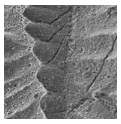
Conodonts across the Devonian/Carboniferous boundary in SE Sardinia (Italy)

ANGELO MOSSONI, NICOLA CARTA, CARLO CORRADINI & CLAUDIA SPALLETTA



The Bruncu Bullai section, located in SE Sardinia, exposes limestones from the *styriacus* Zone (upper Famennian) to the Upper *duplicata* Zone (Tournaisian), but the Upper *praesulcata* Zone is not documented; at the Devonian/Carboniferous boundary a black shales level, equivalent to the Hangenberg Shales, is present. Fifty-six conodont taxa were recovered, three of which are here described as new species: *Polygnathus bicristatus*, *Po. nuragicus*, *Pseudopolygnathus granulobatus*; two more species, probably new, are described, but left in open nomenclature because of the low number of specimens collected. The relative high abundance of *Protognathodus* and low abundance of *Siphonodella* in some levels and the opposite in others is discussed, and a new hypothesis on the occurrences of protognathodids as influenced by ecological factors is suggested. The early phase of the Hangenberg crisis is testified by a faunal turnover in an impoverished fauna within the deposition of limestones of the Lower *praesulcata* Zone. • Key words: conodonts, biostratigraphy, Devonian, Carboniferous, Devonian/Carboniferous boundary, Sardinia.

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The Devonian/Carboniferous boundary is defined by the first occurrence of the conodont *Siphonodella sulcata*; the GSSP is located in the La Serre Trench E', in Montagne Noire, southern France. However, problems both with the type section and the index taxon have been recently evidenced (see below for details), and researches on the Late Devonian and Early Carboniferous received new interest all around the world.

Up to now rocks across the Devonian/Carboniferous boundary in Sardinia have been documented only in the Monte Taccu section (Corradini *et al*. 2003, Mossoni *et al*. 2013). In this paper we present the conodont stratigraphy of the Bruncu Bullai section, located a few km east of Villasalto (Fig. 1), where a dozen of meters of Famennian and Tournaisian limestones are exposed. The Hangenberg equivalent Shales are represented by a few centimeters of black shales, dividing the Famennian from the Tournaisian limestones.

Up to now the occurrence of Lower Carboniferous rocks in Sardinia has been claimed by Olivieri (1970) near Villasalto, and proved in the Monte Taccu section, a few km west, by Barca *et al*. (2000), Corradini *et al*. (2003) and Mossoni *et al.* (2013). In this paper new data on Upper Devonian and Lower Carboniferous conodonts in Sardinia are presented and a special attention is given to the relative abundance of *Protognathodus* and *Siphonodella* across the Devonian/Carboniferous boundary.

The Devonian/Carboniferous boundary: an open problem

The base of the Carboniferous System is defined by the first occurrence of the conodont species *Siphonodella sulcata*, within the claimed *S. praesulcata-S. sulcata* lineage, and the GSSP is located at the La Serre Trench E' section, Montagne Noire, France (Paproth *et al.* 1991). Flajs & Feist (1988) published a biometric study of *S. praesulcata* and *S. sulcata* based on the La Serre faunas, demonstrating that transitional forms are very common. The FAD of *S. sulcata* was chosen to define the base of the Tournaisian, but difficulties in discriminating *S. praesulcata* from *S. sulcata* arose immediately (*e.g.*, Wang & Yin 1984, Ji 1987, Flajs & Feist 1988). Further studies on the stratotype section

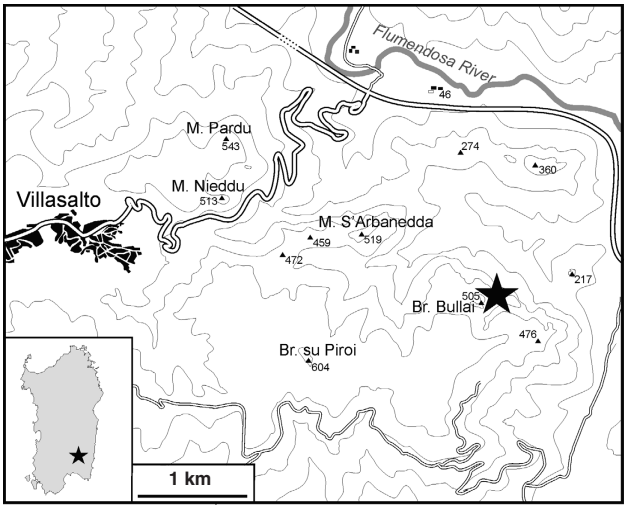


Figure 1. Location map of the Bruncu Bullai section.

have revealed a series of problems, such as lack of other important stratigraphic guides and the existence of reworking (*e.g.*, Flajs & Feist 1988, Ziegler & Sandberg 1996, Casier *et al.* 2002, Kaiser 2009).

A redefinition of the Devonian/Carboniferous boundary was reputed necessary, and in 2008 the International Commission on Stratigraphy established a working group with the goal to propose a new criterion for defining the boundary and finding a new GSSP. In this scenario, all conodont genera of the latest Devonian and earliest Carboniferous are restudied in order to exploit their potential for biostratigraphy across the Devonian/Carboniferous boundary (Corradini *et al.* 2013) and taxonomic revisions of selected taxa are in progress (*i.e.* early siphonodellids, Kaiser & Corradini 2011; protognathodids, Corradini *et al.* 2011). Several sections are under investigation around the world, both restudying already known localities (*i.e.* Mossoni *et al.* 2013, Kumpan *et al.* 2014) and exploiting new ones (*i.e.* Bahrami *et al.* 2011, Becker *et al.* 2013, Girard *et al.* 2014, Kumpan *et al.* 2014, Kalvoda *et al.* 2015).

Geological setting

In Sardinia an almost complete portion of the southern branch of the Variscan orogenic belt crops out. It is characterized by non-metamorphosed to high-grade rocks of Early Cambrian to Early Carboniferous age involved in a complex polyphase deformation. The main result of the Variscan orogeny in Sardinia is a tectono-metamorphic partition with, from north to south: an Inner Zone, with medium to high grade metamorphism, thrusted over a Nappe Zone, with green schist metamorphism that overthrusted a Foreland Zone affected by very low grade regional metamorphism (Funedda & Oggiano 2009, and references therein).

The studied area is located in the External Nappe Zone, and belongs to the Gerrei tectonic unit, where the most complete mid-Palaeozoic sequence of the whole island is preserved. The metamorphic grade is very low (green schist facies) and allows good biostratigraphic investigation. The sequence of the Gerrei tectonic unit starts with a thick pile of sandstones ("Arenarie di San Vito") of Mid Cambrian-Early Ordovician age, followed by a huge amount of Middle Ordovician volcanic rocks. The Upper Ordovician is mainly represented by terrigenous littoral sediments with basaltic intercalations, and silicified limestones at the top. The Silurian and lowermost Devonian exposes black shales and limestones in the classical Thuringian facies triad (Jaeger 1976): Lower Graptolitic Shales, Ockerkalk, and Upper Graptolitic Shales. This unit grades into an alternation of dark pelites and nodular marly limestone ("Tentaculitic shales and limestones") of Early-Middle Devonian age. The calcareous content progressively increases and the Upper Devonian–lowermost Carboniferous sediments are represented by massive limestones known as "Clymeniae limestones" (see below). Above, several dozens of meters of metasandstones and metaconglomerates ("Conglomerato di Villasalto", *Auct.*) are present. They represent the transition to the terrigenous sedimentation terminating the pelagic sequence of the Palaeozoic in SE Sardinia. For a complete description of the Gerrei tectonic unit refer to Corradini *et al.* (2002) and Corradini & Ferretti (2009).

The "Clymeniae limestones" of Sardinia

The Upper Devonian–Lower Carboniferous limestones consist mainly of grey massive limestones, known as "Clymeniae limestones" because of the occurrence of ammonoids in some levels (Lovisato 1894, Corradini 2007). The apparent thickness of this unit may reach hundreds of meters, but tectonic repetitions of the sequence are highly probable (Carmignani *et al.* 1986); the real thickness is more likely about 50–70 m (Corradini 2008). Apart from a few crinoid stems, ammonoids concentrated in a few levels, mainly across the *annulata* and Dasberg events, are the only abundant macrofossils. The microfacies is a poorly fossiliferous micrite with scarce fossil remains in the ammonoid-bearing beds: ostracodes, small shells (bivalves or brachiopods), fragments of echinoderms, gastropods, and rare trilobites. Conodonts are abundant; fish teeth and very rare brachiopods have been reported from acid-insoluble residues (Corradini 1998a, 1998c; Corradini *et al.* 2003; Derycke *et al.* 2008; Mossoni *et al.* 2013). Biofacies and microfacies suggest a pelagic environment for these limestones. The Clymeniae limestones have been biostratigraphically investigated on the basis of conodonts by several authors in the last fifty years (Pomesano Cherchi

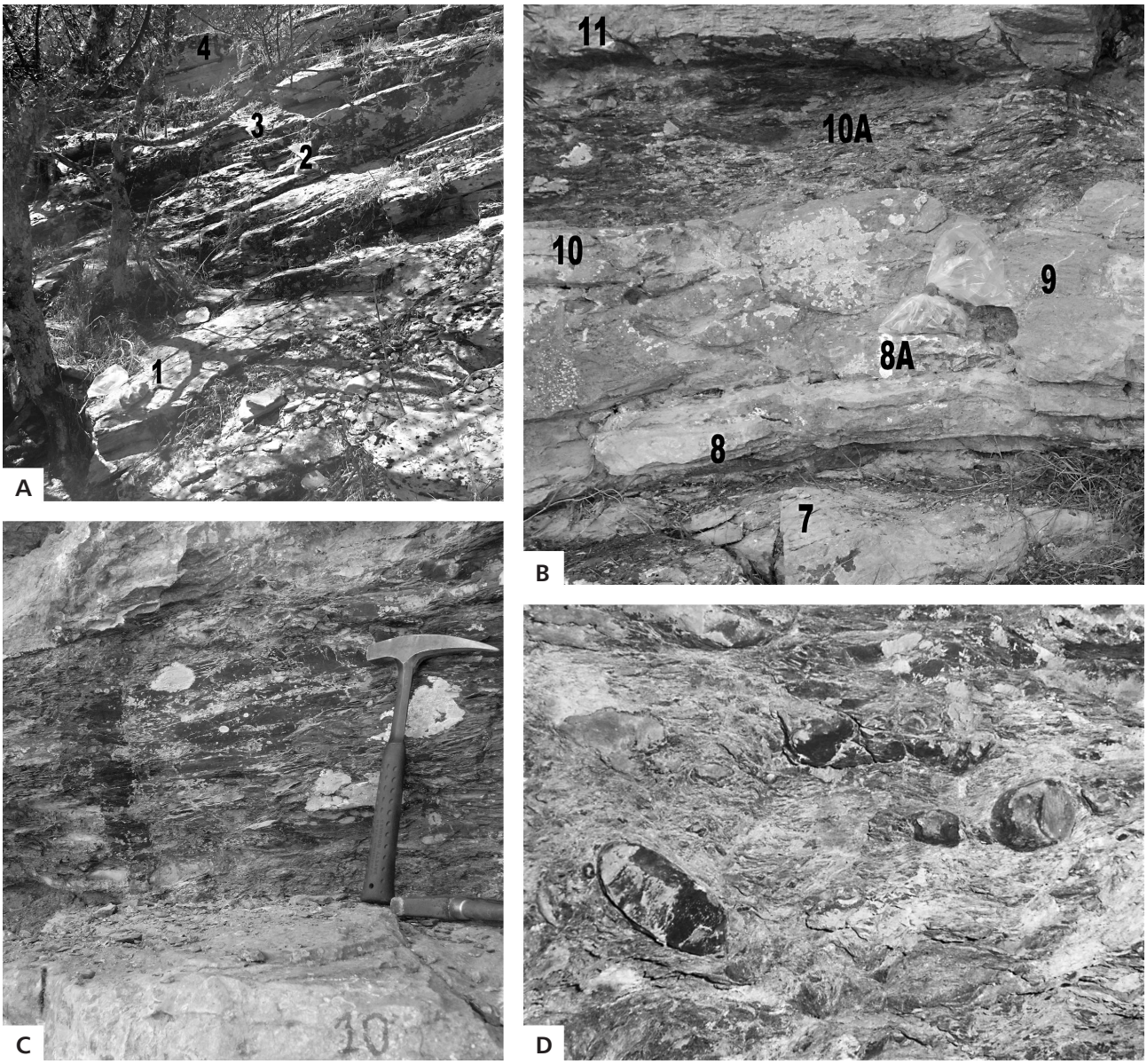


Figure 2. Selected views of the studied section. • A – general view of the lower part of the Bruncu Bullai section. • B – view of the upper part of the section. • C – detail of the black shale level between samples BTE 10, 11. • D – close-up view of nodules in the lower part of the shale level between samples BTE 10, 11.

1963; Olivieri 1965, 1970, 1985; Murru 1975; Spalletta & Vai 1982; Barca & Spalletta 1985; Barca *et al.* 1986; Corradini 1998a, 1998b, 1998c, 1998d, 2002, 2003, 2008; Corradini *et al.* 2001, 2003; Mossoni *et al.* 2013), providing a late Frasnian (Upper *hassi* Zone)–early Tournaisian (Upper *duplicata* Zone) age for this unit.

The Bruncu Bullai section

The Bruncu Bullai (BTE) section is located few km SW of Villasalto in the northern slope of Bruncu Bullai hill at coordinates: 39°29´ 13.42˝ N; 9°26´ 15.25˝ E (Fig. 1).

The section exposes about eleven meters of massive grey limestone arranged in beds with a thickness from 20 cm up to 2 m (Fig. 2C). A few limestone beds are present below the base of the section, but have not been sampled because they are highly tectonized.

Two levels of black shales are present in the upper part of the section. The first level, between samples BTE 7 and BTE 8 is only a few centimeters thick and has a limited calcareous component. The second shaley level (between samples BTE 10 and BTE 11) is about 50 cm thick, with evident small lateral variations, and includes in its lower part a few chert nodules and a thin discontinuous calcareous level. A thrust, or a fault, follows this black shale level,

evidenced in the field by a minor unconformity. Above thick beds of limestones are present.

According to conodont data (see below), the first shale level lies at or just below the Devonian/Carboniferous boundary, and can be considered as an equivalent of the Hangenberg Shales, whereas no data have been obtained from the second shale. However, according to its stratigraphical position it is likely Tournaisian in age and may represent a deeper sedimentation episode within the early phases of the Variscan orogeny. Analogous sediments represented by shales and cherts, some with limestone lenses, are documented in several other regions (*i.e.* Carnic Alps, Schönlaub 1969; Montagne Noire, Kaiser *et al.* 2009; Rhenisches Schiefergebirge, Korn & Weyer 2003; Poland, Dzik 1997; Morocco, Korn 1999). These strata have been dated to the Lower *crenulata* Zone and testify a global transgression and a faunal turnover named "Lower Alum Shale Event" by Becker (1993).

The microfacies is a mudstone-wackestone. Some fossil remains, mainly brachiopods and ammonoids, have been observed in thin section (Fig. 5). Bioclasts, mainly fragments of goniatites, are readily recognizable despite the faint metamorphic imprint; they are more frequent in the uppermost levels. The upper part of the section (samples 7–10A) shows the effect of tectonism with evident calcite recrystallization, stylolite and tension gashes structures (Fig. 5D).

Conodont data

Fifteen samples, weighting 0.4 to 3.7 kg, have been collected from the Bruncu Bullai section, for a total amount of about 30 kg of limestone (Table 1). The samples were dissolved with conventional formic acid technique. All the samples, but BTE 10A were productive, yielding more than 2,500 conodonts (Table 1). The state of preservation is quite good, even if some specimens are broken or tectonically deformed. These deformed elements are present in all samples, while are especially abundant in samples BTE 1 and BTE 11.

The abundance is variable (Fig. 4), from a minimum of 9.7 conodonts/kg in sample BTE 6C to a maximum of 270 conodonts/kg in sample BTE 9; the average of 88.7 conodont/kg is similar to the other sections studied in the Clymeniae limestones of Sardinia.

Conodonts color is black (CAI = 5–5.5), as in all other sections in the Upper Devonian of Sardinia.

Fifty-seven taxa, between species and subspecies, belonging to the genera *Branmehla*, *Bispathodus*, *Icriodus*, *Mehlina*, *Palmatolepis*, *Polygnathus*, *Protognathodus*, *Pseudopolygnathus*, and *Siphonodella* have been recognized (Fig. 3).

Palmatolepis is the dominant genus in the lower part of the section (samples BTE 1–2), up to the lower part of the Lower *expansa* Zone, when *Bispathodus* starts to be very abundant (Fig. 4). *Bispathodus* continues to be very abundant, and together with *Branmehla*, represents the majority of the association of the Upper *expansa* Zone (sample BTE 6–6B). Within the Lower *praesulcata* Zone (sample BTE 6C), *Polygnathus* became the dominant genus. In the Carboniferous part of the section *Polygnathus* constitutes up to 80% of the assemblages. In sample BTE 9 (Lower *duplicata* Zone) *Polygnathus tenuiserratus* represents more than one quarter of the fauna.

Biostratigraphy

The conodont zonation used in this paper is the scheme proposed for Sardinia by Corradini (2008), that is a rielaboration of the Late Devonian Standard Conodont Zonation (Ziegler & Sandberg, 1990) and the Late Devonian-Early Carboniferous Zonation of Sandberg *et al.* (1978). An alternative zonation across the Devonian/Carboniferous boundary has been proposed by Kaiser *et al.* (2009), who replaced the Middle and Upper *praesulcata* zones by Ziegler & Sandberg (1990) with a "*costatus-kockeli* interregnum" (CKI) and a *Pr. kockeli* Zone, respectively, and applied a proposal by Ji (1985) for the *duplicata-sandbergi* interval.

The Lower marginifera Zone. – The Lower *marginifera* Zone is discriminated in the uppermost part of the section, above the tectonic duplication by the occurrence of the marker *Palmatolepis marginifera marginifera* in sample BTE 12. The association is dominated by *Palmatolepis*.

The styriacus Zone. – The *styriacus* Zone corresponds to an undifferentiated *postera* Zone of Ziegler & Sandberg (1990). It has been discriminated at the base of the section (sample BTE 1) by the presence of the marker, *Polygnathus styriacus*. *Palmatolepis gr. gracilis* and *Pa. perlobata schindewolfi* are the most abundant taxa.

A high number of ramiform elements was recovered from this level, representing about one half of the findings, although the state of preservation is quite poor.

The Lower expansa Zone. – The Lower *expansa* Zone (samples 2–3) is recognized by the first occurrence of the marker, *Palmatolepis gracilis expansa*. *Palmatolepis perlobata postera* is here reported for the first time in Sardinia from this interval. This late entry of *Pa. perlobata postera* also occurs in the Carnic Alps (Perri & Spalletta 1998). *Pseudopolygnathus dissimilis* and *Branmehla werneri* are exclusive of this zone, whereas *Bispathodus jugosus* has its first occurrence. *Palmatolepis gracilis gracilis* is the most abundant species of this zone.

The Middle expansa Zone. – The Middle *expansa* Zone

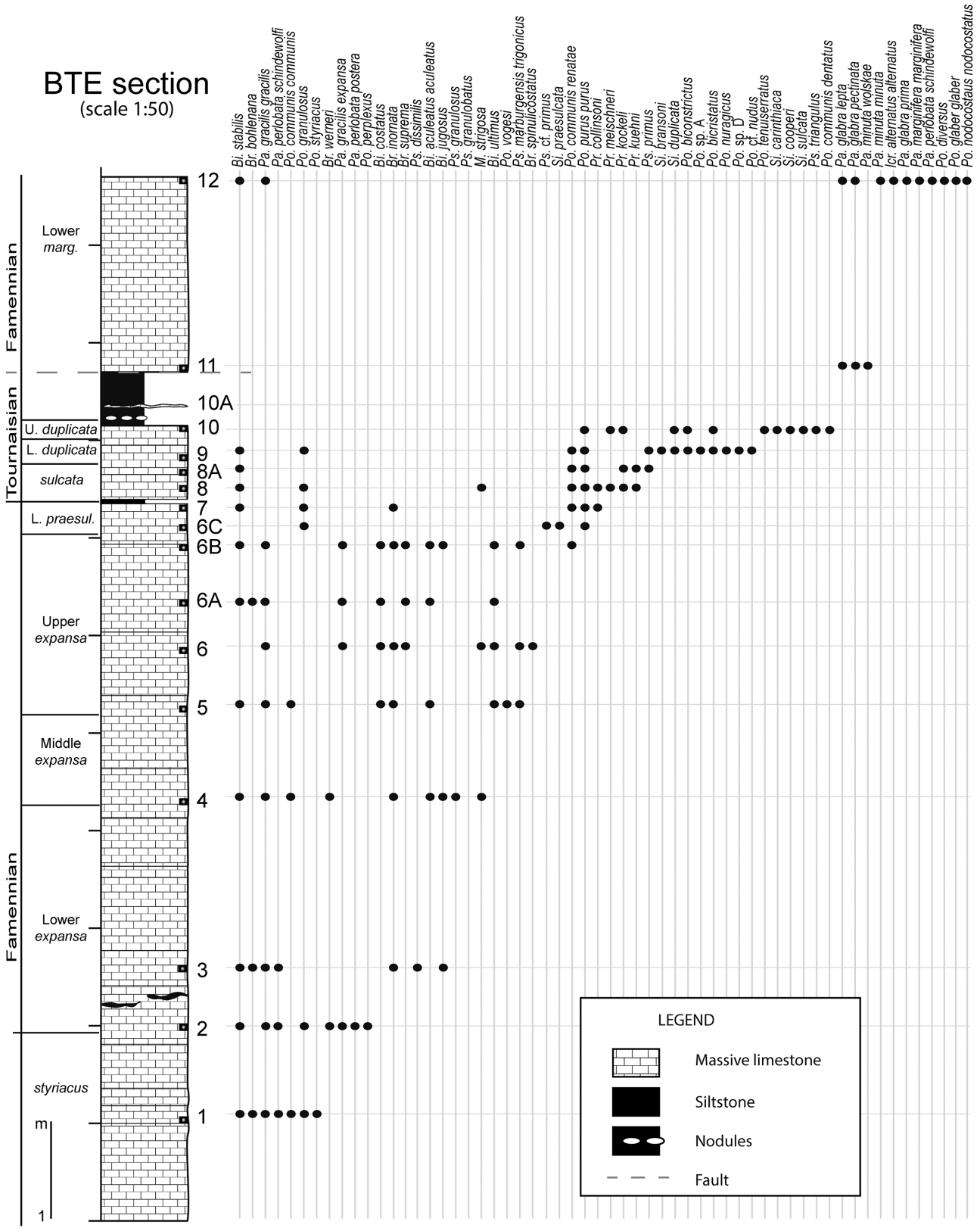


Figure 3. Stratigraphic log, biozonation and conodont occurrence of the Bruncu Bullai section. Abbreviation: *Bi.* – *Bispathodus*, *Br.* – *Branmehla*, *Icr.* – *Icriodus*, *M.* – *Mehlina*, *Pa.* – *Palmatolepis*, *Ps.* – *Pseudopolygnathus*, *Pr.* – *Protognathodus*, *Po.* – *Polygnathus*, *Si.* – *Siphonodella*.

Table 1. Distribution of conodonts in the Bruncu Bullai section. *P.* – *Polygnathus*; *Ps.* – *Pseudopolygnathus*

	Famennian										Tournaisian				?	Famennian		Total
	styriacus	Lower *expansa*		Middle *expansa*	Upper *expansa*				Lower *praesulcata*		*sulcata*		Lower *duplicata*	Upper *duplicata*			Lower *marginifera*	
Species	1	2	3	4	5	6	6A	6B	6C	7	8	8A	9	10	10A	11	12	
Bispathodus aculeatus aculeatus				5	18		15	23										61
Bispathodus costatus			1		51	40	19	38										149
Bispathodus jugosus				1				3										4
Bispathodus spinulicostatus						16												16
Bispathodus stabilis	3	36	8	4	6		2	14		6	15	11	12				1	118
Bispathodus ultimus					49	27	7	18										101
Branmehla bohlenana	1		4				1											6
Branmehla inornata			9	5	6	25		7		1								53
Branmehla suprema						79	18	15										112
Branmehla werneri		3																3
Icriodus alternatus alternatus																	1	1
Mehlina strigosa				5		2					5							12
Palmatolepis glabra lepta																2	4	6
Palmatolepis glabra pectinata																2	17	19
Palmatolepis glabra prima																	14	14
Palmatolepis gracilis expansa		9				2	1	2										14
Palmatolepis gracilis gracilis	15	98	9	23	20	39	15	31									6	256
Palmatolepis marginifera marginifera																	28	28
Palmatolepis minuta minuta																	4	4
Palmatolepis minuta wolskae																1		1
Palmatolepis perlobata postera		4																4
Palmatolepis perlobata schindewolfi	11	29	1														19	60
Polygnathus biconstrictus													6	6				12
Polygnathus bicristatus													43	9				52
Polygnathus communis communis	1			1	5				8	5	44		1					65
Polygnathus communis dentatus														13				13
Polygnathus communis renatae								4		11	3	7	9					34
Polygnathus diversus																	1	1
Polygnathus glaber glaber																	9	9
Polygnathus granulosus	1	1																2
P. nodocostatus nodocostatus																	1	1
Polygnathus nuragicus													30					30
Polygnathus perplexus		1																1
Polygnathus purus purus									1	1	8	46	77	63				196
Polygnathus styriacus	6																	6
Polygnathus tenuiserratus													127	33				160
Polygnathus vogesi					1													1
Protognathodus collinsoni										4	8							12
Protognathodus kockeli											15	7		7				29
Protognathodus kuehni											7	3						10
Protognathodus meischneri											9			3				12
Pseudopolygnathus cf. *nudus*														6				6
Pseudopolygnathus dissimilis			16															16

	Famennian										Tournaisian					Famennian		Total
	styriacus	Lower *expansa*		Middle *expansa*	Upper *expansa*				Lower *praesulcata*		*sulcata*		Lower *duplicata*	Upper *duplicata*	?		Lower *marginifera*	
Species	1	2	3	4	5	6	6A	6B	6C	7	8	8A	9	10	10A	11	12	
Pseudopolygnathus granulobatus				12														12
Pseudopolygnathus granulosus				1														1
Ps. marburgensis trigonicus					2	5		1										8
Pseudopolygnathus primus									cf.			2	24					27
Pseudopolygnathus triangulus														20				20
Siphonodella bransoni													1					1
Siphonodella carinthiaca														1				1
Siphonodella cooperi M1														1				1
Siphonodella duplicata													4	2				6
Siphonodella praesulcata									2									2
Siphonodella sulcata														2				2
Polygnathus sp. A													11					11
Polygnathus sp. B													4					4
Bispathodus sp.						1		2										3
Branmehla sp.							7	8									1	16
Palmatolepis sp.	10															4	43	57
Polygnathus sp.	1				1			1	3	10	15	20	3	51		1	12	118
Pseudopolygnathus sp.				2	4	3	2	1	1	1		2		3				19
Ramiforms	53	20	4	10	23	46	27	40	6	26	36	20	38	22			30	401
Unidentified		82	14	7	18			9	6	1		7	15			13		172
Total	102	283	66	76	204	285	114	217	28	66	165	125	405	242	0	23	191	2592
Weight	1.3	2.0	1.7	2.1	2.3	1.4	0.8	2.3	2.9	1.2	1.8	1.3	1.5	2.2	0.4	1.0	3.0	29.2
Abundance	78.5	141.5	38.8	36.2	88.7	203.6	142.5	94.3	9.7	55.0	90.2	96.2	270.0	110.0	0.0	23.0	63.7	88.7

(sample 4) is discriminated by the entry of the marker *Bispathodus aculeatus aculeatus*. The abundance ratio shows an equity between the genus *Bispathodus*, *Pseudopolygnathus* and *Palmatolepis*.

The Upper expansa Zone. – The Upper *expansa* Zone (samples 5–6B) is recognized by the first occurrence of the marker *Bispathodus ultimus*. *Pseudopolygnathus marburgensis trigonicus* and *Polygnathus vogesi* are exclusive of this zone. Spathognathodids, mainly *Bispathodus* and *Branmehla*, are dominant, and *Branmehla suprema* is especially abundant in the upper part of the zone.

The Lower praesulcata Zone. – The entry of *Siphonodella praesulcata* in sample BTE 6C allows the discrimination of the *Lower praesulcata* Zone. *Polygnathus communis renatae*, *Po. purus* and *Pr. collinsoni* enter, and *Branmehla inornata* has its last occurrence within this zone. Genus *Polygnathus*, relatively rare in the lower part of the section, becomes the dominant genus starting from this zone.

The Upper praesulcata Zone. – The Upper *praesulcata* Zone has not been recognized in this section, as in other sections of the same age in Sardinia.

The sulcata Zone. – Since the marker *Siphonodella sulcata* is missing, the occurrence of *Protognathodus kuehni* in sample BTE 8 allows attributing the interval above the Hangenberg equivalent shales and below the first occurrence of *Siphonodella duplicata* to the *sulcata* Zone. Kaiser *et al.* (2009) used the same taxon to identify the base of the Carboniferous and named this zone *sulcata/kuehni* Zone.

Subspecies of *Polygnathus communis* and Protognathodids are very abundant. *Pseudopolygnathus primus* has its first occurrence within this zone.

The Lower duplicata Zone. – The Lower *duplicata* Zone is documented by the entry of the marker *Siphonodella duplicata* in sample BTE 9. *Siphonodella bransoni* (= *Si. duplicata* M1), *Polygnathus nuragicus* and *Polygnathus* sp. A here have their only occurrence in the section; *Po. teniuserratus*,

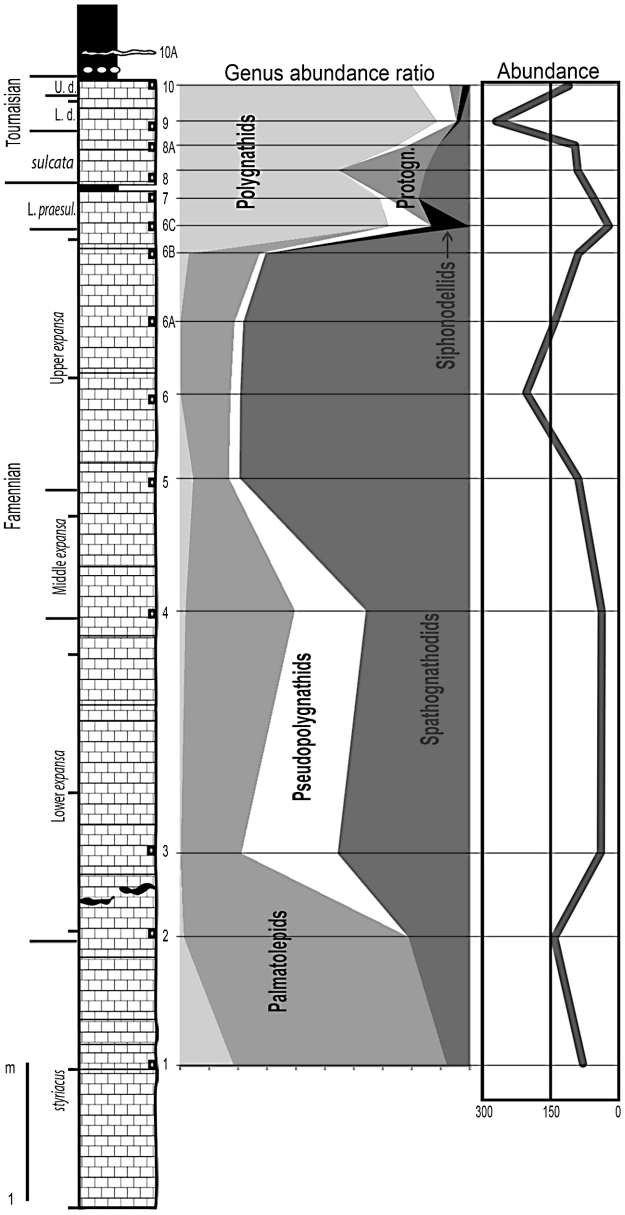


Figure 4. Genus abundance ratio and total abundance of conodonts in the Bruncu Bullai section. The upper part, above the tectonic duplication, is not reported. Spathognathodids includes genera *Bispathodus*, *Mehlina* and *Branmehla*. Abbreviation of biozones: L. *praesul.* = Lower *praesulcata*; L. *d.* = Lower *duplicata*; U. *d.* = Upper *duplicata*.

Polygnathus bicristatus and *Po. biconstrictus* enter, whereas *Po. communis renatae* has its last occurrence.

Polygnathus is the dominant genus. In this zone *Siphonodella* is present whilst *Protognathodus* is absent.

The Upper duplicata Zone. – The Upper *duplicata* Zone is discriminated in sample BTE 10 by the occurrence of *Si. cooperi* M1 and of *Si. carinthiaca*. *Pseudopolygnathus triangulus* and *Po. communis dentatus* have their only occurrence in the section.

Notes on the Hangenberg Event

The Hangenberg Event is one of the major extinction events of the Phanerozoic and is expressed by a sudden anoxic and transgressive event, followed by rapid cooling and a glaciation pulse on Gondwana leading to global regression (Kaiser *et al*. 2008). In most localities it corresponds to the deposition of black shales ("Hangenberg Shales" in Germany, or Hangenberg equivalent elsewhere), but at places the carbonate deposition is continued throughout the event (*i.e*. Grüne Schneid section in the Carnic Alps, Schönlaub *et al*. 1988). The deposition of sandstone immediately before the main event represents a low stand documented in several regions (Kaiser 2005).

Among conodonts, the severe extinction and decrease of abundance is also connected with a change from a palmatolepid-bispathodid biofacies to a protognathodid-polygnathid biofacies during the initial phase of the Hangenberg Event (Kaiser 2005).

In the BTE section a strong decrease of abundance is observed in sample BTE 6C (Lower *praesulcata* Zone), where some typical Famennian pelagic taxa are not present, such as *Bispathodus costatus*, *Bispathodus ultimus* and *Palamatolepis gracilis gracilis*. This low diverse fauna occurs also in sample BTE 7, collected just below the shale level. Also, even if the rock is still represented by limestone, the terrigenous content of beds BTE 6C and 7 is slightly higher than the rest of the section. Therefore, all these data (the impoverished fauna, the change in the biofacies and lithology) may suggest that the early phase of the Hangenberg crisis already start in bed of sample BTE 6C.

On the abundance of *Protognathodus* and *Siphonodella*

Protognathodus and *Siphonodella* are, in general, not abundant in the conodont association, but their occurrence is very important since the zonation across the Devonian/Carboniferous boundary is based on first occurrence of species of these genera.

In the Bruncu Bullai section the two genera do not generally co-occur: in sample BTE 6C only *Siphonodella* have been found; in samples BTE 7–8A *Protognathodus* is present, while *Siphonodella* is absent; in sample BTE 9 (Lower *duplicata* Zone) *Siphonodella* is present, but *Protognathodus* is missing; both taxa co-occur only in sample BTE 10 (Upper *duplicata* Zone). Such irregular occurrence of these genera is documented also in other sections around the world, where in some levels *Protognathodus* only is present, and in others only *Siphonodella*: *i.e.* Grüne Schneid (Schönlaub *et al.* 1988, 1992; Kaiser 2005, 2007), Milles (Kaiser 2005), Puech de la Suque (Kaiser 2005),

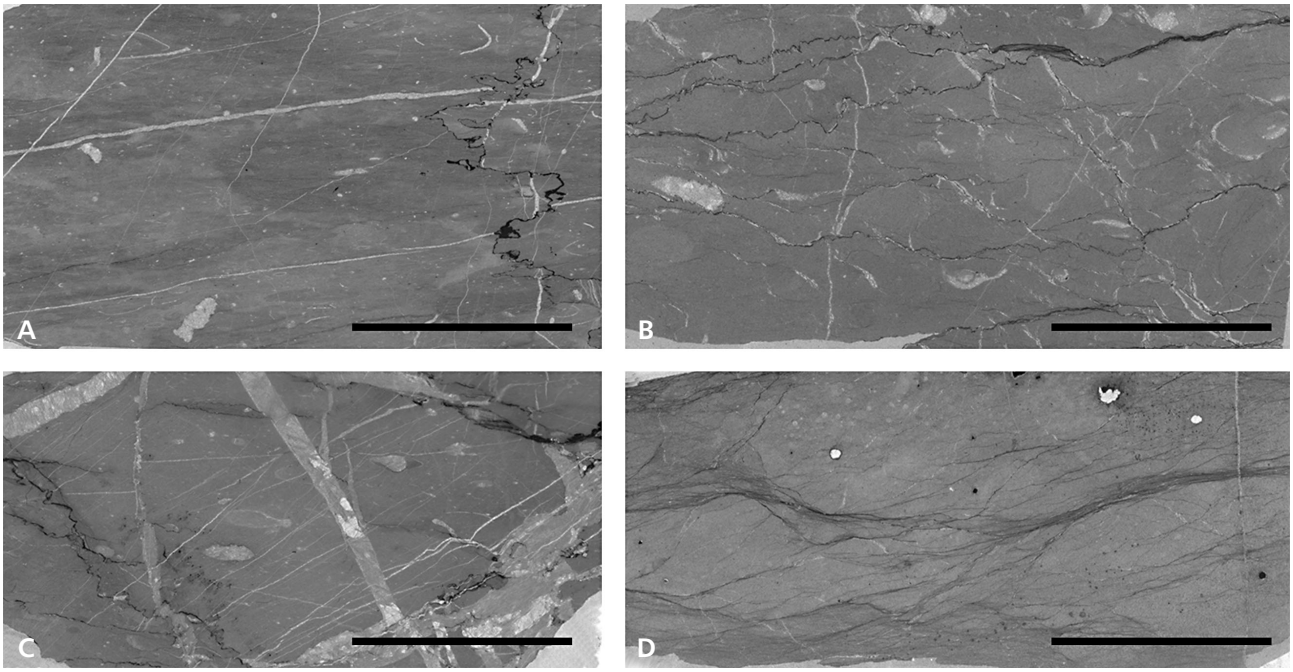


Figure 5. Microfacies of the Bruncu Bullai section. • A – grey wackestone, sample BTE 5. • B – grey wackestone with fossil remains and calcite ricristallization, in sample BTE 7. • C – a grey wackestone with fossil remains and stylolite structures, in sample BTE 8. • D – grey wackestone with tension gashes, sample BTE 10A. Scale bar 1 cm.

Oese (Kaiser 2005), Hasselbachtal (Kaiser 2005), Scharfenberg (Clausen *et al.* 1989), Seiler-Schurf III-I (Clausen *et al.* 1989). In other sections (*i.e*. La Serre E', Kaiser 2005; Trolp, Ebner 1980, Kaiser 2005) the two taxa occur together in almost all samples, but with great variation in relative abundance. In first approximation this "alternate" occurrence of the two genera is more common in the Upper *praesulcata* and *sulcata* zones, and somewhere up to the Lower *duplicata* Zone, whereas they occur together in the Upper *duplicata* Zone.

These sections are characterized by different sedimentary and palaeogeographic contests, and therefore the pattern of occurrence of *Siphonodella* and *Protognathodus* cannot be explained with the conventional biofacies model (Ziegler & Sandberg 1984) where Protognathodids were considered shallow water taxa and Siphonodellids more pelagic taxa. Kaiser *et al*. (2005) suggested that the abundance of *Protognathodus* in the lowermost Carboniferous beds could be related to an opportunistic life-style in deeper environments.

An enhanced model was proposed by Kaiser *et al.* (2008, 2009), who studied in detail the occurrence of the main genera across the Devonian/Carboniferous boundary in selected sections in the Pyrenees (Milles), Carnic Alps (Kronhofgraben) and Graz Palaeozoic (Trolp) and explained the genus occurrence pattern by changes in the depositional basins connected with sea level variations. However, this does not explain the distribution in other sections where there is no lithological evidence of eustatic variations (*i.e*. Grüne Schneid). Corradini *et al.* (2011, p. 20) suggested "the occurrence of the *Prothognathodus* fauna can be related to biotic opportunism during a rise in sea level in the latest Devonian".

Considering the peculiar pattern of the occurrence of *Protognathodus* and *Siphonodella* in pelagic environment, their occurrence in sediments across the Devonian/Carboniferous boundary was likely influenced by ecological factors as competition and feeding.

Comments on the Devonian/Carboniferous boundary in Sardinia

Beside the Bruncu Bullai section, the Monte Taccu section (Corradini *et al.* 2003, Mossoni *et al.* 2013) is the only other locality so far known exposing strata across the Devonian/Carboniferous boundary in Sardinia. It is located about 10 km west of the Bruncu Bullai section.

As in the Bruncu Bullai section, the Hangenberg equivalent shales are represented by a narrow bed, 2–4 cm thick of dark shaley limestone in the Monte Taccu section; above about 1 meter of limestone of Carboniferous age is tectonically covered by Ordovician sandstones. On the basis of conodonts in the Monte Taccu section the youngest resolvable Devonian bed belongs to the Lower *praesulcata* Zone, and the oldest Carboniferous strata are Lower *duplicata* Zone. The Upper *praesulcata* and the *sulcata* zones are not present. The youngest Carboniferous limestone

documented belongs to the Upper *duplicata* Zone (Corradini *et al.* 2003, Mossoni *et al.* 2013).

Even if the upper part of the sections are very similar, exposing about 80 cm of Carbonifeous limestone, a difference in age is reported for the bed just above the Hangenberg equivalent shales: in the Bruncu Bullai section it belongs to the *sulcata* Zone, while in the Monte Taccu section the Lower *duplicata* Zone is documented by the occurrence of a single specimen of the marker *Siphonodella duplicata* in sample MT X2. However, *Siphonodella* is very rare in the lowermost Carboniferous of Sardinia, and at the Bruncu Bullai section no specimens of genus *Siphonodella* have been found in samples BTE 8 and BTE 8A, attributed to the *sulcata* Zone on the presence of *Protognathodus kuehni*, that ranges from the base of the *sulcata* Zone to the *sandbergi* Zone (Corradini *et al.* 2011). The conodont association of these beds cannot exclude that these levels may belong to the Lower *duplicata* Zone, as in the Monte Taccu section, as suggested by preliminary data on magnetic susceptibility (MS). However this hypothesis can be confirmed only by finding specimens of *Si. duplicata* in these beds.

Systematic palaeontology

The conodont collection is housed in the Museum of Palaeontology "Domenico Lovisato" of Cagliari University (MDLCA); catalog numbers of figured elements (Figs 6, 7) can be obtained from the plate caption.

Systematic notes are restricted to new species and necessary taxonomic and/or biostratigraphic remarks. Taxonomy is focused on P1 element only. For suprageneric classification, the scheme proposed by Sweet (1988) is followed.

Order Ozarkodinida Dzik, 1976
Family Polygnathidae Bassler, 1925

Genus *Polygnathus* Hinde, 1879

Type species. – *Polygnathus dubius* Hinde, 1879.

***Polygnathus bicristatus* sp. nov.**
Figure 6A–G

2005 *Polygnathus* sp. Kaiser, pl. 2, figs 3, 4.
2009 *Polygnathus* sp. B Kaiser *et al.*, pl. 2, figs 7, 8.

Holotype. – P1 element MDLCA 30280, illustrated in Fig. 6C, D.

Type horizon and locality. – Bruncu Bullai section, Sardinia, Italy; bed of sample BTE 9.

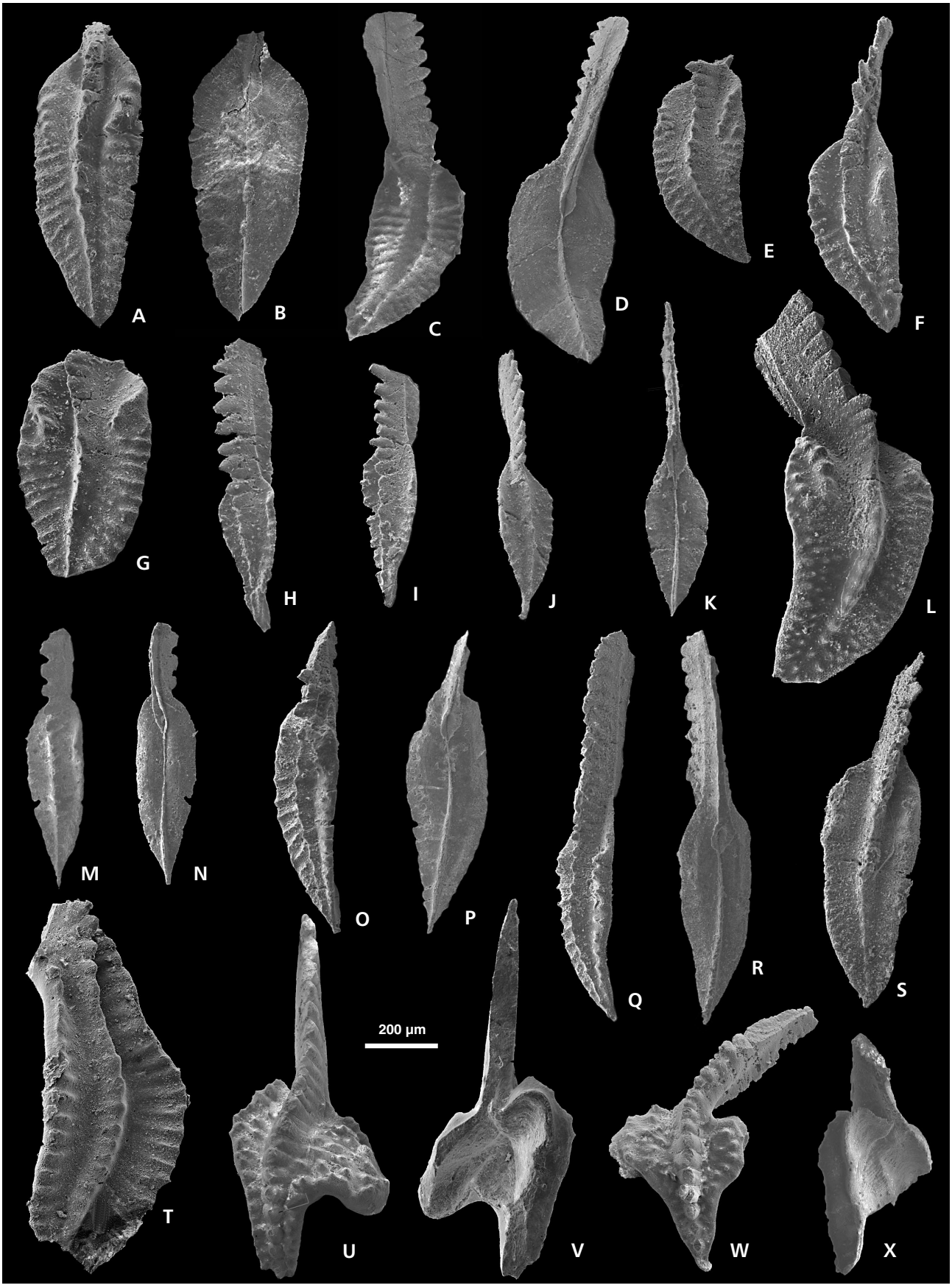
Etymology. – From Latin *cristatus* (= with a crest), referring to the occurrence of the two rows of nodes in the anterior part of the platform

Diagnosis. – Species of *Polygnathus* with a subtriangular elongated platform, strong ornamentation made up of transversal ridges. A row of well-developed nodes is present in the anterior part of each side of the platform. The basal cavity is small, elongated and extends under the free blade.

Description. – *Polygnathus bicristatus* have a subtriangular elongated and slightly asymmetrical platform. The ornamentation is constituted by distinctive transversal ridges that in their inner part almost reach the carina. The ridges tend to be more perpendicular to the carina in the central part of the platform, and with a sharp angle in the posterior part. On the anterior part a row of 2–3 large nodes is present on each side of the platform diverging anteriorly from the carina, forming a structure similar to a collar. The part of the platform between the carina and these anterior rows of nodes is unornamented.

The basal cavity is located under the anterior part of the platform; it is narrow and elongated, and extends as

Figure 6. A, B – *Polygnathus bicristatus* sp. nov.; upper and lower views of MDLCA 30279, sample BTE 9 (Lower *duplicata* Zone). • C, D – *Polygnathus bicristatus* sp. nov.; upper and lower views of the holotype MDLCA 30280, sample BTE 9 (Lower *duplicata* Zone). • E – *Polygnathus bicristatus* sp. nov.; upper view of MDLCA 30281, sample BTE 9 (Lower *duplicata* Zone). • F – *Polygnathus bicristatus* sp. nov.; upper view of MDLCA 30282, sample BTE 9 (Lower *duplicata* Zone). • G – *Polygnathus bicristatus* sp. nov.; upper view of MDLCA 30283, sample BTE 9 (Lower *duplicata* Zone). • H – *Polygnathus* sp. A; upper-lateral view of MDLCA 30284, sample BTE 9 (Lower *duplicata* Zone). • I – *Polygnathus* sp. A; upper-lateral view of MDLCA 30285, sample BTE 9 (Lower *duplicata* Zone). • J – *Polygnathus* sp. A; upper view of MDLCA 30286, sample BTE 9 (Lower *duplicata* Zone). • K – *Polygnathus* sp. A; lower view of MDLCA 30287, sample BTE 9 (Lower *duplicata* Zone). • L – *Polygnathus* sp. B; upper view of MDLCA 30288, sample BTE 9 (Lower *duplicata* Zone). • M, N – *Polygnathus nuragicus* sp. nov.; upper and lower views of MDLCA 30289, sample BTE 9 (Lower *duplicata* Zone). • O, P – *Polygnathus nuragicus* sp. nov.; upper-lateral and lower views of MDLCA 30290, sample BTE 9 (Lower *duplicata* Zone). • Q, R – *Polygnathus nuragicus* sp. nov.; lateral and lower views of the holotype MDLCA 30291, sample BTE 9 (Lower *duplicata* Zone). • S – *Polygnathus nuragicus* sp. nov.; upper view of MDLCA 30292, sample BTE 9 (Lower *duplicata* Zone). • T – *Pseudopolygnathus* sp. A; upper view of MDLCA 30293, sample BTE 10 (Upper *duplicata* Zone). • U, V – *Pseudopolygnathus granulobatus* sp. nov.; upper and lower views of the holotype MDLCA 30294, sample BTE 4 (Middle *expansa* Zone). • W, X – *Pseudopolygnathus granulobatus* sp. nov.; upper view of MDLCA 30295, sample BTE 4 (Middle *expansa* Zone).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a narrow groove under the proximal part of the free blade. The keel is weakly developed posterior of the basal cavity and becomes higher towards the posterior end.

Remarks. – In some elements the ridges on the posterior part of the platform are weak and look to be constituted by narrowly arranged nodes. The size of the anterior rows of nodes can be slightly different on the two sides, being one more developed that the other.

Polygnathus bicristatus is distinguished from the other species of *Polygnathus* because of the characteristic ornamentation and the thin and elongated basal cavity. It differs from *Polygnathus* sp. B because the latter has a somewhat larger platform bearing randomly arranged nodes, instead of ridges, on its posterior part.

Beside Sardinia, this species have been documented in Montagne Noire by Kaiser (2005) and Kaiser *et al.* (2009). A few incomplete specimens of this species occur also in the collection from Monte Taccu (Corradini *et al.* 2003), but were not described by the authors.

Studied material. – 52 elements from samples BTE 9, 10.

Occurrence. – From the Lower *duplicata* Zone to the Upper *duplicata* Zone. The elements reported in the synonymy list came from the Lower *duplicata* Zone.

Polygnathus communis renatae Corradini & Spalletta (*in* Corradini *et al.*), 2003

Figure 7U

2003 *Polygnathus communis renatae* n. ssp. Corradini & Spalletta, p. 236, pl. 2, figs 1–5.

2013 *Polygnathus communis renatae* Corradini & Spalletta. – Mossoni *et al.*, fig. 3.6.

Remarks. – *Polygnathus communis renatae* is characterized by the presence of a single node on the anterior lateral margin on each side of the platform. The presence of these nodes allows distinguishing it from all other subspecies of *Po. communis*. The taxon is up to now known only in Sardinia.

Studied material. – 34 elements from samples BTE 6B–10.

Occurrence. – From the Lower *praesulcata* Zone (Corradini & Spalletta *in* Corradini *et al.*, 2003) to the Lower *duplicata* Zone (this paper).

Polygnathus nuragicus sp. nov.

Figure 6M–S

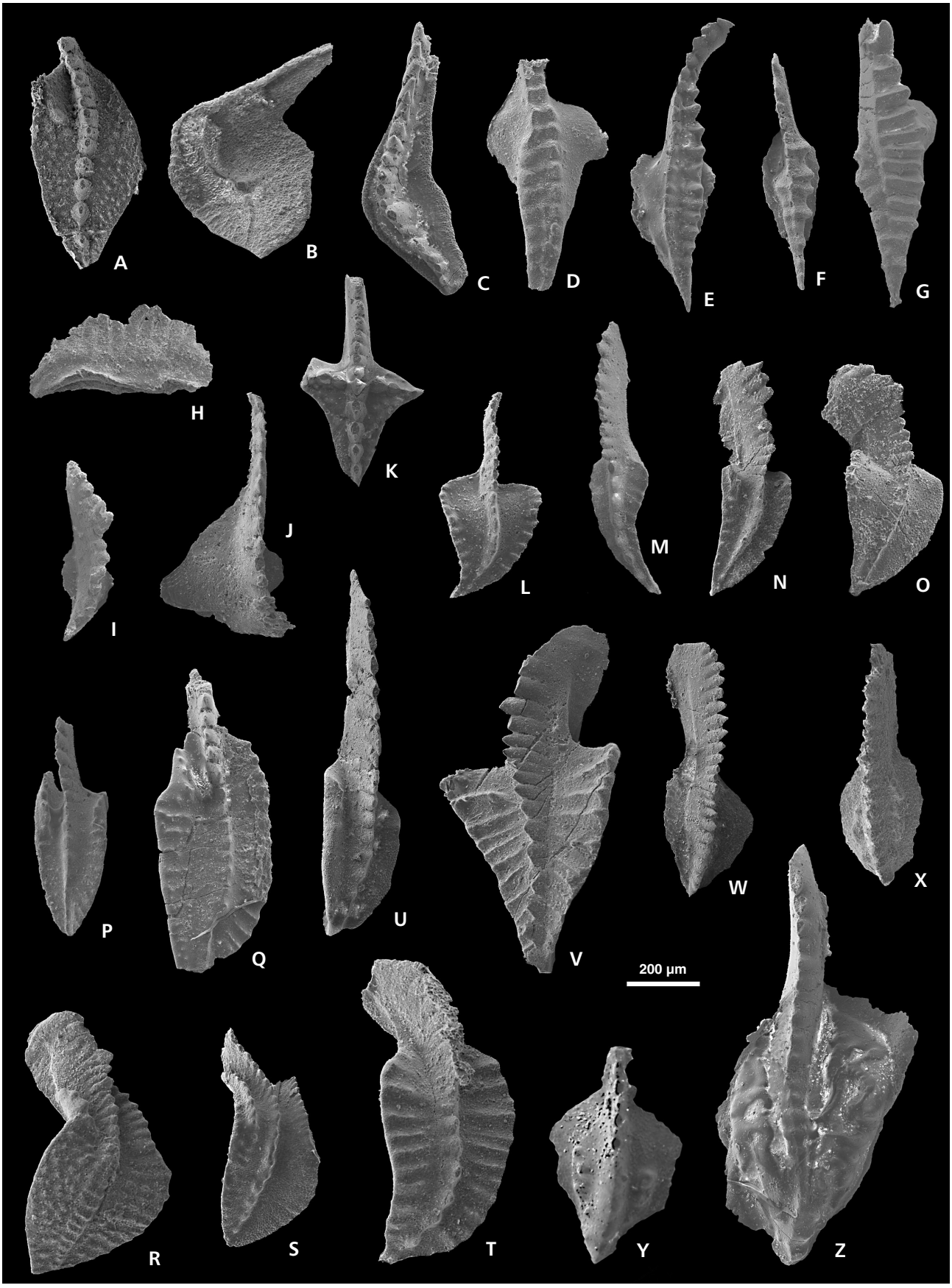
Holotype. – P1 element MDLCA 30291, illustrated in Fig. 6Q, R.

Type horizon and locality. – Bruncu Bullai section, Sardinia, Italy; bed of sample BTE 9.

Etymology. – From the shape of the element that recall an ancient weapon of Nuragic people, the ancient population of Sardinia.

Diagnosis. – Species of *Polygnathus* characterized by a lanceolate and elongated platform, with thickened margins in the anterior part. The platform surface is ornamented by small ridges. The small basal cavity is located under the

Figure 7. A – *Polygnathus styriacus* Ziegler, 1957; upper view of MDLCA 30296, sample BTE 1 (*styriacus* Zone). • B – *Palmatolepis perlobata postera* Ziegler, 1960; upper view of MDLCA 30297, sample BTE 2 (Lower *expansa* Zone). • C – *Palmatolepis gracilis expansa* Sandberg & Ziegler, 1979; upper view of MDLCA 30298, sample BTE 2 (Lower *expansa* Zone). • D – *Bispathodus jugosus* (Branson & Mehl, 1934a); upper view of MDLCA 30299, sample BTE 4 (Middle *expansa* Zone). • E – *Bispathodus costatus* (Branson, 1934); upper view of MDLCA 30300, sample BTE 5 (Upper *expansa* Zone). • F – *Bispathodus spinulicostatus* (Branson, 1934); upper view of MDLCA 30301, sample BTE 6 (Upper *expansa* Zone). • G – *Bispathodus ultimus* (Bischoff, 1957); upper view of MDLCA 30302, sample BTE 5 (Upper *expansa* Zone). • H, I – *Branmehla werneri* (Ziegler, 1957); lateral and upper views of MDLCA 30303, sample BTE 2 (Lower *expansa* Zone). • J – *Branmehla suprema* (Ziegler, 1962); upper view of MDLCA 30304, sample BTE 6 (Upper *expansa* Zone). • K – *Pseudopolygnathus marburgensis trigonicus* Ziegler, 1962; upper view of MDLCA 30305, sample BTE 5 (Upper *expansa* Zone). • L – *Polygnathus tenuiserratus* Corradini & Spalletta (*in* Corradini *et al.*), 2003; upper view of MDLCA 30306, sample BTE 10 (Upper *duplicata* Zone). • M – *Pseudopolygnathus* cf. *nudus* Pierce & Langenheim, 1974; upper view of MDLCA 30307, sample BTE 10 (Upper *duplicata* Zone). • N – *Polygnathus communis dentatus* Druce, 1969; upper view of MDLCA 30308, sample BTE 10 (Upper *duplicata* Zone). • O – *Polygnathus purus purus* Voges, 1959; upper view of MDLCA 30309, sample BTE 8A (*sulcata* Zone). • P – *Siphonodella duplicata* (Branson & Mehl, 1934b); upper view of MDLCA 30310, sample BTE 10 (Upper *duplicata* Zone). • Q – *Siphonodella duplicata* (Branson & Mehl, 1934b); upper view of MDLCA 303111, sample BTE 10 (Upper *duplicata* Zone). • R – *Siphonodella carinthiaca* Schönlaub, 1969; upper view of MDLCA 30312, sample BTE 10 (Upper *duplicata* Zone). • S – *Siphonodella cooperi* Hass, 1959; upper view of MDLCA 303113, sample BTE 10 (Upper *duplicata* Zone). • T – *Siphonodella sulcata* Huddle, 1934; upper view of MDLCA 303114, sample BTE 10 (Upper *duplicata* Zone). • U – *Polygnathus communis renatae* Corradini & Spalletta (*in* Corradini *et al.*), 2003; upper view of MDLCA 30315, sample BTE 8 (*sulcata* Zone). • V – *Pseudopolygnathus triangulus* Voges, 1959; upper view of MDLCA 30316, sample BTE 10 (Upper *duplicata* Zone). • W – *Protognathodus meischneri* Ziegler, 1969; upper view of MDLCA 30317, sample BTE 8 (*sulcata* Zone). • X – *Protognathodus kockeli* Bischoff, 1957; upper view of MDLCA 30318, sample BTE 8 (*sulcata* Zone). • Y – *Protognathodus collinsoni* Ziegler, 1969; upper view of MDLCA 30319, sample BTE 8 (*sulcata* Zone). • Z– *Protognathodus kuehni* Ziegler & Leuteritz, 1970; upper view of MDLCA 30320, sample BTE 8 (*sulcata* Zone).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anterior part of the platform and is followed posteriorly by a keel that reaches the posterior end.

Description. – *Polygnathus nuragicus* has an elongated platform with evident thickened margins in the anterior part. The surface is ornamented with small but distinctive ridges. The carina extends throughout the platform; is higher and made of fused nodes in the anterior part, becoming very low, almost to disappear, close to the posterior end. The free blade is high and as long as the platform.

The basal cavity is small and located under the anterior part of the platform. A narrow keel starts from the basal cavity and reaches the posterior end; it is low under the central part of the platform and became higher posteriorly. A weak depression is present under the central part of the platform.

Remarks. – *Polygnathus nuragicus* is distinguished from representatives of *Po. communis* group because of the lack of the well developed depression just posterior of the basal cavity, and because the keel starts from the basal cavity. It differs from *Po. tenuiserratus* for the shape of the platform and because the latter has the ornamentation limited to the external margins; it is different from *Po. biconstrictus* because the latter has a constricted anterior part of the platform with folded upward margins.

Studied material. – 30 elements from sample BTE 9.

Occurrence. – Lower *duplicata* Zone.

***Polygnathus* sp. A**
Figure 6H–K

Description. – The elements assigned to this species are slender and have a lanceolate platform tipped in the posterior part. The anterior margins of the platform reach the carina with a sharp angle. The platform has reinforced edges at its point of maximum width. Posterior end of the platform tipped.

The ornamentation is weak and made up of transversal ridges stronger close to the lateral margins and disappearing toward the carina. The carina is made by partly fused small nodes that decrease in height from the anterior platform to the posterior end. The free blade is more or less as long as the platform, and bears discrete laterally compressed denticles.

The small basal cavity has an oval shape with raised thickened margins and is located under the anterior part of the platform. A keel extends posteriorly of the basal cavity up to the posterior tip.

Remarks. – In a few elements the posterior part of the platform is so narrow that the end of the carina looks to form a short free blade. *Polygnathus* sp. A is distinguished from *Po. nuragicus* because the latter has thickened margins in the anterior part of the platform. The lanceolate elongated platform distinguish *Po*. sp. A from *Po. tenuiserratus*.

Studied material. – 9 elements from sample BTE 9.

Occurrence. – Lower *duplicata* Zone.

***Polygnathus* sp. B**
Figure 6L

Description. – The elements assigned to this species have a subtriangular elongated and slightly asymmetrical platform. The ornamentation is strong on the anterior and central part of the platform where it consists of evident transversal ridges that interiorly extend almost up to the carina. In the posterior part the platform is covered by nodes randomly distributed. On the anterior part of the platform a row of 2–3 pronounced nodes is present on each side of the platform and diverge anteriorly from the carina. The part of the platform between the carina and these anterior rows of nodes is unornamented.

The basal cavity, located under the anterior part of the platform, is narrow and elongated, and extends as a narrow groove under the proximal part of the free blade. The keel is weakly developed posterior of the basal cavity and it become higher in the posterior part.

Remarks. – *Polygnathus* sp. B is distinguished from *Polygnathus bicristatus* by the generally wider platform and the ornamentation constituted by randomly arranged nodes on the posterior part of the platform.

Studied material. – 4 elements from sample BTE 9.

Occurrence. – Lower *duplicata* Zone.

Genus *Pseudopolygnathus*, Branson & Mehl, 1934a

***Pseudopolygnathus granulobatus* sp. nov.**
Figure 6U–Y

Holotype. – P1 element MDLCA 30294, illustrated in Fig. 6U, V.

Type horizon and locality. – Bruncu Bullai section, Sardinia, Italy; bed of sample BTE 4.

Etymology. – From Latin *granulosus* (= covered by nodes) and *lobatus* (= with a lobe), referring to the shape of the platform.

Diagnosis. – A species of *Pseudopolygnathus* characterized by an asymmetrical, strongly heart-shaped, ornamented platform, with a distinctive lateral lobe. The platform is large in the anterior part and narrow posteriorly. The basal cavity is large and extends below the whole element.

Description. – The elements assigned to *Ps. granulobatus* have a subtriangular or heart-shaped platform, larger in the anterior part of the element and narrow posteriorly. Posterior end tipped. A distinct lobe is present on one side of the platform.

The surface of the platform is strongly ornamented with nodes randomly disposed on the anterior part and more or less aligned with the lateral margin on the narrow posterior part. The carina, constituted by strong nodes, reaches the posterior end of the element; it is high on the anterior part of the platform and decreases in height posteriorly, in connection with the narrowing of the platform. Anteriorly the carina continues in the high free blade that bears discrete denticles.

The basal cavity is wide and extends below the whole platform.

Remarks. – *Pseudopolygnathus granulobatus* is distinguished from *Ps. granulosus* by the pronounced lobe at one side of the platform and from *Ps. marburgensis trigonicus* because the latter shows a row of distinctive nodes in the anterior part of the platform and has a distinctive basal cavity. The ornamentation is more pronounced in the large elements, than in the small ones.

Studied material. – 12 elements from sample BTE 4.

Occurrence. – Middle *expansa* Zone.

Conclusions

The main results of this work on the Bruncu Bullai section can be summarized as follows:

1. fifty-seven taxa, between species and subspecies, belonging to *Branmehla*, *Bispathodus*, *Icriodus*, *Mehlina*, *Palmatolepis*, *Polygnathus*, *Protognathodus*, *Pseudopolygnathus*, and *Siphonodella* have been recognized;

2. a new species of *Pseudopolygnathus* (*Ps. granulobatus*), two of *Polygnathus* (*Polygnathus bicristatus*, *Polygnathus nuragicus*) are described and illustrated. Two more taxa of *Polygnathus* are left in open nomenclature;

3. the range of *Polygnathus communis renatae* have been extended to the Lower *duplicata* Zone;

4. on the basis of the relative abundance of *Prothognathus* and *Siphonodella*, a possible ecological control on the occurrence of the two genera is suggested, where competition and feeding are claimed to explain the "alternate" occurrence of the two genera in the latest Famennian and basal Tournaisian;

5. the Hangenberg crisis is supposed to start already in sample BTE 6C, before the shale level;

6. as for regional geology of Sardinia, the presence of black shales with siliceous nodules above the "Clymeniae limestones" is documented. According to field observations this level is tentatively considered as Tournaisian; however more data are necessary for precisely state its age.

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