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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 illustrates the most important features of Ordovician succession of the Sardinian basement. We focus on stratigraphy and tectonic structures in the tectonic units of External and Nappe zones of the Variscan basement. The Ordovician successions are characterized by unconformities related to tectonics events ascribed to the Sardic and Sarrabese phases. The different time gap of the unconformity-related gaps in the External (17 Ma) and Nappe (6 Ma) zones, the recent work on trilobite fossil content, and the occurrence of a volcanic arc only in the Nappe Zone (Sarrabus and Gerrei units) highlight significant discrepancies suggesting that these domains did not share the same geodynamic setting and palaeogeographic position during the Ordovician. This implies they were 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. The present revision of data on the best-preserved succession of the Sardinian tectonic units suggests that at least two distinct terranes, that did not share the same Ordovician evolution, were amalgamated only during the Variscan Orogeny.

1) Introduction

The sedimentary and volcanic Ordovician successions of Italy are extensively documented in Sardinia and, to a lesser extent, in the Carnic Alps (Vai 1971; Vai & Spalletta 1980; Schönlaub 2000). In other regions of Italy, portions of Ordovician successions 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 two folding events, the first of which are referable to the Early Ordovician Sardic and Sarrabese phases, and the second to the late Paleozoic (Carboniferous) Variscan Orogeny. The Variscan Orogeny (Fig. 1) provides 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 allochthonous tectonic units are recognised in Sardinia (Fig. 2). The stratigraphic successions show strong differences between the SW of Sardinia (External Zone) and all the other successions (Nappe Zone and Inner Zone). An intra-Ordovician unconformity stands out in the sedimentary succession, which is well preserved only in the shallowest tectonic units of External and Nappe zones. The Ordovician unconformity was first detected in the External Zone 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 between the middle Cambrian and the Upper Ordovician (Teichmüller 1931; Stille 1939). In the 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. Many interpretations have been proposed as a result of new discoveries. In particular the better definition of age and stratigraphic features of the successions below and above the unconformities gives a more accurate age constraint of the deformation phase(s). In recent years the stratigraphy of Ordovician successions in Sardinia has been better defined (Gandin & Pillola 1985; Barca *et al.* 1987; Laske *et al.* 1994; Pillola *et al.* 1995, 1998, 2008; Loi *et al.* 1996; Hammann & Leone 1997, 2007; Ferretti *et al.* 1998; Leone *et al.* 1998; Storch & 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 unconformities, has recently been described in detail (Pasci *et al.* 2008; Cocco *et al.* 2018, 2022*a*; Cocco & Funedda 2019, 2021).

Since the 1980s, palaeogeographic reconstructions and some geodynamic models (Carmignani *et al.* 1994; Oggiano *et al.* 2010; Gaggero *et al.* 2012) have assumed that since Cambrian times the Paleozoic basement of Sardinia pertained to a continental platform along the northern Gondwana margin. 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 continental margin involved in a subduction zone, 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*a*). These discrepancies imply that the External and Nappe zones belonged to different and distant palaeogeographic 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 might be ruled out.

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 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 to amphibolite facies, $300 < T < 600$ °C) is divided into External and Internal Nappe (Fig. 2b), composed of stacked tectonic units characterised by lithostratigraphic successions spanning in age from the early Cambrian to early Carboniferous (Carmignani *et al.* 1994, 2001), yet showing some lithological differences between them (Fig. 2a, b). The nappe stack of the External Nappe tectonic units is well exposed in SE Sardinia, in the SE-plunging Flumendosa Antiform (Fig. 2b, c) (Conti *et al.* 1999), whose exhumation and deep erosion/incision allow the identification, from bottom to top, of the Monte Grighini, Riu Gruppa, Gerrei, Meana Sardo and 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 (Carmignani *et al.* 1994, 2001) units, which can be correlated with the Gerrei and Sarrabus units, respectively.

The tectonic units of the Internal Nappe Zone are stratigraphically less well 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 mainly consist of a siliciclastic succession and are characterised by the lack of Silurian-Devonian limestones (Oggiano & 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 one, 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 & Oggiano 2008; Montomoli et al. 2018; Petroccia et al. 2022*a*; 2022*b*). 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*b*).

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

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 (External Zone) and of the Sarrabus and Gerrei Units (External Nappe Zone) will be considered (Fig. 3).

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).

Pre-Sardic sequence

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 1990*a*; 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 indicate an age assignment to the Cambrian lower Stage 3 to lower Stage 4 for the Nebida Group (Rasetti 1972; Debrenne *et al.* 1988; Pillola 1990*b*, 1991).

The Gonnesa Group consists of carbonate deposits. The Santa Barbara Fm. is characterised by alternations of well-stratified stromatolitic dolomites and limestones, which are in turn covered by massive limestones, often dolomitized, of the San Giovanni Fm. The two main Archaeocyatha associations indicate a higher Botomian and a Toyonian age respectively (Debrenne & 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 & Pillola 2004). The succession progressively grades, upwards, to an alternation of variable scale from centimetric to metric of shales, siltstones and sandy levels of the Cabitza Fm. (Drumian to late Tremadoc-early Floian (?)), deposited in terrigenous platform environments with facies ranging from the lower offshore to tidal flats (Loi *et al.* 1996).

Still in the Cabitza Fm. (Figs 3, 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 & Gutiérrez-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 & Gandin 1990). The youngest ages documented in the upper levels of the Cabitza Fm., below the Sardic Unconformity, are Early Ordovician (Tremadocian) based on the finding of acritarchs and graptolites (Gandin & Pillola 1985; Barca *et al.* 1987; Pillola & Gutiérrez-Marco 1988) and the latest Tremadocian-basal Floian (?) beds yielding *Araneograptus murrayi* Biozone (Pillola *et al.* 2008).

<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 upward followed by retrogradational-progradational cycles in storm-dominated terrigenous platform facies.

The first deposits above the Sardic Unconformity (Figs 3, 6) belong to the Monte Argentu Fm. (Laske *et al.* 1994), which starts with beds of matrix-rich conglomerates (Punta Sa Broccia Member) and progresses upwards to beds and layers of sandstones and coarse siltstones of the Riu Is Arrus and Medau Murtas members. The pebbles mainly derive from the erosion of the underlying Cabitza Fm., and in lesser amount 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 fossiliferous level is known in the Monte Argentu Fm.: the *Tariccoia arrusensis* beds (TH0, Riu Is Arrus Mb.) (Hamman *et al.* 1990; Hammann & 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 & 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 & 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 & Dabard 1999, 2002; Loi *et al.* 1999; Botquelen *et al.* 2002, 2004; Dabard & Loi 2012). The rich fossil record (TH1, TH2-3, BH2-4; cf. Figs 6, 7) allows to assign these deposits to the Sandbian and Katian (Leone *et al.* 1991; Hammann & 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 & 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, 2006*b*) 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, 7, BH4, BH5, TH3b, TH4) (Hammann & Leone 1997, 2007; Leone *et al.* 1998). A diversified but poorly preserved conodont fauna has documented the *Amorphognathus ordovicicus* Zone (Ferretti & 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 & 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 & 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 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 & 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.* 2006*a*; Touzeau *et al.*2013; Sumrall *et al.* 2015); bryozoans (Conti 1990 and references therein) and brachiopods (Vinassa De Regny 1927, 1942; Giovannoni & Zanfrà 1978; Havlicek *et al.* 1986; Leone *et al.* 1991; Botquelen *et al.* 2006*b*).

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 & 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, 7), allows us to firmly attribute an Hirnantian age to these deposits, including the TH5 fauna at the base of the Girisi Mb. containing *Mucronaspis mucronata mucronata* (Hammann & Leone 1997, 2007; Leone *et al.* 1998; Štorch & Leone 2003).

The Ordovician deposits are followed in conformity by a Silurian-Devonian pelagic succession, 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 & Serpagli 1996; Ferretti *et al.* 1998).

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

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

Pre-Sarrabese sequence

This sequence is 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 facies, all deposited in a terrigenous platform environment that vary between the lower offshore and the tidal flat. Towards the top of the succession, the depositional sequences are more proximal facies, that consists of fine-grained conglomerates. In the Gerrei Unit, carbonate pelite, 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, 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 & 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 & Piras 2004). The same levels yielded a well-diversified fossiliferous assemblage with graptolites, trilobites, cephalopods, bivalves, gastropods, hyolithids and brachiopods (Gnoli & Pillola 2002; Pillola & Vidal 2022). Among these taxa, A*mpyx priscus*, *Taihungshania shui landeyranensis* 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 the 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 a subduction-accretion orogenic tectonics (Cocco & 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, 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 volcanic rocks 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 and Gerrei tectonic units (Fig. 3) are the Serpeddì and Tuviois formations in the Sarrabus Unit (Fig. 9, Barca & 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 shows 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 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 and Gerrei tectonic units (Fig. 3). These have provided a rich brachiopod fauna (Giovannoni & Zanfrà 1978; Naud 1979; Loi 1993), trilobites (Hammann &

Leone 1997, 2007), cystoids (Helmcke 1972; Helmcke & Koch 1974), bryozoans (Conti 1990) crinoids, conodonts (Helmcke & 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 & 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 intense 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).

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 the one 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 & 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 deformative phases including overturned folds (Cocco *et al.* 2018, 2022*a*; Cocco & Funedda 2019). The first deformative phase, 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). Recent work in the Sulcis-Iglesiente Unit (SW-Sardinia, the External Zone of the Variscan Chain; Cocco *et al.* 2018, 2022*a*; 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 and Gerrei units (SE-Sardinia, the Nappe Zone of the Variscan Chain), is robustly constrained between the early Floian and the

Dapingian-Darriwilian boundary (Fig. 8). The ages and style of deformation of the Sardic and Sarrabese phases are quite similar, but there are important stratigraphic, temporal, palaeontological and geodynamic differences that exclude the proximity of these domains in the Ordovician age.

As shown in Fig. 6, 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 and Gerrei units, there is a short-lived stratigraphic gap (about 6 Ma, between the middle Floian and the Dapingian-Darriwilian boundary) (Fig. 9). This shorter depositional gap ended with accumulation of a thick calc-alkaline volcanic succession. 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 and Gerrei units (and in the entire Nappe Zone of the Sardinian basement), suggests 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*a*). 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 and Gerrei units (Nappe Zone) (Cocco *et al.* 2022*a*).

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 (Carmignani *et al.* 1994).

The most relevant pre-Variscan deformative phases 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 and 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 and Gerrei tectonic units. Noteworthy are the different extension of unconformity-related gaps (17 and 6 Ma in the Sulcis-Iglesiente and Sarrabus and Gerrei units, respectively, Cocco *et al.* (2022*a*), differences in the fossil fauna and the presence of a volcanic arc only in the Nappe Zone units (i.e., Sarrabus and 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 consisted 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 & Funedda (2019) propose for the Sarrabus and 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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Figure Captions

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

Fig. 2. - a: Tectono-metamorphic zones zones in Sardinia; b: Tectonic sketch map of Variscan basement in Sardinia; c: Schematic geological cross-section of the Variscan basement in Sardinia (after Cocco *et al.* 2022*a*, modified after Oggiano *et al.* 2010 and Cocco and Funedda 2019) of the Variscan basement (not to scale).

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 & 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. After Cocco et al. (2022a).

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).

Fig. 6. Schematic 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. After (Cocco *et al.* 2022*a*).

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).

Fig. 8. Hiatus and time surfaces in the External Nappes 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). After (Cocco *et al.* 2022*a*).

Fig. 9. Schematic lithostratigraphic succession of the Post-Sarrabese sequences of 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 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*a*).

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. Summary figure of the main stratigraphic and magmatic correlations between the Sulcis-Iglesiente Unit (External Zone) and the Sarrabus and Gerrei units (External Nappe Zone) 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 number: 1-(Pavanetto *et al.* 2012); 2-(Oggiano *et al.* 2010); 3-(Dack 2009); 4-(Giacomini *et al.* 2006). After (Cocco *et al.* 2022*a*).

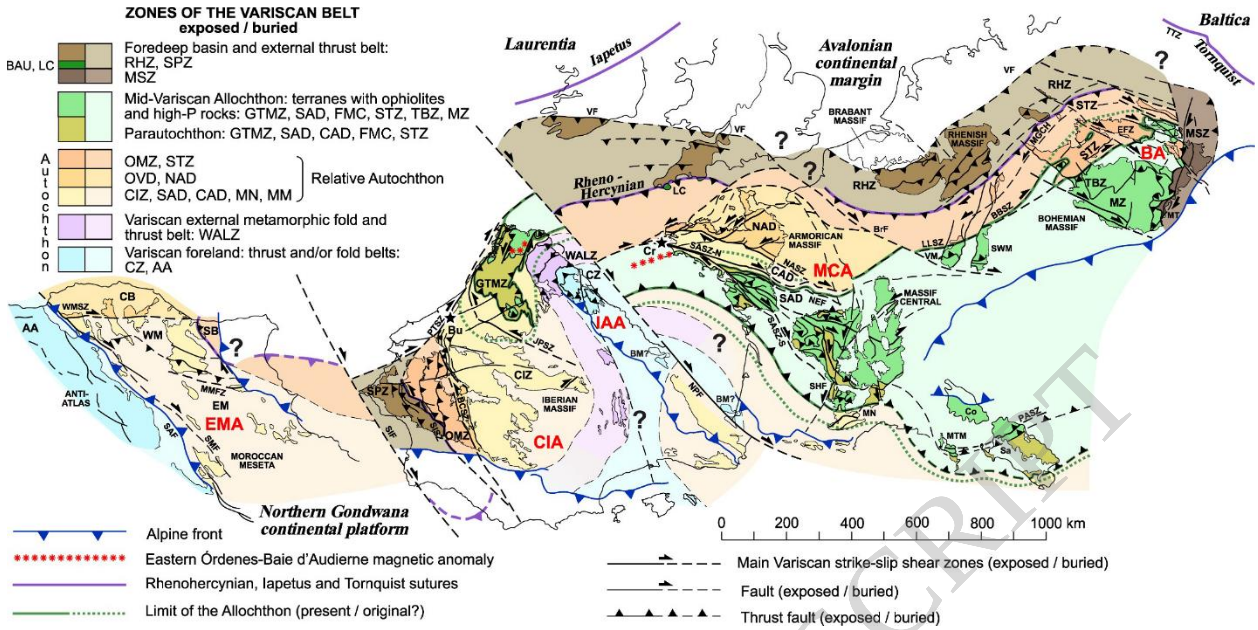

ZONES OF THE VARISCAN BELT
exposed / buried
BAU, LC
Foredeep basin and external thrust belt:
RHZ, SPZ
MSZ
Mid-Variscan Allochthon: terranes with ophiolites and high-P rocks: GTMZ, SAD, FMC, STZ, TBZ, MZ
Parautochthon: GTMZ, SAD, CAD, FMC, STZ
Autochthon
OMZ, STZ
OVD, NAD
CIZ, SAD, CAD, MN, MM
Relative Autochthon
Variscan external metamorphic fold and thrust belt: WALZ
Variscan foreland: thrust and/or fold belts: CZ, AA
Laurentia
Iapetus
Avalonian continental margin
Baltica
Tornquist
Rheno - Hercynian
Northern Gondwana continental platform
EMA
CIA
IAA
MCA
BA
ARMORICAN MASSIF
IBERIAN MASSIF
MASSIF CENTRAL
BOHEMIAN MASSIF
RHENISH MASSIF
BRABANT MASSIF
MOROCCAN MESETA
ANTI-ATLAS
0 200 400 600 800 1000 km
Alpine front
Eastern Órdenes-Baie d'Audierne magnetic anomaly
Rhenohercynian, Iapetus and Tornquist sutures
Limit of the Allochthon (present / original?)
Main Variscan strike-slip shear zones (exposed / buried)
Fault (exposed / buried)
Thrust fault (exposed / buried)

Figure 1

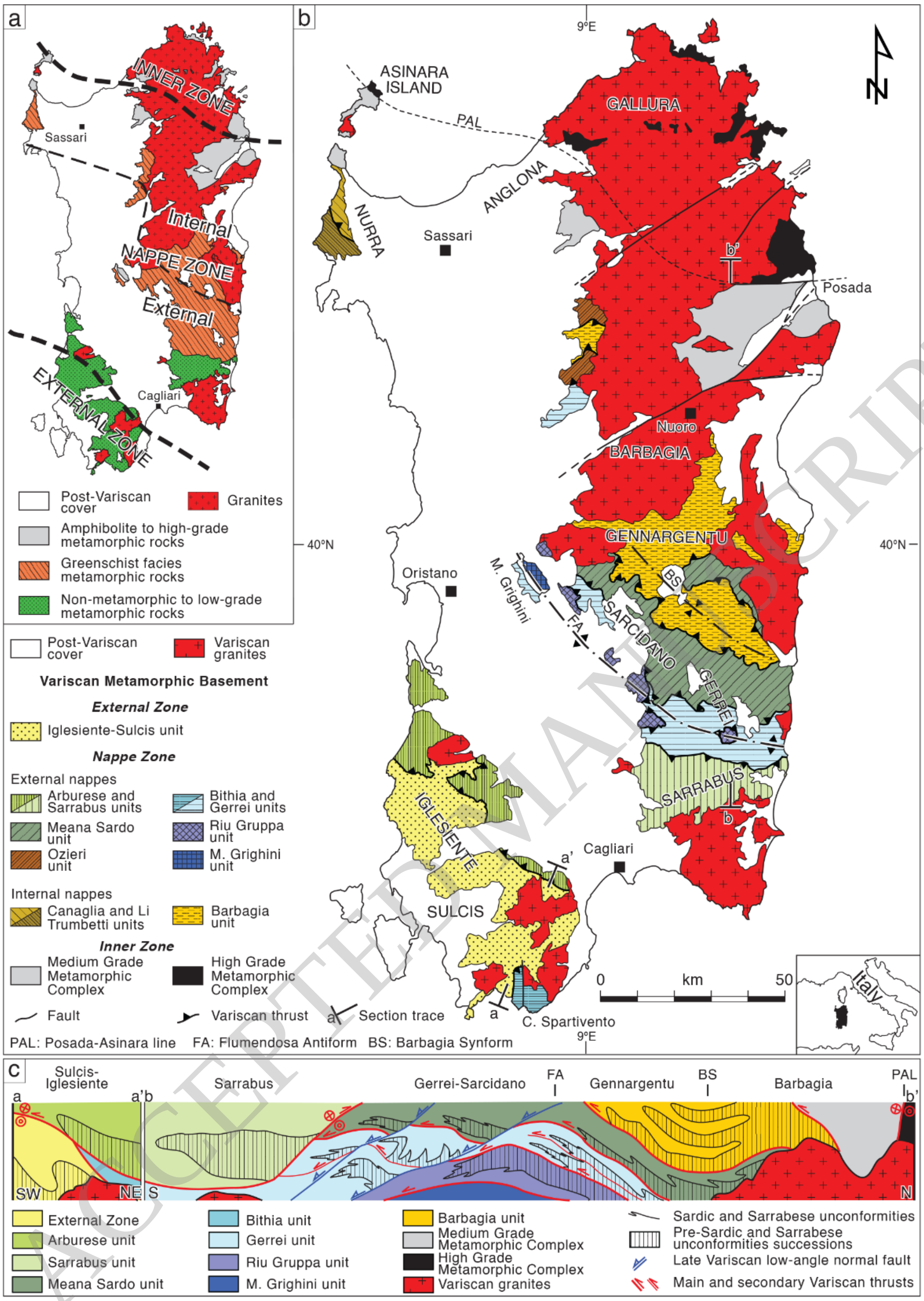
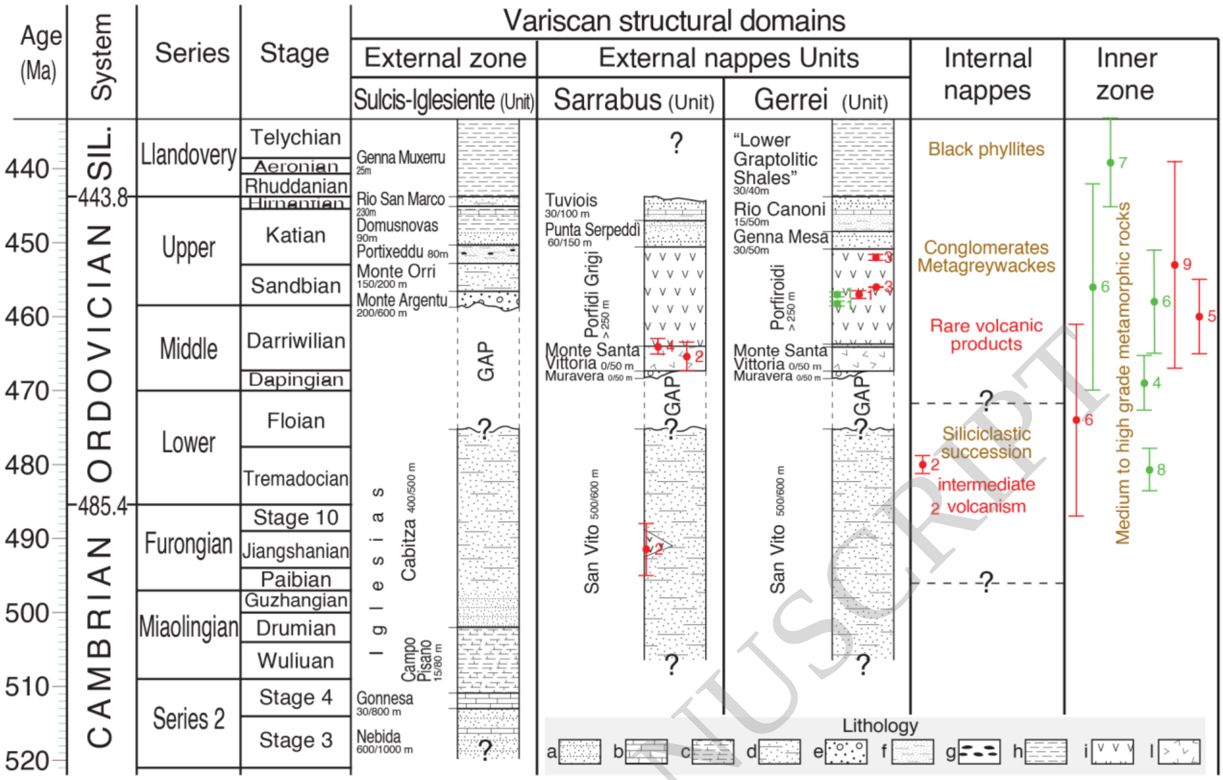

a
INNER ZONE
Sassari
Internal
NAPPE ZONE
External
Cagliari
EXTERNAL ZONE
Post-Variscan cover
Granites
Amphibolite to high-grade metamorphic rocks
Greenschist facies metamorphic rocks
Non-metamorphic to low-grade metamorphic rocks
b
9°E
ASINARA ISLAND
PAL
GALLURA
ANGLONA
NURRA
Sassari
Posada
Nuoro
BARBAGIA
40°N
GENNARGENTU
Oristano
M. Grighini
BS
SARCIDANO
FA
GERREI
SARRABUS
IGLESIENTE
Cagliari
SULCIS
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
Section trace
PAL: Posada-Asinara line FA: Flumendosa Antiform BS: Barbagia Synform
c
Sulcis-Iglesiente
Sarrabus
Gerrei-Sarcidano
FA
Gennargentu
BS
Barbagia
PAL
SW
NE
S
N
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

Figure 2



Age (Ma)
System
Series
Stage
Variscan structural domains
External zone
External nappes Units
Internal nappes
Inner zone
Sulcis-Iglesiente (Unit)
Sarrabus (Unit)
Gerrei (Unit)
SIL.
ORDOVICIAN
CAMBRIAN
443.8
485.4
Llandovery
Upper
Middle
Lower
Furongian
Miaolingian
Series 2
Telychian
Aeronian
Rhuddanian
Hirnantian
Katian
Sandbian
Darriwilian
Dapingian
Floian
Tremadocian
Stage 10
Jiangshanian
Paibian
Guzhangian
Drumian
Wuliuan
Stage 4
Stage 3
Genna Muxerru
Rio San Marco
Domusnovas
Portixeddu
Monte Orri
Monte Argentu
GAP
Iglesias
Cabitza
Campo Pisano
Gonnesa
Nebida
Tuviois
Punta Serpeddì
Porfidi Grigi
Monte Santa Vittoria
Muravera
San Vito
"Lower Graptolitic Shales"
Rio Canoni
Genna Mesa
Porfiroidi
Black phyllites
Conglomerates Metagreywackes
Rare volcanic products
Siliciclastic succession
intermediate volcanism
Medium to high grade metamorphic rocks
Lithology

Figure 3

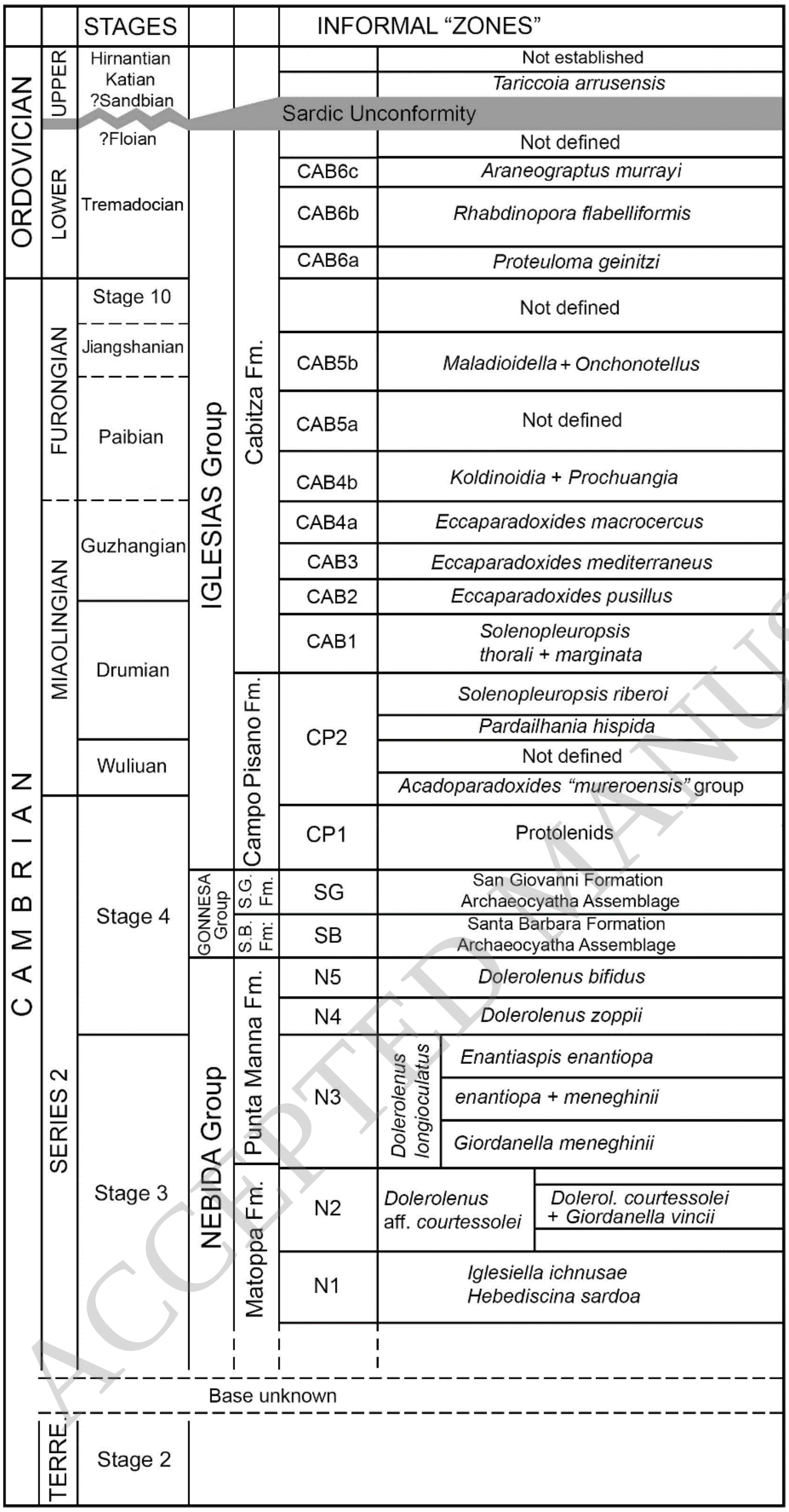
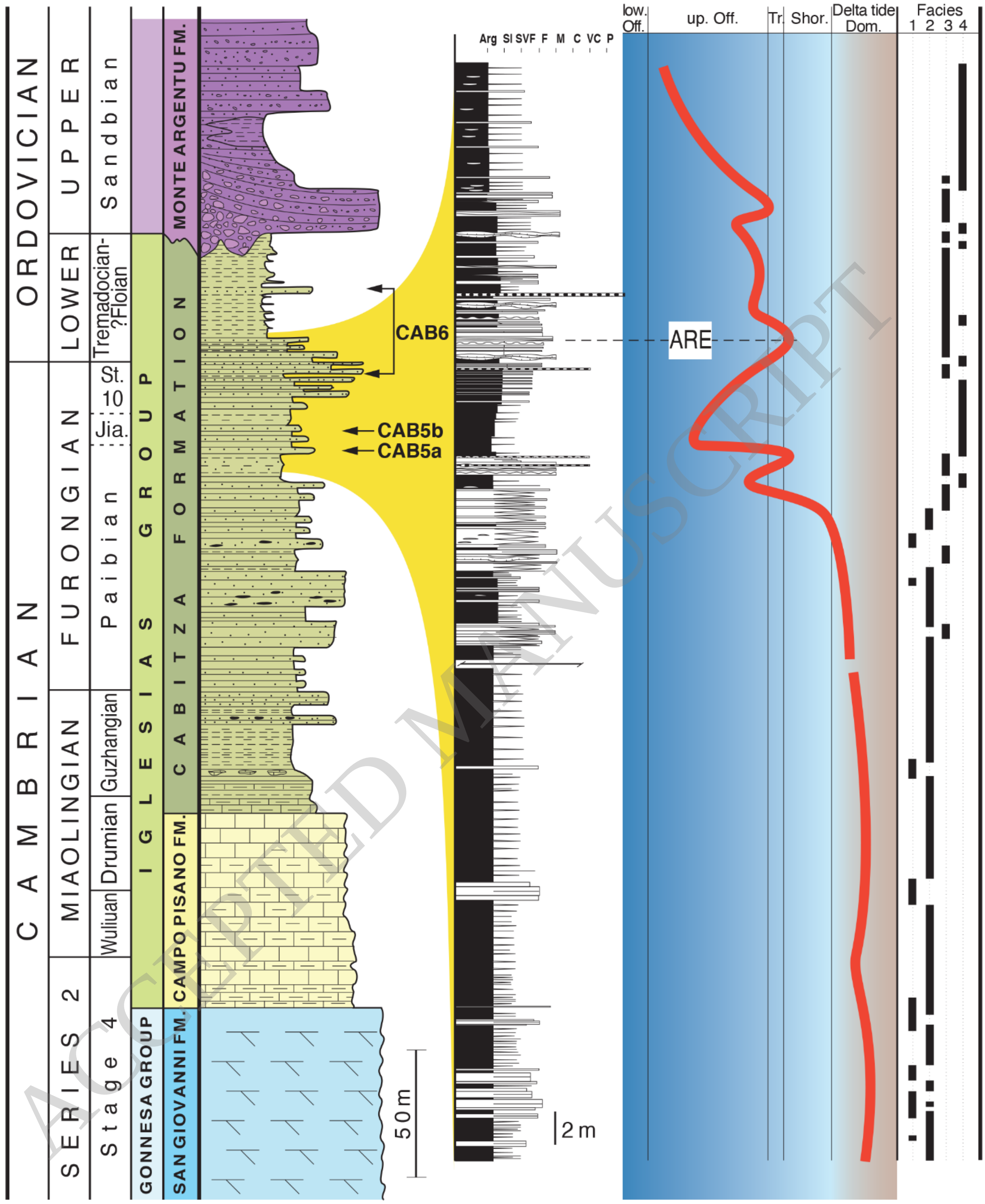

STAGES
INFORMAL “ZONES”
ORDOVICIAN
UPPER
Hirnantian
Katian
?Sandbian
Not established
Tariccoia arrusensis
Sardic Unconformity
LOWER
?Floian
Tremadocian
Not defined
CAB6c
Araneograptus murrayi
CAB6b
Rhabdinopora flabelliformis
CAB6a
Proteuloma geinitzi
C A M B R I A N
FURONGIAN
Stage 10
Not defined
Jiangshanian
CAB5b
Maladioidella + Onchonotellus
Paibian
CAB5a
Not defined
CAB4b
Koldinoidia + Prochuangia
MIAOLINGIAN
Guzhangian
CAB4a
Eccaparadoxides macrocercus
CAB3
Eccaparadoxides mediterraneus
CAB2
Eccaparadoxides pusillus
Drumian
CAB1
Solenopleuropsis thorali + marginata
IGLESIAS Group
Cabitza Fm.
Campo Pisano Fm.
CP2
Solenopleuropsis riberoi
Pardailhania hispida
Not defined
Wuliuan
Acadoparadoxides “mureroensis” group
CP1
Protolenids
SERIES 2
Stage 4
GONNESA Group
S.G. Fm.
SG
San Giovanni Formation Archaeocyatha Assemblage
S.B. Fm.
SB
Santa Barbara Formation Archaeocyatha Assemblage
NEBIDA Group
Punta Manna Fm.
N5
Dolerolenus bifidus
N4
Dolerolenus zoppii
N3
Dolerolenus longioculatus
Enantiaspis enantiopa
enantiopa + meneghinii
Giordanella meneghinii
Stage 3
Matoppa Fm.
N2
Dolerolenus aff. courtessolei
Dolerol. courtessolei + Giordanella vincii
N1
Iglesiella ichnusae
Hebediscina sardoa
Base unknown
TERRE.
Stage 2

Figure 4



ORDOVICIAN
UPPER
LOWER
Sandbian
Tremadocian-?Floian
CAMBRIAN
FURONGIAN
MIAOLINGIAN
SERIES 2
Paibian
St. 10
Jia.
Guzhangian
Drumian
Wuliuan
Stage 4
IGLESIAS GROUP
GONNESA GROUP
MONTE ARGENTU FM.
CABITZA FORMATION
CAMPO PISANO FM.
SAN GIOVANNI FM.
CAB6
CAB5b
CAB5a
50 m
2 m
Arg Sl SVF F M C VC P
low. Off.
up. Off.
Tr.
Shor.
Delta tide Dom.
Facies
1 2 3 4
ARE

Figure 5

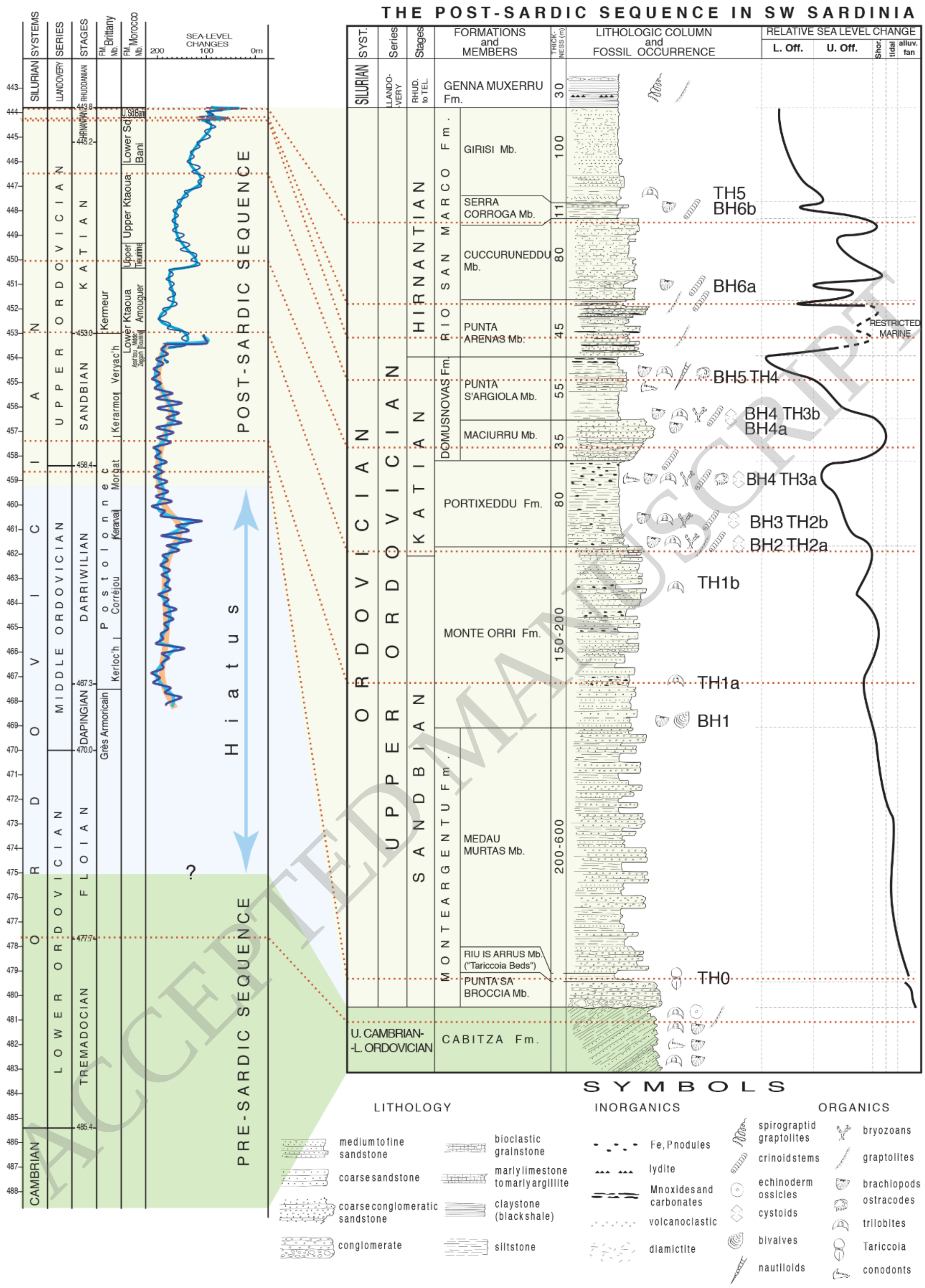

THE POST-SARDIC SEQUENCE IN SW SARDINIA
SYSTEMS
SERIES
STAGES
FM. Mb. Brittany
FM. Mb. Morocco
SEA-LEVEL CHANGES
POST-SARDIC SEQUENCE
Hiatus
PRE-SARDIC SEQUENCE
SYST.
Series
Stages
FORMATIONS and MEMBERS
THICKNESS (m)
LITHOLOGIC COLUMN and FOSSIL OCCURRENCE
RELATIVE SEA LEVEL CHANGE
L. Off.
U. Off.
GENNA MUXERRU Fm.
GIRISI Mb.
SERRA CORROGA Mb.
CUCCURUNEDDU Mb.
PUNTA ARENAS Mb.
RIO SAN MARCO Fm.
PUNTA S'ARGIOLA Mb.
MACIURRU Mb.
DOMUSNOVAS Fm.
PORTIXEDDU Fm.
MONTE ORRI Fm.
MEDAU MURTAS Mb.
RIU IS ARRUS Mb. ("Tariccoia Beds")
PUNTA SA BROCCIA Mb.
MONTE ARGENTU Fm.
U. CAMBRIAN-L. ORDOVICIAN
CABITZA Fm.
TH5
BH6b
BH6a
RESTRICTED MARINE
BH5 TH4
BH4 TH3b
BH4a
BH4 TH3a
BH3 TH2b
BH2 TH2a
TH1b
TH1a
BH1
TH0
SYMBOLS
LITHOLOGY
medium to fine sandstone
coarse sandstone
coarse conglomeratic sandstone
conglomerate
bioclastic grainstone
marly limestone to marly argillite
claystone (black shale)
siltstone
INORGANICS
Fe, P nodules
lydite
Mn oxided and carbonates
volcanoclastic
diamictite
ORGANICS
spirograptid graptolites
crinoid stems
echinoderm ossicles
cystoids
bivalves
nautiloids
bryozoans
graptolites
brachiopods
ostracodes
trilobites
Tariccoia
conodonts

Figure 6

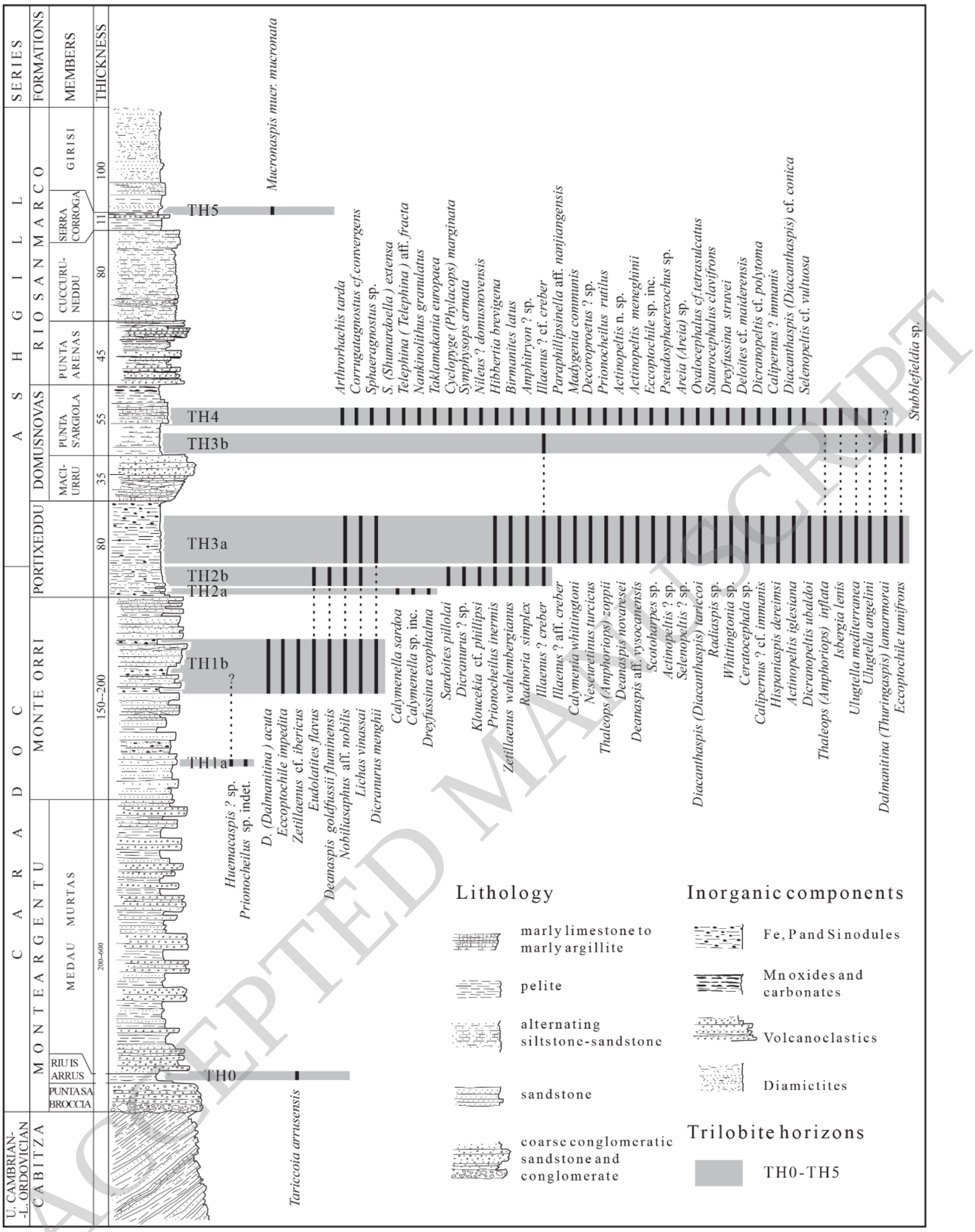
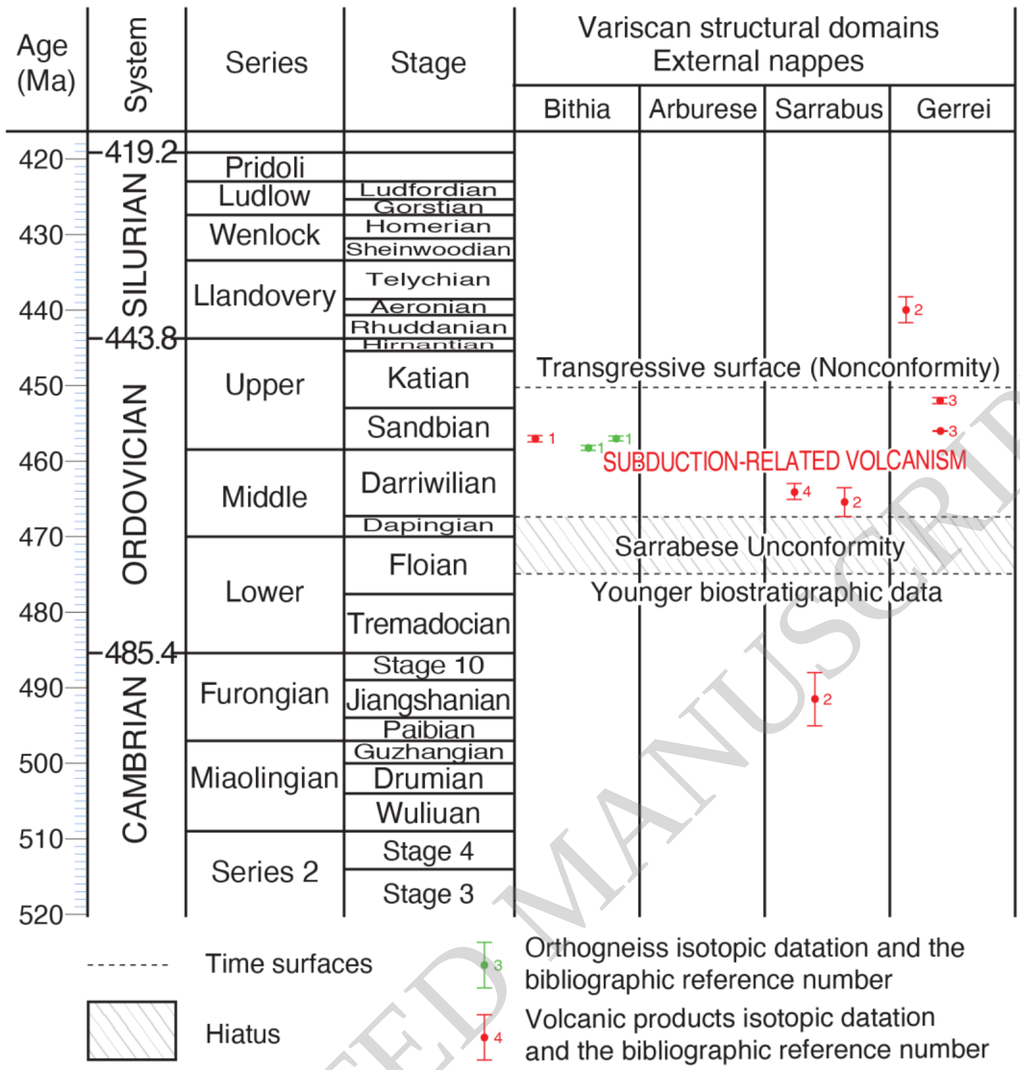

SERIES
FORMATIONS
MEMBERS
THICKNESS
U. CAMBRIAN- -L. ORDOVICIAN
CABITZA
CARADOC
ASHGILL
MONTE ARGENTU
MONTE ORRI
PORTIXEDDU
DOMUSNOVAS
RIO SAN MARCO
PUNTA S'ARGIOLA
PUNTA ARENAS
CUCCURU-NEDDU
SERRA CORROGA
GIRISI
MACI-URRU
MEDAU MURTAS
RIU IS ARRUS
PUNTA SA BROCCIA
200–600
150–200
80
35
55
45
80
11
100
TH0
TH1a
TH1b
TH2a
TH2b
TH3a
TH3b
TH4
TH5
Mucronaspis mucr. mucronata
Tariccoia arrusensis
Huemacaspis ? sp.
Prionocheilus sp. indet.
D. (Dalmanitina) acuta
Eccoptochile impedita
Zetillaenus cf. ibericus
Eudolatites flavus
Deanaspis goldfussi fluminensis
Nobiliasaphus aff. nobilis
Lichas vinassai
Dicranurus menghii
Calymenella sardoa
Calymenella sp. inc.
Dreyfussina exophtalma
Sardoites pillolai
Dicranurus ? sp.
Kloucekia cf. phillipsi
Prionocheilus inermis
Zetillaenus wahlenbergianus
Radnoria simplex
Illaenus ? creber
Illaenus ? aff. creber
Calymenia whittingtoni
Neseuretinus turcicus
Thaleops (Amphoriops) zoppii
Deanaspis novaresei
Deanaspis aff. vysocanensis
Scotoharpes sp.
Actinopeltis ? sp.
Selenopeltis ? sp.
Diacanthaspis (Diacanthaspis) tariccoi
Radiaspis sp.
Whittingtonia sp.
Ceratocephala sp.
Calipernus ? cf. immanis
Hispaniaspis dereimsi
Actinopeltis iglesiana
Dicranopeltis ubaldoi
Thaleops (Amphoriops) inflata
Isbergia lenis
Ulugtella mediterranea
Ulugtella angelini
Dalmanitina (Thuringaspis) lamarmorai
Eccoptochile tumifrons
Arthrorhachis tarda
Corrugatagnostus cf.convergens
Sphaeragnostus sp.
S. (Shumardoella) extensa
Telephina (Telephina) aff. fracta
Nankinolithus granulatus
Taklamakania europaea
Cyclopyge (Phylacops) marginata
Symphysops armata
Nileus ? domusnovensis
Hibbertia brevigena
Birmanites latus
Amphitryon ? sp.
Illaenus ? cf. creber
Paraphillipsinella aff. nanjiangensis
Madygenia communis
Decoroproetus ? sp.
Prionocheilus rutilus
Actinopeltis n. sp.
Actinopeltis meneghinii
Eccoptochile sp. inc.
Pseudosphaerexochus sp.
Areia (Areia) sp.
Ovalocephalus cf.tetrasulcatus
Staurocephalus clavifrons
Dreyfussina struvei
Deloites cf. maiderensis
Dicranopeltis cf. polytoma
Calipernus ? immanis
Diacanthaspis (Diacanthaspis) cf. conica
Selenopeltis cf. vultuosa
Stubblefieldia sp.
Lithology
marly limestone to marly argillite
pelite
alternating siltstone-sandstone
sandstone
coarse conglomeratic sandstone and conglomerate
Inorganic components
Fe, P and Si nodules
Mn oxides and carbonates
Volcanoclastics
Diamictites
Trilobite horizons
TH0-TH5

Figure 7



Age (Ma)
System
Series
Stage
Variscan structural domains
External nappes
Bithia
Arburese
Sarrabus
Gerrei
420
430
440
450
460
470
480
490
500
510
520
419.2
443.8
485.4
SILURIAN
ORDOVICIAN
CAMBRIAN
Pridoli
Ludlow
Wenlock
Llandovery
Upper
Middle
Lower
Furongian
Miaolingian
Series 2
Ludfordian
Gorstian
Homerian
Sheinwoodian
Telychian
Aeronian
Rhuddanian
Hirnantian
Katian
Sandbian
Darriwilian
Dapingian
Floian
Tremadocian
Stage 10
Jiangshanian
Paibian
Guzhangian
Drumian
Wuliuan
Stage 4
Stage 3
Transgressive surface (Nonconformity)
SUBDUCTION-RELATED VOLCANISM
Sarrabese Unconformity
Younger biostratigraphic data
Time surfaces
Hiatus
Orthogneiss isotopic datation and the bibliographic reference number
Volcanic products isotopic datation and the bibliographic reference number

Figure 8

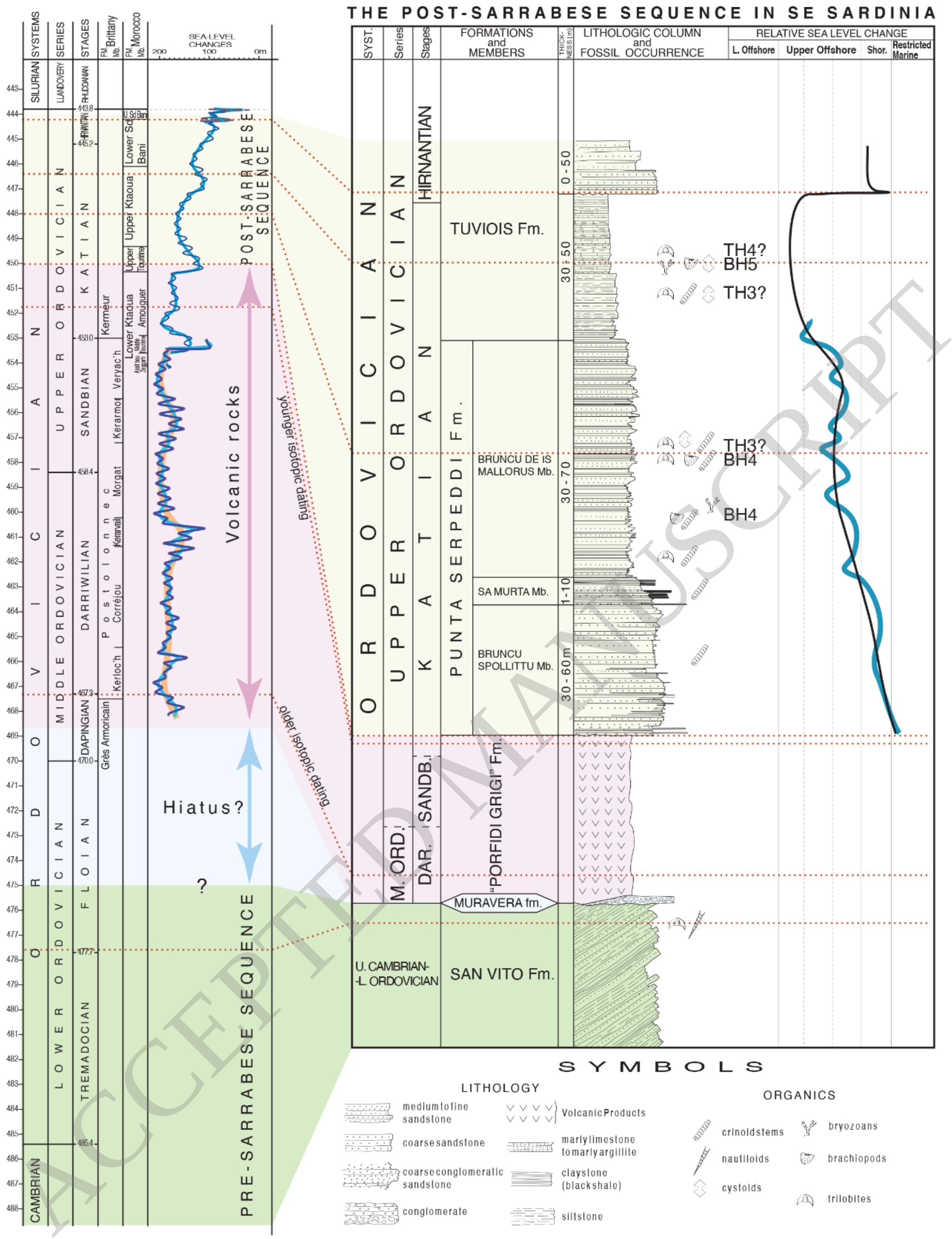
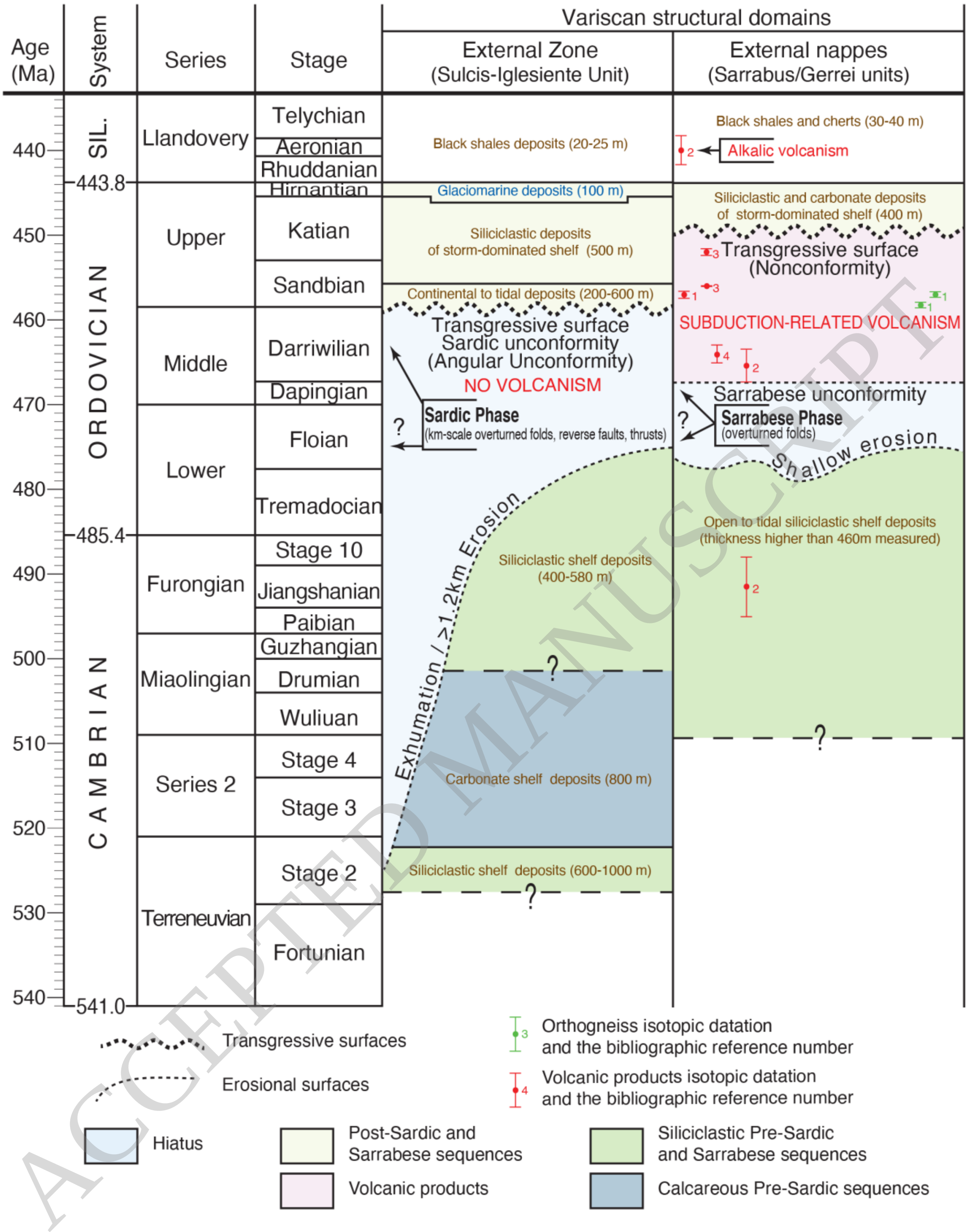

THE POST-SARRABESE SEQUENCE IN SE SARDINIA
SYSTEMS
SERIES
STAGES
SEA-LEVEL CHANGES
POST-SARRABESE SEQUENCE
Volcanic rocks
younger isotopic dating
older isotopic dating
Hiatus?
PRE-SARRABESE SEQUENCE
SILURIAN
ORDOVICIAN
CAMBRIAN
UPPER ORDOVICIAN
MIDDLE ORDOVICIAN
LOWER ORDOVICIAN
HIRNANTIAN
KATIAN
SANDBIAN
DARRIWILIAN
DAPINGIAN
FLOIAN
TREMADOCIAN
SYST.
Series
Stages
FORMATIONS and MEMBERS
LITHOLOGIC COLUMN and FOSSIL OCCURRENCE
RELATIVE SEA LEVEL CHANGE
L. Offshore
Upper Offshore
Shor.
Restricted Marine
TUVIOIS Fm.
PUNTA SERPEDDI Fm.
BRUNCU DE IS MALLORUS Mb.
SA MURTA Mb.
BRUNCU SPOLLITTU Mb.
"PORFIDI GRIGI" Fm.
MURAVERA fm.
U. CAMBRIAN-L. ORDOVICIAN
SAN VITO Fm.
TH4?
BH5
TH3?
BH4
SYMBOLS
LITHOLOGY
medium to fine sandstone
coarse sandstone
coarse conglomeratic sandstone
conglomerate
Volcanic Products
marly limestone to marly argillite
claystone (black shale)
siltstone
ORGANICS
crinoid stems
nautiloids
cystoids
bryozoans
brachiopods
trilobites

Figure 9

Figure 10



Age (Ma)
System
Series
Stage
Variscan structural domains
External Zone (Sulcis-Iglesiente Unit)
External nappes (Sarrabus/Gerrei units)
SIL.
Llandovery
Telychian
Aeronian
Rhuddanian
Hirnantian
443.8
ORDOVICIAN
Upper
Katian
Sandbian
Middle
Darriwilian
Dapingian
Lower
Floian
Tremadocian
485.4
CAMBRIAN
Furongian
Stage 10
Jiangshanian
Paibian
Miaolingian
Guzhangian
Drumian
Wuliuan
Series 2
Stage 4
Stage 3
Terreneuvian
Stage 2
Fortunian
541.0
Black shales deposits (20-25 m)
Black shales and cherts (30-40 m)
Alkalic volcanism
Glaciomarine deposits (100 m)
Siliciclastic and carbonate deposits of storm-dominated shelf (400 m)
Siliciclastic deposits of storm-dominated shelf (500 m)
Transgressive surface (Nonconformity)
Continental to tidal deposits (200-600 m)
SUBDUCTION-RELATED VOLCANISM
Transgressive surface Sardic unconformity (Angular Unconformity)
NO VOLCANISM
Sarrabese unconformity
Sardic Phase
(km-scale overturned folds, reverse faults, thrusts)
Sarrabese Phase
(overturned folds)
Shallow erosion
Exhumation / >1.2km Erosion
Open to tidal siliciclastic shelf deposits (thickness higher than 460m measured)
Siliciclastic shelf deposits (400-580 m)
Carbonate shelf deposits (800 m)
Siliciclastic shelf deposits (600-1000 m)
Transgressive surfaces
Erosional surfaces
Orthogneiss isotopic datation and the bibliographic reference number
Volcanic products isotopic datation and the bibliographic reference number
Hiatus
Post-Sardic and Sarrabese sequences
Volcanic products
Siliciclastic Pre-Sardic and Sarrabese sequences
Calcareous Pre-Sardic sequences

Figure 11