite facies rocks of the Strona–Ceneri zone (Handy et al., 1999). The westward directed extension falls in a late Carboniferous period of circa 330–305 Ma (K–Ar hornblende, white mica, biotite; Handy et al., 1999, and references therein). Timing, kinematics, and orogenic setting of the Val Colla shear zone correlate well with the Sardinian PAL.

The generally westward directed extension, commonly associated with right-lateral displacement and spatiotemporally related to Late Carboniferous Buchan type metamorphism, is also well-documented in other areas of the southern Variscides, such as the Pyrenees (Vissers, 1992) or Montagne Noire (Echtler and Malavieille, 1990).

3.4. Implication for the Variscan belt in Europe

From a Gondwanan point of view, the Variscan belt comprises, from west to east, sections of the Armorican, Avalonian and intra-Alpine terranes (Fig. 15). Unbending the current curvature of the Variscan belt shows that the Armorican and intra-Alpine terranes (including the internal Sardinian Variscides) were originally far apart. The present-day proximity of the Sardinian and Armorican sections results from the bending of the Variscan belt. There is no evidence for an orogenic belt that connects both sections straight away.

The left-lateral displacement identified in Sardinia seems to be related to the oroclinal bending, carrying out a bookshelf type motion. The bending of the Variscan belt could possibly be related to the right-lateral relative motion between Laurussia and Gondwana (see Shelley and Bossière, 2002). However, the Carpathian and Apennine–Maghrebide arcuate orogens are recent examples that propagated independently of the relative motion between the African and Eurasian continents (Durand et al., 1999). Further research is needed to elucidate whether these recent examples of subduction rollback scenarios apply to a Paleotethys active margin regime at the SE Variscan flank. Our study indicates that a closed ocean here cannot be inferred merely on the basis of the occurrence of possibly oceanic and/or eclogitic rock intercalations. Corresponding volcano-sedimentary evidence for an active margin is also required

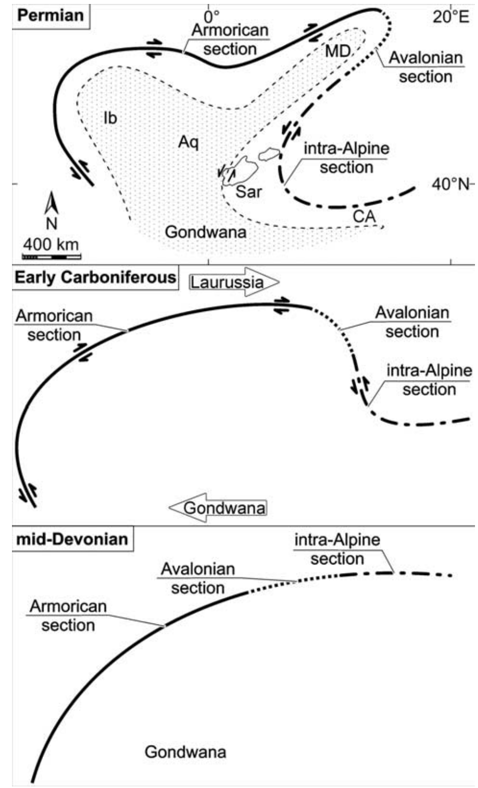

Fig. 15. Permian reconstruction of the Variscan Orogen sketched after Matte (2001) and possible kinematic evolution since Devonian times. Aq—Aquitaine; CA—Carnic Alps; Ib—Iberia; MD—Moldanubian; Sar—Sardinia.

(see discussion in O'Halloran et al., 1998). There is no such combined evidence in Sardinia. Moreover, we follow the argumentation by Matte (2001) that the Ibero–Aquitaine domain belonged to the Gondwana landmass, because so far there is no evidence for an intervening suture that would have remained from a closed Paleotethys oceanic basin, as invoked by Stampfli et al. (2002). Nevertheless, the principally common tectono-metamorphic evolution of the various Variscan terranes since Devonian times (Fig. 3) justifies the assumption of a mid-Devonian belt at the leading edge of the peri-Gondwanan terranes (Stampfli et al., 2002), from where the foreland-directed propagation of the orogenic activity started.

4. Conclusions

The position of the Alpine-dismembered Sardinian section with respect to the Variscan massifs on the European mainland has been clarified. The Variscan tectono-metamorphic evolution generally correlates with all other Gondwana-facing segments on the European mainland. However, the suture hypothesis by Cappelli et al. (1992), and thus the argument that the south Armorican suture zone would continue in Sardinia, has been disproved. Moreover, the observed left-lateral displacement with respect to the foreland excludes a direct correlation with the dominantly right-lateral displacement in the south Armorican section. Instead, the structural and kinematic results are consistent with the Variscan massifs of the Western and Southern Alps. Consequently, they further elucidate the intra-Alpine identity of the internal Sardinian Variscides as well as the suspect entity of the intra-Alpine terrane itself.

Acknowledgements

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