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The Silurian/Lower Devonian sequence at Perda S'altari (SW Sardinia, Italy)

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ABSTRACT - In the Perda S'altari area, north of Fluminimaggiore, black shales of the Silurian Genna Muxerru Formation and limestones of the Devonian Mason Porcus Formation are exposed. The area is strongly tectonized, and poorly preserved fossils occur only in a few outcrops. Graptolites of Telychian and Rhuddanian age have been collected from the shales, whereas conodonts indicate the Lochkovian Icr. postwoschmidti *and* Ad. transitans *zones. The problematic* Eurytholia bohemica *species is here documented from Devonian rocks for the first time outside the Czech Republic. A gradual transition between the Genna Muxerru Fm. and the Mason Porcus Fm. suggests an update to the lithostratigraphical scheme of the Silurian and Lower Devonian of SW Sardinia.*

INTRODUCTION

Silurian and Lower Devonian rocks of SW Sardinia have been investigated for a considerable time owing to their rich and well-preserved fossil content (e.g., La Marmora, 1857; Meneghini, 1857, 1880; Taricco, 1922; Teichmuller, 1931). Modern stratigraphical works started from the sixties of the nineteenth Century mainly by the Palaeozoic group of Modena University led by Enrico Serpagli. As part of a comprehensive investigation of the lower Palaeozoic limestones of Sardinia, several fossil groups were studied, such as conodonts (e.g., Serpagli, 1967, 1971; Serpagli & Mastandrea, 1980; Gnoli et al., 1981a; Mastandrea, 1985a, b; Olivieri & Serpagli, 1990), orthoceratid cephalopods (e.g., Serpagli & Gnoli, 1977; Gnoli, 1990) and bivalves (Kříž & Serpagli, 1983), among others. These studies, combined with preliminary data on graptolites from black shales (e.g., Palmer & Gnoli, 1985) and investigation on microfacies (Ferretti, 1989), allowed Gnoli et al. (1990) to propose a lithostratigraphical scheme for the area. They defined three formations in the Silurian and Lower Devonian of SW Sardinia: the Genna Muxerru Fm., the Fluminimaggiore Fm. and the Mason Porcus Fm. Subsequent studies on graptolites (Štorch & Serpagli, 1993; Rickards et al., 1995; Štorch et al., 2002) and conodonts (Corradini et al., 1998b, c; Ferretti et al., 1998b) contributed to a more precise chronostratigraphical assignment of the formations (e.g., Ferretti et al., 1998a; Corradini et al., 2009a).

Most of these papers were devoted to the area around Fluminimaggiore and Gonnosfanadiga, and, in minor part, near Iglesias and Domusnovas, whereas other sectors of the island were almost ignored. In this paper we present results on the area of Perda S'altari, located between the small towns of Fluminimaggiore and Arbus (Fig. 1), where a tectonized sequence of black shales and limestones belonging to the Genna Muxerru and Mason Porcus formations, respectively, are exposed.

Previous studies on Perda S'altari area

Excluding a few papers related to the nearby Acqua Bona mine (e.g., Stara et al., 1996), the area of Perda S'altari has been mostly ignored in recent geological and palaeontological research in SW Sardinia, probably due to the scarce fossil content and the strong metamorphism of the rocks exposed here, compared to the nearby areas of Genna Muxerru and Fluminimaggiore which have been subject of tens of papers. The Perda S'altari area was mentioned by Taricco (1922), who introduced there the term "Postgotlandiano" to indicate "a rather monotonous clastic succession consisting of alternating sandstone, siltite and anchimetamorphic argillite with scattered phylogenetic conglomerate" (Barca et al., 1981, p. 379) disconformably lying upon the shales and limestones of Gotlandian age. That sequence was later attributed to the Lower Ordovician thanks to the recovery of acritarchs and the "Postgotlandiano" was renamed as the "Arburese Tectonic Unit" (Barca et al., 1981).

The only study mentioning fossils from the Perda S'altari area is the short report on tentaculites by Gessa (1993), who reported the occurrence of *Nowakia* cf. *acuaria* (Richter, 1854), *Nowakia* sp. and *Viriatellina* sp. in marly limestones of the area, but did not provide a precise location of the studied outcrops. The Author reported difficulties for a confident specific determination owing to the poor preservation of the fauna, but nevertheless hypothesized a Pragian age for these rocks.

GEOLOGICAL SETTINGS

The Sardinian basement is part of the south-European Variscan chain (Carmignani & Pertusati, 1979) in which metamorphic rocks of Cambrian to early Carboniferous age are exposed. The Variscan orogeny affected the whole basement producing various degrees of deformation and a tectono-metamorphic zonation from the amphibolitic

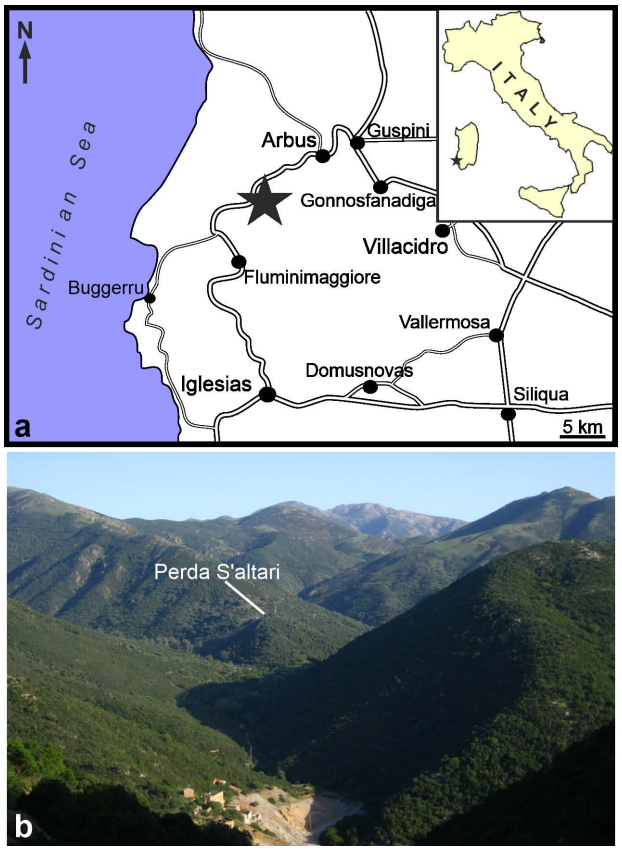


Fig. 1 - (color online) a) Location map of the studied area. b) Panoramic view to the east of the Perda S'altari area. The abandoned Acqua Bona mine in the front.

facies in NE Sardinia to very low grade in the SW, representing the foreland area of the chain (Funedda & Oggiano, 2009, and references therein). During the middle Palaeozoic Sardinia was a terrane within the assemblage of the northern Gondwana margin known as the Galatian Terranes (von Raumer & Stampli, 2008) or the Armorican Terrane Assemblage (Torsvik & Cocks, 2013). The palaeogeographical position of these terranes, which include Bohemia, the Carnic Alps, the Maures mountains, the Montagne Noire and part of Spain, among others, is still debated. For a review and discussion of the palaeogeographical position of Sardinia refer to Ferretti et al. (2009b). Different sequences are exposed in the southwestern and in the southeastern part of the island. These resemble the coeval sequences of Bohemia and Thuringia, respectively (Ferretti et al., 1998a; Corradini et al., 1998a, 2009a; Corradini & Ferretti, 2009).

Silurian and lowermost Devonian rocks of SW Sardinia are among the most studied sediments of the whole Palaeozoic sequence of the island. However, despite the richness and the good preservation of the fossil material, outcrops are in general quite disappointing, since only a few meters of rocks, normally strongly tectonized, or a group of scattered blocks are exposed here and there, without any undisturbed sections (Barca et al., 1992; Corriga & Corradini, 2008; Corradini et al., 2009a; Ferretti et al., 2009c). Instead, good Silurian sections, but with a scarce fossil content, are exposed in SE Sardinia (e.g., Barca et al., 1995; Corradini et al., 1998d, 2009c, d; Serpagli et al., 1998). Three formations that follow each other in succession were described by Gnoli et al. (1990) in the Silurian and Lower Devonian of SW Sardinia (Fig. 2): the Genna Muxerru Formation (Rhuddanian-Telychian), the Fluminimaggiore Formation (Sheinwoodian-lower Lochkovian) and the Mason Porcus Formation (Lochkovian-Emsian). However, as already pointed out by the Authors, "the poor exposures and the complex tectonics of the region make a satisfactory definition of the formations very difficult" (Gnoli et al., 1990, p. 11). Abundant graptolites and conodonts provided a precise age definition of the outcrops, but it results that, even if a complete succession was proposed, several time intervals are still not documented.

The Genna Muxerru Fm., the thickness of which is estimated to be about 20-25 metres, consists of graptolitic, silica-argillaceous and siltitic shales, interbedded by lydites and rare cherts in the lower part (Gnoli et al., 1990). Faulting, cleavage and small-scale folding characterize the whole unit. Graptolites are the only fossils documented (Štorch & Serpagli, 1993; Rickards et al., 1995; Floris, 2009, 2014; Štorch & Piras, 2009c), allowing to discriminate several Llandovery biozones from the *A. ascensus* to the *M. griestonensis* Zone (Štorch & Piras, 2009a). Recently an unusual association of trace fossils from black shales has been described by Baucon et al. (2020) from the Genna Muxerru area.

The boundary between the Genna Muxerru Fm. and the overlying Fluminimaggiore Fm. is never exposed (Gnoli et al., 1990; Corradini et al., 2009a). The latter unit roughly corresponds to the "calcari a *Orthoceras*, *Cardiola*, *Monograptus*, etc." of the early Authors and it is mainly constituted by black calcareous lenses and layers alternating with dark non calcareous pelites and shales (Gnoli et al., 1990). Carbonate deposition is characterized by dominantly fossiliferous wackestone-packstones, that grade into fossiliferous mudstones (Ferretti et al., 2009c). The black colour and the peculiar bituminous smell reveal a high content of organic matter. The thickness of the Fluminimaggiore Fm. is roughly estimated to be 40-50 m, but most of the outcrops are represented by loose blocks of various ages that are randomly exposed (e.g., Serpagli, 1971; Corradini et al., 1998c; Ferretti et al., 1998b, 2009a). Despite the poor exposures, the Fluminimaggiore Fm. is one of the most investigated units of Sardinia due to its spectacular fossil content, most of which is preserved in full three dimensions in the limestone blocks (Gnoli et al., 1980). The fauna is dominated by cephalopods (Gnoli & Serventi, 2009 and references therein) and bivalves (Kříž, 2009 and references therein), associated with pelagic ostracods (Gnoli et al., 2009 and references therein), graptolites (Štorch & Piras, 2009a and references therein), conodonts (Corriga et al., 2009 and references therein) and chitinozoans (Pittau & Del Rio, 2009 and references therein). Gastropods, eurypterid fragments and the problematic *Kolihaia* are rare (Corradini et al., 2009b and references therein). Lobolites of the pelagic scyphocrinitid crinoids occur in the upper part of the unit around the Silurian/Devonian boundary (Gnoli et al., 1988, 1990; Corradini et al., 2009b). Graptolites are frequently found packed together in peculiar pseudo-lenticular limestone bodies preserving three-dimensional specimens. Five graptolite biozones and co-occurring conodonts

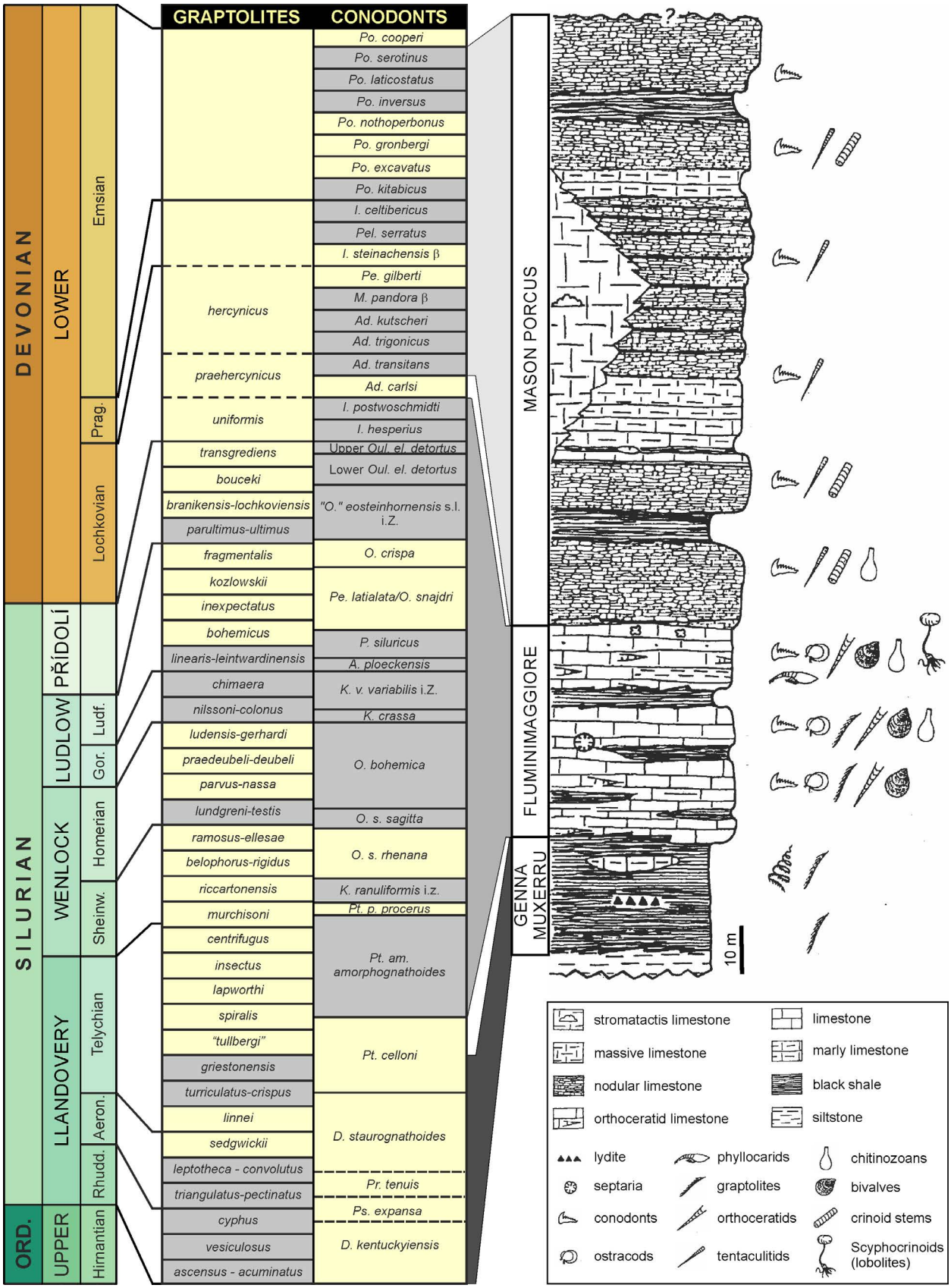


Fig. 2 - (color online) Stratigraphical log of the Silurian and Devonian sequence in SW Sardinia (after Ferretti et al., 1998a, modified). From left to right: Chronostratigraphy (System, Series, Stage), graptolite and conodont zonations (in grey those documented), schematic log with occurrence of main fossil groups. Graptolite zonation after Štorch & Piras (2009a) for Sardinia; conodont zonation for Llandovery and Wenlock after Corradini & Serpagli (1999), Ludlow and Přídolí after Corradini et al. (2015), Přídolí and Lochkovian after Corradini & Corriga (2012) updated in the Lochkovian by Corriga et al. (2016) and Schönlaub et al. (2017), Pragian after Slavík (2004), Emsian after Becker et al. (2020, modified).

document the lower Homerian to lower Přídolí (Ferretti & Serpagli, 1996; Piras & Corradini, 2007), allowing a precise correlation between the two zonation schemes (Corradini & Serpagli, 1998, 1999). A biostratigraphical assignment of the Fluminimaggiore Fm. was established on the basis of the conodont fauna, that documents twelve conodont zones from the *Pt. amorphognathoides* Zone to the *I. postwoschmidti* Zone (Gnoli et al., 1990; Corradini & Serpagli, 1999; Corriga et al., 2009). Some intervals have not been found yet (Fig. 2), and, according to Gnoli et al. (1980), may correspond to black shale deposition. However, there is no evidence for this hypothesis.

The overlying Mason Porcus Fm. consists mainly of nodular and massive limestones alternating with compact dark siltstones and shales (Gnoli et al., 1990). Stromatactis bearing carbonate mounds, forming lenticular bodies of massive limestone have been documented in the Mt. Padenteddu area (Gnoli et al., 1981b). The fauna is dominated by cephalopods, conodonts, tentaculitids and ostracods. Crinoids, trilobites, phyllocarids and corals are also present, whereas foraminifera and sponge spiculae are rare (Gnoli et al., 1990). In the mud mound facies, tabulate and colonial rugose corals are abundant, and stromatactis structures occur (Gnoli et al., 1981b). Conodonts establish a detailed biostratigraphy as several, although not all, biozones from the *Ad. transitans* to the *Po. serotinus* have been documented (e.g., Mastandrea, 1985a, b; Gnoli et al., 1990; Olivieri & Serpagli, 1990; Corradini et al., 1998b; Corriga, 2011). The upper boundary of the Mason Porcus Fm. is never exposed, being often covered by the overthrusting Arburese Tectonic Unit.

THE SILURIAN AND DEVONIAN OF PERDA S'ALTARI AREA

Rocks from Cambrian?-Early Ordovician to Early Devonian age are exposed in the Perda S'altari area. Most of the study area exposes the Genna Muxerru Fm., whereas the limestones of the Mason Porcus Fm. crop out only in a few localities, mainly at Perda S'altari and Palaloala hills where they constitute prominent cliffs (Fig. 3). The Fluminimaggiore Fm. is absent. In the southern part of the area the Girisi Member of the Rio San Marco Fm. (Hirnantian) is exposed. All these units are overthrusted by the Cambrian-Lower Ordovician rocks belonging to the allochthonous sequence of the external Nappe Zone: the "Arburese Tectonic Unit", which is equivalent to the

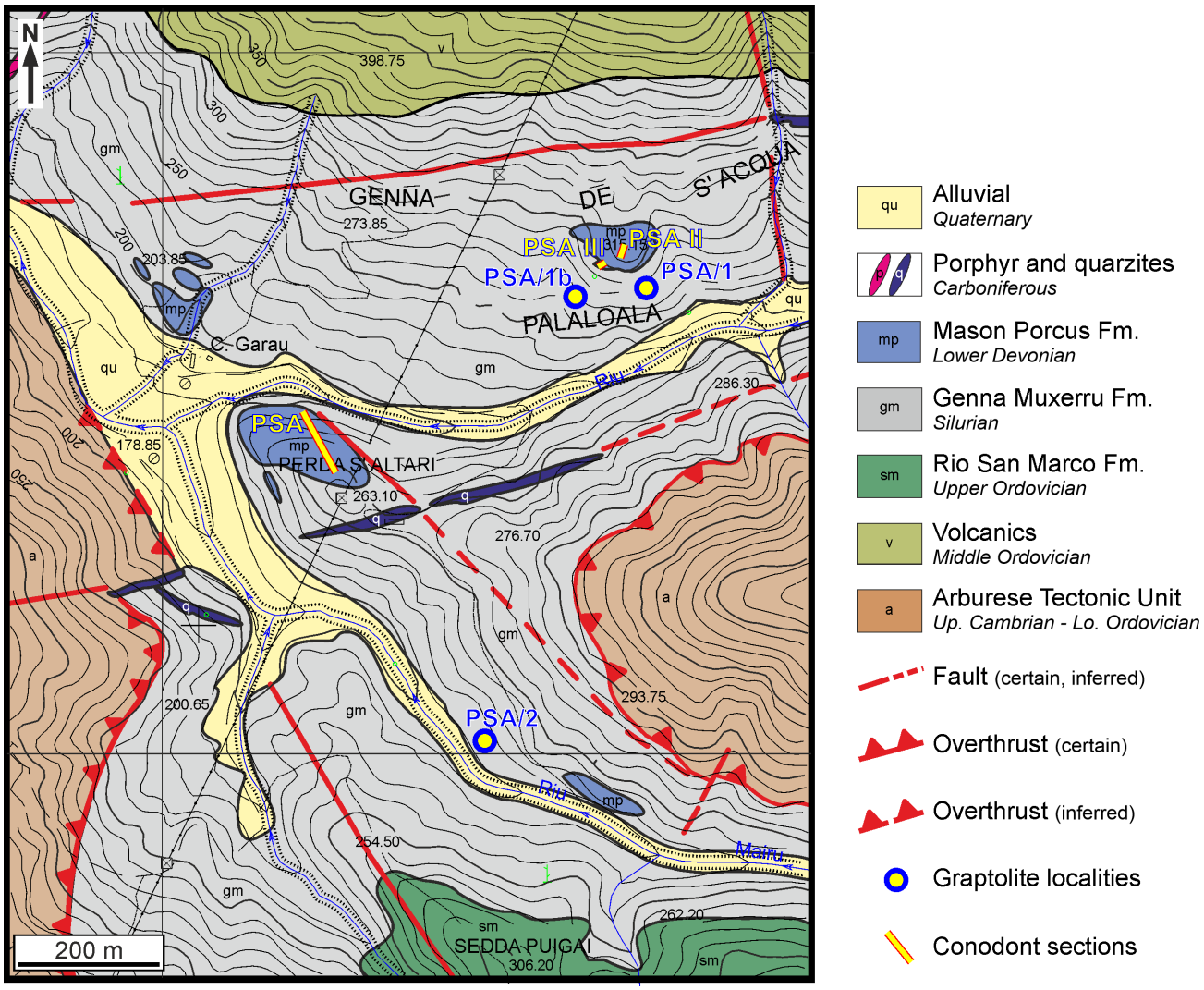


Fig. 3 - (color online) Simplified geological map of the Perda S'altari area.

Fig. 4 - (color online) a) Outcrop of the Genna Muxerru Fm. at the PSA/2 locality. b) The gradual transition between the Genna Muxerru and the Mason Porcus formations in the Palaloala area. c) Typical nodular limestone of the Mason Porcus Fm. in the upper part of the Perda S'altari section. d) The flat area at Palaloala with sub-horizontal bedding where the section PSA II is measured.

San Vito Fm. of SE Sardinia, and crops out in the eastern and western sectors of the study area. In the northern part Middle Ordovician volcanites are widely exposed. At places, veins of porphyry and quartzite connected with the Variscan orogeny occur.

In the study area the Genna Muxerru Fm. is represented by dark grey to black alum slates. Lydites have not been observed. The strong tectonics related to the overthrust of the Arburese Tectonic Unit affected the unit with faulting, fracturing and cleavage and only in a very few outcrops the original lamination is preserved. The upper part of the unit looks to be more clayish and grades into the overlying Mason Porcus Fm., as the Fluminimaggiore Fm. is absent in the Perda S'altari area. In the Riu Mairu area, a thin level of grey marls is exposed between the argillites of the Genna Muxerru Fm. and the limestones of the Mason Porcus Fm., in apparent continuity with the two units. There, crinoid stems, tentaculites and poorly preserved trilobites (*Cheirurus* sp. and *Phacops* sp.) date the outcrop as Early Devonian in age.

In the Palaloala area a gradual transition between the Genna Muxerru Fm. and the Mason Porcus Fm. is exposed (Fig. 4b). The transition occurs through 1.5 m and starts with a level of calcareous nodules in the upper part of the shaley sequence, followed by about 50 cm of dark brown pelites and about 30 cm of interbedded pelites and thin irregular limestone beds; then a 35 cm bed of light grey limestone is present, overlain by about 20 cm of thin alternations of pelite and limestone. Above, about 3 m of light grey nodular limestones are exposed, but thin shaly levels are still present in the basal 30 cm. Unfortunately, no graptolites were found in the shales in this locality, and the limestones were barren of fossils, too. The Mason Porcus Fm. comprises well bedded light grey mudstone. The unit is well exposed in the north-west cliff of Perda S'altari hill and at Palaloala, beside a few other small outcrops. At Palaloala about 2 metres of dark micritic limestone occur in the lower part of the unit, between the light grey nodular beds described above and the typical nodular facies above. The maximum thickness is about 22 m, measured at Perda S'altari (PSA) section. Despite the well exposed rocks, microfacies analysis demonstrated the strong tectonic effects on facies in the outcrops, more marked in the lower part of the PSA section (Fig. 5a). The palaeontological content is scarce and fossils, where present, are often broken or tectonically deformed (see below for details).

FOSSIL CONTENT AND BIOSTRATIGRAPHY

Graptolites and conodonts are the main fossils collected in the study area. Graptolites indicate a Silurian age for the black shales, whereas conodonts allow to date the limestones to the Early Devonian. The biozonation scheme

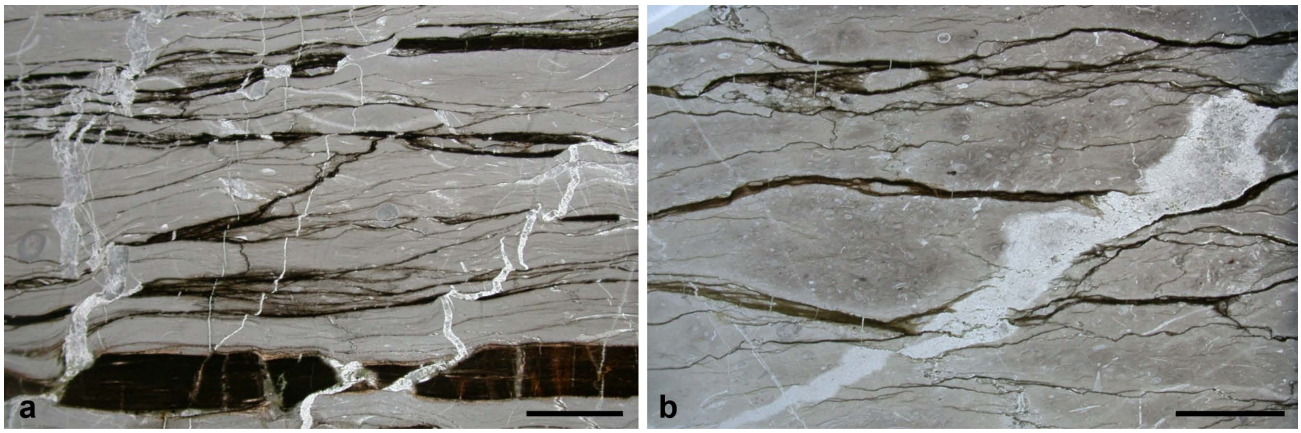


Fig. 5 - (color online) a) Strongly tectonized micritic mudstone from the lower part of the PSA section (sample PSA 2). b) Bioclastic mudstone rich of tentaculitids (sample PSA 10). Scale bars = 4 mm.

followed in this paper for graptolites is that proposed by Štorch & Piras (2009a) based on Sardinia; for conodonts the scheme by Corradini & Corriga (2012), updated by Corriga et al. (2016) is adopted for the Lochkovian.

Graptolites are deposited in the Palaeontological Museum "Domenico Lovisato" of Cagliari University; conodonts are stored in the collections of the Department of Mathematic and Geosciences of Trieste University. Catalogue numbers of illustrated specimens are indicated in the plate captions.

Genna Muxerru Formation

Graptolites (Pl. 1) are the only fossils observed in the black shales of the Genna Muxerru Fm. They are in general abundant, but the poor state of preservation and the tectonic deformations often prevent taxonomic attribution. Only three localities yielded determinable graptolites (Fig. 3): two (PSA/1 and PSA/1b) are located at Palaloala, in the northern part of the study area, and one (PSA/2) close to Riu Mairu in the southern part.

Locality PSA/1 - The locality PSA/1 is located in the southern slope of Palaloala at coordinates 39°28'26.5" N, 8°31'7.3" E, and is represented by an alternation of dark grey argillite and black shales. Graptolites, although often slightly deformed, are in general well preserved. The association is not abundant but well diversified, and includes:

Campograptus sp.
Paradiversograptus capillaris (Carruthers, 1867)
Paradiversograptus runcinatus (Lapworth, 1876)
Parapetalolithus cf. *elongatus* (Bouček & Přibyl, 1941)
Pristiograptus pristinus Přibyl, 1940
Pristiograptus cf. *renaudi* Philippot, 1950
Oktavites contortus (Perner, 1897)
Rastrites schaueri Štorch & Loydell, 1992
Spirograptus cf. *guerichi* Loydell, Štorch & Melchin, 1993
Stimulograptus cf. *halli* (Barrande, 1850)
Streptograptus sp.
Torquigraptus obtusus (Schauer, 1971)

Although the zonal index species is absent, the association can be attributed to the lower Telychian *R. linnaei* Zone based on of the joint occurrence of *Spirograptus* cf. *guerichi*, *Pristiograptus pristinus*, *Pristiograptus* cf. *renaudi* and *Paradiversograptus capillaris.* In fact, the latter species became extinct at the top of the *R. linnaei* Zone, whereas the other three taxa have theirs first appearance within the Zone. It should be pointed out that this is the first documentation of the *R. linnaei* Zone in SW Sardinia.

Locality PSA/1b - The locality PSA/1b is located in the southern slope of Palaloala, about 50 m west of PSA/1, at coordinates 39°28'26.4" N, 8°31'5.1" E. It is a small outcrop of alum slates, a few decimetres thick. Graptolites are poorly preserved and strongly tectonized and only a few specimens are determinable. The association includes:

EXPLANATION OF PLATE 1
(color online)

Selected graptolites from the Genna Muxerru Fm. in the Perda S'altari area. Scale bar = 1 mm.

Fig. 1 - *Spirograptus* cf. *guerichi* Loydell, Štorch & Melchin, 1993, specimen TM/PSA/2/2, locality PSA 2.

Fig. 2 - *Stimulograptus* cf. *halli* (Barrande, 1850), specimen TM/PSA/1/7, locality PSA 1.

Fig. 3 - *Torquigraptus obtusus* (Schauer, 1971), specimen TM/PSA/2/1, locality PSA 2.

Fig. 4 - *Streptograptus* sp., specimen TM/PSA/1/2a (a) and *Paradiversograptus* cf. *capillaris* (Carruthers, 1867), specimen TM/PSA/1/2b (b), locality PSA 1.

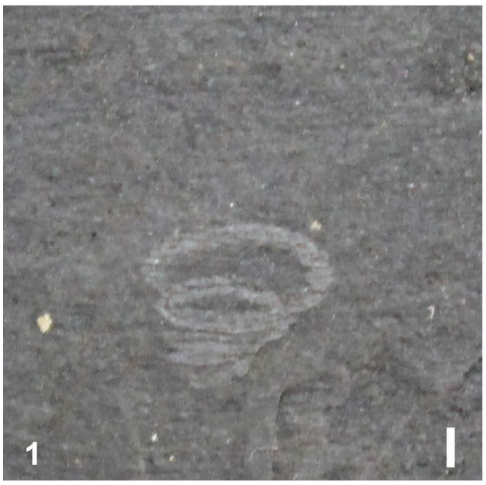
Fig. 5 - *Parapetalolithus* cf. *elongatus* (Bouček & Přibyl, 1941), specimen TM/PSA/1/9, locality PSA 1.

Fig. 6 - *Rastrites schaueri* Štorch & Loydell, 1992, specimen TM/PSA/1/2b, locality PSA 1.

Fig. 7 - *Rhapidograptus toernquisti* (Elles & Wood, 1906), specimen TM/PSA/1b/14, locality PSA 1b.

Fig. 8 - *Oktavites contortus* (Perner, 1897), specimen TM/PSA/1/30, locality PSA 1.

Fig. 9 - *Paradiversograptus runcinatus* (Lapworth, 1876), specimen TM/PSA/1/4a, locality PSA 1.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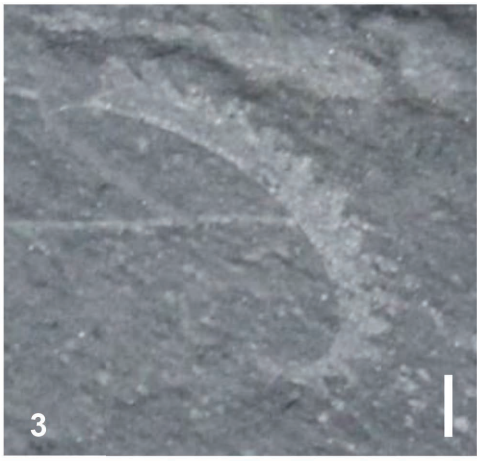
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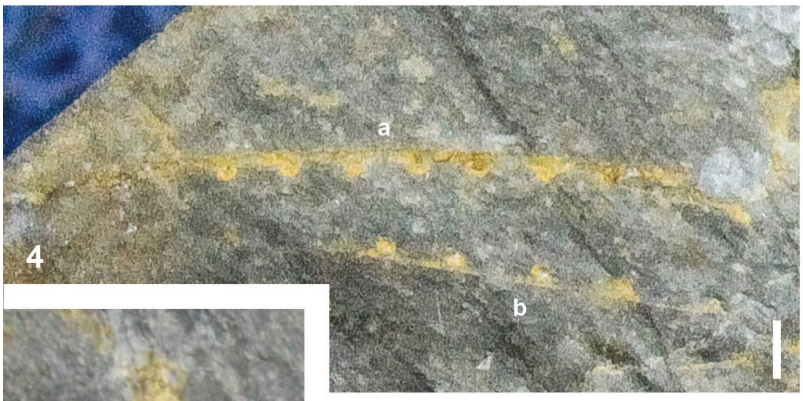

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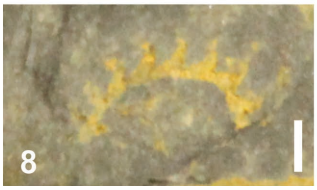
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Coronograptus sp.
Dimorphograptus sp.
Rhaphidograptus cf. *toernquisti* (Elles & Wood, 1906)

The locality is attributed to a Rhuddanian interval within the *Cy. vesiculosus* and *Co. cyphus* zones.

Locality PSA/2 - The locality PSA/2 is located along Rio Mairu, SE of Perda S'altari hill, at coordinates 39°28'7.0" N, 8°31'54.5" E. About 5 m of tectonized alum slates crop out, and the scarce fauna is often longitudinally elongated. The association includes:

"*Monograptus*" sp.
Spirograptus cf. *guerichi* Loydell, Štorch & Melchin, 1993
Torquigraptus obtusus (Schauer, 1971)

and is attributed to the lower Telychian *R. linnaei* Zone based to the joint occurence of *Spirograptus* cf. *guerichi* and *Torquigraptus planus*.

Mason Porcus Formation

A few orthoconic cephalopods and crinoid stems in the Palaloala area are the sole macrofossils observed in the field. Dacryconarids (*Nowakia*? sp., *Paranowakia*? sp.) and *Stilolina* sp. are common in thin sections, whereas crinoids are present at places. Twenty limestone samples were processed and about 50 kg of limestone were dissolved with conventional formic acid technique for conodont extraction. Most of the samples were barren, and the fauna is in general scarce and poorly preserved, being broken or tectonically deformed. Conodont colour is black, corresponding to a Color Alteration Index 5. Details of the fauna are provided below in the description of the sections measured. Beside conodonts, rare brachiopods, a fragment of a scolecodont gnathal lobe and a sclerite of the problematic *Eurytholia bohemica* Ferretti, Serpagli & Štorch, 2006 were obtained from the acid leaching residues.

Three sections were measured in the Mason Porcus Fm. (Fig. 6): one in the Perda S'altari cliff (PSA section), and two at Palaloala (PSA II and PSA III sections).

Perda S'altari section (PSA) - The Perda S'altari (PSA) section was measured in the northern cliff of the Perda S'altari hill, at coordinates 39°28'18.1" N, 8°30'47.8" E. It exposes about 22 m of the typical nodular limestones of the Mason Porcus Fm. (Figs 4c, 6a). At the base of the section about 1 m of black shales are exposed. The thickness of calcareous beds varies between 20 cm and 1.1 m, and, in general, they are thicker in the lower part of the section. In the uppermost part of the section thin pelitic levels are interbedded within the limestones. No fossils were observed in the field. Dacryoconarids are abundant in thin sections from the upper part of the section.

The twelve conodont samples collected were almost all barren, as only a fragment of a P2 element of ozarkodinid in sample PSA 3 and one specimen of *Pseudooneotodus beckmanni* (Bischoff & Sannemann, 1958) in sample PSA 10 were found (Fig. 6c). Beside conodonts, the only other fossil remain collected is a scolecodont gnathal lobe in sample PSA 10. The absence of fauna may be related to the nearby quarzitic vein exposed slightly to the south, beside the overthrust of the Arburese units.

Perda S'altari II section (PSA II) - The Perda S'altari II (PSA II) section was measured in the flat area at Palaloala (Figs 4d, 6b), at coordinates 39°28'28.2" N, 8°31'05.3" E. The section starts with about 50 cm of dark micritic limestone beds and continues, after a short covered interval with 1.6 m of light grey nodular limestone. A few orthoceratid cephalopods and crinoid stems are present in the upper part of the section. Microfacies analysis revealed the presence of dacryoconarids, crinoids and rare cephalopods and trilobites. A sclerite of *Eurytholia bohemica* and a few microbrachiopods were collected from the conodont residue.

Four conodont samples yielded a poorly preserved lower/middle Lochkovian fauna. No stratigraphically diagnostic taxa have been collected from the lower part of the section, but the presence of *Oulodus aclys* Mawson, 1986 in sample PSA II 2 suggests that that level is not older than the *Icr. postwoschmidti* Zone. Also, based on the data from the underlying PSA III section (see below) the lower part of the section can likely be assigned to the same zone. The upper part of the section can be assigned to the *Ad. transitans* Zone thanks to the occurrence of the index taxon *Ancyrodelloides transitans* (Bischoff & Sannemann, 1958) in sample PSA II 1 (Fig. 6b).

Perda S'altari III section (PSA III) - The Perda S'altari III (PSA III) section is located on the SW slope of Palaloala at coordinates 39°28'28.2"N, 8°31'05.3"E. The section was measured in the first undisturbed calcareous beds just above the transition with the shales of the Genna Muxerru Fm. and the Mason Porcus Fm. About 50 cm of nodular limestones, followed by 1.8 m of dark micritic limestones, organized in beds 15-30 cm thick, are exposed (Fig. 6c). The top of the PSA III section is more or less equivalent to the base of the PSA II, but a precise correlation is not possible in the field. No macrofossils were observed in the field, whereas tentaculites, small shells (ostracods), fragments of bivalves and very rare trilobites are present in thin sections.

Three samples were collected for conodonts and yielded a scarce but diverse fauna (Fig. 6c). *Zieglerodina eladioi* (Valenzuela-Ríos, 1994) is the sole species collected in sample PSA III 1, indicating a general lower-middle Lochkovian age for the base of the section. The occurrence of *Lanea omoalpha* Murphy & Valenzuela-Ríos, 1999 and *Pandorinellina optima* (Moskalenko, 1966) in sample PSA III 2 allows assignment of that level to the *Icr. postwoschmidti* Zone. The upper part of the section likely belongs to the same Zone.

DISCUSSION

The absence of the Fluminimaggiore Fm. and the gradual transition between the Genna Muxerru Fm. and the Mason Porcus Fm. suggest a variation from the previous stratigraphical scheme of the Silurian and Devonian of the SW Sardinia, extending the Genna Muxerru Fm. to the entire Silurian and lowermost Devonian (Fig. 7). However, stratigraphical data only partly support such hypothesis, as no graptolites younger than the early Telychian have been collected in the area. It should be pointed out that in the whole area only one outcrop yielded a relatively well-

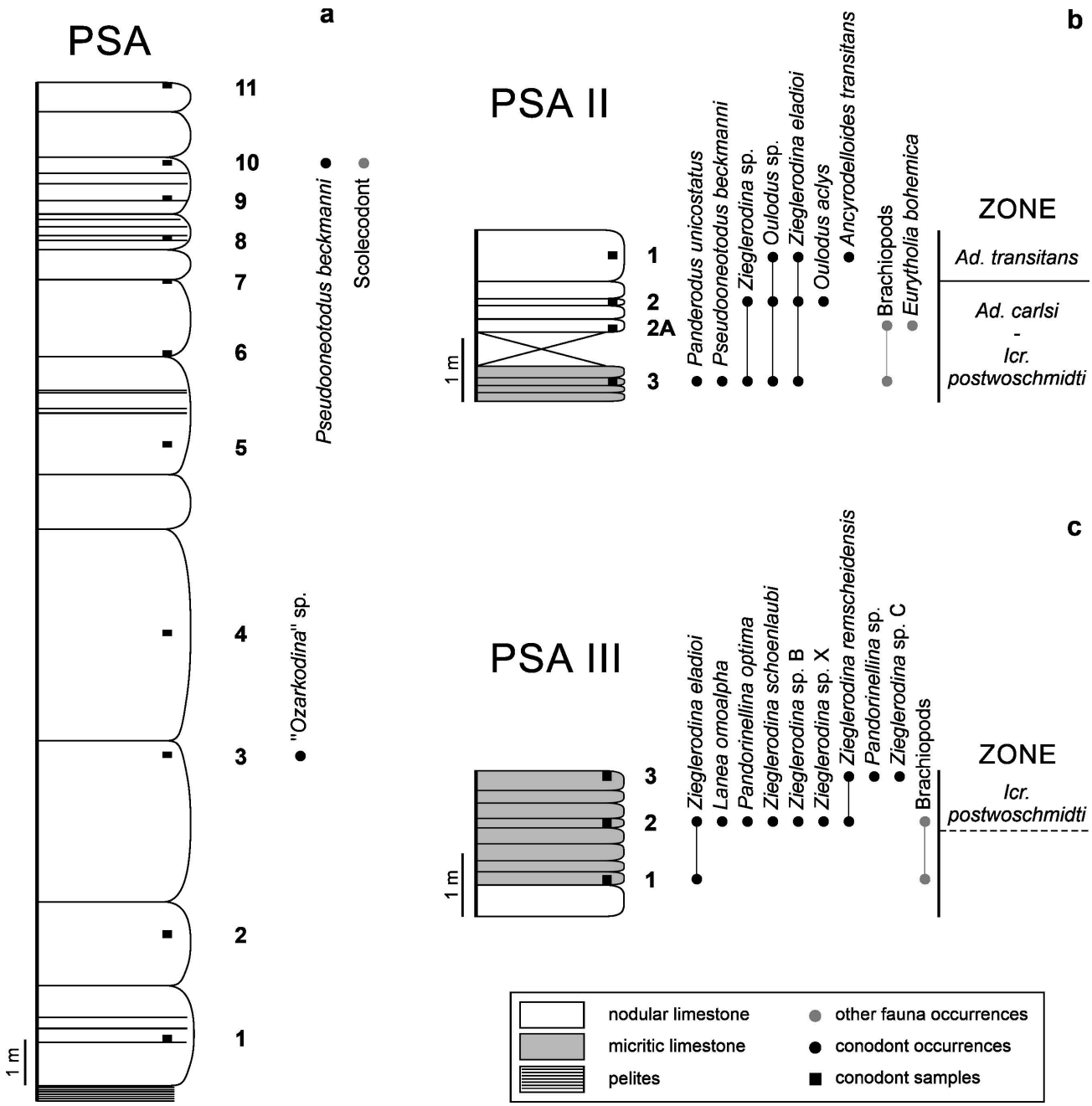


Fig. 6 - Log, conodont and other fauna occurrences, and biostratigraphy of the sections measured in the Mason Porcus Fm. in the Perda S'altari area. a) Perda S'altari section. b) Perda S'altari II section. c) Perda S'altari III section.

preserved fauna, and other two just a few poorly preserved graptolites. In the rest of the area no graptolites were found, due to the strong tectonics connected with the overthrust of the Arburese Tectonic Unit, which obliterated the original stratigraphic features of the shales and its fossil content.

The lack of biostratigraphical evidence of a late Silurian age of the black shales may challenge our hypothesis, as the absence of evidence is not an evidence of absence. If we consider the stratigraphical scheme by Gnoli et al. (1990), the dark "*Orthoceras* limestones" of the Fluminimaggiore Fm. should occur between the black shales of the Genna Muxerru Fm. and the nodular limestone of the Mason Porcus Fm., but there is no evidence of that unit in the area. Also, the gradual transition between black shales and limestone is difficult to explain, if not extending the stratigraphical range of the Genna Muxerru Fm.

The limestones just above the transition are represented by 50 cm of nodular limestone, followed by about 2 m of dark massive micritic mudstone organized in beds 10-15 cm thick. The first limestone bed above the transition with the black shales did not yield any conodonts, but the dark micritic limestones just above (PSA III section and base of the PSA II section) yielded a fauna of the *Icr. postwoschmidti* Zone. These are the oldest rocks attributed to the Mason Porcus Fm., but according to Gnoli et al. (1990) limestones of that age were documented only from the Fluminimaggiore Fm. However, it should be noted that in the Mason Porcus section, the type section of the

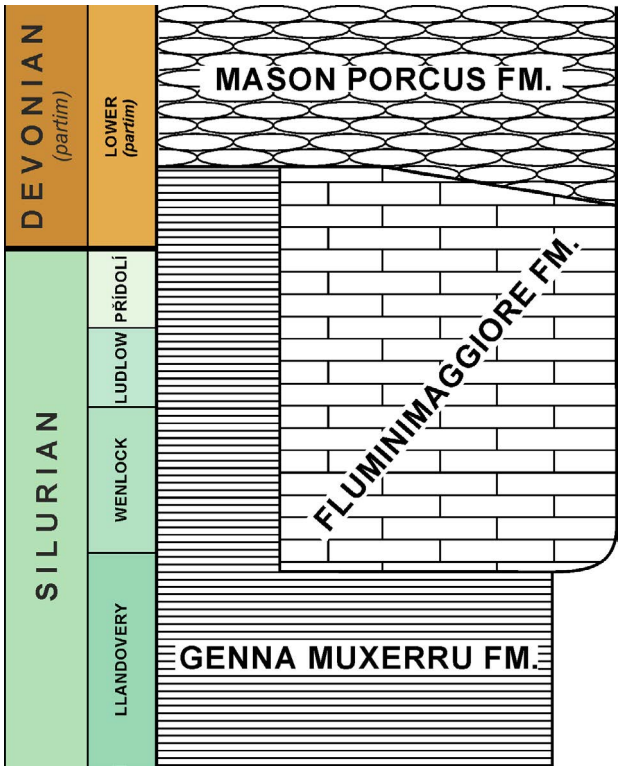


Fig. 7 - (color online) Sketched stratigraphic scheme of the Silurian and lowermost Devonian of SW Sardinia, updated on the basis of the data from Perda S'altari. For discussion and details see the text.

Mason Porcus Fm., 30 cm of dark limestone just below the first nodular limestone were attributed by Gnoli et al. (1990) to the Fluminimaggiore Fm., and dated to the *Icr. postwoschmidti* Zone. At the Mason Porcus section nodular limestones are missing below those dark limestone (Gnoli et al., 1988), whereas they occur in the Perda S'altari area. As the lower boundary of the Mason Porcus Fm. is defined by the first bed of nodular limestone, according to the definition of the formation it is more appropriate to attribute this interval in the study area to the Mason Porcus Fm.

Therefore, a heteropic relation between the Fluminimaggiore and the Genna Muxerru formations is proposed for most of the Silurian and the basal Lochkovian, and between the Fluminimaggiore and the Mason Porcus formations during the lower Lochkovian *Icr. postwoschmidti* Zone (Fig. 7). It should be noted that the *Ad. carlsi* Zone has not been documented in Sardinia to date.

SYSTEMATIC PALAEONTOLOGY

Systematic notes are limited to phosphatic taxa newly documented in Sardinia and necessary taxonomic remarks. For the suprageneric classification of conodonts the scheme proposed by Sweet (1988) is followed.

Class Conodonta Pander, 1856
Order Ozarkodinida Dzik, 1976
Family Prioniodinidae Bassler, 1925

Genus *Oulodus* Branson & Mehl, 1933
Type species *Cordylodus serratus* Stauffer, 1930

Oulodus aclys Mawson, 1986
(Pl. 2, fig. 12)

1986 *Oulodus aclys* Mawson, p. 47, Pl. 2, figs 1-16.
1999 *Oulodus aclys* Mawson - Talent & Mawson, p. 87, Pl. 7, figs 19-20.
2003 *Oulodus aclys* Mawson - Farrell, p. 126, Pl. 3, figs 3-6 (cum syn.).
2007 *Oulodus aclys* Mawson - Suttner, p. 26, Pl. 10, figs 12-13; Pl. 11, figs 2, 4-5.

Remarks - The only element attributed to this species is a S2 element partly incomplete, being the posterior process mostly broken. The anterior process is bent downward; denticles on both processes are closely spaced and discrete and show a nearly circular cross-section. The cusp is high and slightly out of alignment with the denticles on processes. Even if the element is incomplete the misalignment between the cusp and the denticles allows a species determination of the element, as it is the diagnostic feature of the species (Mawson, 1986). The species is here documented for the first time in Sardinia.

Material - One S2 element from sample PSA II 2.

Stratigraphical distribution - According to Farrell (2003) the species occurs from the lower Lochkovian (*eurekaensis* Zone) to the Pragian (*sulcatus* Zone). In terms of the present zonation, it ranges from the *Icr. postwoschmidti* Zone into the *Icr. steinachensis* β Zone. The studied element came from the *Icr. postwoschmidti* Zone.

Family Spathognathodontidae Hass, 1959

Genus *Zieglerodina* Murphy, Valenzuela-Ríos & Carls, 2004
Type species *Spathognathodus remscheidensis* Ziegler, 1960

Zieglerodina eladioi (Valenzuela-Ríos, 1994)
(Pl. 2, figs 4-8)

1994 *Ozarkodina eladioi* n. sp. Valenzuela-Ríos, p. 59-63, Pl. 5, figs 1-35.
2019 *Zieglerodina eladioi* (Valenzuela-Ríos) - Corriga & Corradini, p. 182-183, figs 2-3 (cum syn.).
2021 *Zieglerodina eladioi* (Valenzuela-Ríos) - Corriga et al., Pl. 2, fig. 15.

Remarks - The apparatus of *Z. eladioi* was reconstructed by Corriga & Corradini (2019), mainly on the basis of material from Morocco and the Carnic Alps. In the collection from Perda S'altari a few poorly preserved elements of the whole apparatus are present, with the only exception of the M element.

Material - Five P1, two P2, one S0, two S1 and four S2 elements from samples PSA II 1, PSA II 3, PSA III 1 and PSA III 2.

Stratigraphical distribution - From the uppermost Přídolí (Upper *Oul. el. detortus* Zone; Corradini et al., 2020) to the middle Lochkovian (*Ad. trigonicus* Zone; Corradini & Corriga, 2012).

Zieglerodina cf. *schoenlaubi* Corradini et al., 2019

2019 *Ozarkodina schoenlaubi* n. sp. Corradini et al., p. 167-168, Fig. 12K-M (cum syn.).

Remarks - *Zieglerodina schoenlaubi* is characterized by a short blade bearing closely spaced denticles of different size on both processes. The element tentatively attributed to the species is incomplete and poorly preserved, and broke during the preparation for SEM photograph. This is the first report of the species in Sardinia, as up to date was documented only in the Carnic Alps and Podolia (Corradini et al., 2019).

Material - One P1 element from sample PSA III 2.

Stratigraphical distribution - The studied element came from the *Icr. postwoschmidti* Zone, and represents the younger occurrence of the species, previously documented only from the *Icr. hesperius* Zone (Corradini et al., 2019).

Zieglerodina sp. B Corriga et al., 2016
(Pl. 2, fig. 3)

1980 *Ozarkodina remscheidensis remscheidensis* (Ziegler) - Schönlaub, Pl. 2, fig. 1/32; Pl. 6, fig. 7.
1985 *Ozarkodina remscheidensis remscheidensis* (Ziegler) - Schönlaub, Pl. 2, fig. 1.
2016 *Zieglerodina* sp. B Corriga et al., p. 268-269, Fig. 5F.

Remarks - *Zieglerodina* sp. B is characterized by strong denticles that are triangular in lateral view and have an alternating pattern on the posterior process; on the anterior process the size of denticles decreases from the distal end towards the cusp. The taxon is here reported for the first time in Sardinia, as it was previously documented only in the Carnic Alps (Corriga et al., 2016).

Material - One P1 element from sample PSA III 2.

Stratigraphical distribution - The species is up to now documented only from the *Icr. postwoschmidti* Zone.

Zieglerodina sp. C Corriga et al., 2021
(Pl. 2, fig. 9)

1980 *Ozarkodina remscheidensis* (Ziegler) - Schönlaub, Pl. 3, fig. 20 (only).
2021 *Zieglerodina* sp. C Corriga et al., p. 202-203, Pl. 2, figs 16-18.

Remarks - *Zieglerodina* sp. C is characterized by discrete strong denticles, triangular in lateral view, on both processes; in the anterior process, smaller denticles are intercalated between higher ones. The taxon is here reported for the first time in Sardinia, and was previously documented only in the Carnic Alps (Corriga et al., 2021).

Material - One P1 element from sample PSA III 3.

Stratigraphical distribution - The studied element came from the *Icr. postwoschmidti* Zone, and represents the stratigraphically highest record of the species: in fact, in the Carnic Alps it was documented only from the *Icr. hesperius* Zone (Corriga et al., 2021).

Zieglerodina sp. X
(Pl. 2, Fig. 2)

Description - The P1 element is carminate with the anterior and posterior processes straight and aligned, bearing discrete denticles ovoidal in cross section. The three distal denticles of the anterior process decrease in height and have a somewhat cockscomb shape. The cusp is slightly larger than adjacent denticles. The platform lobes are unornamented and wider than long, and are developed along an oblique axis forming an angle of about 60° with the blade.

Remarks - The angle between the processes and the axis of the platform distinguishes this taxon from the other species of *Zieglerodina*.

Material - One P1 element from sample PSA III 2.

Stratigraphical distribution - The studied element came from the *Icr. postwoschmidti* Zone.

Class, Order, and Family unknown

Genus *Eurytholia* Sutton, Holmer & Cherns, 2001
Type species *Eurytholia prattensis* Sutton, Holmer & Cherns, 2001

Remarks - The genus *Eurytholia* is represented by subovoidal phosphatic plates with a high transverse ridge in the upper part. The genus is documented from around the Middle/Upper Ordovician boundary (Sutton et al., 2001) to the Eifelian (Mergl, 2020). Three species have been documented: *E. prattensis* Sutton et al., 2001 from the Ordovician of Baltica and Laurussia, *E. elibata* Sutton et al., 2001 from the Ordovician of Baltica, and *E. bohemica* Ferretti et al., 2006 from the Silurian to Middle Devonian of Baltica and various Perigondwana regions. The biological affinities of *Eurytholia* are still unknown. Sutton et al. (2021) interpreted the plates as dermal sclerites of a dorsoventrally flattened animal of uncertain affinity. Mergl (2020) hypothesized a possible relationship with the conodont genus *Pseudooneotodus*, which is represented by simple cones with a subcircular basal outline and has a similar stratigraphical range.

Eurytholia bohemica Ferretti, Serpagli & Štorch, 2006
(Pl. 2, Fig. 1)

2006 *Eurytholia bohemica* n. sp. Ferretti, Serpagli & Štorch, p. 1027-1031, Pl. 1, figs 1-11; Pl. 2, figs 1-12.
2007 *Eurytholia* cf. *bohemica* Ferretti, Serpagli & Štorch - Corriga, Fig. 4.14.

2008 *Eurytholia bohemica* Ferretti, Serpagli & Štorch - Ferretti & Serpagli, Pl. 1, figs 1-8.
2009c *Eurytholia* cf. *bohemica* Ferretti, Serpagli & Štorch - Corradini et al., Pl. 1, fig. 15.
2013 *Eurytholia bohemica* Ferretti, Serpagli & Štorch - Ferretti et al., Fig. 8A-B.
2016 *Eurytholia bohemica* Ferretti, Serpagli & Štorch - Kaminski et al., Fig. 5i-j.
2020 *Eurytholia* aff. *bohemica* Ferretti, Serpagli & Štorch - Mergl, p. 5-8, Pl. 1, figs 1-14; Pl. 2, figs 1-8.
2021 *Eurytholia* cf. *bohemica* Ferretti, Serpagli & Štorch - Ferretti et al., Fig. 3Q-R.

Remarks - The single sclerite collected has a subovoidal profile of the base and a high transversal ridge more or less in central position. These characteristics fit well into the variability of the species described by Ferretti et al. (2006).

Geographical distribution - *Eurytholia bohemica* is documented from the Czech Republic (Ferretti et al., 2006; Mergl, 2020), the Carnic Alps (Ferretti & Serpagli, 2008), Sardinia (Corradini et al., 2009c, and this paper) and Ireland (Kaminski et al., 2016; Ferretti et al., 2021).

Stratigraphical range - The species is documented from the Ludlow (*K. crassa* conodont Zone; Ferretti et al., 2006) to the Eifelian (*Po. partitus* conodont Zone; Mergl, 2020). However, before this report the species was reported from the Devonian only in Bohemia, whereas all the other recoveries came from Silurian rocks. The studied sclerite is collected from the lower Lochkovian (*Icr. postwoschmidti* Zone).

Material - One sclerite from sample PSA II 2a.

CONCLUSIONS

The main results of this study on the Perda S'altari area can be summarized as follows:

1. Some graptolite species are documented for the first time in the Genna Muxerru Fm. of SW Sardinia: *Paradiversograptus capillaris*, *P. runcinatus*, *Parapetalolithus* cf. *elongatus*, *Pristiograptus pristinus*, *P.* cf. *renaudi*, *Stimulograptus* cf. *halli*, *Torquigraptus obtusus*.

2. The *R. linnaei* graptolite Zone is discriminated for the first time in the Genna Muxerru Fm. of southwestern Sardinia. Previously this zone was recognized from the "Lower graptolitic shales" of the southeastern part of the island (Gerrei and Sarrabus tectonic units) in the Rio Ollastu area (Barca & Jaeger, 1990) and at Sedda de S'Ortu section (Štorch & Piras, 2009b; Paschina, 2011).

3. The conodont species *Zieglerodina* sp. X is here described, but left in open nomenclature awaiting to collect more material.

4. The conodont species *Oulodus aclys*, *Zieglerodina schoenlaubi*, *Z.* sp. B and *Z.* sp. C are documented for the first time in Sardinia.

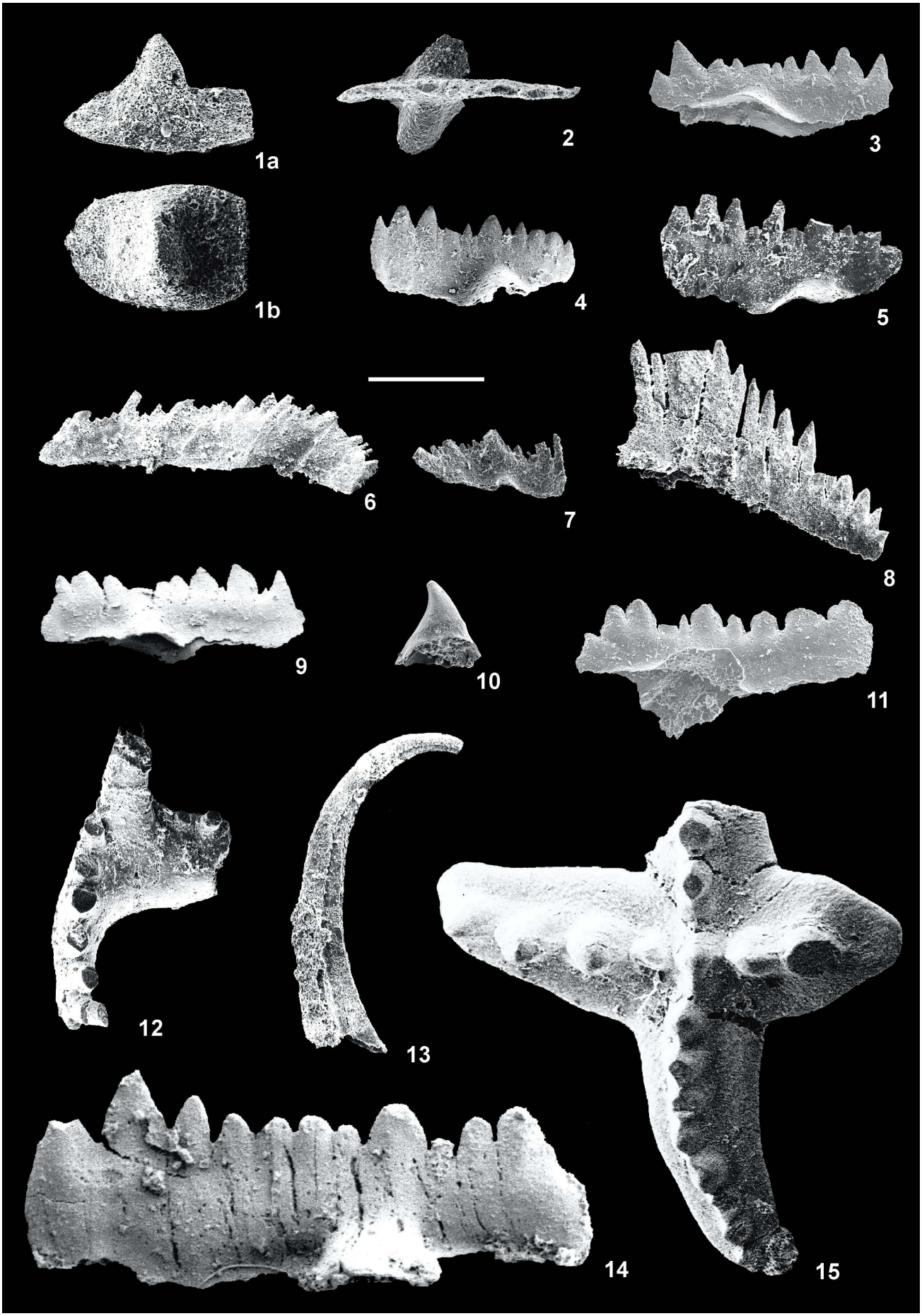
5. The problematic *Eurytholia bohemica* is collected from Devonian rocks for the first time outside the Barrandian.

6. The lithostratigraphical scheme of the Silurian and Lower Devonian of SW Sardinia is updated extending the Genna Muxerru Fm. at least to the lower Lochkovian in the northern part of the External Zone. The base of the Mason Porcus Fm. is extended to the *I. postwoschmidti* Zone, and a heteropic relationship between the Fluminimaggiore and the Mason Porcus formations is proposed within this zone.

EXPLANATION OF PLATE 2

Selected phosphatic microfossils from the Mason Porcus Fm. in the Perda S'altari area. Scale bar = 300 μm.

Fig. 1 - *Eurytholia bohemica* Ferretti, Serpagli & Štorch, 2006. Lateral (a) and upper views of sclerite DMGTS 101, sample PSA II 2A.
Fig. 2 - *Zieglerodina* sp. X. Upper view of element DMGTS 110, sample PSA III 2 (*I. postwoschmidti* Zone).
Fig. 3 - *Zieglerodina* sp. B Corriga et al., 2016. Lateral view of element DMGTS 108, sample PSA III 2 (*I. postwoschmidti* Zone).
Figs 4-8 - *Zieglerodina eladioi* (Valenzuela-Ríos, 1994).
4 - Lateral view of P1 element DMGTS 102, sample PSA II 3 (*I. postwoschmidti* Zone).
5 - Lateral view of P1 element DMGTS 103, sample PSA III 2 (*I. postwoschmidti* Zone).
6 - Lateral view of S1 element DMGTS 105, sample PSA II 3 (*I. postwoschmidti* Zone).
7 - Lateral view of S2 element DMGTS 106, sample PSA III 2 (*I. postwoschmidti* Zone).
8 - Lateral view of P2 element DMGTS 104, sample PSA II 3 (*I. postwoschmidti* Zone).
Fig. 9 - *Zieglerodina* sp. C Corriga et al., 2021. Lateral view of element DMGTS 109, sample PSA III 2 (*I. postwoschmidti* Zone).
Fig. 10 - *Pseudooneotodus beckmanni* (Bischoff & Sannemann, 1958). Lateral view of element DMGTS 107, sample PSA III 2 (*I. postwoschmidti* Zone).
Fig. 11 - *Zieglerodina remscheidensis* (Ziegler, 1960). Lateral view of element DMGTS 111, sample PSA III 2 (*I. postwoschmidti* Zone).
Fig. 12 - *Oulodus aclys* Mawson, 1986. Lateral view of S2 element DMGTS 112, sample PSA II 2 (*I. postwoschmidti* Zone).
Fig. 13 - *Panderodus unicostatus* (Branson & Mehl, 1933). Lateral view of element DMGTS 113, sample PSA II 3 (*I. postwoschmidti* Zone).
Fig. 14 - *Lanea omoalpha* Murphy & Valenzuela-Ríos, 1999. Lateral view of element DMGTS 114, sample PSA II 2 (*I. postwoschmidti* Zone).
Fig. 15 - *Ancyrodelloides transitans* (Bischoff & Sannemann, 1958). Upper view of element DMGTS 115, sample PSA II 1 (*Ad. transitans* Zone).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