International Journal of Earth Sciences (2023) 112:321–344
https://doi.org/10.1007/s00531-022-02250-w

ORIGINAL PAPER

Ordovician tectonics of the South European Variscan Realm: new insights from Sardinia

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Received: 15 March 2022 / Accepted: 19 September 2022 / Published online: 2 October 2022

Abstract

Although much is known about the Ordovician tectonics of the South European Variscides, aspects of their geodynamic evolution and palaeogeographic reconstruction remain uncertain. In Sardinia, Variscan tectonic units include significant vestiges of Ordovician evolution, such as a fold system that affected only the Cambrian–Lower Ordovician successions, and are cut by a regional angular unconformity. A comparison of the stratigraphy and tectonic structures of the successions below and above the Lower Ordovician unconformity and a reinterpretation of biostratigraphic data allow us to identify significant differences between the stacked tectonic units. The unconformity is sealed as follows: (i) in the Sulcis–Iglesiente Unit (Variscan External Zone, SW Sardinia) by Middle–Upper Ordovician continental and tidal deposits; and (ii) in the Sarrabus and Gerrei units (part of the Variscan Nappe Zone, SE Sardinia) by Middle–Upper Ordovician calc–alkaline volcanic rocks. Therefore, at the same time, one tectonic unit was situated close to a rifting setting and the others were involved in a convergent margin. Of note are the different durations associated with the unconformities in the tectonic units (17 Myr in the Sulcis–Iglesiente Unit, 6 Myr in the Sarrabus and Gerrei units) and the occurrence (or absence) of glacio-marine deposits indicating that the units were located at different palaeo-latitudes during the Ordovician. These results suggest that the SW and SE Sardinia blocks did not share the same geodynamic setting during the Ordovician, implying that they were situated in different palaeogeographic positions at this time and subsequently amalgamated during the Variscan Orogeny. Furthermore, stratigraphic and tectonic correlations with neighbouring areas, such as the eastern Pyrenees, imply alternative palaeogeographic reconstructions to those proposed previously for some peri-Mediterranean Variscan terranes.

Keywords Sardic phase · Pre-Variscan geodynamics · Gondwana · Rheic Ocean · Ordovician magmatic arc · Qaidam Ocean

Introduction

Several terranes that were involved in the Variscan Orogeny (Fig. 1) and are now scattered from Europe to North Africa (Álvaro et al. 2021; Martínez Catalán et al. 2021, and references therein) record polyphase tectonic activity during the Ordovician (Lancelot et al. 1998; Roger et al. 2004; Trombetta et al. 2004; Correia Romão et al. 2005; Alexandre 2007; Laumonier 2008; Castiñeiras et al. 2008; Chichorro et al. 2008; Solá et al. 2008; Rossi et al. 2009; Casas 2010; Casas and Palacios 2012; Casas et al. 2012; Zurbriggen 2015, 2017; Álvaro et al. 2016; Dias da Silva et al. 2016; Maino et al. 2019; Pereira et al. 2022). In central and southern Sardinia, two Variscan tectonic domains—the External Zone in SW Sardinia and the Nappe Zone in SE Sardinia—preserve evidence of a regional unconformity

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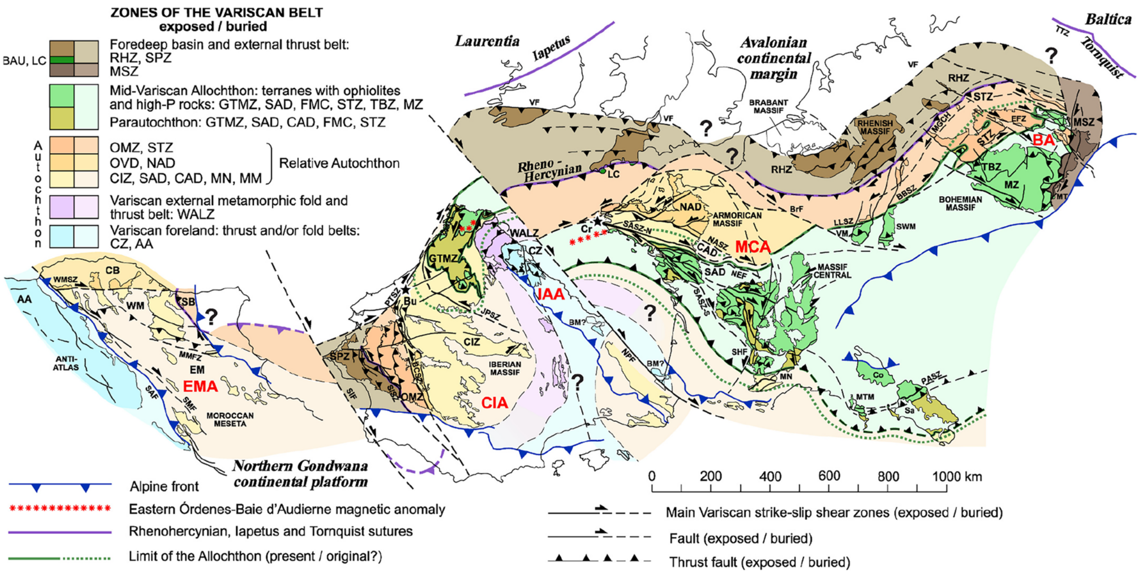


Fig. 1 HYPERLINK "sps:id::fig1||locator::gr1||MediaObject::0" Tectonic sketch map of the Southern Variscan Realm at the end of the Paleozoic (after Martínez Catalán et al. 2021). Zones (Z): *CZ* Cantabrian, *CIZ* Central Iberian (OVD, Obejo-Valsequillo Domain), *GTMZ* Galicia-Trás-os-Montes, *MSZ* Moravo-Silesian, *MZ* Moldanubian, *OMZ* Ossa-Morena, *RHZ* Rhenohercynian, *SPZ* South Portuguese, *STZ* Saxo-Thuringian, *TBZ* Teplá–Barrandian, *WALZ* West Asturian–Leonese. Armorican Domains (AD): *CAD* Central, *NAD* North, *SAD* South, *MM* Moroccan Meseta (AA, Anti-Atlas; CB, Coastal Block; EM, Eastern Meseta; SB, Sehoul Block; WM, Western Meseta). Shear zones (SZ), faults (F) and fault zones (FZ): *BBSZ* Baden–Baden, *BCSZ* Badajoz–Córdoba, *BrF* Bray, *EFZ* Elbe, *JPSZ* Juzbado-Penalva, *LLSZ* Lalaye–Lubine, *MMFZ* Middle Meseta, *MT* Moldanubian Thrust, *NASZ* North Armorican, *NEF* Nort-sur-Erdre, *NPF* North Pyrenean, *PASZ* Posada–Asinara, *PTSZ* Porto-Tomar, *SAF* South Atlas, *SASZ* South Armorican (N and S, northern and southern branches), *SHF* Sillon Houiller, *SIF* South Iberia, *SISZ* Southern Iberian, *SMF* South Meseta, *TTZ* Teisseyre–Tornquist Zone, *VF* Variscan Front, *WMSZ* Western Meseta. Arcs (A): *BA* Bohemian, *CIA* Central Iberian, *EMA* Eastern Meseta, *IAA* Ibero-Armorican, *MCA* Massif Central. Other: *BAU* Beja–Acebuches Unit, *BM* Basque Massifs, *Bu* Buçaco, *Co* Corsica, *Cr* Crozon. *FMC* French Massif Central, *LC* Lizard Complex, *MTM* Maures–Tanneron Massif, *MGCH* Mid-German Crystalline High, *MN* Montagne Noire, *Sa* Sardinia, *SWM* Schwarzwald Massif, *VM* Vosges Massif

together with a folding event related to Ordovician tectonic evolution (Cocco et al. 2018). Ordovician tectonics in the South European Variscides have long been referred to in terms of the Sardic Phase (Stille 1939), so named on account of the angular unconformity first detected in SW Sardinia (the "Sardic Unconformity"; Teichmüller 1931). At the time of its discovery, the stratigraphic gap associated with this unconformity was defined as middle Cambrian to Upper Ordovician. The Sardic Phase was also recognised by Stille (1935) in the eastern Pyrenees, where its existence has since been confirmed by recent studies (Casas 2010; Puddu et al. 2018, 2019; Casas et al. 2019) that describe a similar angular unconformity truncating folded Lower Ordovician successions. The same unconformity has been described in other zones of the Variscan belt, i.e., Occitanie (Álvaro et al. 2016) and Galicia (Dias da Silva et al. 2016). In Sardinia, an angular unconformity has been recognised in the SE part of the island (i.e., the "Sarrabese Unconformity"; Calvino 1959; Naud 1981) and marks the contact between a Lower Ordovician sedimentary succession (Barca et al. 1988; Carmignani et al. 2001; Cocco and Funedda 2019) and a Middle–Upper Ordovician volcano-sedimentary succession. The superposition of Variscan deformation on Ordovician stratigraphic and tectonic features has led to oversimplified interpretations of the timing and significance of the Ordovician unconformities. Thus, in recent decades, many studies (e.g., Barca et al. 1981, 1982; Carmignani et al. 2001) have merged the Sardic Unconformity with the Sarrabese Unconformity on the basis of temporal correlation but without providing robust chronostratigraphic constraints.

In Sardinia, the Variscan orogenic wedge consists of several tectonic units considered as vestiges of adjacent pre-Variscan palaeogeographic domains, each of which has a distinct lithostratigraphic succession. The main stratigraphic and tectonic features show differences in the occurrence (or absence) of Ordovician volcanic products, the occurrence (or absence) of thick Cambrian and Devonian carbonate platform deposits, and various other sedimentological, geochemical, and chronostratigraphic features, including the duration of intra-Ordovician hiatuses. To reconstruct the Ordovician evolution of the Sardinian Palaeozoic basement, in this paper we summarise and compare the lithostratigraphic successions and deformation events that characterise the different tectonic units, where pre-Variscan evolution is recorded. In particular, we assess the proper chronostratigraphic positions of the regional angular unconformities representing the Early Ordovician deformation phases and evaluate the associated time gaps. Accurate documentation of the ages and durations of the hiatus associated with unconformities does not in itself provide an unambiguous account of a tectonic scenario, and geodynamic characterisation of the deposits sealing the time gap is also required. Hence, published biostratigraphic data were revisited, and cross-correlations were performed based on eustatic curves, taking into account the environments and depositional facies of the post-unconformity successions in both areas. From these analyses arose a more complicated framework than has been established previously. The stratigraphic and tectonic differences between the different units reveal their differing exotic provenances (Cocco et al. 2018), as well as their more complex geodynamic settings than those proposed previously. This paper tests the hypothesis that the pre- and post-Sardic Unconformity successions of SW and SE Sardinia did not share the same pre-Variscan evolution and that a similar scenario might also apply to some Variscan terranes in the eastern Pyrenees and Occitanie.

Geological setting

The Sardinian Variscan basement (Fig. 2) is composed of several tectonic units, each of which is characterised by a sedimentary and volcanic succession spanning in age from the early Cambrian to the early Carboniferous. These units were affected by shortening events during Variscan collision and by post-collisional extensional tectonics, leading to uplift of the entire basement and emplacement of Variscan granitoids (Carmignani et al. 1994, 2016; Conti et al. 1999; Conte et al. 2017; Secchi et al. 2021; Cocco et al. 2022). The collisional events occurred with associated regional metamorphism, which ranged from very low grade in the southwestern part of the island to high grade in the northern part of the island and produced a nappe stack with dominant top-to-the-SSW and subordinate top-to-the-W tectonic transport directions (Conti and Patta 1998; Conti et al. 2001; Casini et al. 2010; Montomoli et al. 2018; Carosi et al. 2022; Petroccia et al. 2022a, 2022b). In all tectonic units, an increasing grade of metamorphism is accompanied by an increasing level of rock deformation. In the SW (the Variscan External Zone), the Sulcis–Iglesiente Unit is deformed by thrusts and folds developed at upper-crustal levels (Funedda 2009), whereas in the SE (the Variscan Nappe Zone), the Sarrabus and Gerrei tectonic units are deformed by large kilometre-sized isoclinal recumbent folds and ductile shear zones that developed under low-grade metamorphism (Conti et al. 2001). In central and northern Sardinia (the Variscan Internal Nappe and Inner zones; Fig. 2), high-temperature deformation led to extensive crustal reworking and complete transposition of the sedimentary features, rendering any stratigraphic correlation with South Sardinian tectonic units meaningless. In the Internal Nappe and Inner zones, pre-Variscan tectonics are recorded only by the occurrence of Ordovician magmatism (Fig. 3).

The successions in the Sulcis–Iglesiente Unit (SW Sardinia) show significant lithostratigraphic differences from those of the Sarrabus and Gerrei units and those of the Internal Nappe and Inner zone (Fig. 3; Carmignani et al. 2016). The most notable differences are in the pre-Miaolingian formations, which are characterised in the Sulcis–Iglesiente Unit by carbonate platform deposits that record warm climatic conditions, whereas time-equivalent carbonate deposits have not been documented in the Sarrabus and Gerrei units (SE Sardinia). Sedimentary rocks of Furongian to earliest Floian age, although represented by terrigenous platform deposits in both areas, yield distinct biota (Barca et al. 1988; Pillola and Gutierrez-Marco 1988; Gnoli and Pillola 2002). The Middle Ordovician succession of the Sarrabus and Gerrei units is characterised by a thin deposit of conglomerate overlain by a thick subaerial calc–alkaline volcanic sequence that is absent in the Sulcis–Iglesiente Unit, where, conversely, the period of emergence is represented by a thick (up to 600 m) conglomeratic deposit. However, the Sulcis–Iglesiente Unit and the Sarrabus and Gerrei units share two intra-Ordovician angular unconformities: the Sardic Unconformity (Teichmüller 1931) ascribed to the Sardic Phase (Stille 1939) in SW Sardinia and the Sarrabese Unconformity ascribed to the Sarrabese Phase (Calvino 1959) in SE Sardinia. The time gaps and ages of these angular unconformities are described and discussed below.

Methods of stratigraphic correlation

Comparison of the stratigraphic and geodynamic characteristics of the pre-Variscan succession in the Sulcis–Iglesiente Unit (SW Sardinia) and the Sarrabus and Gerrei units (SE Sardinia) of the Sardinian Variscides focused on the Ordovician formations bracketing the two angular unconformities. Several sources of geological data are available for these units: (a) clearly recognisable sedimentological and statigraphic features; (b) well-constrained biostratigraphic correlations; and (c) absolute ages (see references in Cocco et al. 2018). In addition, to strengthen chronostratigraphic cross-correlations, a comparison was made between (i) the curve of variations in sedimentary environments and related fauna in the post-Sardic Phase and post-Sarrabese Phase successions and (ii) the time-calibrated eustatic curve established for the Upper Ordovician of the Moroccan Anti Atlas (Loi et al. 2010) and the Middle to Upper Ordovician of the Armorican massif (Figs. 4 and 5; Dabard et al. 2015).

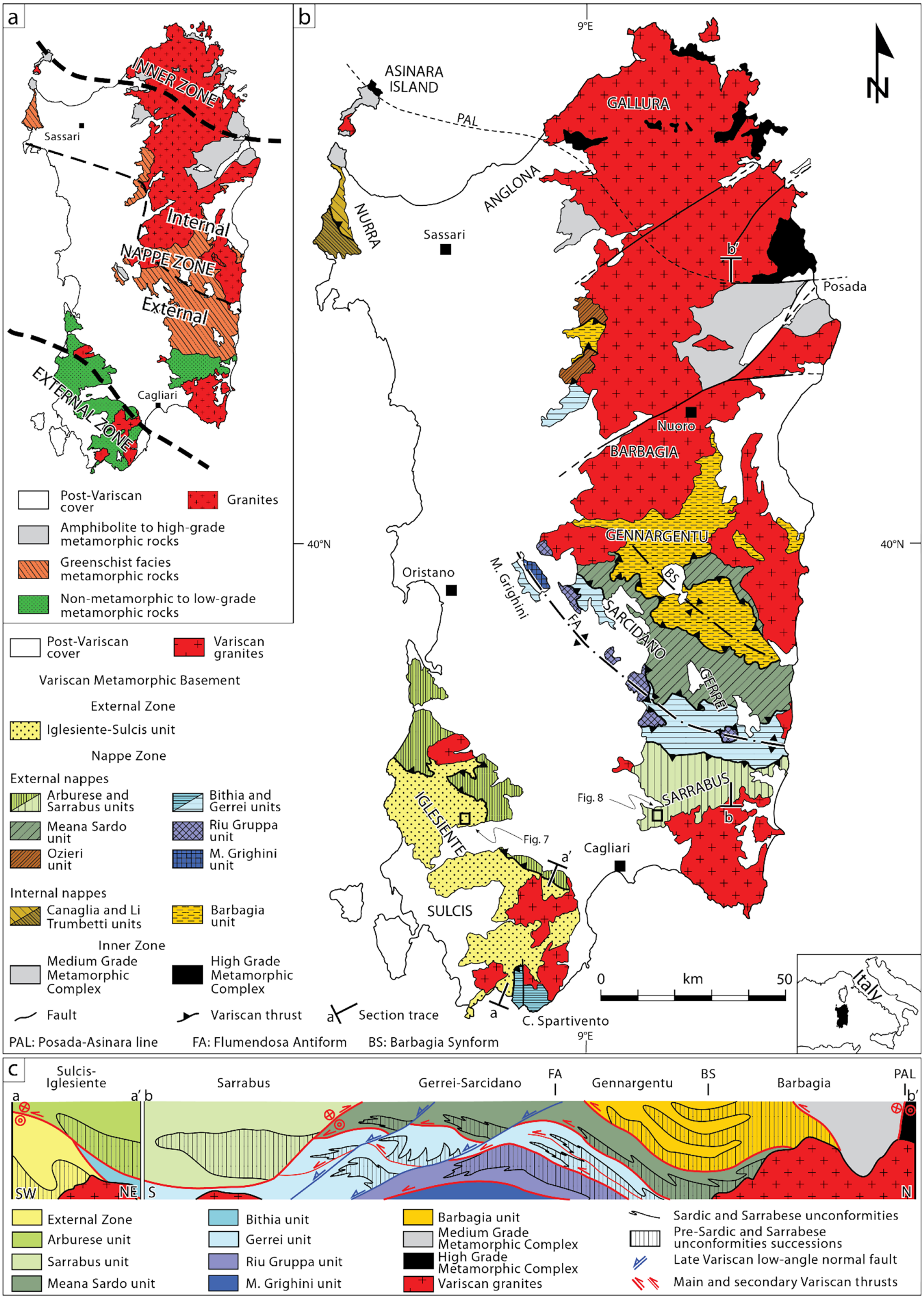


Fig. 2 **a** Tectono-metamorphic zones in Sardinia; **b** Tectonic sketch map of Variscan basement in Sardinia (modified after Oggiano et al. 2010); **c** Schematic geological cross-section (modified after Cocco et al. 2018) of the Variscan basement (not to scale). Boxes in (**b**) depict the locations of the maps in Figs. 7 and 8

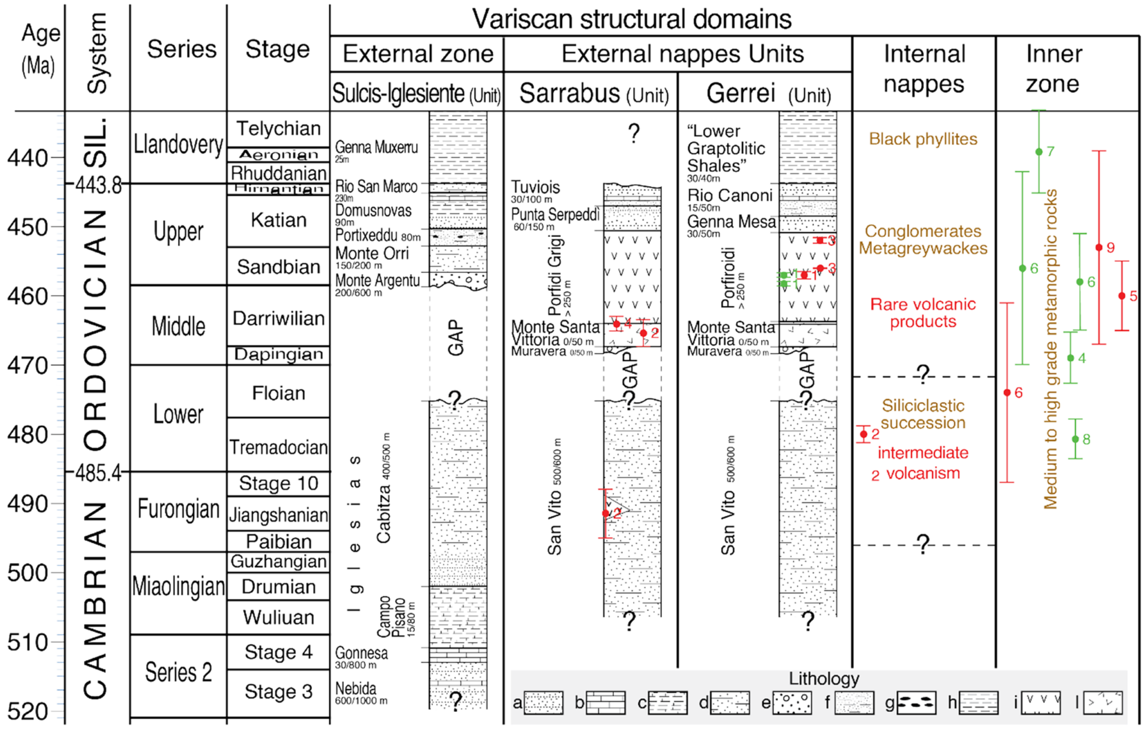


Fig. 3 Main stratigraphic correlations of sedimentary and magmatic formations characterising the various tectonic zones of the Variscan basement in Sardinia. U–Pb zircon ages are shown for volcanic (in red) and plutonic (in green) magmatic rocks. Bibliographic reference numbers: 1—Pavanetto et al. (2012); 2—Oggiano et al. (2010); 3—Dack (2009); 4—Giacomini et al. (2006); 5—Giacomini et al. (2005); 6—Helbing and Tiepolo (2005); 7—Rossi et al. (2009); 8—Casini et al. (2015); 9—Palmeri et al. (2004). **a**: Sandstones; **b**: Limestones; **c**: Marly limestones; **d**: Alternating siltstones and sandstones; **e**: Conglomerates; **f**: Siltstones; **g**: Fe and P nodules; **h**: Claystones; **i**: Ignimbrites and lava flows; **l**: Andesitic lavas and epiclastites

Lower Paleozoic stratigraphy of Sardinia

The Sulcis–Iglesiente unit (SW Sardinia)

In the Sulcis–Iglesiente Unit, the Sardic angular unconformity separates a lower Cambrian to Lower Ordovician succession (referred to as pre-Sardic hereafter) from an Upper Ordovician to lower Carboniferous succession (post-Sardic hereafter). The pre-Sardic succession consists of three groups, i.e., the Nebida, Gonnesa and Iglesias groups in ascending stratigraphic order (Pillola 1990, 1991; Pillola et al. 1998; Loi et al. 1996) (Fig. 3). The Nebida Group contains a siliciclastic formation of alternating thick sandstone beds and thin siltstone layers (Matoppa Fm.). In the upper part of the formation, calcimicrobial–archaeocyathan mounds, trilobites, and echinoderms are common. The Punta Manna Fm., which lies above the Matoppa Fm., is characterised by thinner sandstone beds and an interlayered oolitic shoal belt at the base and by peloidal wackestone, grainstone, and back shoal ooid–grainstone (spillovers) at the top. Lagoonal deposits contain calcimicrobial–archaeocyathan biostromes. The Punta Manna Fm. is assigned to the Atdabanian–Botomian of the Siberian Stages (Series 2 of the Cambrian), according to the association of Trilobita and Archaeocyatha (Rasetti 1972; Debrenne et al. 1988).

The Gonnesa Group lies in stratigraphic continuity above the Nebida Group and consists of the Santa Barbara and San Giovanni formations. The Santa Barbara Fm. is characterised by alternating dolostones and well-stratified limestones (historical name "Dolomia Rigata"); these are overlain by massive limestones of the San Giovanni Fm. (historical name "Calcare Ceroide") that is commonly dolomitised (historical name "Dolomia Grigia"). The Archaeocyatha associations (Debrenne and Gandin 1985) allow us to assign a late Botomian to late Toyonian age (Series 2, middle Stage 4).

The lower part of the Iglesias Group consists of alternating massive limestones, nodular limestones, marls, and thin layers of silty argillites of the Campo Pisano Fm. (historical name "Calcari Nodulari"; Pillola et al. 1998; uppermost Stage 4 to mid-Drumian) that overlie the San Giovanni Fm. of the Gonnesa Group (Gandin et al. 1987; Pillola 1991). The succession changes gradually upward to alternating layers of variable (from centimetric to metric) thickness of argillites, siltstones, and sandstones of the Cabitza Fm. (Drumian to late Tremadocian–early Floian (?)). The top of the Iglesias Group is cut by the Sardic Unconformity.

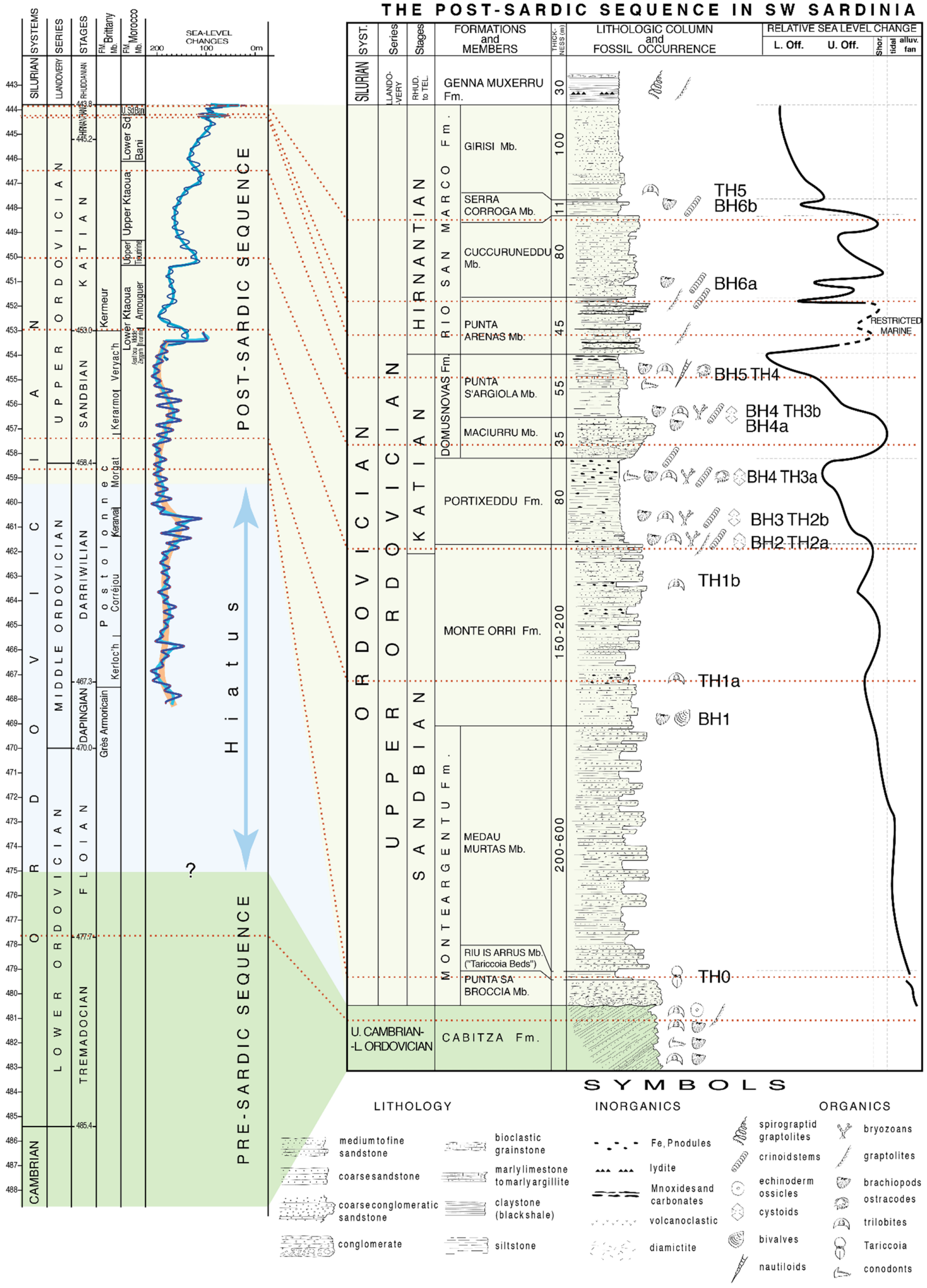


Fig. 4 Lithostratigraphic succession of the post-Sardic sequences of SW Sardinia. The relative sea-level curve and the main fossiliferous occurrence of trilobites (TH) and brachiopods (BH) identified by Leone et al. (1998) and Hammann and Leone (1997, 2007) are reported. Chronostratigraphic correlation based on the time-calibrated eustatic curve established for the Upper Ordovician of the Moroccan Anti Atlas (Loi et al. 2010) and the Middle–Upper Ordovician of the Armorican Massif (Dabard et al. 2015) is shown

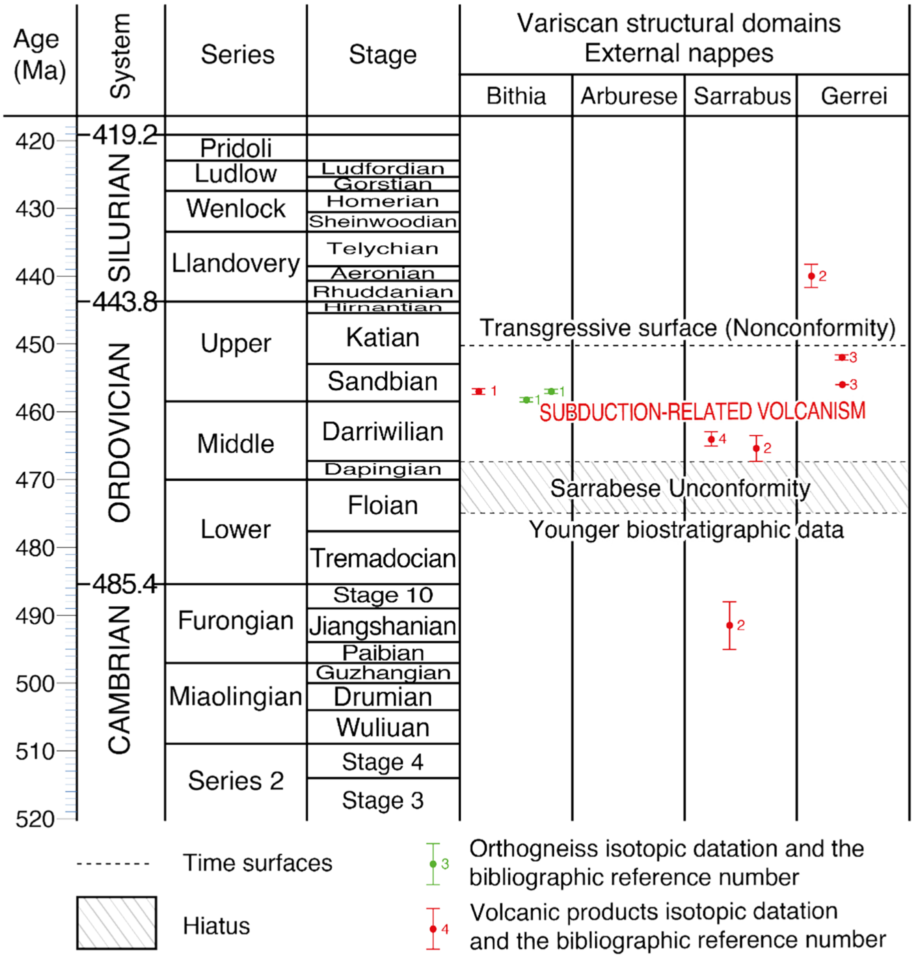


Fig. 5 Hiatus and time surfaces in the External Nappe Zone. U–Pb zircon ages are shown for volcanic (in red) and plutonic (in green) magmatic rocks. Bibliographic reference numbers: 1—Pavanetto et al. (2012); 2—Oggiano et al. (2010); 3—Dack (2009); 4—Giacomini et al. (2006)

The estimated preserved thickness of Iglesias Group is at least 600 m (Cocozza 1979; Cocozza and Gandin 1986). A middle Cambrian age for the Campo Pisano Fm. has been inferred on the basis of the trilobite association (Rasetti 1972; Pillola 1990; Elicki and Pillola 2004), and the youngest age documented in the upper levels of the Cabitza Fm. (below the Sardic Unconformity) is Early Ordovician (early Tremadocian, based on the occurrence of acritarchs and of the graptolite *Rhabdinopora flabelliformis*; Barca et al. 1987; Pillola and Gutierrez-Marco 1988), which has been subsequently re-evaluated to Tremadocian–earliest Floian (?) by Pillola et al. (2008) on the basis of recent findings of *Araneograptus murrayi, Clonograptus (Clonograptus)* cf. *rigidus, Cl. (Clonograptus)* cf. *multiplex*, and *Didymograptus* spp.

The pre-Sardic succession in the Sulcis–Iglesiente Unit records an environmental transition during the early Cambrian from a terrigenous ramp and mixed-carbonate shallow-water platform (Nebida Group) to an extensive carbonate platform (Gonnesa Group), deposits of which are capped by condensed argillites of the Campo Pisano Fm., in turn overlain by condensed deeper-facies carbonates of the base of the Cabitza Fm. (Iglesias Group). The Cambrian Guzhangian/Paibian transition is recorded as a decrease in deposit bathymetry and an increase in terrigenous flow. A gradual increase in deposit bathymetry is observed in sedimentary rocks of Tremadocian age (Loi et al. 1996).

The post-Sardic succession (Fig. 4) starts with matrix-supported conglomerate beds (Punta Sa Broccia Mb, historical name “Puddinga”) and sandstone and coarse siltstone strata belonging to the Monte Argentu Fm. (Laske et al. 1994). The conglomerate clasts were derived mainly from erosion of the underlying Cabitza Fm., with smaller amounts sourced from the underlying Gonnesa and Nebida groups. Megabreccias and large olistolites (10–100 m in size) of dolostones and limestones form the base of the Monte Argentu Fm., which is considered to have been deposited in a cone-shaped, alluvial to fan-delta environment (Martini et al. 1991). This coarse-grained deposit fines gradually toward the top, where bioturbated sandstones and siltstones that were deposited in shallow-marine environments (tidal plain and lagoon) prevail. The thickness of the Monte Argentu Fm. varies from 200 to 600 m (Laske et al. 1994; Leone et al. 1998). The age of the formation is constrained between the Tremadocian–earliest Floian (?) (Pillola et al. 2008) of the uppermost fossiliferous beds of the Cabitza Fm. and the Sandbian (Soudleyan–Longvillian) trilobite and brachiopod fauna of the Monte Orri Fm. (Hammann and Leone 1997, 2007; Leone et al. 1998). The Monte Argentu Fm. contains a single fossiliferous horizon of *Tariccoia arrusensis* (Hamman et al. 1990) that has been tentatively assigned to the Soudleyan (?) (Sandbian base) by Hammann and Leone (1997, 2007) and Leone et al. (1998).

Above the Monte Argentu Fm. is a 200–280-m-thick succession (the Monte Orri and Portixeddu Fms) of alternating siltstones, mudstones, and silty sandstones deposited in the upper-offshore and partially in the lower-offshore environments of a storm-dominated terrigenous platform. The high fossil content allows these deposits to be assigned to the Sandbian and lower Katian, respectively (Fig. 4; Leone et al. 1991; Hammann and Leone 1997, 2007).

The overlying Domusnovas Fm. (90 m thick) is characterised at the base by quartz arenites and quartz microconglomerates, with concentrations of rutile and zircon in heavy-mineral horizons (placers) that were deposited in a shoreface environment dominated by storm waves (Loi 1993; Loi and Dabard 1997; Leone et al. 1998). The formation continues above an abrupt but conformable boundary with marly limestones, marly argillites, and limestones with a rich fossil fauna (brachiopods, trilobites, and bryozoans) and represents a high degree of sedimentary condensation (Botquelen et al. 2002, 2004, 2006), consistent with a carbonate seabed and involving taphonomic feedback. The formation has been assigned to the Ashgill (upper Katian) on the basis of brachiopods and trilobite associations (Hammann and Leone 1997, 2007; Leone et al. 1998). The Upper Ordovician succession ends with the 230-m-thick Rio San Marco Fm. (Fig. 4; Leone et al. 1991). The base of this formation consists of heterogeneous conglomerates that contain volcanic pebbles and layers of manganese oxides, as well as manganese carbonates interbedded with argillites that were deposited in lagoonal environments during the first glacio-eustatic pulsation of the Hirnantian (Ghienne et al. 2000). The upper Rio San Marco Fm. comprises pelitic–arenaceous beds and glacio-marine deposits. The fossil fauna indicates a Hirnantian age (Hammann and Leone 1997, 2007; Leone et al. 1998; Storch and Leone 2003). The Silurian–Devonian succession is characterised by black mudstones with lydites at the base and limestones at the top (Gnoli et al. 1990). The maximum thickness of the post-Ordovician succession is approximately 200 m.

The Sarrabus and Gerrei units (SE Sardinia)

The tectonic units of SE Sardinia (Fig. 2) show more or less the same stratigraphic succession, where three sequences separated from each other by two regional unconformities are recognisable (Figs. 3 and 5). The oldest sequence (referred to hereafter as pre-Sarrabese), the base of which is unknown, probably encompasses the entire Cambrian up to the Tremadocian (Naud and Pittau Demelia 1987; Di Milia and Tongiorgi 1993), ending with the Sarrabese Unconformity (Calvino 1959). The second sequence seals the Sarrabese Unconformity (post-Sarrabese hereafter) and consists of a continental succession composed mainly of volcanic rocks with minor sedimentary deposits confined to the base or as minor intercalations (Funedda 2000). The post-Sarrabese succession is bracketed between the Middle and Upper Ordovician and is bounded to the top by a Katian nonconformity, the Caradocian transgressive surface (Calvino 1959). Above this unconformity lies the third sedimentary succession, which extends from the Upper Ordovician to the lower Carboniferous.

The pre-Sarrabese succession (Fig. 3) consists of a thick siliciclastic succession (Arenarie di San Vito, Calvino 1959) composed of alternating sandstones, siltstones, and argillites with well-developed sedimentary structures that suggest a complex superposition of facies representing deposition on terrigenous platforms from lower-offshore to tidal-flat environments (Cocco and Funedda 2019). These clastic deposits generally coarsen in the upper part of the formation to fine-grained conglomerates. In the Gerrei Unit, limestone lenses and quartz microconglomerates are interlayered in the upper part of the succession. In the Sarrabus Unit, the Arenarie di San Vito hosts intermediate to felsic volcanic rocks with a transitional affinity that have been dated at 491.4 ± 3.5 Ma (Oggiano et al. 2010). The stratigraphic base of the Arenarie di San Vito is not exposed, and its top is ubiquitously erosional, so a minimum thickness of 500–600 m can be inferred (Carmignani et al. 1982, 2001; Oggiano 1994). No clear evidence of the Sarrabese Unconformity has been observed in the Internal Nappe Zone, where a siliciclastic succession similar to the Arenarie di San Vito (i.e., Gennargentu phyllites) reaches an apparent thickness of approximately 2000 m (Meloni et al. 2017). The age of the Arenarie di San Vito, based on palynological content (Acritarchs), is Miaolingian to Floian (Barca and Mascia 1982; Barca et al. 1982, 1988; Naud and Pittau Demelia 1987). An interval of a few metres of this formation has yielded body fossils of trilobites, didymograptid species, cephalopods, bivalves, gastropods, hyolithids, and brachiopods (Gnoli and Pillola 2002), as well as abundant trace fossils (Testa 1922; Pillola and Piras 2004), which have together given an early Floian age. The age assigned to the fauna agrees with the age of interlayered volcanic rocks in the Arenarie di San Vito (Figs. 3 and 5).

The post-Sarrabese succession in the Sarrabus and Gerrei units (Fig. 2) consists of a volcano-sedimentary succession that lies unconformably above the Arenarie di San Vito (Fig. 5). The base of this succession consists of conglomerates (Metaconglomerati di Muravera; Carmignani et al. 2001) containing pebbles derived from the underlying terrigenous succession (Arenarie di San Vito), interbedded with sandstones and siltstones. This continental deposit is lens shaped and has a maximum thickness of approximately 50 m. The overlying volcanic succession consists of andesitic lavas and epiclastites (Monte Santa Vittoria Fm.; Carmignani et al. 2001) covered by ignimbrites and lava flows of rhyolitic to dacitic compositions (Porfidi Grigi del Sarrabus in the Sarrabus Unit: Calvino 1959; Porfiroidi Fm. in the Gerrei Unit: Calvino 1972). This volcanic succession is classified as calc–alkaline series (Gaggero et al. 2012). In the Gerrei Unit, the transition between the Monte Santa Vittoria and Porfiroidi Fms is commonly marked by the occurrence of a layer that is composed mainly of conglomerates and coarse quartzarenites and is 10 m thick on average (Su Muzzioni Fm., Funedda 2000). In the different tectonic units of the Nappe Zone, volcanic rocks differ in both volume and evolutionary trend. For example, in the Gerrei Unit, the 300-m-thick volcanic sequence starts with andesites and ends with rhyolitic lavas. The age of the volcano-sedimentary succession in the post-Sarrabese succession is constrained between the youngest age of the underlying Arenarie di San Vito (early Floian) and the age of transgressive fossiliferous deposits (Katian: Punta Serpeddì Fm.; Loi et al. 1992b; Argilloscisti di Rio Canoni, Naud 1979). In addition, a series of U−Pb zircon ages (Fig. 5) has constrained the ages of the volcanic rocks to between 465.4 ± 1.9 Ma (Oggiano et al. 2010) and 452 ± 0.3 Ma (Dack 2009). This latter age matches the age of the overlying transgressive Punta Serpeddì Fm. (Katian) and suggests a negligible time interval between the last volcanic events and the Katian transgression.

The volcanic rock succession is overlain by continuous sedimentary deposits from the Upper Ordovician to the lower Carboniferous. Siliciclastic deposits prevail at the base of this succession, with a single Upper Ordovician carbonate horizon. These deposits are overlain by Silurian deposits composed of typical black shales with graptolites and intercalations of massive to nodular argillaceous limestone (Ockerkalk facies; Corradini et al. 1998). The succession ends with Devonian to lower Carboniferous carbonate platform deposits, which are in turn unconformably overlain by a lower Carboniferous Culm-type deposit.

The Upper Ordovician deposits document a marine transgression above the volcanic succession. This sedimentary succession consists of lithic sandstones, greywacke, and rare arkose sandstones, silty mudstones, and limestones (Genna Mesa Fm. in the Gerrei Unit; Carmignani et al. 2001; Punta Serpeddì Fm. in the Sarrabus Unit; Loi et al. 1992a and b). Despite some small differences in depositional facies between the tectonic units, a general transgressive trend can be inferred, with an evolution from lagoon and shoreface environments to a storm-dominated platform and a trend clearly controlled by a strong third-order eustatic rise (Fig. 6). This strong retrogradation generated extremely high contents (up to ~ 15%) of heavy minerals (placers) in the succession (Pistis et al. 2016). Several of these placer horizons have been interpreted as the result of sedimentary condensation. These condensation levels coincide with the points of inflection of the eustatic rise curve of the high-frequency cycles of the third-order retrograde phase (Pistis et al. 2016). The fossiliferous content is abundant and well-preserved, especially in the successions of the Sarrabus and Gerrei tectonic units. The fauna (brachiopods, trilobites, and crinoids) found in the lowermost few metres of the succession has been studied by Leone et al. (1991) and Hammann and Leone (1997, 2007), who identified an association of brachiopods and trilobites (from TH3 to TH4 for trilobites, BH4 and BH5 for brachiopods) that allows these deposits to be assigned to the Katian. The underlying volcanic rocks dated at 452 ± 0.3 Ma (Dack 2009) ties the early transgressive deposits to the middle–upper Katian. Furthermore, the strongly transgressive trend of the succession tightly correlates these deposits with the retrogradation of sequence 3r of the eustatic curve for the Upper Ordovician of the Moroccan Anti Atlas (Loi et al. 2010) (Fig. 6).

Ordovician deformation phases

Markers of Ordovician tectonics

Evidence for Ordovician deformation preserved in the Variscan basement of Sardinia includes the following: (1) folds affecting only the Cambrian–Lower Ordovician successions; (2) an angular unconformity between the Lower Ordovician folded successions and the overlying deposits; (3) thick continental deposits, mainly conglomerates, which lie directly above the Sardic Unconformity surface and are restricted to the External Zone (Sulcis–Iglesiente Unit, SW Sardinia); and (4) calc–alkaline intrusive and effusive magmatic rocks of Middle–Late Ordovician age that are restricted to the Nappe Zone (e.g., Sarrabus and Gerrei units, SE Sardinia). Notwithstanding the Variscan overprinting, during which the emplacement of the different tectonic units occurred, the folding events that affected only the Cambrian–Lower Ordovician succession are still recognisable in both the Sulcis–Iglesiente Unit (SW Sardinia) and the Sarrabus and Gerrei units (SE Sardinia). The geometry and style of the folds associated with the Ordovician deformation (both the Sardic and Sarrabese phases) are described below with reference to detailed geological maps of two selected areas in SW and SE Sardinia (Figs. 7 and 8).

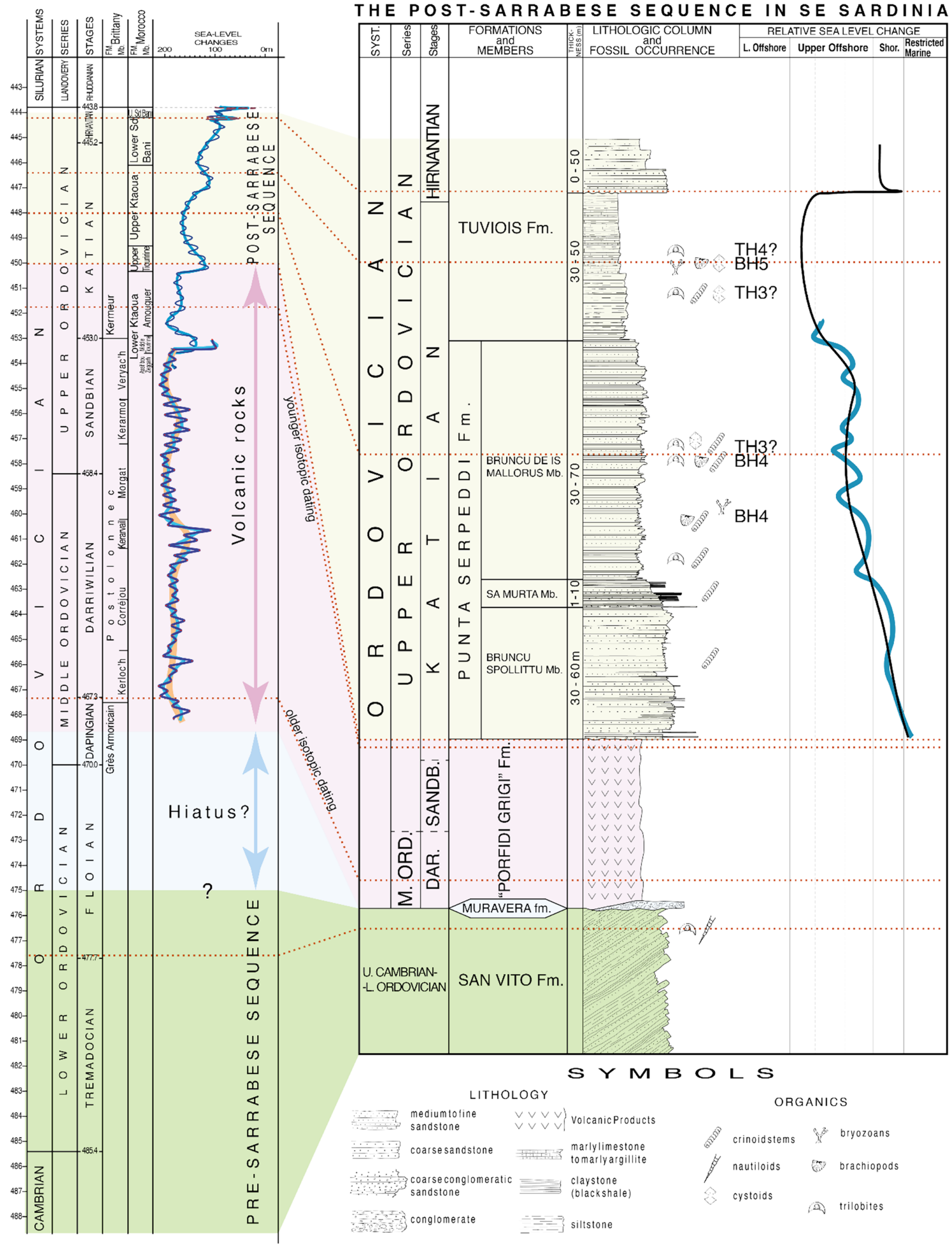
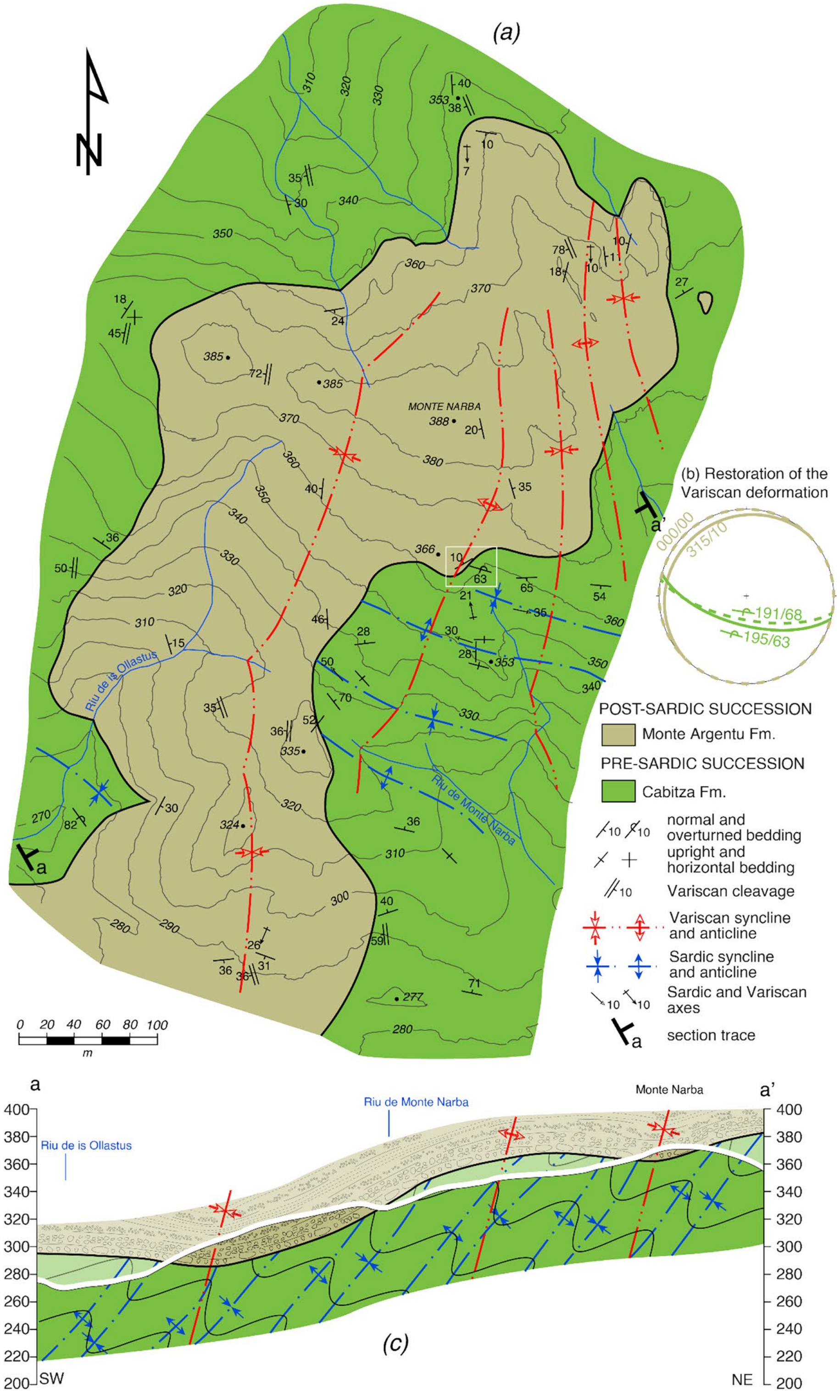


Fig. 6 Schematic lithostratigraphy of the post-Sarrabese succession of the Sarrabus tectonic Unit. The relative sea-level curve and the main fossiliferous occurrence of trilobites (TH) and brachiopods (BH) identified by Leone et al. (1998) and Hammann and Leone (1997, 2007) are shown. Chronostratigraphic correlation based on the time-calibrated eustatic curve established for the Upper Ordovician of the Moroccan Anti Atlas (Loi et al. 2010) and the Middle–Upper Ordovician of the Armorican Massif (Dabard et al. 2015) is shown

Fig. 7 **a** Geological map of the Monte Narba area, showing the Sardic angular unconformity and the Sardic Phase folds. **b** Geological cross section highlighting the different deformation styles below and above the unconformity; note that the Sardic and Variscan axial plane traces are roughly perpendicular to each other, and that the wavelengths of the Variscan and Sardic folds are different, meaning that the superimposed Variscan deformation on Sardic folds results in an interference pattern characterised by gentle folding of the Sardic axial plane trace. **c** Equal-area, lower-hemisphere stereographic projection of bedding surfaces in the Cabitza and Monte Argentu Fms and their attitude after restoration of the Sardic Unconformity to the horizontal. It is noted that after restoration, the bedding in the Cabitza Fm. still has a reverse polarity. The white box shows the locations of the data plotted in the stereographic projection. The location is shown in Fig. 2b



Sardic phase (Sulcis–Iglesiente unit, SW Sardinia)

The Sardic Phase affects only the pre-Sardic succession, showing E–W-trending folds related to N–S shortening (Carmignani et al. 1994; Pasci et al. 2008; Conti et al. 2001). Folds related to the Sardic Phase are generally upright with slightly overturned limbs, with first-order wavelengths of several kilometres, subvertical axial planes, and axes plunging either to the E or W, depending on the effect of subsequent deformation. The superposition of Variscan structures

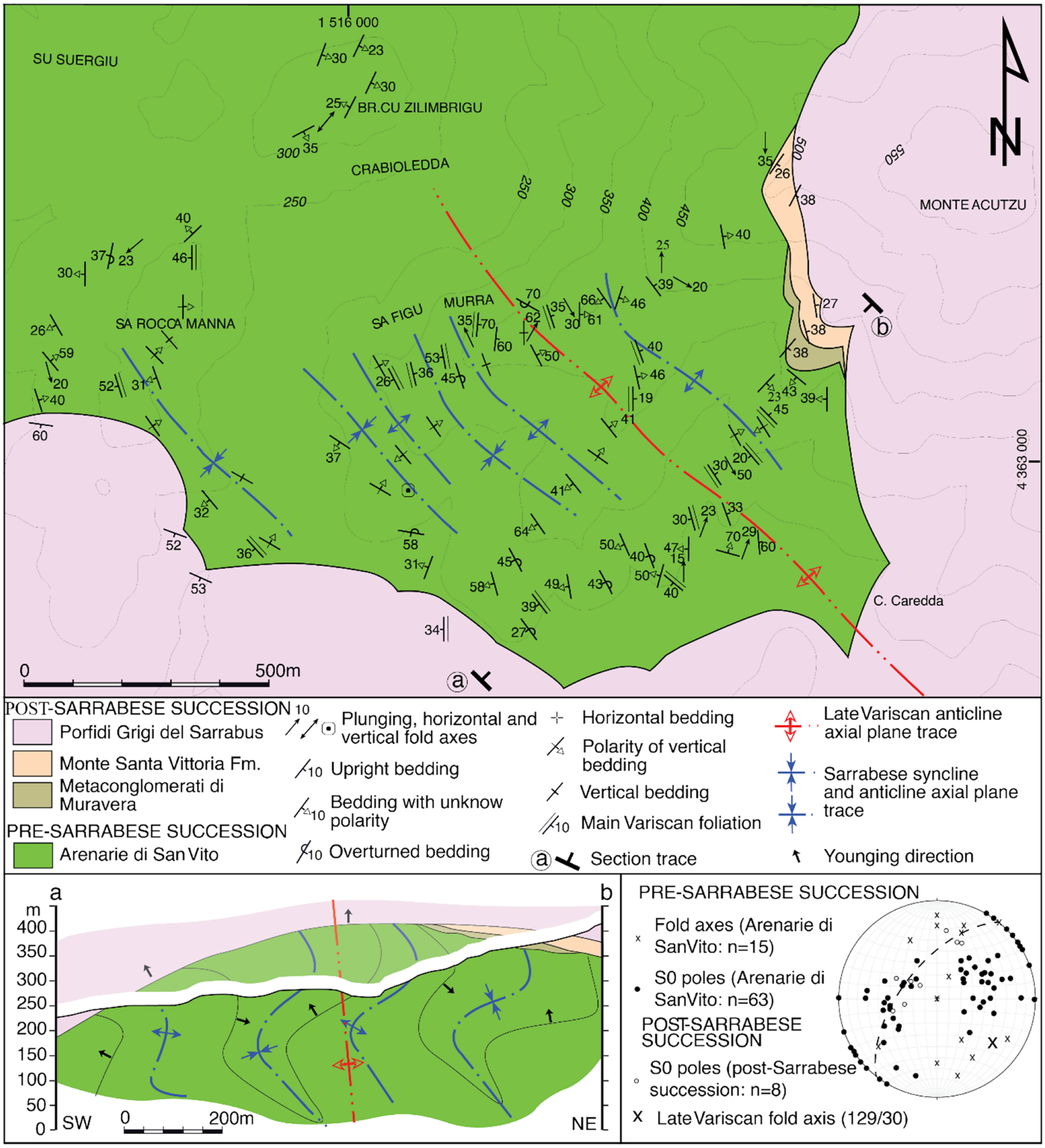


Fig. 8 Geological map of the Monte Acutzu area. Equal-area, lower-hemisphere stereographic projection of fold axes and bedding planes from the Arenarie di San Vito and bedding planes from the post-Sarrabese Unconformity succession in the Monte Acutzu area. Cross section showing the geometric relationships between the pre-Sarrabese and post-Sarrabese Unconformity successions (modified after Cocco and Funedda 2019). The location is shown in Fig. 2b

has caused the Sardic folds to be strongly noncylindrical. Importantly, no pervasive axial plane tectonic foliation is associated with the Sardic folds. The Sardic Unconformity seals this deformation phase, and the surface of the unconformity intersects the limbs of Sardic folds at a high angle (~ 90° locally).

Two Variscan shortening phases affect the entire stratigraphic succession from the lower Cambrian to the lower Carboniferous. The first Variscan phase is characterised by a shortening direction similar to that of the Sardic Phase, giving rise to a type 0 interference pattern (Ramsay 1967). Open folds developed with a subvertical axial plane, which slightly deform the Sardic Unconformity and the overlying succession, only gently accentuate the Sardic folds. The second Variscan phase is characterised by fold axes approximately perpendicular to those of the Sardic and initial Variscan phases and exhibits a type 1 dome-and-basin interference pattern (Ramsay 1967). The fold axes related to the second

Variscan phase are N−S trending and characterised by very steep W-dipping axial planes with a well-developed cleavage. The plunge of the N−S axes varies according to the attitude of the beds affected by the previous E−W-trending folds. In particular, the Variscan N−S axes are subvertical in the subvertical limbs of the Sardic folds and gradually tend to become subhorizontal with decreasing distance from the hinge zones of the Sardic folds.

The interference pattern between the three superimposed folding events is clearly recognisable in the area of Monte Narba, a few kilometres north of Domusnovas village (Fig. 7). Here, strata of the Cabitza Fm. are deformed by E−W-trending Sardic folds with steep S-dipping axial planes and strong asymmetry and by later N−S-trending Variscan folds. The angle that the unconformity surface makes with the underlying bedding is, therefore, highly variable, depending on which sector of the Sardic fold is cutoff: a high angle, where the Monte Argentu Fm. directly covers a subvertical limb and a low angle, where it covers the hinge zones (Cocco and Funedda 2021). The Sardic Unconformity and the overlying Monte Argentu Fm. succession are affected by N−S Variscan folds, which deform the Sardic folds by modifying the plunge direction of the axes toward either the W or E, and by shortening their upright limbs, developing vertical folds with metric to centimetric wavelengths. The axes of the Variscan folds below the Sardic Unconformity have variable plunge according to the attitude of the Cabitza Fm. At outcrop scale, the superposition of the N−S Variscan folds on the E−W Sardic folds is further highlighted by the Variscan cleavage that cuts across both limbs of the Sardic folds. It is important to emphasise that the occurrence of overturned beds in the Cabitza Fm. is related to Sardic folds rather than the Variscan shortening phases. Accordingly, once the unconformity surface is restored to the horizontal, the Cabitza Fm. still shows beds with reverse polarity (see the stereographic projection in Fig. 7). The Sardic folds recognised in the Monte Narba area are parasitic folds within kilometre-scale folds that characterise the structural setting of the Sulcis–Iglesiente Unit. The asymmetry of the folds recognised in the Monte Narba area is consistent with their location on the southern limb of the first-order Malacalzetta synform (see Figs. 1 and 3 in Cocco and Funedda 2021). The lack of an axial-plane foliation in the Sardic folds suggests that the deformation occurred at shallow structural levels, although a substantial amount of shortening has been accommodated.

Sarrabese phase (Sarrabus and Gerrei units, SE Sardinia)

In SE Sardinia, the imprint of the Variscan deformation and metamorphism is more intense than in SW Sardinia (Carmignani et al. 1994). Nevertheless, in some areas of the Sarrabus Unit, some structures related to the Sarrabese Phase can still be recognised (Cocco and Funedda 2019). In particular, in the area of Monte Acutzu (Fig. 8), the bedding of Arenarie di San Vito is perpendicular to the Sarrabese Unconformity, and overturned limbs commonly lie directly beneath the Muravera, Santa Vittoria, or Porfidi Grigi Fms. In these areas, the orientation of bedding in the Arenarie di San Vito is highly scattered compared with the post-Sarrabese succession. This suggests the occurrence of a deformation phase affecting only the Arenarie di San Vito (see the stereonet in Fig. 8). The folds ascribed to the Sarrabese Phase are approximately NW trending, with a wavelength of approximately 200–300 m and NW- or SE-trending axes of variable plunge depending on the effect of Variscan folding events (Cocco and Funedda 2019). In addition to the angular unconformity, the occurrence of the Sarrabese Phase is corroborated by the evidence that the main Variscan foliation cross-cuts both limbs of the Sarrabese folds with a constant attitude. The superposition of the Variscan foliation on the Sarrabese folds has caused the structural facing direction in the Arenarie di San Vito to show opposing directions dependent on location through the Sarrabese folds, whereas it is consistently westward in the post-Sarrabese Unconformity formations (Cocco and Funedda 2019), according to the kinematics of Variscan tectonics (Conti et al. 2001). Furthermore, in this case, the lack of axial-plane foliation suggests a shallow structural level of deformation, as recognised in the Sulcis–Iglesiente Unit.

Time constraints on Ordovician unconformities

Intra-Ordovician unconformities in Sardinia

In the Sulcis–Iglesiente Unit, the younger sedimentary rocks below the Sardic Unconformity that were deformed during the Sardic Phase are assigned to the Tremadocian–lowermost Floian (?) (Pillola et al. 2008) of the Cabitza Fm. Biostratigraphic analyses of the post-Sardic Unconformity succession have been performed by Leone et al. (1991) and Hammann and Leone (1997, 2007). Taking into account the brachiopod and trilobite fauna, those authors related the biozones identified in the oldest fossiliferous level of the Monte Orri Fm. (TH1 and BH1) to the Soudleyan Regional Stage, which coincides with the lower Sandbian. Below these fossiliferous levels, in the Monte Argentu Fm., which measures up to 600 m thick, the unique occurrence of *Tariccoia arrusensis* suggests a possible Soudleyan age (base of the Sandbian; Leone et al. 1991; Hammann and Leone 1997, 2007).

The depositional features and facies of the Monte Argentu Fm. indicate very high sedimentation rates. The large thickness of the deposit, which was formed under constant water depth (i.e., isobathymetric conditions), demonstrates that the deposit was controlled by a high rate of subsidence that balanced the sedimentary accommodation over time.

Throughout the entire formation, no marked major bathymetric variations related to major eustatic variations are observed, suggesting that the Monte Argentu Fm. was deposited during a single high eustatic cycle. The time-calibrated eustatic curve established for the Upper Ordovician of the Moroccan Anti Atlas (Loi et al. 2010) and the Middle–Upper Ordovician of the Armorican massif (Dabard et al. 2015) is compared with the curve of variations in sedimentary environments and fauna contained in the post-Sardic sequences (Fig. 4). This comparison shows that the Monte Argentu Fm. was deposited during the time span between the third-order retrogradation phase PS7 and the progradation phase PS8 detected in the eustatic curve calibrated in the Armorican Massif by Dabard et al. (2015). Thus, the Monte Argentu Fm. is possibly assigned to the lower Sandbian. These data suggest that the time gap (Fig. 9) represented by the Sardic Unconformity, in which neither sedimentary deposits nor magmatic episodes occur, spans 17 Myr from the base of the Floian to the base of the Sandbian.

In the Sarrabus and Gerrei units, two regional unconformities have been detected in the Ordovician succession: the Sarrabese Unconformity (Calvino 1959) and the Katian nonconformity. The Sarrabese Unconformity is a continental erosional surface that seals the deformation affecting only the Arenarie di San Vito (Cocco and Funedda 2019) and is unconformably sealed by the Metaconglomerati di Muravera, which is in turn covered by Middle–Upper Ordovician volcanic rocks. To determine the age of the Sarrabese Unconformity, we must consider that the younger sedimentary rocks truncated by the unconformity in the Sarrabus and Gerrei units are assigned to the Lower Ordovician (Floian) on the basis of palaeontological constraints (Barca et al. 1988; Gnoli and Pillola 2002), and that the oldest deposit covering the unconformity is a volcanic rock with a U–Pb

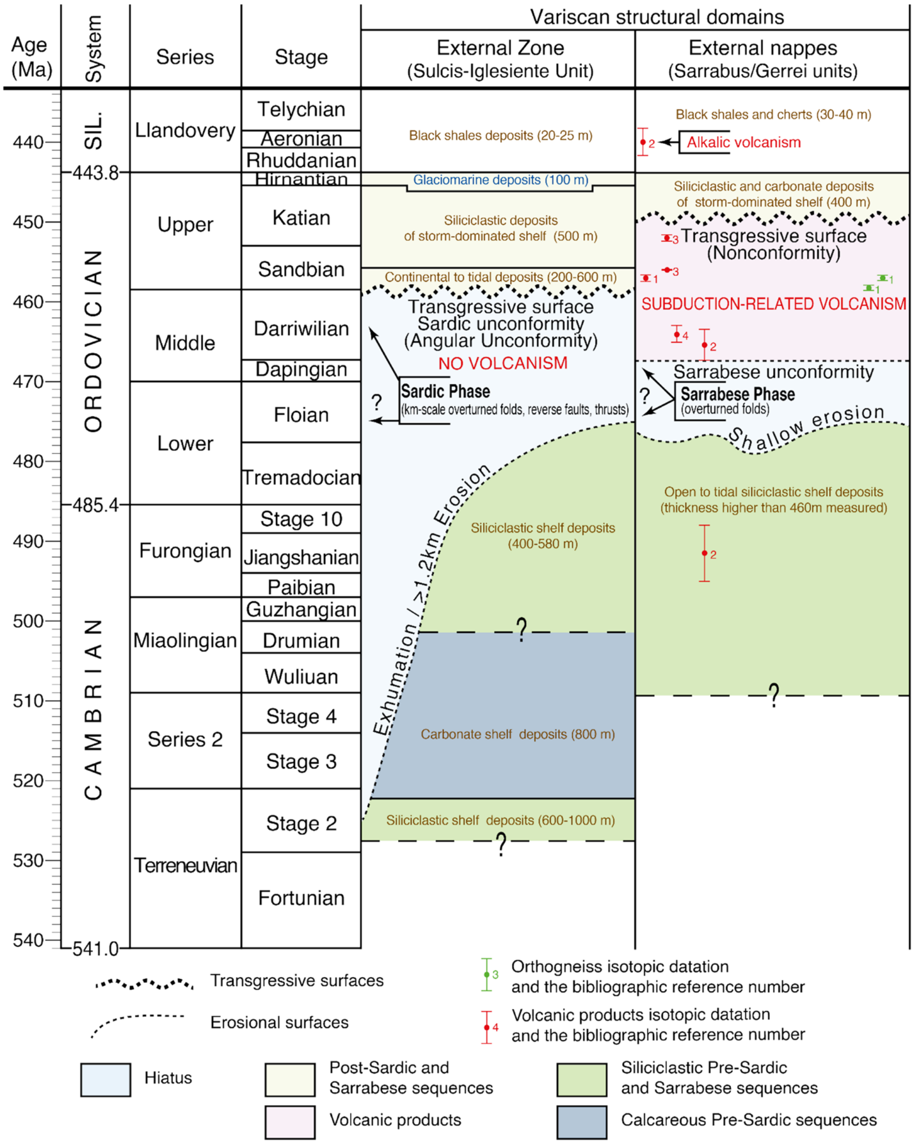


Fig. 9 Summary figure of the main stratigraphic and magmatic correlations between the External Zone (Sulcis–Iglesiente Unit) and the Nappe Zone (Sarrabus and Gerrei units) of the Variscan basement in Sardinia. Correlation of the major unconformity surfaces of the Middle–Upper Ordovician on a linear time scale is shown. U–Pb zircon ages are shown for volcanic (red) and plutonic (green) magmatic rocks. Bibliographic reference numbers: 1—Pavanetto et al. (2012); 2—Oggiano et al. (2010); 3—Dack (2009); 4—Giacomini et al. (2006)

zircon age of 465.4 ± 1.9 Ma (Oggiano et al. 2010). These data (Figs. 5 and 9) suggest that the Sarrabese Unconformity coincides with a restricted 6 Myr time gap spanning from the middle Floian to the Dapingian–Darriwilian boundary.

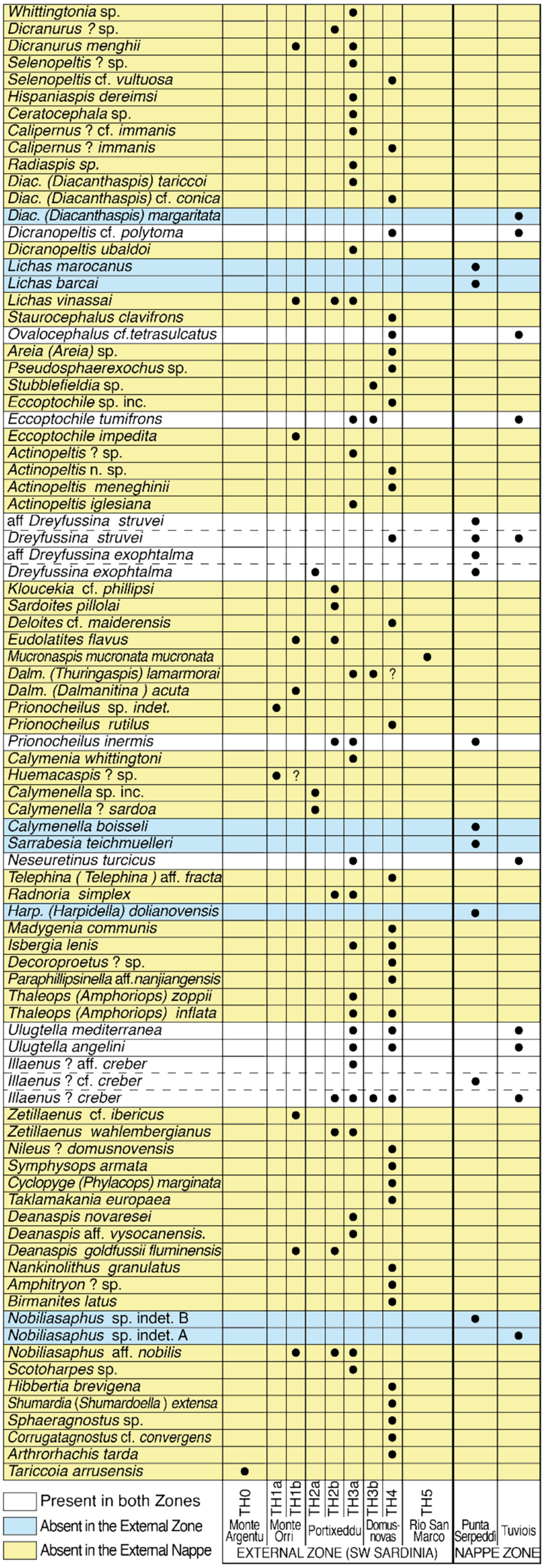
The Katian nonconformity marks a marine transgression with predominantly terrigenous deposits over the calc–alkaline volcanic complex (Figs. 6 and 9). The age is constrained by the youngest age measured for volcanic rocks, which is 452 ± 0.3 Ma (Dack 2009) and by the Katian fauna found in the overlying Punta Serpeddì Fm. (Fig. 6). The sedimentary rocks of the Punta Serpeddì Fm. are strongly condensed, suggesting a low sedimentation rate. In addition, they show a progressively deepening depositional environment, indicating retrogradation that can be correlated with sequence 3r of the eustatic curve established for the Upper Ordovician of the Moroccan Anti Atlas (Fig. 6; Loi et al. 2010). This sequence is temporally calibrated and begins at approximately 450 Ma. These data define a very short-lasting or at least restricted time gap (< 2 Myr) for the Katian nonconformity. Furthermore, both biostratigraphic and radiometric data suggest that this transgressive surface above the calc–alkaline volcanic complex is isochronous in the whole stack of tectonic units of the Nappe Zone in Sardinia, although in some areas, the Katian transgressive deposits overlie older volcanic rocks.

Faunal affinities in the Sulcis–Iglesiente and Sarrabus and Gerrei units

The Lower Ordovician (Tremadocian–Floian) succession has yielded fossil associations that are not strictly comparable in the two examined Sardinian blocks. In the Sulcis–Iglesiente Unit, the pre-Sardic lowermost fossiliferous levels in the Cabitza Fm. contain unassigned echinoderm fragments and scarce remains of *Proteuloma geinitzi* (Pillola et al. 1998). This unique diagnostic early Tremadocian taxon is known in southern Montagne Noire (Álvaro and Vizcaïno 1997; Álvaro et al. 1998; Shergold et al. 2000), Bohemia, and Germany. The rest of the macrofauna correspond to graptolites (Pillola and Gutierrez-Marco 1988; Pillola et al. 2008) of widespread taxa with low palaeogeographic significance. In the Sarrabus and Gerrei units, the pre-Sarrabese fossiliferous levels, in addition to discoveries of sparse palynomorphs (Naud and Pittau Demelia 1987), contain Floian biota dominated by benthic trilobites (mainly asaphids and *Ampyx priscus*), and they show close relationships with the equivalent strata in southern Montagne Noire on the basis of the occurrence of *Taihungshania shuy landayranensis* and, to a lesser degree, with strata in Taurus (Turkey), Iran, and China. Therefore, the Lower Ordovician successions from the Sulcis–Iglesiente and Sarrabus and Gerrei units do not share equivalent-age benthic taxa, preventing accurate comparison.

In contrast, the Upper Ordovician succession (Sandbian–Hirnantian) of the Sulcis–Iglesiente and Sarrabus and Gerrei units has yielded abundant trilobite fauna, which allows investigation of Ordovician palaeogeographic affinities (Fortey and Cocks 2003). Hammann and Leone (1997, 2007) described 75 species of trilobites in the Sulcis–Iglesiente Unit and 18 species in the Sarrabus and Gerrei units, of which only 10 are common to both areas (Fig. 10). However, Upper Ordovician deposits of the two examined Sardinian blocks do not cover the same time span, and a robust comparison to better establish the faunal differences should be performed only between coeval formations, i.e., the Domusnovas Fm. in the Sulcis–Iglesiente Unit and the Punta Serpeddì and Tuviois Fms in the Sarrabus and Gerrei units. Taking into account these formations only, 42 species are present in the Sulcis–Iglesiente Unit and 18 in the Sarrabus and Gerrei units, of which only 7 are shared. The very high diversity in the Sulcis–Iglesiente Unit is correlated not only with a longer time span but also with a larger environmental diversity of faunas, especially in the Domusnovas Fm., in which a well-diversified distal biofacies dominated by pelagic cyclopygids (with *Cyclopyge*, *Symphysops*, and *Telephina* comprising more than 70% of the assemblage; Hammann and Leone 2007) occurs together with Agnostids and benthic genera, blind for some of them (e.g., *Shumardia, Ulugtella,* and *Nankinolithus*). This well-diversified distal biofacies is not present in the Sarrabus and Gerrei units, where the collected trilobite fauna is restricted to shallower environments in the Punta Serpeddì and Tuviois Fms, constituting a completely different succession in the Upper Ordovician. Therefore, the comparison of fauna from the same environment involves the shallower Homalonotid and, to a lesser extent, the Trinucleid–Dalmanitid biofacies, which are not entirely synchronous between the Portixeddu and Punta Serpeddì Fms. Considering the occurrence of the genera *Lichas* and *Calymenella* (TH2a), the species belonging to the Portixeddu and Punta Serpeddì Fms are clearly different for *Lichas* (Fig. 10; see Hammann and Leone 2007 for discussion).

Considering the palaeogeographical affinities (Fortey 1999; Fortey and Cocks 2003; Hammann and Leone 2007), the taxa of both SW and SE Sardinia are clearly Gondwanan, with both western and southern Gondwanan influences (i.e., *Calymenella*, *Calymenia*, *Prionocheilus*, *Eccopotochile*, *Dreyfussina*, *Kloucekia*, *Dalmanitina*, *Eudolatites*, *Selenopeltis*, *Nobiliasaphus*, and *Deanaspis*), together with eastern and warmer palaeo-latitude origins closer to China (with *Ovalocephalus*, *Neseuretinus*, and *Ulugtella*). In the Sulcis–Iglesiente Unit, the Sandbian and lower Katian diversified fauna from the Monte Orri and Portixeddu Fms (from TH1a to TH2b) are typical of western (in present-day coordinates) Gondwana, closer to southern hemisphere palaeo-latitudes, whereas the warmer and Chinese faunas



	TH0	TH1a	TH1b	TH2a	TH2b	TH3a	TH3b	TH4	TH5		
	Monte Argentu	Monte Orri		Portixeddu			Domus-novas		Rio San Marco	Punta Serpeddì	Tuviois
	EXTERNAL ZONE (SW SARDINIA)									NAPPE ZONE	
🟨 *Whittingtonia* sp.						●					
🟨 *Dicranurus ?* sp.					●						
🟨 *Dicranurus menghii*			●			●					
🟨 *Selenopeltis* ? sp.						●					
🟨 *Selenopeltis* cf. *vultuosa*								●			
🟨 *Hispaniaspis dereimsi*						●					
🟨 *Ceratocephala* sp.						●					
🟨 *Calipernus* ? cf. *immanis*						●					
🟨 *Calipernus* ? *immanis*								●			
🟨 *Radiaspis sp.*						●					
🟨 *Diac. (Diacanthaspis) tariccoi*						●					
🟨 *Diac. (Diacanthaspis)* cf. *conica*								●			
🟦 *Diac. (Diacanthaspis) margaritata*											●
⬜ *Dicranopeltis* cf. *polytoma*								●			●
🟨 *Dicranopeltis ubaldoi*						●					
🟦 *Lichas marocanus*										●	
🟦 *Lichas barcai*										●	
🟨 *Lichas vinassai*			●		●	●					
🟨 *Staurocephalus clavifrons*								●			
⬜ *Ovalocephalus cf.tetrasulcatus*								●			●
🟨 *Areia (Areia)* sp.								●			
🟨 *Pseudosphaerexochus* sp.								●			
🟨 *Stubblefieldia* sp.							●				
🟨 *Eccoptochile* sp. inc.								●			
⬜ *Eccoptochile tumifrons*						●	●				●
🟨 *Eccoptochile impedita*			●								
🟨 *Actinopeltis* ? sp.						●					
🟨 *Actinopeltis* n. sp.								●			
🟨 *Actinopeltis meneghinii*								●			
🟨 *Actinopeltis iglesiana*						●					
⬜ aff *Dreyfussina struvei*										●	
⬜ *Dreyfussina struvei*								●		●	●
⬜ aff *Dreyfussina exophtalma*										●	
⬜ *Dreyfussina exophtalma*				●						●	
🟨 *Kloucekia* cf. *phillipsi*					●						
🟨 *Sardoites pillolai*					●						
🟨 *Deloites* cf. *maiderensis*								●			
🟨 *Eudolatites flavus*			●		●						
🟨 *Mucronaspis mucronata mucronata*									●		
🟨 *Dalm. (Thuringaspis) lamarmorai*						●	●	?			
🟨 *Dalm. (Dalmanitina) acuta*			●								
🟨 *Prionocheilus sp. indet.*		●									
🟨 *Prionocheilus rutilus*								●			
⬜ *Prionocheilus inermis*					●	●				●	
🟨 *Calymenia whittingtoni*						●					
🟨 *Huemacaspis* ? sp.		●	?								
🟨 *Calymenella* sp. inc.				●							
🟨 *Calymenella* ? *sardoa*				●							
🟦 *Calymenella boisseli*										●	
🟦 *Sarrabesia teichmuelleri*										●	
⬜ *Neseuretinus turcicus*						●					●
🟨 *Telephina (Telephina)* aff. *fracta*								●			
🟨 *Radnoria simplex*					●	●					
🟦 *Harp. (Harpidella) dolianovensis*										●	
🟨 *Madygenia communis*								●			
🟨 *Isbergia lenis*						●		●			
🟨 *Decoroproetus* ? sp.								●			
🟨 *Paraphillipsinella* aff.*nanjiangensis*								●			
🟨 *Thaleops (Amphoriops) zoppii*						●					
🟨 *Thaleops (Amphoriops) inflata*						●		●			
⬜ *Ulugtella mediterranea*						●		●			●
⬜ *Ulugtella angelini*						●		●			●
⬜ *Illaenus* ? aff. *creber*						●					
⬜ *Illaenus* ? cf. *creber*										●	
⬜ *Illaenus* ? *creber*					●	●	●	●			●
🟨 *Zetillaenus* cf. *ibericus*			●								
🟨 *Zetillaenus wahlembergianus*					●	●					
🟨 *Nileus* ? *domusnovensis*								●			
🟨 *Symphysops armata*								●			
🟨 *Cyclopyge (Phylacops) marginata*								●			
🟨 *Taklamakania europaea*								●			
🟨 *Deanaspis novaresei*						●					
🟨 *Deanaspis* aff. *vysocanensis.*						●					
🟨 *Deanaspis goldfussii fluminensis*			●		●						
🟨 *Nankinolithus granulatus*								●			
🟨 *Amphitryon* ? sp.								●			
🟨 *Birmanites latus*								●			
🟦 *Nobiliasaphus* sp. indet. B										●	
🟦 *Nobiliasaphus* sp. indet. A											●
🟨 *Nobiliasaphus* aff. *nobilis*			●		●	●					
🟨 *Scotoharpes* sp.						●					
🟨 *Hibbertia brevigena*								●			
🟨 *Shumardia (Shumardoella) extensa*								●			
🟨 *Sphaeragnostus* sp.								●			
🟨 *Corrugatagnostus* cf. *convergens*								●			
🟨 *Arthrorhachis tarda*								●			
🟨 *Tariccoia arrusensis*	●										

⬜ Present in both Zones
🟦 Absent in the External Zone
🟨 Absent in the External Nappe

Fig. 10 Occurrence of trilobite faunas in the Upper Ordovician succession of the Sulcis–Iglesiente and Sarrabus units

influences (with *Neseuretinus* and *Ulugtella*) start in the uppermost (TH3a) Portixeddu Fm. and are dramatically enhanced in the upper Katian TH4 Domusnovas Fm. (with *Birmanites*, *Nankinolithus*, *Taklamakania*, *Ovalocephalus*, and *Paraphillipsinella*; the S'Argiola Mb.; Fig. 4). In the Sarrabus Unit, the Katian shallow assemblage of the Punta Serpeddì Fm. displays an eastern influence with *Sarrabesia*, which is related to the Chinese genus *Vietnamia* according to Turvey (2005); these influences persist in the upper Katian part of the Tuviois Fm. (with *Ulugtella*, *Neseuretinus*, and *Ovalocephalus*). In both SW and SE Sardinia, these faunal warmer pulses are linked to transgressive phases. The faunal succession clearly differs between SW and SE Sardinia (Fig. 10), which, although a detailed comparison is difficult owing to differences in age and environment between the two successions, suggests that these two areas were not joined during Late Ordovician as they are today. Furthermore, although Chinese faunas influences exist in the Floian and Katian in the Sarrabus and Gerrei units, they appear in the upper Katian in the Sulcis–Iglesiente Unit at the position corresponding to the "Boda event" (Fortey 1985), a global warming promoting massive dispersion of taxa. Therefore, the palaeogeographical significance of the warmer faunas of the Sulcis–Iglesiente Unit is less noticeable than that of the Sarrabus and Gerrei units.

Intra-Ordovician unconformities in the areas neighbouring Sardinia

Since the earliest study that recognised an early Paleozoic tectonic phase in the European Variscan basement (Stille 1939), a correlation has been proposed between the Sardinian successions and the closest areas on the European continent, particularly the eastern Pyrenees (Stille 1935) and the Montagne Noire (Arthaud 1970). The main stratigraphic and tectonic features are outlined below based on the most recent literature, with particular attention to Ordovician regional unconformities.

In the eastern Pyrenees, several Paleozoic successions belonging to the Aspres/Conflent, Cerdanya, Ribes de Freser, and Bruguera tectonic units were involved in the Pyrenean Orogeny and, therefore, underwent post-Variscan allochthony. In these successions, an intra-Ordovician angular unconformity has been consistently detected, with the younger deposits covered by the angular unconformity surface being assigned to the Lower Ordovician. Here, the stratigraphic features below and above the angular unconformity are used to compare the lower Paleozoic successions of the Pyrenees and Sardinia. The Aspres/Conflent Unit is characterised by a succession (Jùjols Group in Padel et al. 2018; Casas et al. 2019) consisting of monotonous succession of argillites (Err Fm.) assigned to the basal Cambrian, overlain by a lower Cambrian limestone formation with nodular limestones (Valcebolière Fm.) at the top, which passes upward to argillites interbedded with sandstones (Serdinya Fm.) whose top is assigned to the Tremadocian–Floian boundary. This succession is interrupted by an angular unconformity that Casas et al. (2019) correlate with the Sardic Unconformity. The Aspres/Conflent unit in the Pyrenees and the pre-Sardic Unconformity formations of SW Sardinia show a convincing correlation: the Nebida, Gonnesa, and Cabitza Fms are readily correlated with the Err, Valcebolière, and Serdinya Fms by means of lithological, biostratigraphic, and palaeoenvironmental criteria (Casas et al. 2019). In the Cerdanya unit, an analogous angular unconformity separates the Serdinya Fm. from the overlying Rabassa Fm. The Rabassa Fm. consists mainly of conglomerates and is assigned to the Sandbian, and a correlation with the Monte Argentu Fm. has, therefore, been proposed (Casas et al. 2019). In addition, the Upper Ordovician succession of the Cerdanya Unit has very similar characteristics to the coeval succession of the Sulcis–Iglesiente Unit (SW Sardinia). A further relevant commonality between the lower Paleozoic successions of the Aspres/Conflent and Cerdanya units and the Sulcis–Iglesiente Unit is the lack of Ordovician magmatic rocks. It is also important to note that considering the ages of the sedimentary rocks immediately below and above the unconformity (Hartevelt 1970), the stratigraphic gap in these tectonic units of the Pyrenees corresponds to approximately 20 Myr, covering a time span similar to that of the stratigraphic gap (17 Myr) recognised in the Sulcis–Iglesiente Unit.

The Ribes de Freser and Bruguera units show some differences in the lithostratigraphic succession from the Aspres/Conflent and Cerdanya units. These former units are characterised by a Cambrian–Lower Ordovician stratigraphic succession composed predominantly of siliciclastic deposits and whose top is assigned to the lowermost Floian. This is unconformably overlain by pre-Katian volcanic rocks (e.g., the Campelles ignimbrites) that are similar in age to the Monte Santa Vittoria, Porfidi Grigi, and Porfiroidi Fms of the Sarrabus and Gerrei units (458 Ma in the Ribes de Freser Unit; Martínez et al. 2011; 455 Ma in the Bruguera Unit, Martí et al. 2019). Furthermore, numerous orthogneiss bodies (the Canigò, Roc de Frausa, and L'Albera orthogneisses; Casas et al. 2019) assigned to the Middle–Upper Ordovician intrude the Ribes de Freser and Bruguera units and other adjacent units (the Puigmal and Vallespir units). The stratigraphic gap between the Cambrian–Lower Ordovician (Jùjols Fm.) and the Middle–Upper Ordovician volcanic succession in the Ribes, Freser, and Bruguera units spans approximately 15 Myr, considering the age of the youngest detrital zircon (475 Ma) identified in the Serdinya Fm. (Margalef et al. 2016) and the maximum age of the overlying volcanic rocks (460.4 ± 2.2 to 459.1 ± 5.3 Ma, Campelles Ignimbrite; Martí et al. 2019). The volcanic arc activity lasted throughout the Sandbian, as evidenced by the Els Metges rhyolites dated at 455.2 ± 1.8 Ma (Navidad et al. 2010, 2018), and through part of the Katian, considering the 452 ± 4 Ma age of the St. Martí pyroclastic rocks (Martínez et al. 2011; for a summary of Ordovician magmatism, ages, and interpretation, see Casas et al. 2019). The features of the Ordovician rocks in the Ribes, Freser, and Bruguera units allow a very convincing correlation to the Sarrabus and Gerrei units.

In the Occitanie Domain, that is, Montagne Noire (Cabrières unit) and the Mouthoumet Massif, three Ordovician volcanic cycles have been recognised, but no radiometric dating is available. However, on the basis of stratigraphic relationships, two of these cycles have been assigned to the Lower Ordovician (Pouclet et al. 2017), whereas the third has been tentatively assigned either to the Lower (Berger et al. 1997) or Upper Ordovician (Álvaro et al. 2016). The older two volcanic cycles belong to a volcano-sedimentary succession cut by an erosive surface with a gap that extends from the Floian to Darriwilian. The age of the youngest volcanic cycle (the Roque de Bandies Fm. in Montaigne Noire and the Villerouge Fm. in Mouthoumet), which is characterised by mafic lavas and pyroclastic flows, is constrained between the age of the underlying volcano-sedimentary cycle and the overlying Katian sedimentary succession. The latter is composed of conglomerates with volcanic clasts and arkose sandstones at the base and a succession of marls, limestones, and siltstones at the top. Although no radiometric data are available for the volcanic rocks, the occurrence of several Darriwilian to Katian magmatic bodies intruding the Cambrian succession (Álvaro et al. 2016) suggests that the magmatic activity lasted at least until the Katian, as recognised in SE Sardinia.

Discussion

Having reconstructed Ordovician stratigraphy and tectono-sedimentary events that characterise the SW and SE Sardinia blocks and identified similarities and differences between them, here we compare the successions of the SW and SE domains of the Sardinian Variscan basement and discuss the related Ordovician tectonics of the eastern Pyrenees and Occitanie. The Sulcis–Iglesiente and Sarrabus and Gerrei units share few similarities and show several chronostratigraphic, sedimentary, and faunal differences. A common feature between them is the deformation affecting the pre-unconformity successions, which has generated a system of locally overturned folds, undoubtedly indicating a shortening phase (Pasci et al. 2008; Cocco and Funedda 2019). Precise ages for the Sardic and Sarrabese phases are difficult to determine because of the lack of a syn-folding metamorphism event or fault rocks developed during the

Sardic overthrusting recognised in the Sulcis–Iglesiente Unit (Pasci et al. 2008). Therefore, unless more precise dating can be obtained and better constraints placed on the differing time gaps related to the Sardic and Sarrabese unconformities, full diachrony between the Sardic and Sarrabese phases cannot be ruled out. A primary difference between the successions can be observed in the erosion processes. In the Sulcis–Iglesiente Unit, the erosive surface deeply incises the previously folded and thickened substrate for approximately 1200 m (the thickness of the Gonnesa and Iglesias groups) to reach the lower Cambrian Nebida Fm. (Fig. 9). This episode of strong subaerial erosion is supported by intense rubefaction of the substrate. In the Sarrabus and Gerrei units, although the stratigraphic markers of the Arenarie di San Vito are poorly defined, the depositional features of the Metaconglomerati di Muravera suggest weak incision (Fig. 9), and no rubefaction of the substrate is observed. Another difference between the SW and SE domains of Sardinia is the length of time represented by the Sardic and Sarrabese unconformities: for the Sardic Unconformity, a gap of approximately 17 Myr (Figs. 3 and 9) is documented, which ends in the Sandbian as marked by conglomerates of the Monte Argentu Fm. For the Sarrabese Unconformity, the gap ends at the Dapingian–Darriwilian boundary with the Metaconglomerati di Muravera and the volcanic complex, which allows us to infer a temporal gap of approximately 6 Myr (Figs. 3 and 9).

In addition to the differing lengths of time represented by the Sardic and Sarrabese unconformities, magmatic activity is completely lacking in the Sulcis–Iglesiente Unit, in contrast to the Sarrabus and Gerrei units, in which thick volcanic successions occur. It is worth noting that the emplacement of the volcanic complex in the Sarrabus and Gerrei units started during the period of continentalisation and erosion in the Sulcis–Iglesiente Unit and persisted during deposition of the thick strata (Monte Argentu Fm.) that record a phase of subsidence linked to rift basin opening. When the volcanic activity ended in the Sarrabus and Gerrei units, continental platform sediments (Portixeddu Fm.) typical of a passive margin were already depositing in the Sulcis–Iglesiente Unit. This presents another chronostratigraphic and tectonic difference between SW and SE Sardinia during Ordovician evolution. The Katian nonconformity on the volcanic complex is younger than the Sandbian marine transgression in the Sulcis–Iglesiente Unit. Therefore, while the crustal block of present-day SE Sardinia was fully involved in a volcanic arc system on continental crust (Oggiano et al. 2010; Gaggero et al. 2012; Cocco et al. 2018), and therefore, in a convergent margin, the crustal block of present-day SW Sardinia was in a terrigenous platform environment, far from tectonically active areas. In addition, the two areas differ from each other in their Ordovician fossil contents. Both successions below and above the unconformity surfaces contain abundant fossil fauna (mainly brachiopods, trilobites, and crinoids), showing substantial differences in both genera and species. According to Pillola (1991), the Cambrian trilobite associations of SW Sardinia are similar to those described between Turkey and Kazakhstan, whereas the faunal association of SE Sardinia shows affinity with South China terranes. Hence, these differences in the fossil fauna of the Ordovician successions can be ascribed to the palaeogeographic distance and difference in climatic conditions between the Ordovician platforms of the present Sulcis–Iglesiente and Sarrabus and Gerrei units. Different palaeogeographic positions can also be inferred from the occurrence of Hirnantian glacio-marine deposits in the Sulcis–Iglesiente Unit (Hammann and Leone 1997, 2007; Ghienne et al. 2000), which are absent from the Sarrabus and Gerrei units. These points suggest a palaeolatitudinal position under glacio-marine influence for the Upper Ordovician deposits of SW Sardinia. Therefore, for reconstruction of the Ordovician, SW Sardinia should be placed close to southern hemisphere palaeo-latitudes, whereas SE Sardinia, owing to the presence of other characteristics, such as faunal affinities and arc volcanism, should be placed further to the north at lower palaeo-latitudes.

In summary, data on the Ordovician tectonic evolution from the Sardinia Variscan basement show (i) different ages of the Sardic and Sarrabese unconformities, (ii) different lengths of the time gaps represented by the unconformities, (iii) different geodynamic settings of the post-unconformity successions, (iv) different faunal affinities, (v) the presence or absence of a magmatic arc, and (vi) the possible different ages of Early Ordovician deformation. All of these observations corroborate the hypothesis of two independent crustal blocks that during the Ordovician were part of two distinct tectonic settings, with a significant palaeogeographic distance between them, and which are now juxtaposed as a result of Carboniferous Variscan events. Current knowledge does not allow us to propose the exact locations of these blocks during the Ordovician. Because there is no evidence of the Cadomian Orogeny (570–545 Ma) in either the External or the Nappe Zones of Sardinia, the blocks were most likely in a sector of the Gondwana margin not involved in the oblique collision involving Avalonia and Cadomia (Chantraine et al. 2001; Linnemann et al. 2014).

Taking into account the tectonic–sedimentary characteristics recognised in some tectonic units of the Paleozoic basement of the eastern Pyrenees and Occitanie, in particular the age of the unconformity and the underlying and overlying sequences, two different Ordovician domains can also be recognised in those locations. In the eastern Pyrenees, the angular unconformity recognised in the Aspres/Conflent and Cerdanya units is correlative to the Sardic Unconformity recognised in SW Sardinia. Likewise, the angular unconformity recognised in the Ribes de Freser and Bruguera units is correlative to the Sarrabese Unconformity recognised in

SE Sardinia. In the Occitanie Domain, although data are less clear, the hiatus between the Tremadocian and Darriwilian could correspond to the coeval gap represented by the Sarrabese Unconformity, and the transgressive surface at the top of the Roque de Bandies and Villerouge Fms corresponds in time to the Katian nonconformity. Thus, the Ordovician evolution of part of the Montaigne Noire and Mouthoumet appears to be similar to that of SE Sardinia.

Considering the Ordovician evolution of the two Sardinian blocks, it is appropriate to consider their role in the framework of the opening of the Rheic Ocean, the main geodynamic event that involved the margin of Gondwana, where pre-Variscan terranes were located during the early Paleozoic. The Rheic Ocean opened diachronously from west to east (from present-day Morocco toward Arabia) during the early and middle Cambrian (von Raumer and Stampfli 2008; von Raumer et al. 2015), roughly reactivating the previous collision suture. The youngest phase of the opening of the Rheic Ocean, that is, an extensional context, is recorded in the Lower Ordovician (Floian) of the central Armorican domain, for which a palaeogeographic position close to the Sahara Metacraton and Arabian–Nubian Shield has recently been proposed (Dabard et al. 2021). This extensional geodynamic context and the timing of the ongoing processes pose major palaeogeographic problems for the positioning of the Sardinian blocks, as, at the same time, they were affected by crustal shortening leading to the formation of folds that record a compressive or transpressive tectonic regime during the Floian. SW Sardinia then underwent a long period of continentalisation, as evidenced by the deep incision of the Cambrian succession, which ended during the Sandbian when nonvolcanic rifting processes were initiated. Magmatic activity in SE Sardinia started as early as the Furongian (dated at 491.4 ± 3.5 Ma; Oggiano et al. 2010), before the Sarrabese Phase that occurred in a compressive tectonic regime between the Floian and the Dapingian. The convergent setting persisted until the Katian and gave rise to the emplacement of a volcanic arc on continental crust. At the same time, during Early Ordovician, the Rheic Ocean was still widening. These temporal and geodynamic inconsistencies with the Rheic Ocean system suggest that during Ordovician, the SW and SE Sardinia blocks were positioned in the vicinity of the northeastern Gondwanan margin.

The above discussion suggests the following points:

a. After the Cambrian, both the Sulcis–Iglesiente and Sarrabus and Gerrei units were located in more easterly sectors of the Gondwanan margin than most parts of Variscan Europe;
b. The Sarrabus and Gerrei units were located close to a subduction system most likely related to the evolution of the Qaidam Ocean, the closest convergent margin according to most palaeogeographic reconstructions, and in the vicinity of regions showing characteristics typical of convergent margins (e.g., Chamrousse ophiolites in the Alps; Burda et al. 2021). According to some studies, the Ordovician features of the Nappe Zone of the Variscan Chain are highly consistent with a subduction–accretion system (Zurbriggen 2015, 2017; Cocco et al. 2018; Cocco and Funedda 2019);
c. The Sulcis–Iglesiente Unit, which lacks magmatic rocks, was far from and not connected to the Nappe Zone during the Ordovician, as it was situated in an extensional setting evolving to a passive margin at palaeo-latitudes closer than the Sarrabus and Gerrei units to the Gondwana ice sheets;
d. Parts of the eastern Pyrenees and Occitanie domains can be interpreted in the same way as for Sardinia, distinguishing two different Ordovician evolutions for tectonic units subsequently juxtaposed during the Variscan Orogeny.

Conclusions

In Sardinia, two deformation events—the Sardic and Sarrabese phases—and two associated eponymous regional unconformities record the Ordovician tectonics of SW and SE Sardinia. Prior to this study, these unconformities were poorly temporally constrained and were regarded as the same unconformity, making it difficult to unravel the Ordovician evolution of the Sardinian basement. Our investigations show that the Sardic Phase, which is recognised in the Sulcis–Iglesiente Unit (SW Sardinia, the External Zone of the Variscan chain), occurred between the early Floian and the earliest Sandbian. In contrast, the age of the Sarrabese Phase, which is recognised in the Sarrabus and Gerrei units (SE Sardinia, the Nappe Zone of the Variscan chain), is robustly constrained between the early Floian and the Darriwilian–Dapingian boundary. Although the ages of the Sardic and Sarrabese phases partially overlap and the style of deformation is similar in the Sulcis–Iglesiente and Sarrabus and Gerrei units (which has given rise to confusion in the literature), major stratigraphic, temporal, palaeontological, and tectonic differences rule out the proximity of these two domains during the Ordovician. This interpretation is further confirmed by the 17 Myr gap observed in the Sulcis–Iglesiente Unit after the Sardic Phase. This prolonged phase of continentalisation marked by the unconformity gave rise to appreciable topography involving the erosion of approximately 1200 m of lower Cambrian–Ordovician deposits. Following this period of erosion, a continental rift system was established, and a thick sequence of continental sedimentary rocks was deposited during the Sandbian, finally evolving into shelf deposits in a passive continental margin environment. In contrast, the Sarrabus and Gerrei units of SE Sardinia record only a short-lived (6 Myr) stratigraphic gap after the Sarrabese Phase, constrained between the middle Floian and the Dapingian–Darriwilian boundary. The Sarrabese Unconformity is sealed by a thick calc–alkaline volcanic succession related to a subduction system, which lasted for approximately 19 Myr, during which the Sulcis–Iglesiente Unit (SW Sardinia) underwent a process of continental rifting and subsequent development of a passive margin (in which was deposited the post-Sardic succession). Subsequently, approximately 25 Myr after the Sarrabese Phase, a marine transgression above the volcanic arc occurred during the middle Katian (forming a nonconformity). A preliminary comparison of the Sardinian blocks with tectonic units in the eastern Pyrenees and Occitanie reveals a similar evolution during the Ordovician.

The identified unambiguous temporal and tectonic differences between the studied units of SW and SE Sardinia support the hypothesis that the sectors of the Gondwana margin, where the Sardinian blocks were situated were influenced by high tectonic mobility during the Ordovician and that the amalgamation of the Sulcis–Iglesiente Unit with the Sarrabus and Gerrei units occurred exclusively as a result of subsequent Variscan geodynamics. In addition, the allochthony that is inferred from the Sardinian Variscan basement, particularly the juxtaposition of the Nappe Zone against the External Zone, is more important than has hitherto been acknowledged, although more data are needed to estimate the displacement occurred during Variscan Orogeny.

Acknowledgements We thank I. Dias da Silva and an anonymous reviewer for their considered comments and suggestions, which helped to strengthen the paper. Editor-in-Chief Ulrich Riller is thanked for careful management of the manuscript.

Author contributions Conceptualization: FC, AL, AF, and GO; methodology: FC, AL, and AF; formal analysis and investigation: FC, AL, AF, LC, JFG, GLP, MV, MAM, and GO; writing—original draft preparation: FC, AL, AF, LC, JFG, GLP, MV, MAM, and GO; writing—review and editing: FC, AL, and AF; funding acquisition: AL, AF, and GO; supervision: AL. All authors read and approved the final manuscript.

Funding Open access funding provided by Università degli Studi di Cagliari within the CRUI-CARE Agreement. This research was funded by Regione Autonoma della Sardegna, L.R. 7/2007, [Grant number J81G17000110002] and by the Fondazione Banco di Sardegna [Grant numbers F74I19000960007 and F75F21001270007].

Declarations

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

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