The Ordovician of Sardinia (Italy): from the "Sardic Phase" to the end-Ordovician glaciation, palaeogeography and geodynamic context

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Abstract

This review shows the most important features of Ordovician succession of the Sardinian basement. We focus on stratigraphy and tectonic structures in the different tectonic units of External and Nappe zones of the Variscan basement. These Ordovician successions are characterized by unconformities related to tectonics events ascribed to the Sardic and Sarrabese phases. The different extent of the unconformity-related gaps in the External (17 Ma) and Nappe (6 Ma) zones, the recent works on trilobite fossil content, and the occurrence of a volcanic arc only in the Sarrabus/Gerrei units highlight significant discrepancies suggesting that these domains did not share the same geodynamic setting and, possibly, paleogeographic position during the Ordovician, implying they drew close and amalgamated only in Variscan times. Whereas for the external and nappe zones the Ordovician features are clear, on the contrary the high-grade metamorphic Inner Zone, where numerous Ordovician ortho- and para-gneiss, needs more detailed studies to define a complete framework of the Ordovician evolution of Sardinia. From the data on the best-preserved succession of the Sardinian tectonic units, arise that at least two distinct terranes were amalgamated only during the Variscan Orogeny, entails alternative correlations for them and a different arrangement in early Paleozoic time.

Keywords: *Sardic Phase; Sarrabese Phase; Gondwana; Rheic Ocean; Ordovician magmatic arc; Qaidam Ocean*

1) Introduction

The Ordovician successions of Italy are extensively documented in Sardinia and, to a lesser extent, in the Carnic Alps (Vai 1971; Vai and Spalletta 1980; Schönlaub 2000). In other regions of Italy, portions of Ordovician crust are reported in the northern Apennines (Apuan Alps, Conti *et al.* 1993), and in the southern Apennines (Calabrian-Peloritanian Arc, Cirrincione *et al.* 2015), consisting of rocks of various metamorphic grades made up of sedimentary and volcanic protoliths. Some volcanic products of these metamorphic complexes have provided absolute Ordovician ages (Trombetta *et al.* 2004; Paoli *et al.* 2017).

The Ordovician successions of Sardinia are affected by several folding events, the oldest of which are referable to the Early Ordovician Sardic and Sarrabese phases, and the most recent to the Variscan Orogeny. The Variscan Orogeny (Fig. 1) provide the main structure of the Sardinian basement and deformed, with different metamorphic grades, a Cambrian to lower Carboniferous sedimentary and volcanic succession. Three tectono-metamorphic zones (Carmignani *et al.* 1994) and numerous allochton tectonic units are recognised in Sardinia (Fig. 2). In these different tectonic units, the stratigraphic successions show strong differences between the SW of Sardinia (External Zone) and all the other successions involved in the Variscan structuring of the Sardinian basement (Nappe Zone and Inner Zone). An intra-Ordovician unconformity stands out in the sedimentary succession, which is well preserved in the shallowest tectonic units and less detectable in the high grade tectonic units. This unconformity was first detected in south-western Sardinia and was referred to the tectonic event called the Sardic Phase (Stille 1939). This tectonic event was defined through an angular unconformity (Sardic Unconformity, (Teichmüller 1931) associated with a stratigraphic gap constrained, at the time, between the middle Cambrian and the Upper Ordovician. Subsequently, in south-eastern Sardinia (Nappe Zone), an angular unconformity (Sarrabese Unconformity) was recognised between the Cambrian- Lower Ordovician sedimentary series and a thick Ordovician volcanic and sedimentary complex, and ascribed to the Sarrabese Phase (Calvino 1959; Naud 1981).

For many years the meaning of the Sardic and Sarrabese phases (and their unconformities) was the focus of several scientific discussions. As the years went by, many interpretations followed one another as a result of new discoveries, especially concerning the age and stratigraphic features of the successions below and above the unconformities, allowing a more and more accurate age constraint of the deformation phase(s). In recent years the stratigraphy of Ordovician successions in Sardinia has been better defined (Gandin and Pillola 1985; Barca *et al.* 1987; Laske *et al.* 1994; Pillola *et al.* 1995, 1998, 2008; Loi *et al.* 1996; Hammann and Leone 1997, 2007; Ferretti *et al.* 1998; Leone *et al.* 1998; Storch and Leone 2003) and the increasing number of isotopic ages (Palmeri *et al.* 2004; Giacomini *et al.* 2005, 2006; Dack 2009; Rossi *et al.* 2009; Oggiano *et al.* 2010; Pavanetto *et al.* 2012; Casini *et al.* 2015) have allowed a more robust interpretation of the widespread stratigraphic gap referred to the Sardic and Sarrabese phases. In addition, the structural style of the deformation, characterized by overturned fold, and the related intra-Ordovician continentalisation, has recently been described in detail (Pasci *et al.* 2008; Cocco *et al.* 2018, 2022_submitted; Cocco and Funedda 2019, 2021).

Since the 1980s, palaeogeographic reconstructions and some geodynamic models (Oggiano *et al.* 2010; Gaggero *et al.* 2012) have assumed that the Variscan basement of Sardinia pertained to a platform connected to a single coherent crustal block since Cambrian times. Thus, the stratigraphic differences between the External and Nappe zones observed in the Ordovician successions were interpreted as due to a coeval evolution in neighbouring areas of a subduction margin, where a back-arc basin and a continental volcanic arc developed during the Middle Ordovician in the External and Nappe zones, respectively. The most recent and accurate analyses of stratigraphic and palaeontological data, sediment provenance, chronology of magmatic products and gap ages indicate strong differences between tectonic units in Sardinia, with no comparable geodynamic settings and timescales (Cocco *et al.* 2018, 2022_submitted). These discrepancies imply that the External and Nappe zones belonged to different and possibly distant palaeogeographical and geodynamical domains. Moreover, these data suggest that the current zonation of the Paleozoic basement of Sardinia is the product of extensive crustal reworking and amalgamation in Variscan times. Therefore, a palaeogeography where Sardinia is considered a single crustal block during the Ordovician can be ruled out.

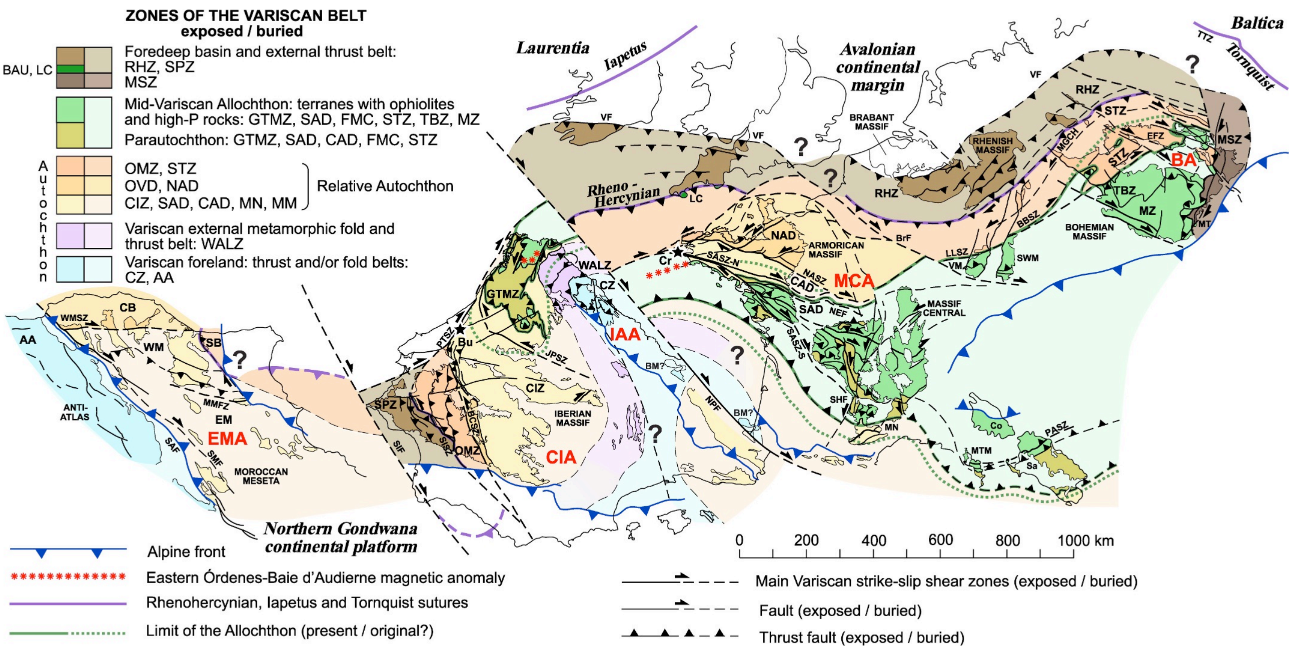

Fig. 1. Tectonic sketch map of the Southern Variscan Realm at the end of the Paleozoic, modified after Martínez Catalán *et al.* (2021)

2) Variscan tectono-metamorphic framework of Sardinia

The complete section of the Variscan chain exposed in Sardinia comprises three tectono-metamorphic zones (Carmignani *et al.* 1994) (Fig. 2a): an External Zone in SW Sardinia, a Nappe Zone in central-eastern Sardinia and, finally, an Inner Zone in the northern sector of the island. During the Variscan collisional phase, a regional (Barrovian) metamorphism developed, increasing from south-west to north-east, from a very low grade in the External Zone, to greenschist facies in the Nappe Zone, and to high grade in the Inner Zone.

The External Zone is considered to be the parautochthonous above which the external Nappe of the Nappe Zone overthrust and was deformed by at least three Variscan folding events with no or very low-grade metamorphism (T < 250 °C, Casini et al., 2010).

The Nappe Zone (greenschist facies, T < 500 °C) is divided into External and Internal Nappe (Fig. 2b), which are composed of several stacked tectonic units characterised by litho-stratigraphic successions attributable to the same time period, yet showing some lithological differences between them (Fig. 2a and 2b). The overlapping of the External Nappe tectonic units is well exposed in SE Sardinia, where they are involved in a Variscan antiformal structure known as the Flumendosa Antiform (Fig. 2b and 2c) (Conti *et al.* 1999), whose deep erosion/incision allows the identification, from bottom to top, of the Monte Grighini, Riu Gruppa, Gerrei, Meana Sardo and, finally, Sarrabus units (Carmignani *et al.* 1994; Conti *et al.* 2001; Funedda *et al.* 2011, 2015; Meloni *et al.* 2017). Two main allochthonous tectonic units have been identified in southwestern Sardinia: the Bithia (Pavanetto *et al.* 2012) and Arburese (biblio) units, which can be correlated with the Gerrei and Sarrabus units, respectively.

The tectonic units of the Internal Nappe Zone are stratigraphically less defined, due to the higher metamorphic degree (Casini *et al.* 2010) and the intensity of deformation (Conti *et al.* 1998). In central Sardinia (Fig. 2b) they reveal some differences in stratigraphic stacking and are characterised by the lack of Silurian-Devonian limestones (Oggiano and Mameli 2006). Tectonic units have been displaced with a general southward transport direction, which turns westward in the late evolution of the Variscan collision (Conti *et al.* 2001). Two main Variscan deformation events have been recognised in the External Nappe (Carmignani *et al.* 1994): the first, related to continental collision and shortening, is responsible to the formation of overthrusts marked by well-expressed thick milonitic bands and isoclinal folds with well-developed axial plane foliation. The second event is more likely related to the collapse of the chain in an extensional regime, with consequent total thinning accommodated by ductile shear zones (Casini *et al.* 2010) combined with asymmetric folds, low- and high-angle normal faults, and crustal-scale strike-slip zones (Conti *et al.* 1999; Casini and

Oggiano 2008). Finally, during late Carboniferous-Permian the large-scale emplacement of Variscan granitoids occurred, leading to the development of HT-LP metamorphism (Casini *et al.* 2015; Conte *et al.* 2017; Secchi *et al.* 2021; Cocco *et al.* 2022).

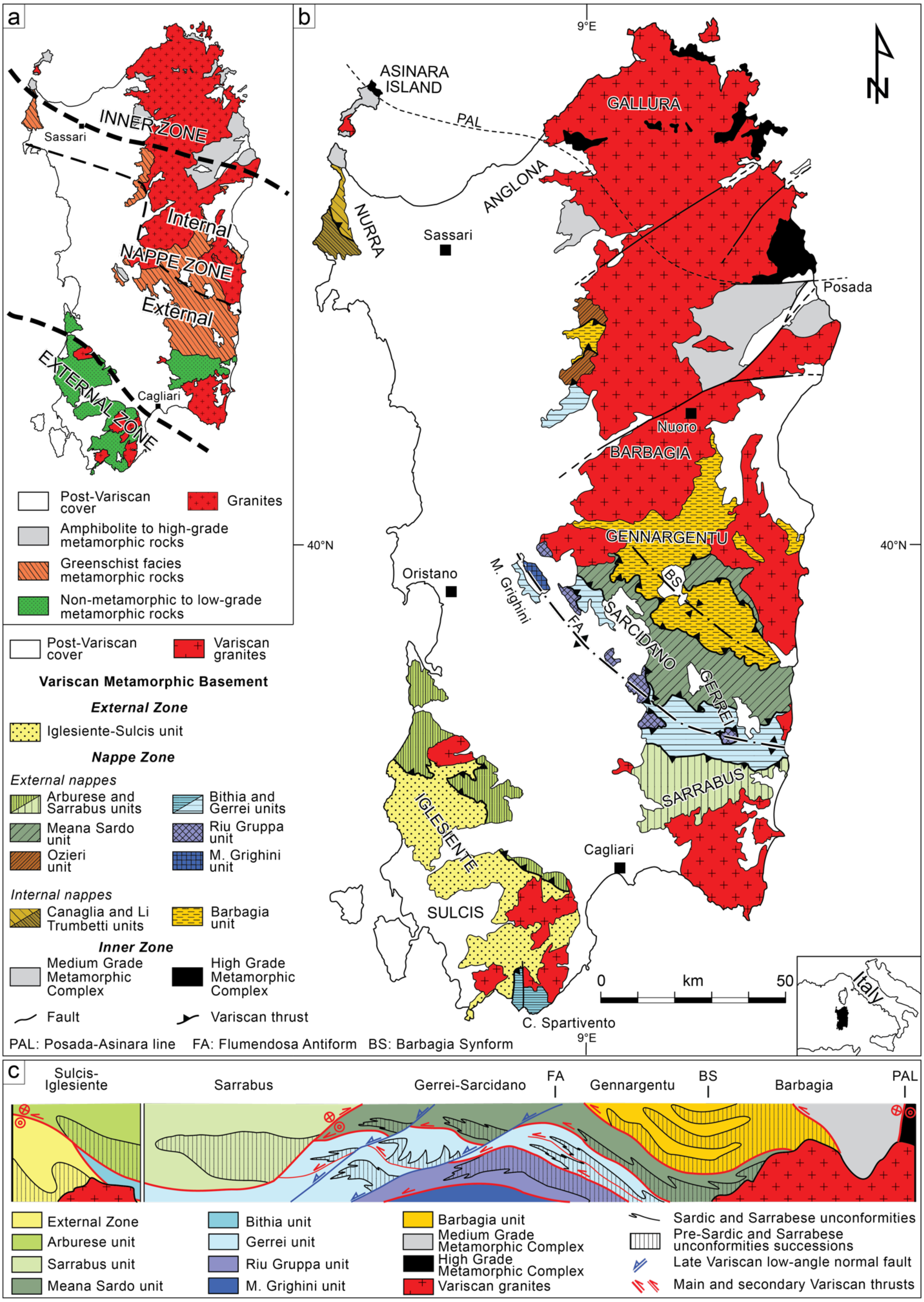
a
INNER ZONE
Sassari
Internal
NAPPE ZONE
External
EXTERNAL ZONE
Cagliari
Post-Variscan cover
Granites
Amphibolite to high-grade metamorphic rocks
Greenschist facies metamorphic rocks
Non-metamorphic to low-grade metamorphic rocks
b
9°E
ASINARA ISLAND
PAL
GALLURA
ANGLONA
NURRA
Sassari
Posada
Nuoro
BARBAGIA
GENNARGENTU
40°N
Oristano
M. Grighini
BS
FA
SARCIDANO
GERREI
SARRABUS
IGLESIENTE
SULCIS
Cagliari
C. Spartivento
0 km 50
Italy
Post-Variscan cover
Variscan granites
Variscan Metamorphic Basement
External Zone
Iglesiente-Sulcis unit
Nappe Zone
External nappes
Arburese and Sarrabus units
Bithia and Gerrei units
Meana Sardo unit
Riu Gruppa unit
Ozieri unit
M. Grighini unit
Internal nappes
Canaglia and Li Trumbetti units
Barbagia unit
Inner Zone
Medium Grade Metamorphic Complex
High Grade Metamorphic Complex
Fault
Variscan thrust
PAL: Posada-Asinara line FA: Flumendosa Antiform BS: Barbagia Synform
c
Sulcis-Iglesiente
Sarrabus
Gerrei-Sarcidano
FA
Gennargentu
BS
Barbagia
PAL
External Zone
Arburese unit
Sarrabus unit
Meana Sardo unit
Bithia unit
Gerrei unit
Riu Gruppa unit
M. Grighini unit
Barbagia unit
Medium Grade Metamorphic Complex
High Grade Metamorphic Complex
Variscan granites
Sardic and Sarrabese unconformities
Pre-Sardic and Sarrabese unconformities successions
Late Variscan low-angle normal fault
Main and secondary Variscan thrusts

Fig. 2. - a: Tectono-metamorphic zones, b: tectonic sketch map and c: schematic geological cross-section of the Variscan basement in Sardinia (after Cocco *et al.* (2022_submitted), modified after Oggiano *et al.* (2010) and Cocco and Funedda (2019).

3) Stratigraphy, biostratigraphy, palaeoenvironments and glacio-eustatic variations

The External Zone and Nappe Zone of the Variscan basement only share few common traits in the sedimentary stacking and palaeontological content, and both show widespread evidences of tectonic instability during the Ordovician. The stratigraphic successions (Fig. 3) of the External Zone and the External Nappe have a well-defined stratigraphy based on their rich palaeontological record and sedimentary facies. Due to the general SW-NE increase in metamorphic conditions, only the successions of the Sulcis-Iglesiente Unit (Variscan External Zone) and of the Sarrabus and Gerrei Units (Variscan External Nappe Zone) will be considered (Fig. 3).

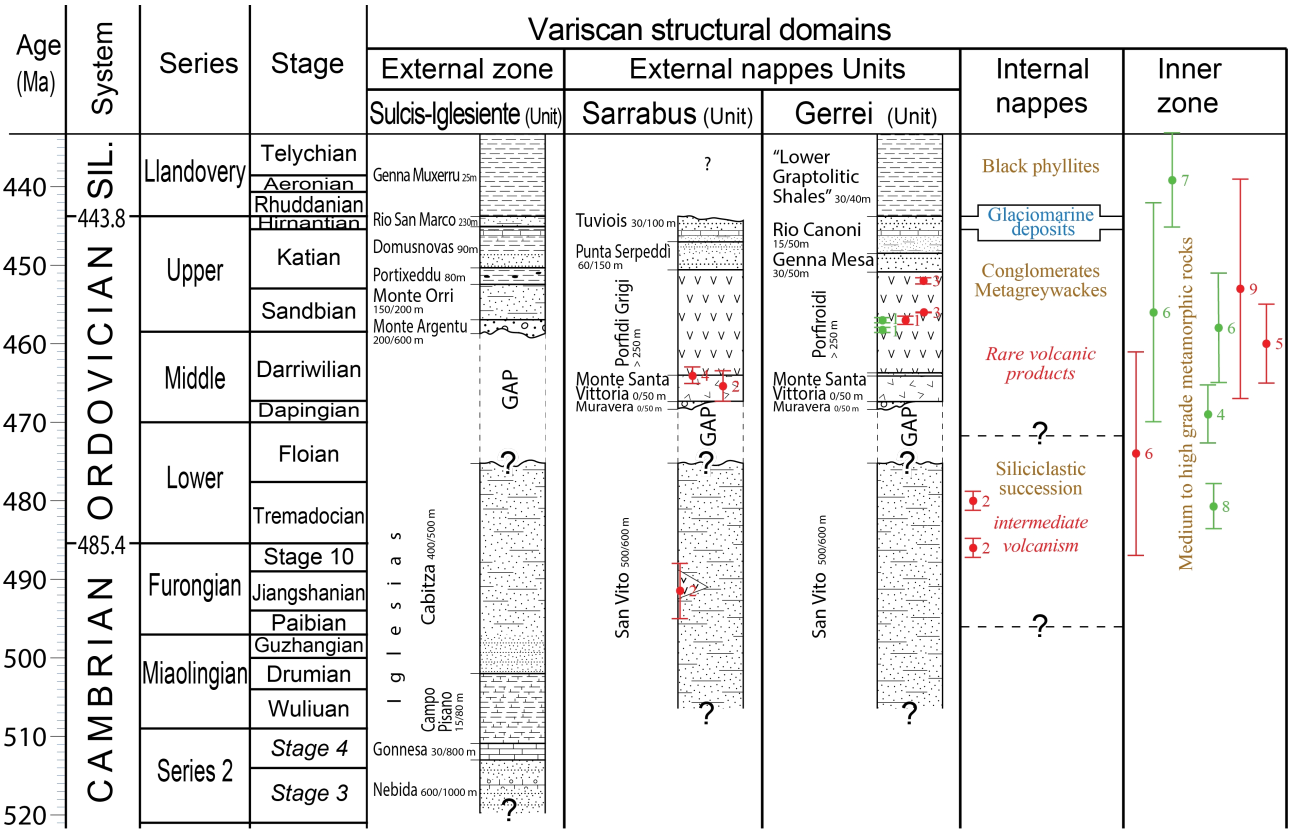

Fig. 3. Main stratigraphic correlations of sedimentary and magmatic formations characterising the several tectonic zones of the Variscan basement in Sardinia. U-Pb zircons age of magmatic rocks (volcanic in red and plutonic in green) and

bibliographic reference number: 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). After Cocco *et al.* (2022_submitted).

3.1) *Sulcis-Iglesiente Unit (External Zone– SW Sardinia)*

The Sulcis-Iglesiente Unit consists of two main sedimentary successions (Fig. 3) separated by a regional angular unconformity (Sardic Unconformity; Teichmüller (1931): a succession from the lower Cambrian to the Lower Ordovician (hereafter Pre-Sardic sequence) and a succession from the Upper Ordovician to the lower Carboniferous (hereafter Post-Sardic sequence).

<u>*Pre-Sardic sequence*</u>

The Pre-Sardic sequence extends from the lower Cambrian to the Lower Ordovician and is divided into three groups: the Nebida Group (Matoppa and Punta Manna formations), Gonnesa Group (Santa Barbara and San Giovanni formations) and the Iglesias Group (Campo Pisano and Cabitza formations) (Pillola 1990a; Pillola *et al.* 1998) (Fig. 4).

The Matoppa Fm. consists mainly of a siliciclastic succession of sandstones and minor siltstones layers, with oscillation and unidirectional current ripples, parallel and cross laminations at low angle (HCS) and, occasionally, ball-and-pillows. Calcimicrobial-archaeocyathan mounds are recurrent in the middle and upper part of this unit. The overlying Punta Manna Fm. is mainly a terrigenous deposit with widespread carbonate intercalations of a basal oolitic shoal belt and back shoal deposits, made-up of peloidal wackestone, grainstone and ooid-grainstone (spillovers). Backshoal facies also include calcimicrobial-archaeocyathan biostromes, massive limestones, few *Protopharetra* dominated bioherms and stromatolitic beds. The rich associations of Archaeocyatha and trilobites indicates an age assignment to the Cambrian lower Stage 3 to lower Stage 4 for the Nebida Group (Rasetti 1972; Debrenne *et al.* 1988; Pillola 1990b, 1991).

The Gonnesa Group consists of carbonate deposits. The Santa Barbara Fm. is characterized by alternations of well-stratified stromatolitic dolomites and limestones, which are in turn covered by massive limestone, often dolomitized, of the San Giovanni Fm. The two main Archaeocyatha associations indicates a higher Botomian and a Toyonian age respectively (Debrenne and Gandin 1985), corresponding to the middle portion of the Cambrian Stage 4.

The Iglesias Group begins with an alternation of nodular and massive grey limestones, marls and thin levels of silty argillites of the Campo Pisano Fm. (uppermost Stage 4 to mid-Drumian) which rests in continuity or with local gaps and erosive surfaces over the San Giovanni Fm. (Gandin *et al.* 1987; Pillola 1991; Elicki and Pillola 2004). The succession progressively grades, upwards, to an alternation of variable scale from centimetre to metric of shales, siltstones and sandy levels of the Cabitza Fm. (Drumian to late Tremadoc/?early Floian), deposited in a terrigenous platform environments with facies ranging from the lower offshore to tidal flats (Loi *et al.* 1996).

Still in the Cabitza Fm. (Figs 3 and 4) the Cambrian/Ordovician boundary is observed in stratigraphic continuity (Loi *et al.* 1996). This boundary has been bracketed between the CAB5b fauna (*Maladioidella* - *Onchonotellus*) and the CAB6 fauna (*Proteuloma geinitzi* - *Rhabdinopora flabelliformis flabelliformis*) (Fig. 5), and correlated with the Acerocare Regressive Event (ARE, Erdtmann 1986) according to the relative sea level variation curves (Pillola and Gutierrez-Marco 1988; Loi *et al.* 1996; Pillola *et al.* 2008; Pillola 2019). The estimated thickness of the Cabitza Fm. is at least 600 m (Cocozza 1979; Cocozza and Gandin 1990). The youngest ages documented in the upper levels of the Cabitza Fm., below the Sardic Unconformity, are the Lower Ordovician (Tremadocian) based on the finding of acritarchs and graptolites (Gandin and Pillola 1985; Barca *et al.* 1987; Pillola and Gutierrez-Marco 1988) and the latest Tremadocian-?basal Floian beds yielding *Araneograptus murrayi* Biozone (Pillola *et al.* 2008).

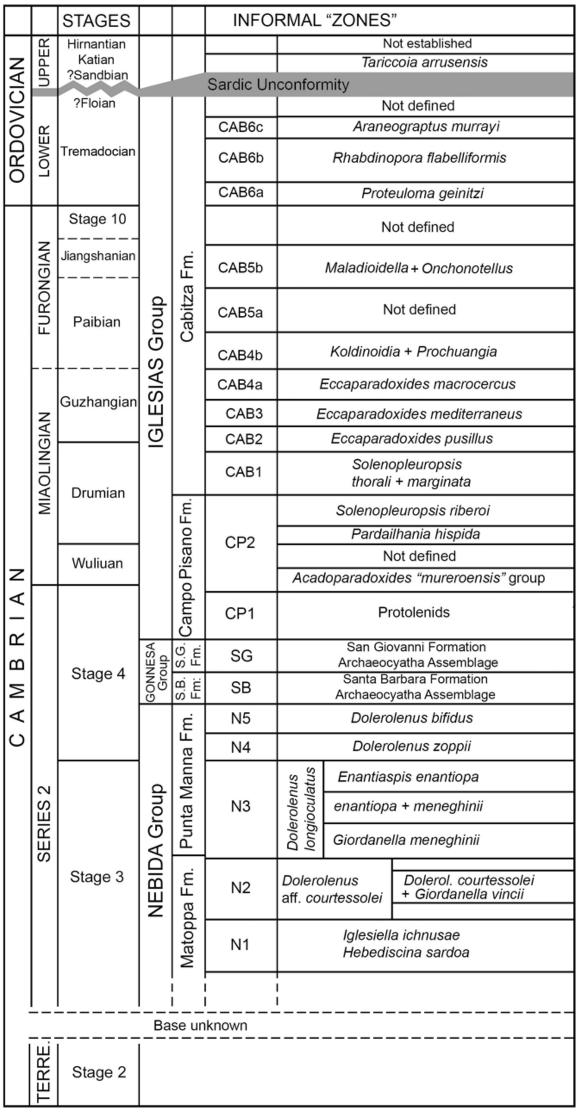

Fig. 4. Main stratigraphic and informal "zones" for the Cambrian Stage 3 to Lower Ordovician strata of the Sulcis-Iglesiente Unit (SW Sardinia).

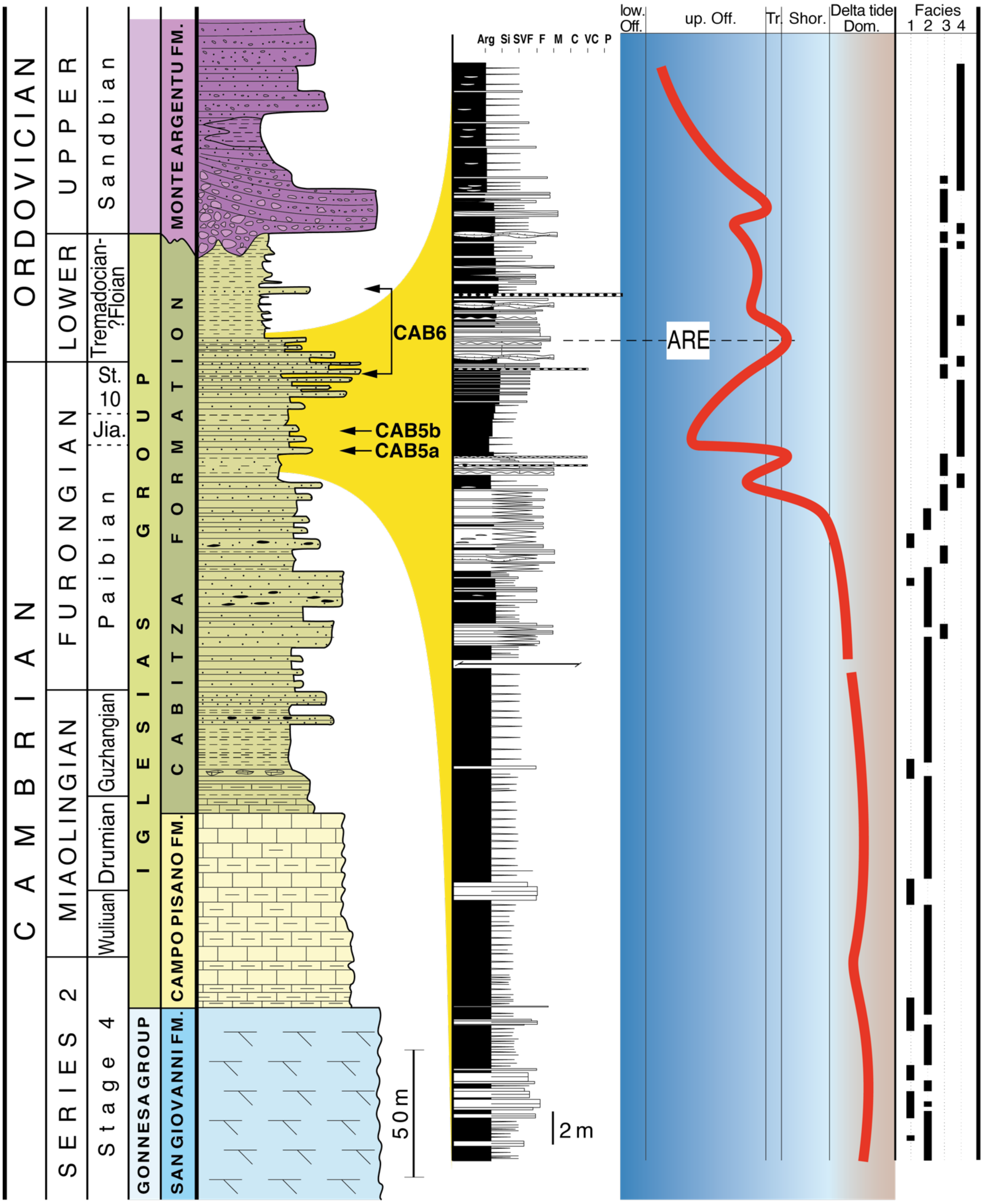

Fig. 5. Schematic log of the Iglesias Group, together with a detailed sea level curve for Furongian strata in the "Tubi" Section. ARE = Acerocare Regressive Event. Modified after Loi *et al.* (1996).

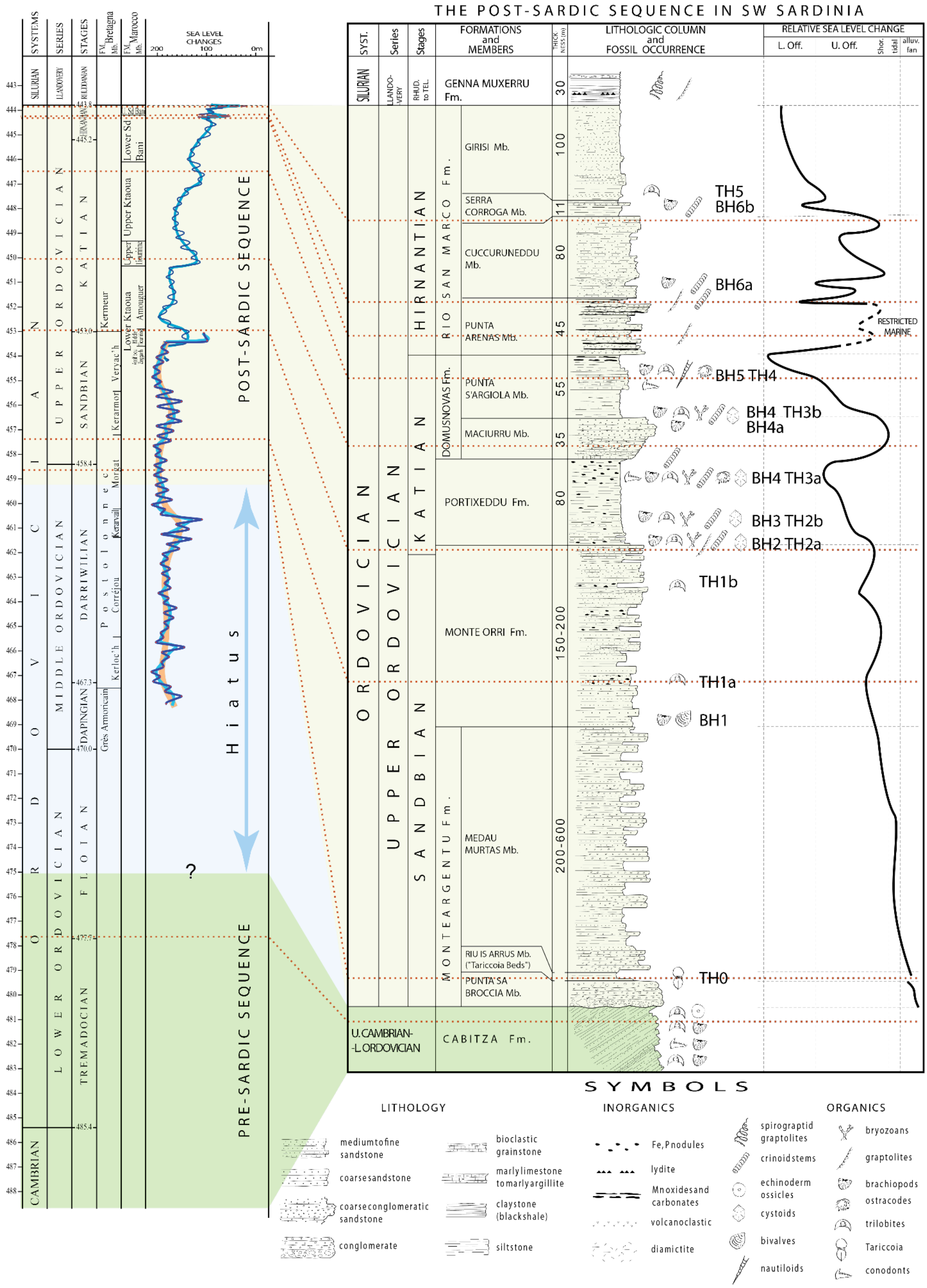
THE POST-SARDIC SEQUENCE IN SW SARDINIA
SYSTEMS
SERIES
STAGES
SEA LEVEL CHANGES
POST-SARDIC SEQUENCE
PRE-SARDIC SEQUENCE
Hiatus
SYST.
Series
Stages
FORMATIONS and MEMBERS
LITHOLOGIC COLUMN and FOSSIL OCCURRENCE
RELATIVE SEA LEVEL CHANGE
L. Off.
U. Off.
GENNA MUXERRU Fm.
GIRISI Mb.
SERRA CORROGA Mb.
CUCCURUNEDDU Mb.
PUNTA ARENAS Mb.
PUNTA S'ARGIOLA Mb.
MACIURRU Mb.
PORTIXEDDU Fm.
MONTE ORRI Fm.
MEDAU MURTAS Mb.
RIU IS ARRUS Mb. ("Tariccoia Beds")
PUNTA SA BROCCIA Mb.
CABITZA Fm.
U.CAMBRIAN-L.ORDOVICIAN
RIO SAN MARCO Fm.
DOMUSNOVAS Fm.
MONTE ARGENTU Fm.
ORDOVICIAN
UPPER ORDOVICIAN
HIRNANTIAN
KATIAN
SANDBIAN
TH5 BH6b
BH6a
BH5 TH4
BH4 TH3b BH4a
BH4 TH3a
BH3 TH2b
BH2 TH2a
TH1b
TH1a
BH1
TH0
RESTRICTED MARINE
SYMBOLS
LITHOLOGY
mediumtofine sandstone
coarsesandstone
coarseconglomeratic sandstone
conglomerate
bioclastic grainstone
marlylimestone tomarlyargillite
claystone (blackshale)
siltstone
INORGANICS
Fe,Pnodules
lydite
Mnoxidesand carbonates
volcanoclastic
diamictite
ORGANICS
spirograptid graptolites
crinoidstems
echinoderm ossicles
cystoids
bivalves
nautiloids
bryozoans
graptolites
brachiopods
ostracodes
trilobites
Tariccoia
conodonts

Fig. 6. Schematic lithostratigraphic succession of the Post Sardic-sequences of SW Sardinia. Curve of relative sea-level changes and main fossiliferous occurrence of trilobites (TH) and brachiopods (BH) identified by Leone *et al.* (1998) and Hammann and Leone (1997, 2007). Chronostratigraphic correlation by the time-calibrated eustatic curve established in 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). After (Cocco *et al.* 2022_submitted).

<u>*Post-Sardic sequence*</u>

The Upper Ordovician deposits of the Sulcis-Iglesiente Unit, which lie in angular unconformity above the Cambrian-Lower Ordovician succession (Post-Sardic sequence), begin with a thick aggradational succession of continental facies and subsequently follow retrogradational-progradational cycles in storm-dominated terrigenous platform facies.

The first deposits observed above the Sardic Unconformity (Figs 3 and 6) belong to the Monte Argentu Fm. (Laske *et al.* 1994), which starts with banks of matrix-rich conglomerates (Punta Sa Broccia Member) and progresses upwards to banks and layers of sandstones and coarse siltstones of the Riu Is Arrus and Medau Murtas Members. The pebbles derive mainly from the erosion of the underlying Cabitza Fm., and in smaller quantities come from the Gonnesa and Nebida Groups. Megabreccias and large olistolites (10-100 metres in size) composed of dolostones and limestones characterise the base of the Monte Argentu Fm., which is interpreted as a deposit settled in an alluvial fan to fan-delta environment (Martini *et al.* 1991). This very coarse deposit gradually becomes finer towards the top, grading into bioturbated sandstones and siltstones deposited in shallow water marine environments with tidal flat and lagoon facies (Loi 1993; Leone *et al.* 1998). A single rich but low diversified fossiliferous level is known in the Monte Argentu Fm.: the *Tariccoia arrusensis* beds (TH0, Riu Is Arrus Mb.) (Hamman *et al.* 1990; Hammann and Leone 1997, 2007). This endemic taxon does not provide any biostratigraphic indication because it is restricted to the Fluminimaggiore area (Iglesiente). In addition, unassigned plants remains (in TH0) and a few ichnofossils have been reported (*Rusophycus carleyi*, ?*Arthropycus* cf. *harlani*, *Skolithos;* (Pillola 2020). Hammann and Leone (1997, 2007) and Leone *et al.* (1998) proposed a ?Soudleyan (basal Sandbian) age for the

Tariccoia beds. The thickness of the Monte Argentu Fm. varies between 200 and 600 m (Laske *et al.* 1994; Leone *et al.* 1998). Its age is constrained between the Tremadocian-early Floian? of the upper Cabitza Fm. (Pillola *et al.* 2008) and the Sandbian (Soudleyan-Longvillian) trilobite and brachiopod fauna (BH1-TH1) of the Monte Orri Fm. (Hammann and Leone 1997, 2007; Leone *et al.* 1998).

The Monte Argentu Fm. is conformably capped by a 200-280 m thick succession of the Monte Orri and Portixeddu formations. These latter consist of an alternation of siltstone, argillite and silty sandstone deposited in an upper offshore and, only partially, lower offshore storm-dominated terrigenous platform. Both in the Monte Orri Fm. and, more commonly, in the upper part of the Portixeddu Fm., there are several levels containing phosphatic and silico-aluminous nodules and thick shell-beds (Leone *et al.* 1991, 1998), which have been interpreted as sedimentary expression of the condensation (very low sedimentation rate) during eustatic rises (Loi and Dabard 1999, 2002; Loi *et al.* 1999; Botquelen *et al.* 2002, 2004; Dabard and Loi 2012). The rich fossil record (TH1, TH2-3, BH2-4; cfr. Figs 6 and 7) allows to assign these deposits to the Sandbian and Katian (Leone *et al.* 1991; Hammann and Leone 1997, 2007).

The Domusnovas Fm. (thickness 90 m) begins with quartzarenites and quartz microconglomerates (Maciurru Mb.), with concentrations of heavy minerals (rutile and zircon placers) (Loi 1993; Loi and Dabard 1997; Leone *et al.* 1998), features consistent with a shoreface environment dominated by storm waves.

The succession suddenly and conformably evolves into marly limestones, marly shales and limestones of the Punta S'Argiola Mb. This member yields a rich fossil fauna and shows a high degree of sedimentary condensation (Botquelen *et al.* 2002, 2004, 2006b) documented by a carbonation of the seabed (taphonomic feedback). The late Katian ("Ashgill") age is suggested by the rich and significative content in brachiopods and trilobites (Figs 6 and 7, BH4, BH5, TH3b, TH4) (Hammann and Leone 1997, 2007; Leone *et al.* 1998). A diversified but poorly preserved conodont fauna has documented the *Amorphognathus ordovicicus* Zone (Ferretti and Serpagli 1991, 1998). *Hamarodus brevirameus*, *Scabbardella altipes* and *Amorphognathus* (*A. ordovicicus* and *A. duftonus*) numerically dominate the fauna, mirroring diversity and abundance of the conodont assemblages reported from the Carnic Alps (Serpagli 1967; Bagnoli *et al.* 1998; Ferretti and Schönlaub 2001; Ferretti *et al.*, this volume). Investigations of the relative abundance of multielement conodont taxa in representative conodont faunas have the potential to provide useful biogeographical and biofacies information, and the major conodont biofacies in much of the Upper Ordovician had already been introduced by Sweet and Bergström (1984). Conodont data of the last 30 years have reinforced this subdivision, documenting a Mediterranean Province fauna (*Sagittodontina robusta*-*Scabbardella altipes* biofacies: Thuringia, France, Spain, Lybia) that apparently occupied high latitude, relatively cold waters near the pole and at lower latitudes the *Hamarodus europaeus* (now *brevirameus*)-*Dapsilodus mutatus*-*Scabbardella altipes* biofacies (Sardinia, Carnic Alps, Baltoscandia) and the *Amorphognathus*-*Plectodina* biofacies (middle to upper Katian British faunas from Wales and England) (Ferretti *et al.* 2014; Bergström and Ferretti 2015).

In addition, the whole Monte Orri, Portixeddu and Domusnovas formations yield a diversified fauna rich, among other, in echinoderms (Maccagno 1965; Botquelen *et al.* 2006b); bryozoans (Conti 1990 and references therein) and brachiopods (Vinassa De Regny 1927, 1942; Giovannoni and Zanfrà 1978; Havlicek *et al.* 1986; Leone *et al.* 1991; Botquelen *et al.* 2006a).

The Upper Ordovician succession ends with the Rio San Marco Fm. (230 m thick; Leone *et al.* 1991). The base of this formation (Punta Arenas Mb.) is made up of siltstones and shales, interbedded with layers of heterogeneous conglomerates that also host volcanic pebbles and strata of manganese carbonates and oxides. The Punta Arenas Mb. deposits were laid down in restricted marine environments, subsequent to the rapid glacio-eustatic sea level fall of the first Hirnantian glacial pulsation (Ghienne *et al.* 2000). This member is topped by a condensed level rich in *Normalograptus ojsuensis* (Štorch and Leone 2003), testifying an ensuing rapid sea level rise. This condensed level is overlain by classic upper offshore storm facies showing rhythmic alternations of HCS sandstone layers separated by shales of the basal Cuccuruneddu Mb. After a few metres from the base of Cuccuruneddu Mb, a first glacio-marine layer including ice-rafted debris is observed. Then follow terrigenous deposits with storm-dominated platform facies, organised by three cycles of sea-level change, from Cuccuruneddu and Serra Corroga members (Fig. 6). The Upper Ordovician succession ends with ice-distal glacio-marine deposits of the Girisi Mb, composed of dark grey finely laminated to massive shales, siltstones and fine to very fine sandstones.

The fauna, present in the Rio San Marco Fm (Figs 6 and 7), allows us to robustly attribute an Hirnantian age to these deposits, included the TH5 fauna at the base of the Girisi Mb. containing *Mucronaspis mucronata mucronata* (Hammann and Leone 1997, 2007; Leone *et al.* 1998; Štorch and Leone 2003).

The Ordovician deposits are followed in conformity by a pelagic succession of the Silurian-Devonian, characterized at the base by black shales with lydites and, in the upper part, by limestones (Gnoli *et al.* 1990; Barca *et al.* 1992; Ferretti and Serpagli 1996; Ferretti *et al.* 1998).

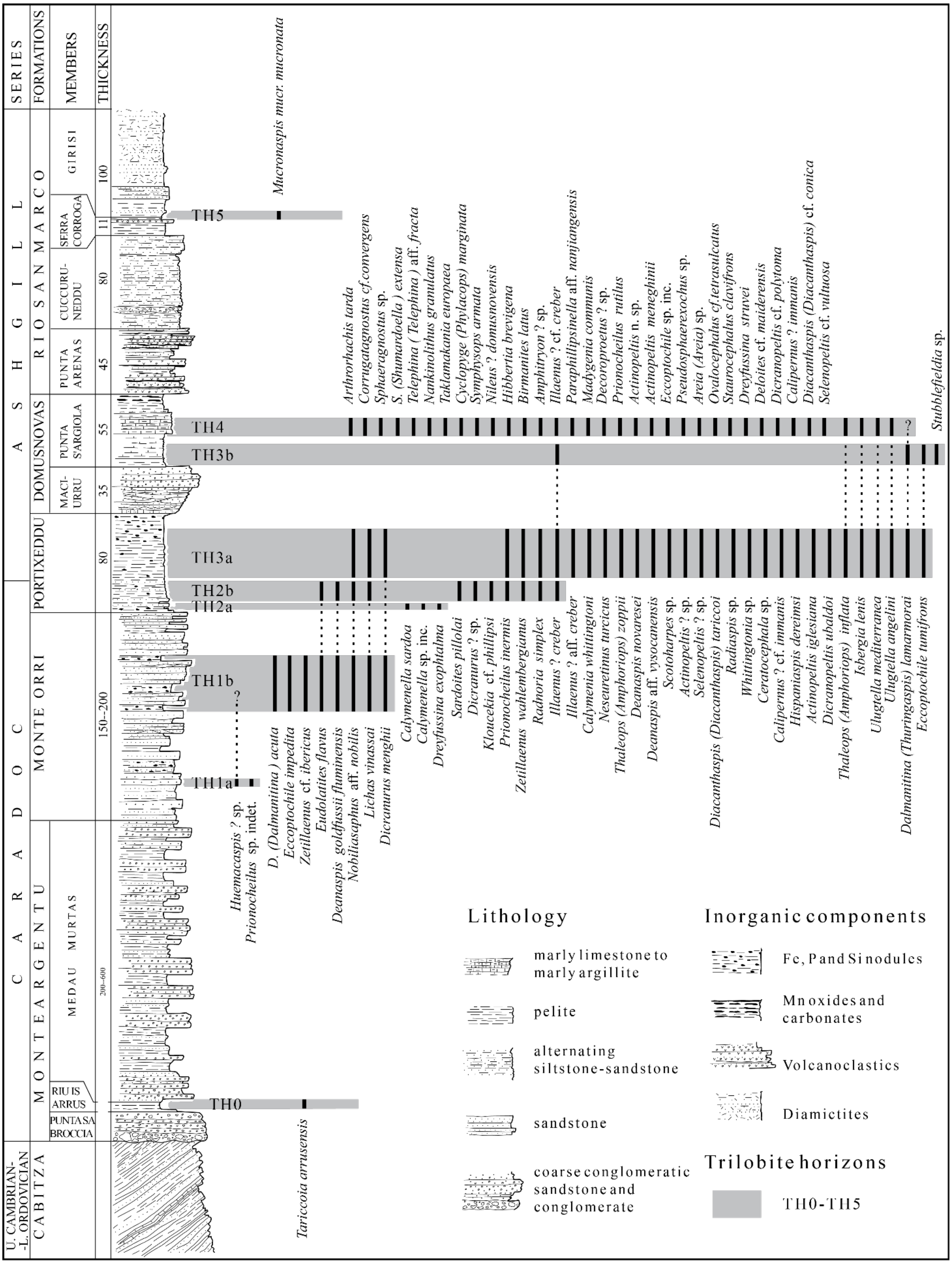

Fig. 7. Schematic lithostratigraphic succession of the Post-Sardic sequences of SW Sardinia. Occurrence of trilobites (TH) identified by Hammann and Leone (1997, 2007). After Hammann and Leone (2007).

3.2) *Sarrabus and Gerrei Units (External Nappe Zone, Central eastern Sardinia)*

Two unconformities (Fig. 3 and 8) separate three successions with similar lithostratigraphic characteristics in all the tectonic units of the External Nappe. The oldest is an angular unconformity that separates the lower Cambrian-Ordovician sedimentary succession from the Middle-Upper Ordovician volcano-sedimentary succession and is known as the Sarrabese Unconformity (Calvino 1959). The second is a nonconformity and represents the surface of marine transgression on effusive magmatic rocks, referred to as the Caradocian transgression by ancient authors. The latter sedimentary succession is continuous from the Upper Ordovician to the lower Carboniferous.

The stratigraphic features of the three successions are better preserved and complete in the tectonic units less affected by metamorphism and at the top of the nappe stack (Sarrabus and Gerrei units, Figs 2 and 3). The succession below the Sarrabese Unconformity will hereafter be called the Pre-Sarrabese sequence, while, the succession above it will be called the Post-Sarrabese sequence.

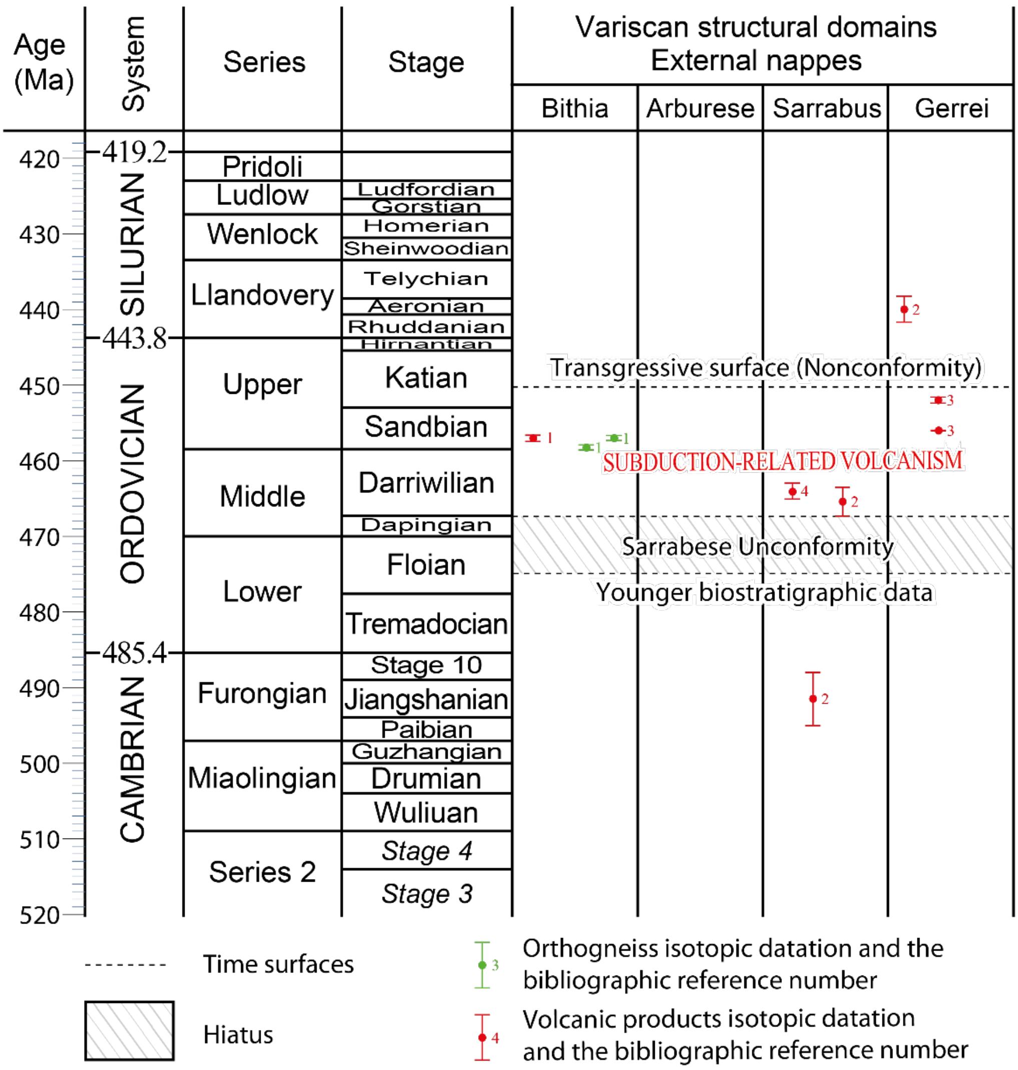

Fig. 8. Hiatus and time surfaces in the External Nappes Zone. U-Pb zircons age of magmatic rocks (volcanic in red and plutonic in green) and bibliographic reference number: [1](Pavanetto *et al.* 2012); [2](Oggiano *et al.* 2010); [3](Dack 2009); [4](Giacomini *et al.* 2006). After (Cocco *et al.* 2022_submitted).

Pre-Sarrabese sequence

Below the Sarrabese Unconformity lies a thick siliciclastic succession (Arenarie di San Vito; Calvino 1959) composed of sandstones, siltstones and shales with well-developed sedimentary structures such as parallel and cross laminations, HCS, unidirectional current ripples, flute and load casts. This sedimentary succession consists of an articulated stacking of facies, all deposited in a terrigenous platform in environments that vary between the lower offshore and the tidal flat. Towards the top of the succession, the depositional sequences are expressed with more proximal facies, up to finegrained conglomerates. In the Gerrei Unit, carbonate pelites, limestone layers and microconglomerates, with quartz elements, occur in the upper part of the succession.

In the Sarrabus Unit, the Arenarie di San Vito hosts Furongian intermediate to acid volcanic rocks with transitional affinity (Figs 3 and 8), dated 491.4 ± 3.5Ma (Oggiano *et al.* 2010). The base of the Arenarie di San Vito has never been identified, while its top is always erosive, at least in the External Nappe, where a minimum thickness of 500-600 m can be cartographically measured (Carmignani *et al.* 1982; Oggiano 1994).

The age of the Arenarie di San Vito is Miaolingian to (?)Floian based on sparse palynological content (acritarchs) (Barca *et al.* 1982, 1988; Naud and Pittau Demelia 1987), body and ichnofossils. Trace fossils are quite abundant in the upper part of the succession and are dominated by *Phycodes circinatum* and less *Rusophycus* sp. *Diplichnites* sp., *Cruziana* sp. and very rare *Glockerichnus glockeri* and *Tomaculum* sp. (Pillola and Piras 2004). The same levels yielded a well-diversified fossiliferous assemblage with graptolites, trilobites, cephalopods, bivalves, gastropods, hyolithids and brachiopods (Gnoli and Pillola 2002; Pillola and Vidal 2022_submitted). Among these taxa, A*mpyx priscus*, *Taihungshania shui landayranensis* and didymograptid species are relevant of the Floian age. This attribution is in agreement with the age of the interlayered volcanic rocks.

The stratigraphic evolution of the pre-Sarrabese Unconformity succession in the Nappe Zone testifies the deposition in a passive margin geodynamic condition, as the source areas of the sedimentary flow came from a crystalline craton. The volcanic rocks and the onset of shallowest marine sediments at the top of the Arenarie di San Vito, may be linked to the ongoing tectonic event responsible for the Sarrabese Unconformity (Oggiano *et al.* 2010).

Post-Sarrabese sequence

In all tectonic units of the External Nappe, a thick continental volcanic-sedimentary succession covers the Arenarie di San Vito in angular unconformity. The basis of this sequence consists of conglomerates containing pebbles from the underlying terrigenous succession, intercalated with

sandstones and siltstones (Metaconglomerati di Muravera Fm., Carmignani *et al.* 2001). This continental deposit is discontinuous, and the thickness varies from 0 to 50 m. The overlying volcanic succession consists of epiclastites and andesitic lavas (Monte Santa Vittoria Fm.; (Carmignani *et al.* 2001; Conti *et al.* 2001), in turn covered by rhyolitic to dacitic ignimbrites and lava flows (Porfidi Grigi Fm. in the Sarrabus Unit, Calvino 1959); Porfiroidi Fm. in the Gerrei Unit, Calvino 1972).
The volcanic products differ in volume and evolutionary tendency within the different tectonic units. The intrusive counterparts of these volcanic successions are the Monte Filau orthogneiss present in the Bithia Unit (Pavanetto *et al.* 2012), and a swarm of sills and necks intruding the Arenarie di San Vito. This volcanic succession is attributed to a calc-alkaline series (Gaggero *et al.* 2012) associated with a subduction system (Carmignani *et al.* 1994; Oggiano *et al.* 2010) and recently reinterpreted as the possible product of an accretionary tectonics (Cocco and Funedda 2019).
The age of these volcanic rocks is bracketed at the base by the Floian biota from the San Vito Sandstone Fm. and at the top by Katian BH4 TH3 associations (Punta Serpeddì Fm., Loi *et al.* 1992); Riu Canoni schists, Naud 1979). A series of U-Pb ages on zircon (Figs 3 and 8, see references) allows us to better identify the timespan of the volcano-sedimentary succession. The upper part is bounded by an age U-Pb of 452 ± 0.32 Ma (Dack 2009) which confirms the biostratigraphic assignment of the overlying Serpeddì Fm. and allows to exclude an extended gap between the volcanites and the Katian sedimentary succession. The so far available dating allows to extend the lower volcano-sedimentary limit up to at least 465.4 ± 1.9 Ma (Oggiano *et al.* 2010), but it could be older depending on further dating.

Katian nonconformity sequence

The unconformable sedimentary succession overlying the volcanics (Fig. 9) comprises an Upper Ordovician-lower Carboniferous continuous sedimentary series. This succession in the External Nappe begins in the middle Katian and the stratigraphic formations recognised in the Sarrabus/Gerrei tectonic units (Fig. 3) are the Serpeddì and Tuviois formations in the Sarrabus Unit (Fig. 9, Barca and Di Gregorio 1979; Loi *et al.* 1992) and the Genna Mesa and Rio Canoni formations in the Gerrei Unit (Naud 1979; Carmignani *et al.* 2001).

In both tectonic units, the stratigraphic organisation of the Upper Ordovician deposits reflects widespread transgression and show variable compositions, depending on the source areas from which the sediments originate as well as stratigraphic and palaeoenvironmental conditions. These deposits are therefore typical of each tectonic unit and consist of lithic sandstones, greywacke, rare arkose and silty mudstones with rare limestones. In the different tectonic units these successions evolve in a similar way, with deposits of lagoon and shoreface environments grading upwards into storm-dominated offshore environments. This strongly retrogradational trend is clearly controlled by a third-order eustatic rise (Fig. 9). This strong forcing resulted in deposits characterized by placers; the heavy mineral concentration of which locally exceeds 15% of the total composition. Rutile, pseudo-rutile, zircons, monazites and tourmalines are the main mineral phases present in these deposits (Loi *et al.* 1992; Loi 1993; Pistis *et al.* 2016). These placer accumulations have been interpreted as sedimentary condensation levels coinciding with the inflection points of the eustatic rise curve of the high-frequency cycles of the third-order retrogradational phase (Pistis *et al.* 2016). In the upper part of the Katian succession (Tuviois and Rio Canoni formations) a carbonatic, locally silicified horizon is observed.

The fossiliferous content is abundant and well preserved especially in the transgressive stratigraphic successions of the Katian of the Sarrabus/Gerrei tectonic units (Fig. 3). These have provided a rich brachiopod fauna (Giovannoni and Zanfrà 1978; Naud 1979; Loi 1993), trilobites (Hammann and Leone 1997, 2007), cystoids (Helmcke 1972; Helmcke and Koch 1974), bryozoans (Conti 1990) crinoids, conodonts (Helmcke and Koch 1974; Ferretti *et al.* 1998), gastropods and rare orthoconic cephalopods.

The trilobite and brachiopod faunas have been studied by (Leone *et al.* 1991) and Hammann and Leone (1997, 2007), who identified an association of brachiopods and trilobites (TH3 and TH4 for trilobites, BH4 and BH5 for brachiopods) which allows to assign the base of these deposits to the

Katian. The underlying volcanics dated 452±0.32 Ma (Dack 2009) ties the first transgressive deposits to the Middle-Upper Katian. Furthermore, the strongly transgressive trend of the succession allows us to correlate precisely these deposits with the retrogradation of sequence 3r of the eustatic curve established in the Upper Ordovician of the Moroccan Anti Atlas (Loi *et al.* 2010).

Unfortunately, the strong deformations do not permit a secure evaluation of the facies in the transition from the Ordovician to the Silurian; consequently, the possible occurrence of Upper Ordovician glaciogenic deposits in central and south-eastern Sardinia still remains an open question. In the Gerrei Tectonic unit the Silurian rests on the Katian succession with the classical Thuringian facies triad: "Lower Graptolitic Shales", "Ockerkalk" and "Upper Graptolitic Shales" (Corradini *et al.* 1998). Local occurrences of Silurian metabasites dated 440±1.7 Ma (Fig. 8) (Oggiano *et al.* 2010), overlying the Katian sequence, indicates a submarine volcanic activity, represented by spilites and rare pillow structures (e.g., near San Basilio and Brecca); the alkaline to subalkaline basaltic magmas of this volcanic activity have been ascribed to a within plate extensional context (Di Pisa *et al.* 1992).

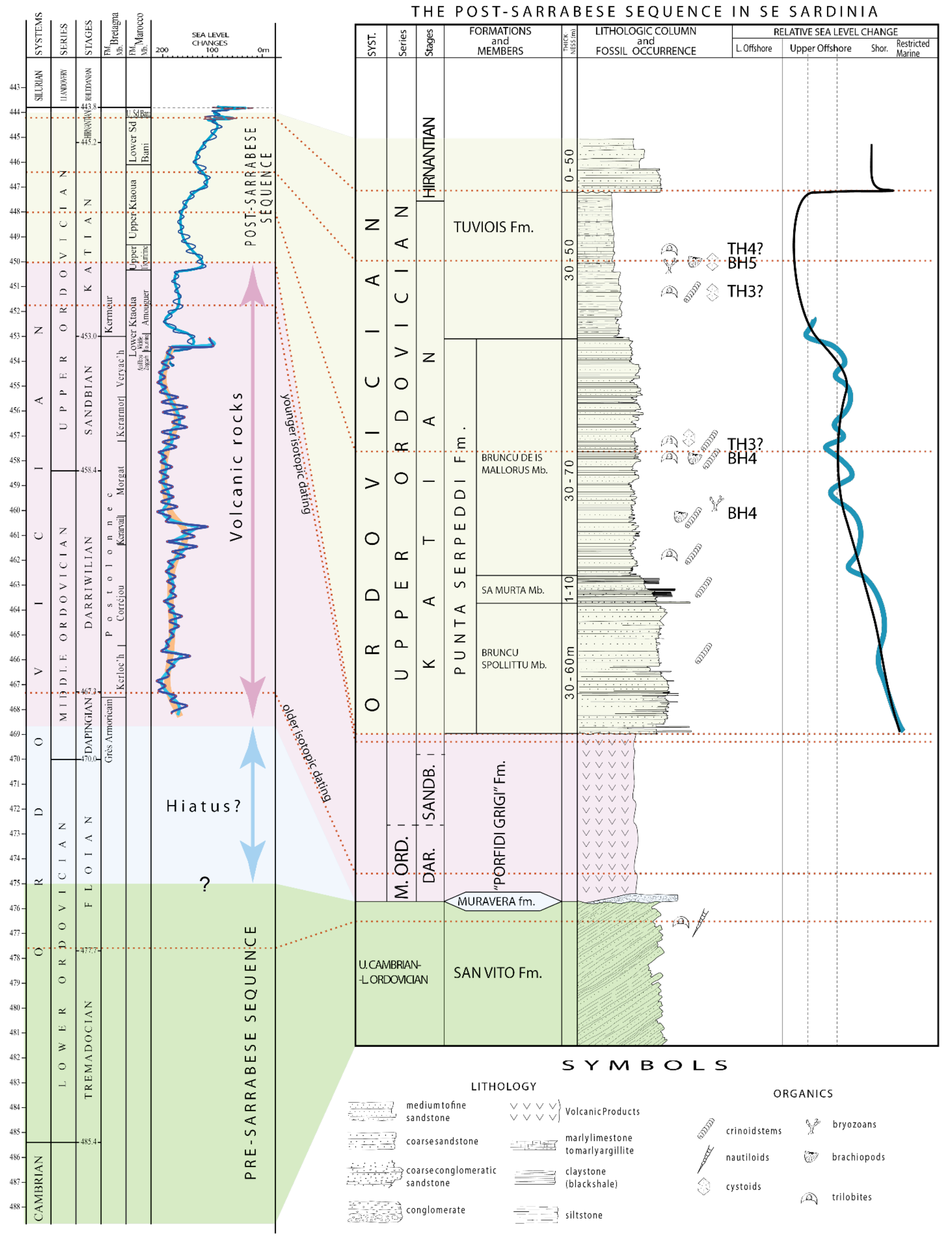

Fig. 9. Schematic lithostratigraphic succession of the Post-Sarrabese sequences of Sarrabus tectonic unit. Curve of relative sea-level changes and main fossiliferous occurrence of trilobites (TH) and brachiopods (BH) identified by Leone *et al.* (1998) and Hammann and Leone (1997, 2007). Chronostratigraphic correlation by the time-calibrated eustatic curve

established in 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). After (Cocco *et al.* 2022_submitted).

3.3) *Internal Nappe Zone*

In the Internal Nappes, neither the Sardic Unconformity nor the volcanic rocks of the Middle Ordovician have ever been detected. Within the low-grade units of north-western Sardinia, calcalkaline meta-rhyolites with a transitional character provided a U-Pb zircon age of 486 ± 1.2 and 479.9 ± 2.1 Ma (Furongian and Tremadocian) (Oggiano *et al.* 2010; Gaggero *et al.* 2012) (Table 2) and can be considered to belong to the same volcanic cycle as that those contained in the Arenarie di San Vito Fm. of the External Nappe (Fig.3).
The succession of the Upper Ordovician in the Internal Nappes is poorly defined (Fig. 3). In the Gennargentu Massif (Fig. 2b), the meta-sediments attributed to the Upper Ordovician are mainly quartzites (Dessau *et al.* 1982) which suggest the erosion of an older and more mature crystalline craton, rather than a volcanic arc. In northwestern Sardinia, a deposit of laminated dark fine metasiltite hosting phosphate layers, oolitic ironstones and possible glacio-marine diamictite, has been reported in the Upper Ordovician (Oggiano and Mameli 2006). Here, the transition to the Silurian black shales is marked by an erosional unconformity evidenced by conglomerates. Based on the observed exposure, the minimum thickness of the typical Silurian euxinic phyllite can be estimated to be about 100 m. In NW Sardinia Internal Nappes, on the other hand, the Devonian platform limestones (commonly cropping out in the External Nappe zone) are absent.

4) *The Sardic and Sarrabese Phases and their unconformities*

Ordovician tectonics in Sardinia is documented by two deformational events including overturned folds (Cocco *et al.* 2018, 2022_submitted; Cocco and Funedda 2019). The deformation event known as the Sardic Phase (Stille 1939) is defined on the basis of the angular unconformity first detected in SW-Sardinia (Fig: 10) (Sardic Unconformity, Teichmüller 1931). The second has been recognised in SE-Sardinia and is called Sarrabese Unconformity (i.e. “Sarrabese Phase”: Calvino 1959). The overlapping of Variscan deformation with Ordovician unconformities has led to confusions and simplified interpretations of the timing and meaning of Ordovician unconformities. Recent work in the Sulcis-Iglesiente Unit (SW-Sardinia, the External Zone of the Variscan Chain; Cocco *et al.* 2018, 2022_submitted; Fig.11) highlights that the Sardic Phase occurred between early Floian and early Sandbian, whereas the age of the Sarrabese Phase, recognised in the Sarrabus/Gerrei Units (SE-Sardinia, the Nappe Zone of the Variscan Chain), is robustly constrained between the early Floian and the Darriwilian-Dapingian boundary (Fig. 8). Although the ages and style of deformation of the Sardic and Sarrabese phases are potentially similar, there are important stratigraphic, temporal, palaeontological and geodynamic differences that exclude the proximity of these domains in the Ordovician age.

(Cocco *et al.* 2022_submitted) also recognise in the Sulcis-Iglesiente unit, after the Sardic Phase, a sedimentary gap with continentalisation that lasted 17 Ma. A continental rift system was then established in the Sandbian, finally evolving into passive continental margin platform deposits. In contrast, after the Sarrabese phase in the Sarrabus/Gerrei units, there is a short-lived stratigraphic gap (about 6 Ma, between the middle Floian and the Dapingian-Darriwilian boundary). This shorter depositional gap ended with accumulation of a thick calc-alkaline volcanic succession in a continental environment. The latter is linked to a subduction system, which lasted for a period of time of about 19 Ma. At the same time, the Sulcis-Iglesiente Unit (SW Sardinia) underwent a process of continental rift and subsequent oceanic opening with the development of a passive continental margin (Post-Sardic succession). Finally, approximately 25 Ma after the Sarrabese Phase, an unconformable transgressive marine deposit overlaps the volcanic arc in the middle Katian (Nonconformity). The distinct temporal extent of the unconformities and the presence of a continental volcanic arc exclusively present in the Sarrabus/Gerrei units (and in the entire Nappe

Zone of the Sardinian basement), allows to propose that these domains did not share the same geodynamic setting, and, consequently, not even the same palaeogeographic position during the Ordovician age, implying that they approached and amalgamated only during the Variscan period (Cocco *et al.* 2018, 2022_submitted). The possible substantial separation is also supported by the comparisons between the Katian trilobites assemblages that, even if influenced by palaeoecological constraints, clearly suggest an earlier "Chinese" affinity in the Sarrabus-Gerrei units (Nappe Zone) (Cocco *et al.* 2022_submitted).

Fig. 10. Sardic Unconformity along the Masua shoreline (SW Sardinia). The basal heterometric conglomerates of the M. Argentu Fm. (base Sandbian) unconformably lie on the Cabitza Fm. (middle Cambrian–lower Floian). After (Cocco *et al.* 2018).

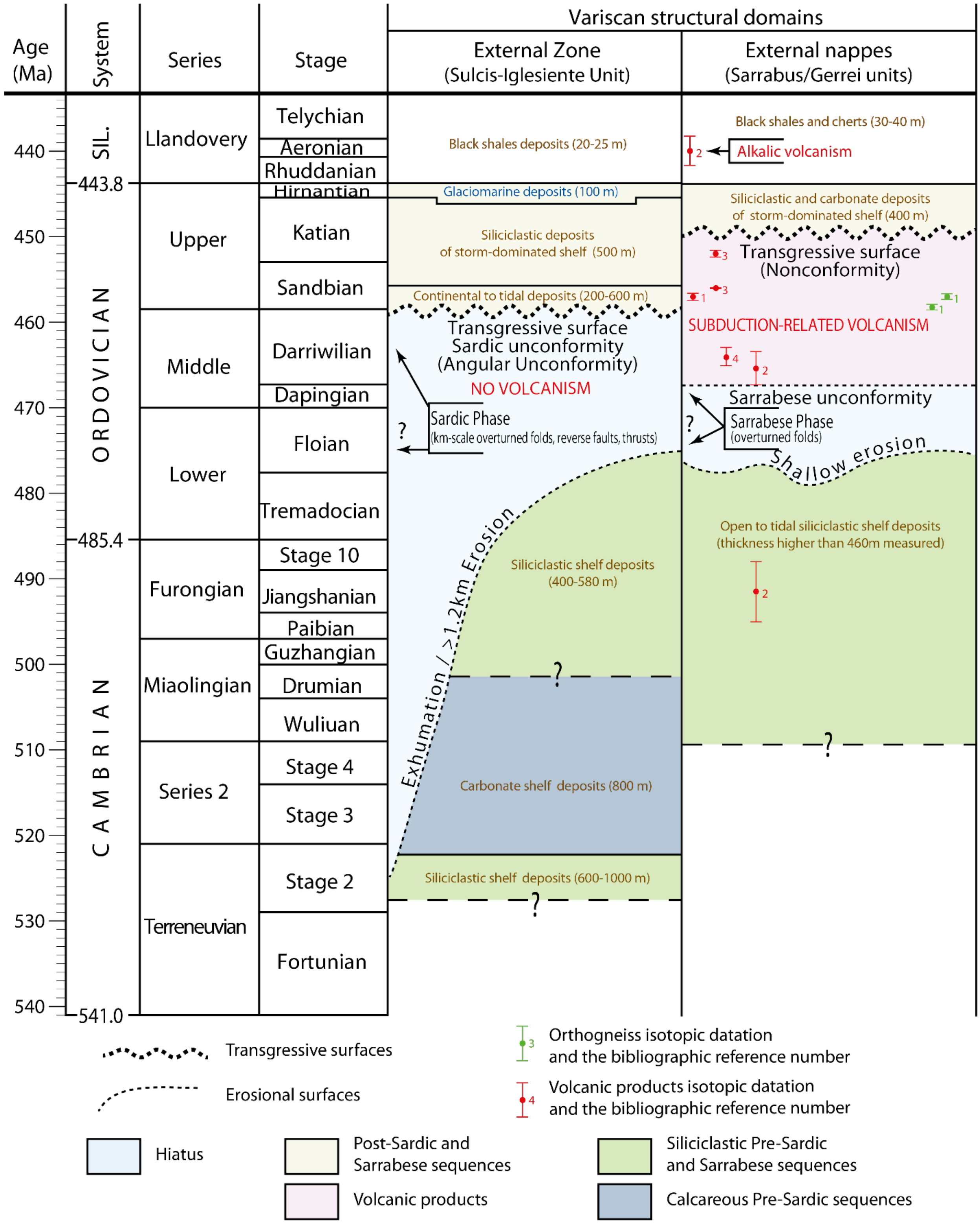

Fig. 11. Synoptic figure of the main stratigraphic and magmatic features between the Sulcis-Iglesiente Unit (External Zone) and the Sarrabus/Gerrei Units (External Nappe Zone). Correlation, in linear time scale, of the major unconformities of Ordovician. U-Pb zircons age of magmatic rocks (volcanic in red and plutonic in green) and bibliographic reference number: 1-(Pavanetto *et al.* 2012); 2-(Oggiano *et al.* 2010); 3-(Dack 2009); 4-(Giacomini *et al.* 2006). After (Cocco *et al.* 2022_submitted).

5) Conclusion

In several reconstructions of pre-Variscan palaeogeography, Sardinia is considered a single block forming part of the Gondwana margin that experienced, since the Cambrian, different geodynamic contexts linked to the evolution of the Rheic Ocean, before being involved in the Variscan orogeny during the Lower Carboniferous.

The most relevant pre-Variscan geodynamic events recorded in Sardinia occurred during the Ordovician, and are testified by a folding event affecting only the lower Cambrian-Ordovician successions. The resulting angular unconformity is sealed by thick continental and shallow-marine deposits in the Sulcis-Iglesiente unit (SW Sardinia) and by volcanic products with calc-alkaline affinity in the Sarrabus/Gerrei units (SE Sardinia).

The comparison of the stratigraphy and tectonic structures of the successions below and above the Ordovician unconformities along with better time constraints have allowed to highlight significant differences in the Ordovician evolution between the Sulcis-Iglesiente and Sarrabus/Gerrei tectonic units. Noteworthy are the different extension of unconformity-related gaps (17 and 6 Ma in the Sulcis-Iglesiente and Sarrabus/Gerrei units, respectively, (Cocco *et al.* 2022_submitted), differences in the fossil fauna and the presence of a volcanic arc only in the Nappe Zone units (i.e., Sarrabus/Gerrei units), which suggest that these domains did not share the same palaeogeographic position during the Ordovician, implying that their current juxtaposition is entirely of Variscan origin.

The recognition that the Sardinian block consisting of several distinct terranes before Variscan orogeny implies alternative correlations to those hitherto known and a different reconstruction of their position, also depending on the dynamics related to the diachronous opening of the Rheic Ocean (Burda *et al.* 2021), suggesting an extreme tectonic mobility of the Rheic margin of Gondwana. In particular, the External Zone and the Nappe Zone should be placed in different and distant positions to fit the correct geodynamic context. In this regard, (Cocco and Funedda 2019) propose for the

Sarrabus/Gerrei units (and consequently all the Sardinian Variscan Nappe Zone) a position close to the subduction margin of the Qaidam Ocean, in such a way to be consistent with the occurrence of the Ordovician arc volcanic products.

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