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

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14

15 **Abstract**

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

30

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

32 *Qaidam Ocean*

33

34 **1) Introduction**

35 The Ordovician successions of Italy are extensively documented in Sardinia and, to a lesser
36 extent, in the Carnic Alps (Vai 1971; Vai and Spalletta 1980; Schönlaub 2000). In other regions of
37 Italy, portions of Ordovician crust are reported in the northern Apennines (Apuan Alps, Conti *et al.*
38 1993), and in the southern Apennines (Calabrian-Peloritanian Arc, Cirrincione *et al.* 2015),
39 consisting of rocks of various metamorphic grades made up of sedimentary and volcanic protoliths.
40 Some volcanic products of these metamorphic complexes have provided absolute Ordovician ages
41 (Trombetta *et al.* 2004; Paoli *et al.* 2017).

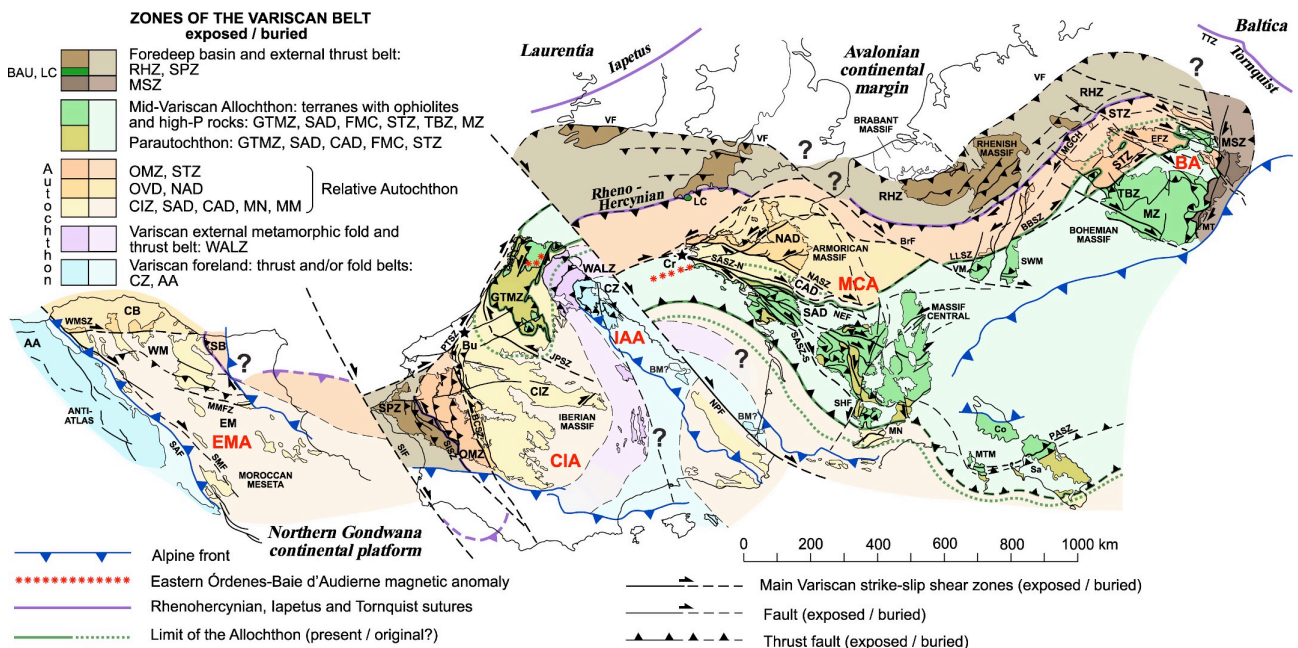
42 The Ordovician successions of Sardinia are affected by several folding events, the oldest of
43 which are referable to the Early Ordovician Sardic and Sarrabese phases, and the most recent to the
44 Variscan Orogeny. The Variscan Orogeny (Fig. 1) provide the main structure of the Sardinian
45 basement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

56 in south-eastern Sardinia (Nappe Zone), an angular unconformity (Sarrabese Unconformity) was
57 recognised between the Cambrian- Lower Ordovician sedimentary series and a thick Ordovician
58 volcanic and sedimentary complex, and ascribed to the Sarrabese Phase (Calvino 1959; Naud 1981).

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

73 Since the 1980s, palaeogeographic reconstructions and some geodynamic models (Oggiano
74 *et al.* 2010; Gaggero *et al.* 2012) have assumed that the Variscan basement of Sardinia pertained to
75 a platform connected to a single coherent crustal block since Cambrian times. Thus, the stratigraphic
76 differences between the External and Nappe zones observed in the Ordovician successions were
77 interpreted as due to a coeval evolution in neighbouring areas of a subduction margin, where a back-
78 arc basin and a continental volcanic arc developed during the Middle Ordovician in the External and
79 Nappe zones, respectively. The most recent and accurate analyses of stratigraphic and
80 palaeontological data, sediment provenance, chronology of magmatic products and gap ages indicate
81 strong differences between tectonic units in Sardinia, with no comparable geodynamic settings and

82 timescales (Cocco *et al.* 2018, 2022_submitted). These discrepancies imply that the External and
 83 Nappe zones belonged to different and possibly distant palaeogeographical and geodynamical
 84 domains. Moreover, these data suggest that the current zonation of the Paleozoic basement of
 85 Sardinia is the product of extensive crustal reworking and amalgamation in Variscan times.
 86 Therefore, a palaeogeography where Sardinia is considered a single crustal block during the
 87 Ordovician can be ruled out.



88
 89
 90 **Fig. 1.** Tectonic sketch map of the Southern Variscan Realm at the end of the Paleozoic, modified after Martínez Catalán *et al.* (2021)

91

92

93 **2) Variscan tectono-metamorphic framework of Sardinia**

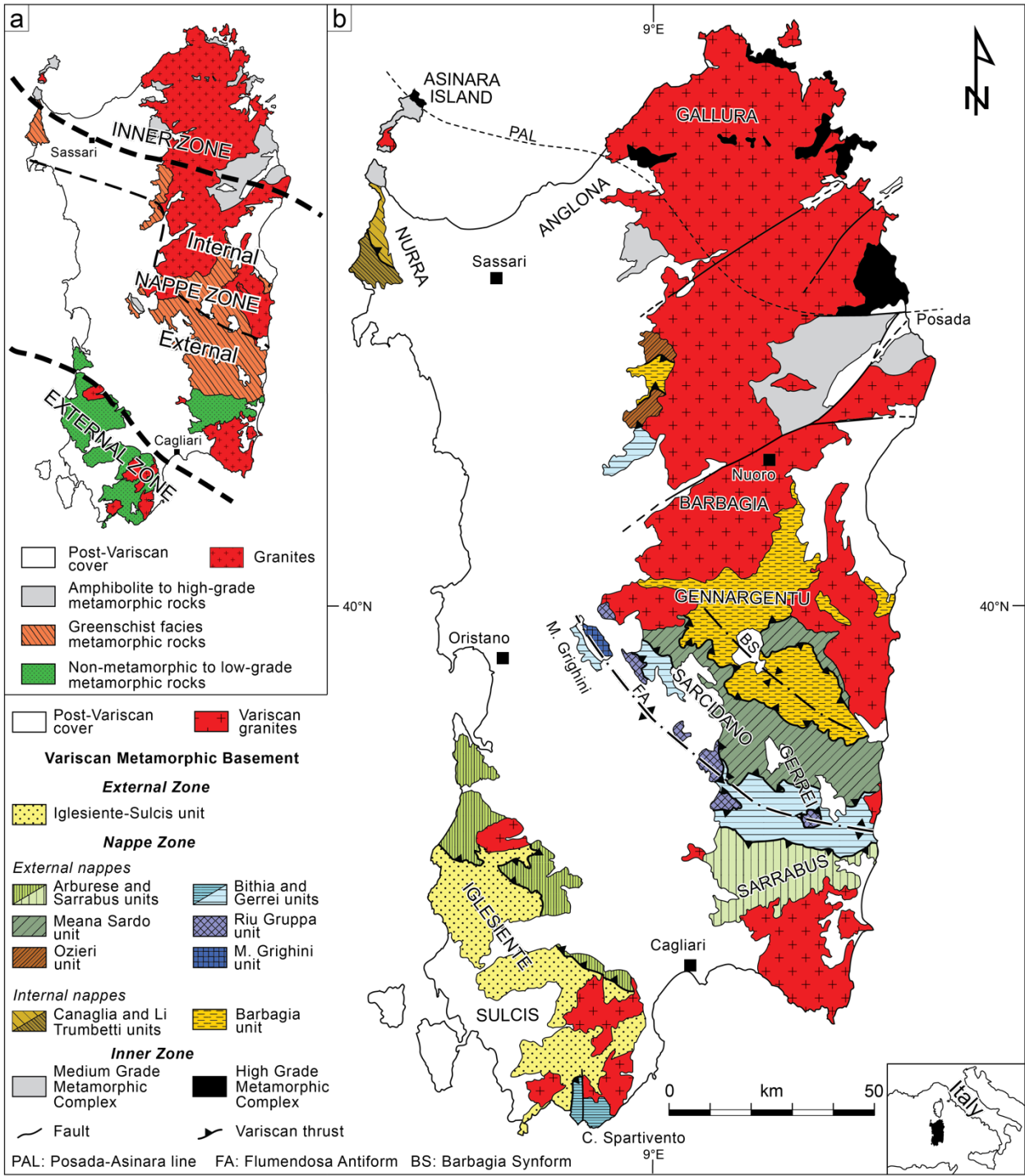
94 The complete section of the Variscan chain exposed in Sardinia comprises three tectono-
 95 metamorphic zones (Carmignani *et al.* 1994) (Fig. 2a): an External Zone in SW Sardinia, a Nappe
 96 Zone in central-eastern Sardinia and, finally, an Inner Zone in the northern sector of the island.
 97 During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

100 The External Zone is considered to be the parautochthonous above which the external Nappe
101 of the Nappe Zone overthrust and was deformed by at least three Variscan folding events with no or
102 very low-grade metamorphism ($T < 250\text{ }^{\circ}\text{C}$, Casini *et al.*, 2010).

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

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

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



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

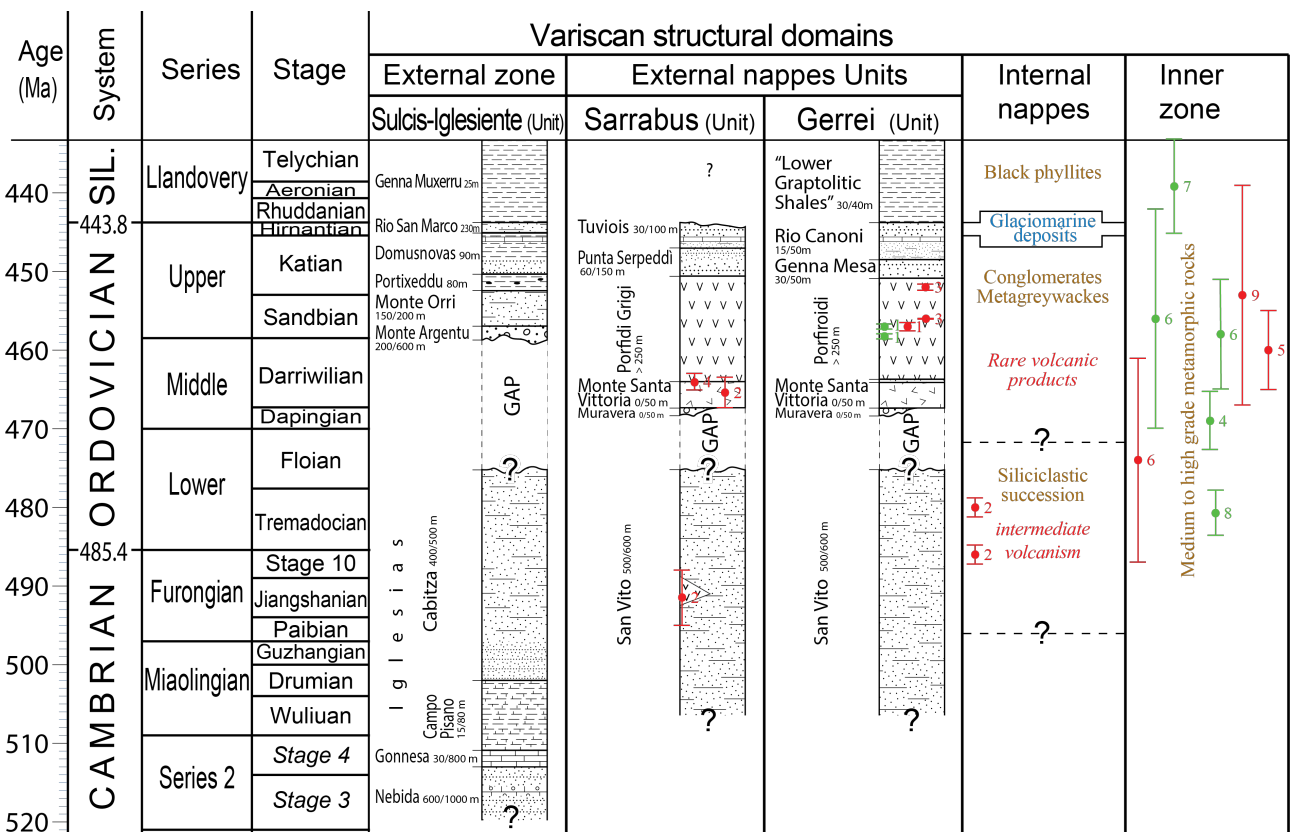
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133

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

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

142



143

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

146 bibliographic reference number: 1-(Pavanetto *et al.* 2012); 2-(Oggiano *et al.* 2010); 3-(Dack 2009); 4-(Giacomini *et al.*
147 2006); 5-(Giacomini *et al.* 2005); 6-(Helbing and Tiepolo 2005); 7-(Rossi *et al.* 2009); 8-(Casini *et al.* 2015); 9-(Palmeri
148 *et al.* 2004). After Cocco *et al.* (2022_submitted).

149

150 **3.1) Sulcis-Iglesiente Unit (External Zone– SW Sardinia)**

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

155

156 Pre-Sardic sequence

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

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

171 The Gonnese Group consists of carbonate deposits. The Santa Barbara Fm. is characterized by
172 alternations of well-stratified stromatolitic dolomites and limestones, which are in turn covered by
173 massive limestone, often dolomitized, of the San Giovanni Fm. The two main Archaeocyatha
174 associations indicates a higher Botomian and a Toyonian age respectively (Debrenne and Gandin
175 1985), corresponding to the middle portion of the Cambrian Stage 4.

176 The Iglesias Group begins with an alternation of nodular and massive grey limestones, marls and
177 thin levels of silty argillites of the Campo Pisano Fm. (uppermost Stage 4 to mid-Drumian) which
178 rests in continuity or with local gaps and erosive surfaces over the San Giovanni Fm. (Gandin *et al.*
179 1987; Pillola 1991; Elicki and Pillola 2004). The succession progressively grades, upwards, to an
180 alternation of variable scale from centimetre to metric of shales, siltstones and sandy levels of the
181 Cabitza Fm. (Drumian to late Tremadoc/?early Floian), deposited in a terrigenous platform
182 environments with facies ranging from the lower offshore to tidal flats (Loi *et al.* 1996).

183 Still in the Cabitza Fm. (Figs 3 and 4) the Cambrian/Ordovician boundary is observed in stratigraphic
184 continuity (Loi *et al.* 1996). This boundary has been bracketed between the CAB5b fauna
185 (*Maladioidella* - *Onchonotellus*) and the CAB6 fauna (*Proteuloma geinitzi* - *Rhabdinopora*
186 *flabelliformis flabelliformis*) (Fig. 5), and correlated with the Acerocare Regressive Event (ARE,
187 Erdtmann 1986) according to the relative sea level variation curves (Pillola and Gutierrez-Marco
188 1988; Loi *et al.* 1996; Pillola *et al.* 2008; Pillola 2019). The estimated thickness of the Cabitza Fm.
189 is at least 600 m (Cocozza 1979; Cocozza and Gandin 1990). The youngest ages documented in the
190 upper levels of the Cabitza Fm., below the Sardic Unconformity, are the Lower Ordovician
191 (Tremadocian) based on the finding of acritarchs and graptolites (Gandin and Pillola 1985; Barca *et*
192 *al.* 1987; Pillola and Gutierrez-Marco 1988) and the latest Tremadocian-?basal Floian beds yielding
193 *Araneograptus murrayi* Biozone (Pillola *et al.* 2008).

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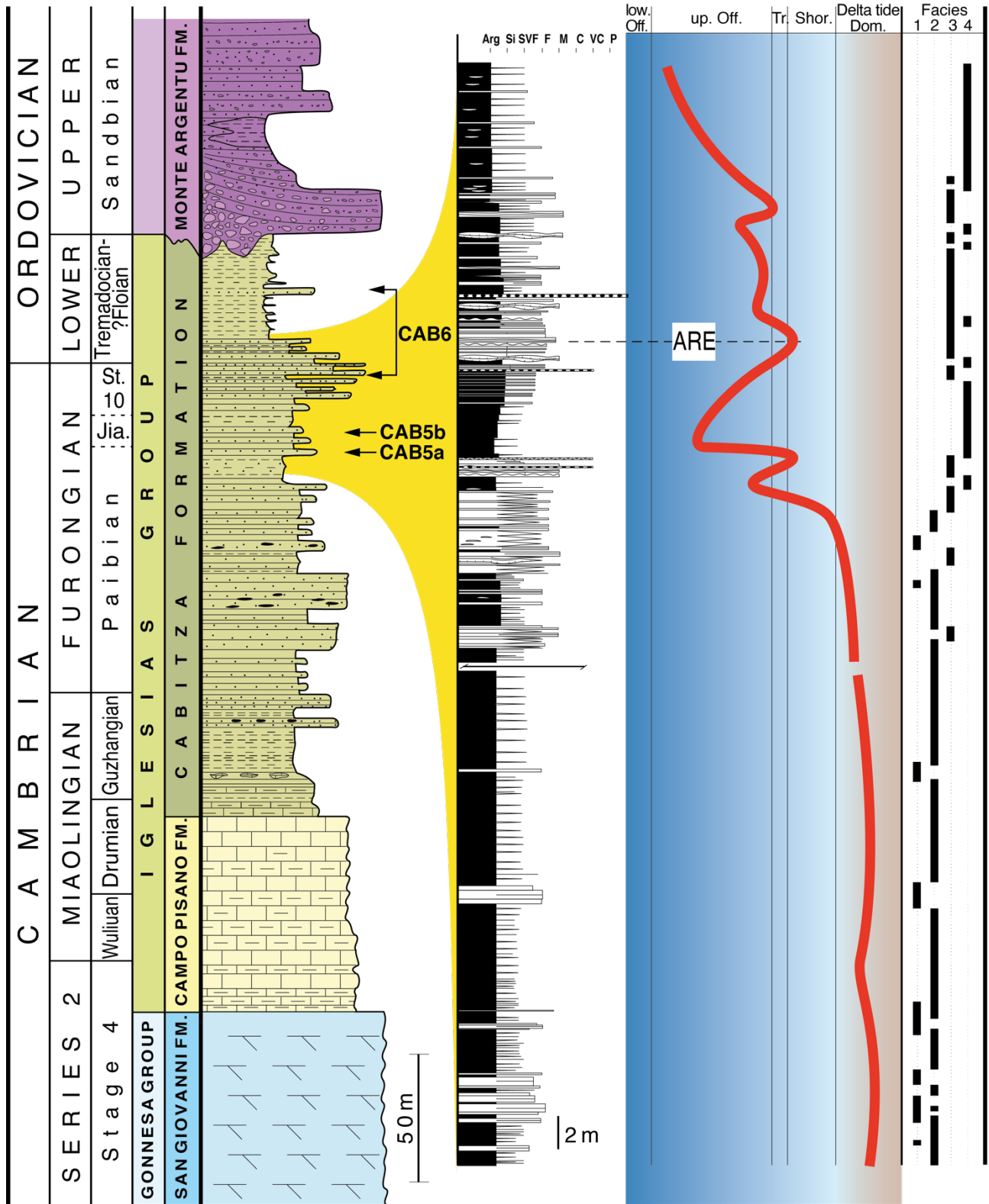
ORDOVICIAN		STAGES	INFORMAL "ZONES"							
UPPER	Hirnantian			Not established						
	Katian ?Sandbian			<i>Tariccoia arrusensis</i>						
LOWER		?Floian		Sardic Unconformity						
		Tremadocian		Not defined						
C A M B R I A N		MIAOLINGIAN	IGLESIA Group	CAB6c	<i>Araneograptus murrayi</i>					
				CAB6b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

195

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

198

199



200

Fig. 5. Schematic log of the Iglesias Group, together with a detailed sea level curve for Furongian strata in the “Tubi”

201

Section. ARE = Acerocare Regressive Event. Modified after Loi *et al.* (1996).

202

204 **Fig. 6.** Schematic lithostratigraphic succession of the Post Sardinian sequences of SW Sardinia. Curve of relative sea-level
205 changes and main fossiliferous occurrence of trilobites (TH) and brachiopods (BH) identified by Leone *et al.* (1998) and
206 Hammann and Leone (1997, 2007). Chronostratigraphic correlation by the time-calibrated eustatic curve established in
207 the Upper Ordovician of the Moroccan Anti Atlas (Loi *et al.* 2010) and the Middle-Upper Ordovician of the Armorican
208 Massif (Dabard *et al.* 2015). After (Cocco *et al.* 2022_submitted).

209

210 Post-Sardinian sequence

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

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

231 *Tariccoia* beds. The thickness of the Monte Argentu Fm. varies between 200 and 600 m (Laske *et al.*
232 1994; Leone *et al.* 1998). Its age is constrained between the Tremadocian-early Floian? of the upper
233 Cabitza Fm. (Pillola *et al.* 2008) and the Sandbian (Soudleyan-Longvillian) trilobite and brachiopod
234 fauna (BH1-TH1) of the Monte Orri Fm. (Hammann and Leone 1997, 2007; Leone *et al.* 1998).

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

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

249 The succession suddenly and conformably evolves into marly limestones, marly shales and
250 limestones of the Punta S'Argiola Mb. This member yields a rich fossil fauna and shows a high degree
251 of sedimentary condensation (Botquelen *et al.* 2002, 2004, 2006b) documented by a carbonation of
252 the seabed (taphonomic feedback). The late Katian ("Ashgill") age is suggested by the rich and
253 significant content in brachiopods and trilobites (Figs 6 and 7, BH4, BH5, TH3b, TH4) (Hammann
254 and Leone 1997, 2007; Leone *et al.* 1998). A diversified but poorly preserved conodont fauna has
255 documented the *Amorphognathus ordovicicus* Zone (Ferretti and Serpagli 1991, 1998). *Hamarodus*
256 *brevirameus*, *Scabbardella altipes* and *Amorphognathus* (*A. ordovicicus* and *A. duftonus*)

257 numerically dominate the fauna, mirroring diversity and abundance of the conodont assemblages
258 reported from the Carnic Alps (Serpagli 1967; Bagnoli *et al.* 1998; Ferretti and Schönlaub 2001;
259 Ferretti *et al.*, this volume). Investigations of the relative abundance of multielement conodont taxa
260 in representative conodont faunas have the potential to provide useful biogeographical and biofacies
261 information, and the major conodont biofacies in much of the Upper Ordovician had already been
262 introduced by Sweet and Bergström (1984). Conodont data of the last 30 years have reinforced this
263 subdivision, documenting a Mediterranean Province fauna (*Sagittodontina robusta-Scabbardella*
264 *altipes* biofacies: Thuringia, France, Spain, Lybia) that apparently occupied high latitude, relatively
265 cold waters near the pole and at lower latitudes the *Hamarodus europaeus* (now *brevirameus*)-
266 *Dapsilodus mutatus-Scabbardella altipes* biofacies (Sardinia, Carnic Alps, Baltoscandia) and the
267 *Amorphognathus-Plectodina* biofacies (middle to upper Katian British faunas from Wales and
268 England) (Ferretti *et al.* 2014; Bergström and Ferretti 2015).

269 In addition, the whole Monte Orri, Portixeddu and Domusnovas formations yield a diversified fauna
270 rich, among other, in echinoderms (Maccagno 1965; Botquelen *et al.* 2006b); bryozoans (Conti 1990
271 and references therein) and brachiopods (Vinassa De Regny 1927, 1942; Giovannoni and Zanfrà
272 1978; Havlicek *et al.* 1986; Leone *et al.* 1991; Botquelen *et al.* 2006a).

273 The Upper Ordovician succession ends with the Rio San Marco Fm. (230 m thick; Leone *et al.* 1991).

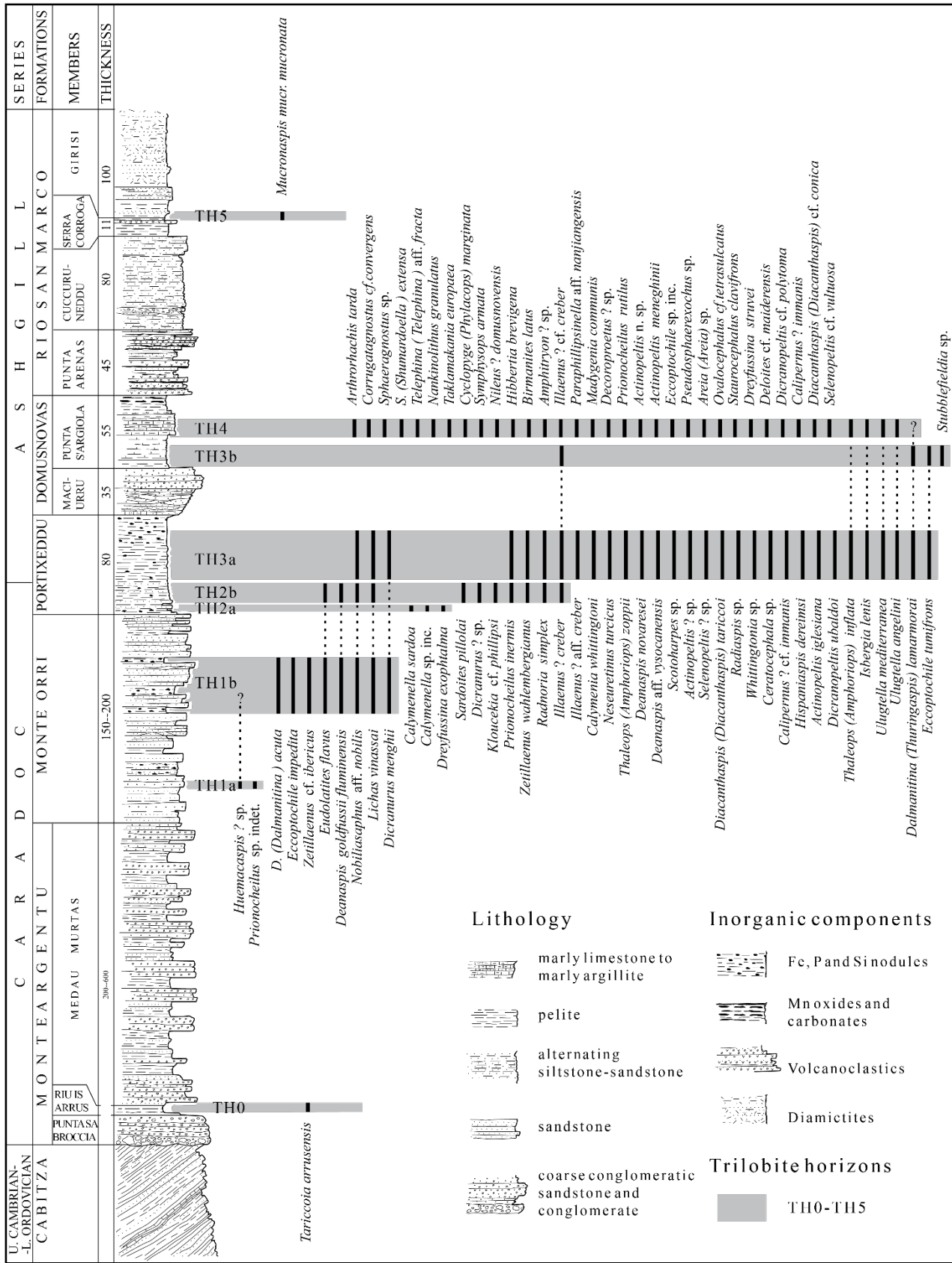
274 The base of this formation (Punta Arenas Mb.) is made up of siltstones and shales, interbedded with
275 layers of heterogeneous conglomerates that also host volcanic pebbles and strata of manganese
276 carbonates and oxides. The Punta Arenas Mb. deposits were laid down in restricted marine
277 environments, subsequent to the rapid glacio-eustatic sea level fall of the first Hirnantian glacial
278 pulsation (Ghienne *et al.* 2000). This member is topped by a condensed level rich in *Normalograptus*
279 *ojsuensis* (Štorch and Leone 2003), testifying an ensuing rapid sea level rise. This condensed level
280 is overlain by classic upper offshore storm facies showing rhythmic alternations of HCS sandstone
281 layers separated by shales of the basal Cuccuruneddu Mb. After a few metres from the base of
282 Cuccuruneddu Mb, a first glacio-marine layer including ice-rafted debris is observed. Then follow

283 terrigenous deposits with storm-dominated platform facies, organised by three cycles of sea-level
284 change, from Cuccuruneddu and Serra Corroga members (Fig. 6). The Upper Ordovician succession
285 ends with ice-distal glacio-marine deposits of the Girisi Mb, composed of dark grey finely laminated
286 to massive shales, siltstones and fine to very fine sandstones.

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

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

294



295

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

298

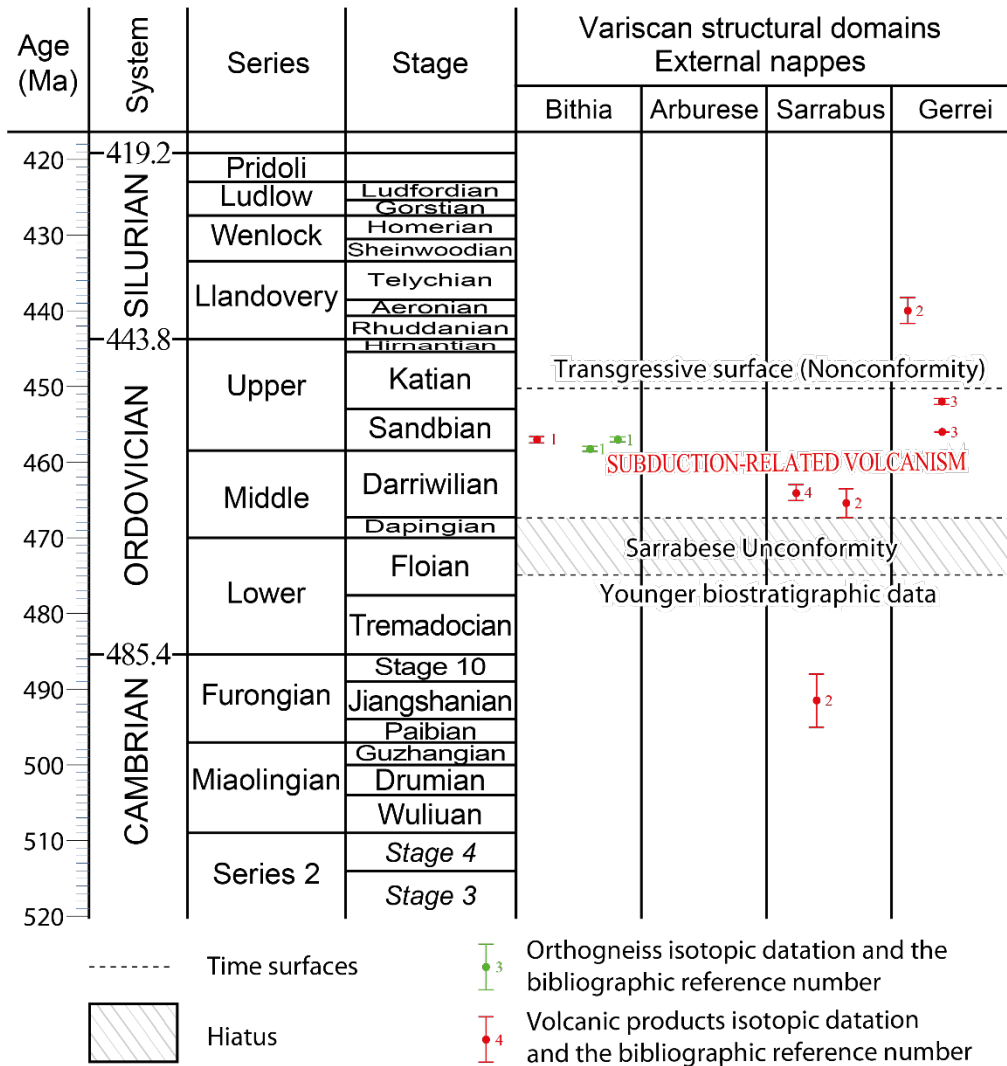
299 **3.2) Sarrabus and Gerrei Units (External Nappe Zone, Central eastern Sardinia)**

300

301 Two unconformities (Fig. 3 and 8) separate three successions with similar lithostratigraphic
302 characteristics in all the tectonic units of the External Nappe. The oldest is an angular unconformity
303 that separates the lower Cambrian-Ordovician sedimentary succession from the Middle-Upper
304 Ordovician volcano-sedimentary succession and is known as the Sarrabese Unconformity (Calvino
305 1959). The second is a nonconformity and represents the surface of marine transgression on effusive
306 magmatic rocks, referred to as the Caradocian transgression by ancient authors. The latter
307 sedimentary succession is continuous from the Upper Ordovician to the lower Carboniferous.

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

312



313

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

317

318 Pre-Sarrabese sequence

319 Below the Sarrabese Unconformity lies a thick siliciclastic succession (Arenarie di San Vito; Calvino
 320 1959) composed of sandstones, siltstones and shales with well-developed sedimentary structures
 321 such as parallel and cross laminations, HCS, unidirectional current ripples, flute and load casts. This
 322 sedimentary succession consists of an articulated stacking of facies, all deposited in a terrigenous
 323 platform in environments that vary between the lower offshore and the tidal flat. Towards the top of
 324 the succession, the depositional sequences are expressed with more proximal facies, up to fine-

325 grained conglomerates. In the Gerrei Unit, carbonate pelites, limestone layers and
326 microconglomerates, with quartz elements, occur in the upper part of the succession.

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

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

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

346

347 Post-Sarrabese sequence

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

351 sandstones and siltstones (Metaconglomerati di Muravera Fm., Carmignani *et al.* 2001). This
352 continental deposit is discontinuous, and the thickness varies from 0 to 50 m. The overlying volcanic
353 succession consists of epiclastites and andesitic lavas (Monte Santa Vittoria Fm.; (Carmignani *et al.*
354 2001; Conti *et al.* 2001), in turn covered by rhyolitic to dacitic ignimbrites and lava flows (Porfidi
355 Grigi Fm. in the Sarrabus Unit, Calvino 1959); Porfiroidi Fm. in the Gerrei Unit, Calvino 1972).
356 The volcanic products differ in volume and evolutionary tendency within the different tectonic units.
357 The intrusive counterparts of these volcanic successions are the Monte Filau orthogneiss present in
358 the Bithia Unit (Pavanetto *et al.* 2012), and a swarm of sills and necks intruding the Arenarie di San
359 Vito. This volcanic succession is attributed to a calc-alkaline series (Gaggero *et al.* 2012) associated
360 with a subduction system (Carmignani *et al.* 1994; Oggiano *et al.* 2010) and recently reinterpreted
361 as the possible product of an accretionary tectonics (Cocco and Funedda 2019).
362 The age of these volcanic rocks is bracketed at the base by the Floian biota from the San Vito
363 Sandstone Fm. and at the top by Katian BH4 TH3 associations (Punta Serpeddi Fm., Loi *et al.* 1992);
364 Riu Canoni schists, Naud 1979). A series of U-Pb ages on zircon (Figs 3 and 8, see references) allows
365 us to better identify the timespan of the volcano-sedimentary succession. The upper part is bounded
366 by an age U-Pb of 452 ± 0.32 Ma (Dack 2009) which confirms the biostratigraphic assignment of the
367 overlying Serpeddi Fm. and allows to exclude an extended gap between the volcanites and the Katian
368 sedimentary succession. The so far available dating allows to extend the lower volcano-sedimentary
369 limit up to at least 465.4 ± 1.9 Ma (Oggiano *et al.* 2010), but it could be older depending on further
370 dating.

371

372 *Katian nonconformity sequence*

373 The unconformable sedimentary succession overlying the volcanics (Fig. 9) comprises an Upper
374 Ordovician-lower Carboniferous continuous sedimentary series. This succession in the External
375 Nappe begins in the middle Katian and the stratigraphic formations recognised in the Sarrabus/Gerrei
376 tectonic units (Fig. 3) are the Serpeddi and Tuviois formations in the Sarrabus Unit (Fig. 9, Barca

377 and Di Gregorio 1979; Loi *et al.* 1992) and the Genna Mesa and Rio Canoni formations in the Gerrei
378 Unit (Naud 1979; Carmignani *et al.* 2001).

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

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

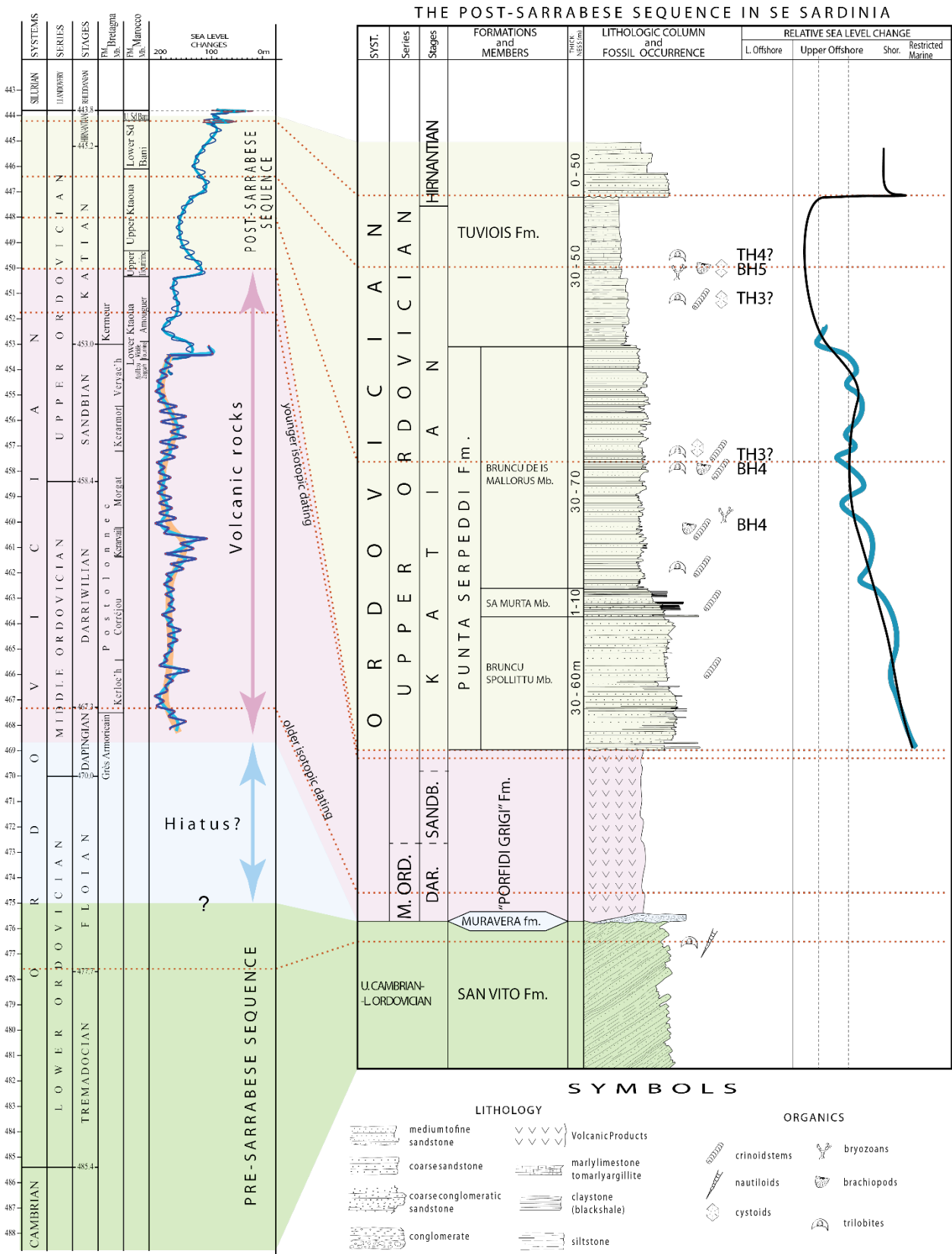
400 The trilobite and brachiopod faunas have been studied by (Leone *et al.* 1991) and Hammann and
401 Leone (1997, 2007), who identified an association of brachiopods and trilobites (TH3 and TH4 for
402 trilobites, BH4 and BH5 for brachiopods) which allows to assign the base of these deposits to the

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

407 Unfortunately, the strong deformations do not permit a secure evaluation of the facies in the transition
408 from the Ordovician to the Silurian; consequently, the possible occurrence of Upper Ordovician
409 glaciogenic deposits in central and south-eastern Sardinia still remains an open question. In the Gerrei
410 Tectonic unit the Silurian rests on the Katian succession with the classical Thuringian facies triad:
411 “Lower Graptolitic Shales”, “Ockerkalk” and “Upper Graptolitic Shales” (Corradini *et al.* 1998).

412 Local occurrences of Silurian metabasites dated 440 ± 1.7 Ma (Fig. 8) (Oggiano *et al.* 2010), overlying
413 the Katian sequence, indicates a submarine volcanic activity, represented by spilites and rare pillow
414 structures (e.g., near San Basilio and Brecca); the alkaline to subalkaline basaltic magmas of this
415 volcanic activity have been ascribed to a within plate extensional context (Di Pisa *et al.* 1992).

416



417

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

421 established in the Upper Ordovician of the Moroccan Anti Atlas (Loi *et al.* 2010) and the Middle Upper Ordovician of
422 the Armorican Massif (Dabard *et al.* 2015). After (Cocco *et al.* 2022_submitted).

423

424 **3.3) Internal Nappe Zone**

425

426 In the Internal Nappes, neither the Sardinic Unconformity nor the volcanic rocks of the Middle
427 Ordovician have ever been detected. Within the low-grade units of north-western Sardinia,
428 calcalkaline meta-rhyolites with a transitional character provided a U-Pb zircon age of 486 ± 1.2 and
429 479.9 ± 2.1 Ma (Furongian and Tremadocian) (Oggiano *et al.* 2010; Gaggero *et al.* 2012) (Table 2)
430 and can be considered to belong to the same volcanic cycle as that those contained in the Arenarie di
431 San Vito Fm. of the External Nappe (Fig.3).

432 The succession of the Upper Ordovician in the Internal Nappes is poorly defined (Fig. 3). In the
433 Gennargentu Massif (Fig. 2b), the meta-sediments attributed to the Upper Ordovician are mainly
434 quartzites (Dessau *et al.* 1982) which suggest the erosion of an older and more mature crystalline
435 craton, rather than a volcanic arc. In northwestern Sardinia, a deposit of laminated dark fine
436 metasilite hosting phosphate layers, oolitic ironstones and possible glacio-marine diamictite, has
437 been reported in the Upper Ordovician (Oggiano and Mameli 2006). Here, the transition to the
438 Silurian black shales is marked by an erosional unconformity evidenced by conglomerates. Based on
439 the observed exposure, the minimum thickness of the typical Silurian euxinic phyllite can be
440 estimated to be about 100 m. In NW Sardinia Internal Nappes, on the other hand, the Devonian
441 platform limestones (commonly cropping out in the External Nappe zone) are absent.

442

443 **4) The Sardinic and Sarrabese Phases and their unconformities**

444

445 Ordovician tectonics in Sardinia is documented by two deformational events including overturned
446 folds (Cocco *et al.* 2018, 2022_submitted; Cocco and Funedda 2019). The deformation event known

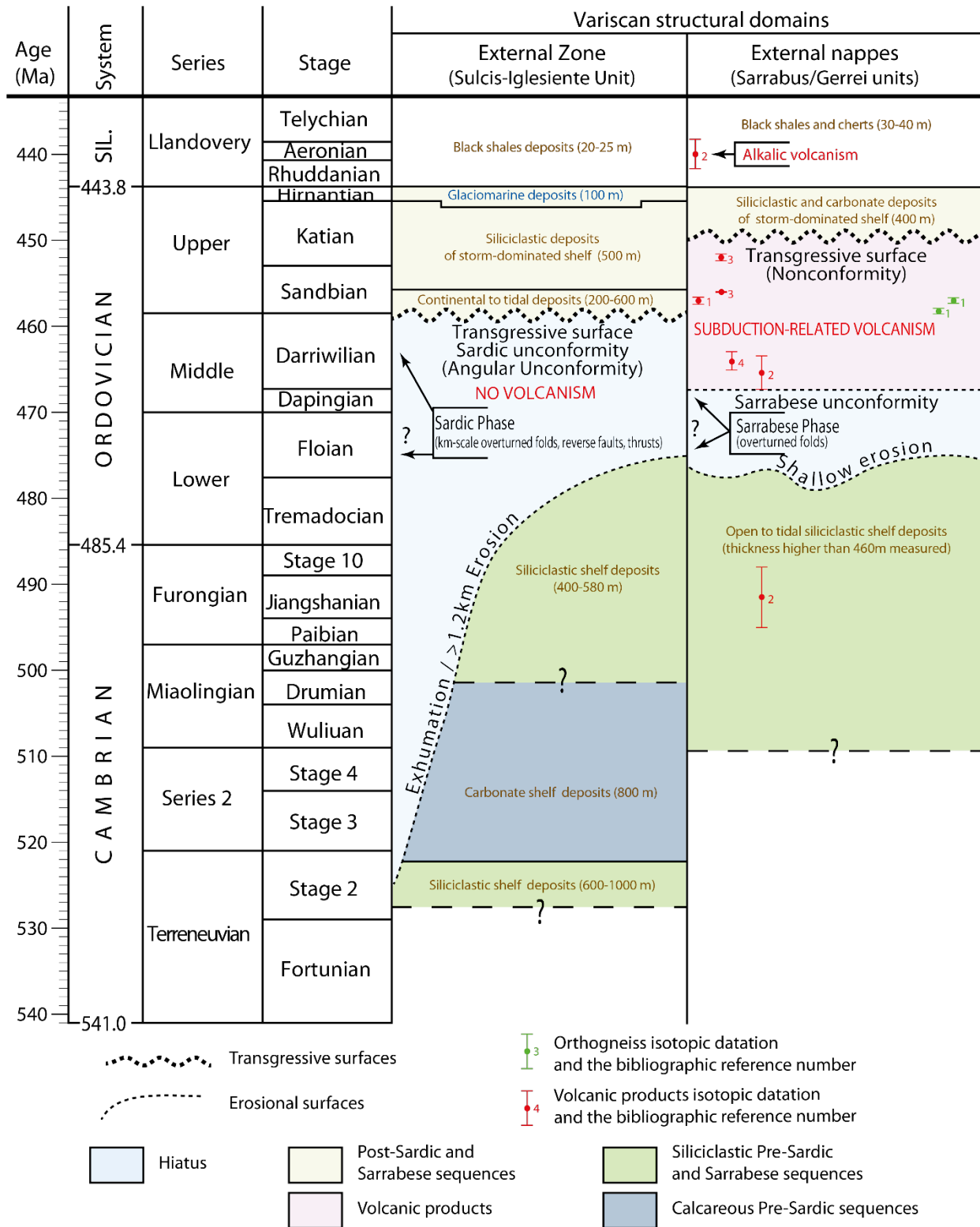
447 as the Sardinic Phase (Stille 1939) is defined on the basis of the angular unconformity first detected in
448 SW-Sardinia (Fig: 10) (Sardinic Unconformity, Teichmüller 1931). The second has been recognised in
449 SE-Sardinia and is called Sarrabese Unconformity (i.e. “Sarrabese Phase”: Calvino 1959). The
450 overlapping of Variscan deformation with Ordovician unconformities has led to confusions and
451 simplified interpretations of the timing and meaning of Ordovician unconformities. Recent work in
452 the Sulcis-Iglesiente Unit (SW-Sardinia, the External Zone of the Variscan Chain; Cocco *et al.* 2018,
453 2022_submitted; Fig.11) highlights that the Sardinic Phase occurred between early Floian and early
454 Sandbian, whereas the age of the Sarrabese Phase, recognised in the Sarrabus/Gerrei Units (SE-
455 Sardinia, the Nappe Zone of the Variscan Chain), is robustly constrained between the early Floian
456 and the Darriwilian-Dapingian boundary (Fig. 8). Although the ages and style of deformation of the
457 Sardinic and Sarrabese phases are potentially similar, there are important stratigraphic, temporal,
458 palaeontological and geodynamic differences that exclude the proximity of these domains in the
459 Ordovician age.

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

473 Zone of the Sardinian basement), allows to propose that these domains did not share the same
474 geodynamic setting, and, consequently, not even the same palaeogeographic position during the
475 Ordovician age, implying that they approached and amalgamated only during the Variscan period
476 (Cocco *et al.* 2018, 2022_submitted). The possible substantial separation is also supported by the
477 comparisons between the Katian trilobites assemblages that, even if influenced by palaeoecological
478 constraints, clearly suggest an earlier “Chinese” affinity in the Sarrabus-Gerrei units (Nappe Zone)
479 (Cocco *et al.* 2022_submitted).
480



481
482 **Fig. 10.** Sardinian Unconformity along the Masua shoreline (SW Sardinia). The basal heterometric conglomerates of the M. Argentu Fm. (base
483 Sandbian) unconformably lie on the Cabitza Fm. (middle Cambrian–lower Floian). After (Cocco *et al.* 2018).
484



485

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

491

492 **5) Conclusion**

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

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

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

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

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

520

521

522

523

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