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The Silurian of Sardinia (Italy): more than one and half century of researches

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ABSTRACT - This paper is a synthetic historical review of researches on the Silurian of Sardinia, that, starting from the XVIII Century, were carried out by manly Italian scientists (palaeontologists, geologists, mining engineers) often with the valuable contribution by other European experts.

KEY WORDS - Historical studies, stratigraphy, palaeontology, Silurian, Sardinia.

INTRODUCTION

Silurian sediments have been recognized for the first time in Sardinia on a palaeontological basis by La Marmora (1857) - pioneer of geological studies on the island. Such rocks crop out mainly in southern Sardinia, both in the southwestern (Sulcis, Iglesiente, Fluminese, Guspinese, Arburese subregions) and in the southeastern part (Sarrabus and Gerrei subregions; Fig. 1). Silurian sediments are part of the Cambrian-Lower Carboniferous sequences developed in the "External Zone" and in the "External Nappes Zone" of the "Sardic Hercynian Chain", respectively (Barca, 1998; Carmignani et al, 2001b; and references therein). The metamorphic grade is always quite low in these zones, but tectonic deformations (folds, overthrusts, etc.) are responsible of considerable discontinuity of Silurian outcrops.

In the Inner Nappes Zone (North-central Sardinia: Barbagia, Ogliastra, Anglona, Logudoro, Baronie, Nurra subregions; Fig. 1) the Silurian outcrops are scarce and fossils are very rare due to increasing metamorphic grade and stronger Variscan tectonic deformations. In these areas, owing to the lack of palaeontological data, rocks are referred to Silurian (or to indifferentiated "Silurian-Devonian") on the basis of lithological analogies (black shales, lydites, metalimestones, marbles) with fossiliferous facies occurring in southern Sardinia.

For better understanding old papers, it should be pointed out that stratigraphical and structural features of the Variscan Basement of Sardinia were made clear only recently. Therefore, several outcrops of dark slates, metasandstones and quarzites, mainly in southeastern Sardinia, were referred to Silurian or indifferentiated Silurian-Devonian (i.e.: Servizio Geologico d'Italia, 1959, 1963, 1976). These rocks actually belong to various lower Palaeozoic periods. Furthermore, large Silurian olistoliths (namely graptolitic black shales and/or lydites) within the thick siliciclastic Lower Carboniferous succession of the so called "Sardic Hercynian Flysch" (Pala Manna Formation; Barca, 1991; Barca & Olivieri, 1991; Barca et al., 1998) were previously considered as true outcrops, both in the eastern part of Sulcis-Iglesiente (southwestern Sardinia) and in the Sarrabus-Gerrei (southeastern Sardinia).

Fig. 1 - Main sub-regions of Sardinia with location of historical Silurian fossiliferous localities.

This paper is a brief historical review of researches that, starting from the middle of the XVIII Century, brought to the present lithostratigraphical and biostratigraphical knowledge of the Silurian of Sardinia. Many papers arose from cooperation between palaeontologists and mining engineers (Taricco, Testa, Novarese, Sartori) and geologists, responsible for discovering new localities, mapping and even collecting fossils.

Scientists from several European countries (mainly Germany and Czech Republic) spent time and efforts on the Silurian of Sardinia, sometimes working alone, more often in collaboration with Italian geologists and palaeontologists.

Studies on the Silurian of Sardinia

According to what mentioned above, the large majority of the papers on the Silurian of Sardinia deals with the low metamorphic grade fossiliferous rocks of the southern part of the island.

The first palaeontological paper on the Silurian of Sardinia was published by Meneghini (1857), author of a chapter on "Paléontologie de l'Ile de Sardaigne" in the historical "Voyage en Sardaigne" by La Marmora (1857). There the author describes and beautifully figures several fossil groups of various Palaeozoic age. As regards the Silurian, Meneghini reports a dozen of new species of graptolites from samples collected by La Marmora in the famous Goni locality (Gerrei). The Meneghini`s collection was restudied sixty-five years later by Gortani (1923a), who examined also new material from the same locality and describing about thirty new graptolite species. Gortani (1923b, 1934) published two more monographs on graptolites from southeastern Sardinia, describing several species and recognizing for the first time the occurrence of Llandovery (with *Diplograptus palmeus, D. tamariscus, Climacograptus normalis, Rastrites*) and Wenlock (with *Monograptus sardous, M. vomerinus, M. falcatus, M. antennularius, Cyrtograptus rigidus*) sediments in Sardinia. The same author (Gortani, 1922, 1927, 1935) described the Silurian-Devonian sequences of Sardinia, comparing with the coeval succession of the Carnic Alps (northeastern Italy). An unconformity between Silurian and Upper Devonian of the Gerrei (southeastern Sardinia) was supposed by Gortani (1922) and later denied by the same author (Gortani, 1927).

Most of the Gortani's original graptolite collection is now housed in the museum of the University of Pisa, together with the Meneghini's collection. Other graptolites collected by Gortani are preserved in the university museums in Bologna, Parma, Pavia and Cagliari (Piras et al., 2008).

In the same period of Gortani's researches, Taricco (1922a,b) listed some Lower Silurian graptolites from the Fluminimaggiore area (southwestern Sardinia), but unfortunately without any illustration. The same author (Taricco, 1911) had already reported the occurrence of graptolites near Gadoni village (Barbagia, central Sardinia), published a short note on the "Gotlandian" of Sardinia (Taricco, 1913) and discovered Silurian fossiliferous localities in the Sarrabus subregion (Taricco, 1915).

Important papers on graptolites from southeastern Sardinia are also due to Teichmüller (1931), Helmcke (1973), Helmcke & Koch (1974) and mainly Jaeger (1976, 1977). The latter author observed the strong affinities between the Silurian sequence of southeastern Sardinia and Thuringia and reported for the first time Early Devonian graptolites (*Monograptus uniformis* and *M. hercynicus* biozones) from the Baccu Scottis section. The knowledge on graptolites from southeastern Sardinia considerably increased owing to Jaeger (in Barca & Jaeger, 1990; Jaeger, 1991). Further occurrences of graptolitic black shales in that area were also reported by Barca (1981), Tistl (1981) and Schwab (1982).

In southwestern Sardinia, outcrops with Silurian graptolites are described by Amadei et al. (1957) and Barca & Marini (1983) at Genna Muxerru and Genna Gruxi, close to the Guspini village, by Barca & Salvadori (1974) and Barca et al. (1992a, b) in the Arburese subregion, and by Barca et al. (1986; 1998) in the Sulcis area. Finally Palmer & Gnoli (1985) reported an important find of *Saetograptus* cf. *fritschi* Perner close to the Fluminimaggiore village.

Recent papers dealing with these important Silurian fossils from Sardinia are due to Gnoli et al. (1990), Storch & Serpagli (1993), Rickards et al. (1995), Pittau & Del Rio (1998), Pittau et al. (2002), Storch et al. (2002) and Corradini (2007). Finally, Piras et al. (2008) described graptolites from the Gortani collection housed in the Palaeontological Museum "D. Lovisato" of Cagliari University, which includes seven Wenlockian taxa from Goni and one from the Llandovery of Fluminimaggiore. The current knowledge on Silurian graptolite fauna of southern Sardinia and its application in biostratigraphy is reviewed by Storch & Piras (2009, this volume).

Beside graptolites, Meneghini (1857) described and illustrated several taxa of nautiloid cephalopods from the Silurian "*Orthoceras* limestone" of southern Sardinia. Reports on these abundant fossils are also due to Taricco (1913), from central-eastern Sardinia, and Teichmüller (1931) and Ristedt (1968) from the South. A rare "*Orthoceras* breccia", reported by Venerandi (1965) from the Nurra sub-region, is probably Silurian in age and represents one of the few Palaeozoic fossils found in the northwestern part of the island.

A revision of the Meneghini collection was carried on by Gnoli & Serpagli (1977). The same authors (Serpagli & Gnoli, 1977) published also an important monograph on Silurian nautiloid cephalopods from southwestern Sardinia, describing and illustrating several species, a few of them new. Later on, Gnoli et al. (1979) emphasized palaeoecological significance of the middle-upper Silurian "Calcare ad *Orthoceras*" of southwestern Sardinia, and Gnoli (1990) evidenced the affinities between nautiloid communities of Sardinia and Bohemia. Other important papers on these fossils were published by Gnoli et al. (1988, 1990), Gnoli & Serpagli (1991) and Histon & Gnoli (1994) from southwestern Sardinia, and by Gnoli (1993) from southeastern Sardinia.

Occurrences of Silurian limestones with orthoceratids from southeastern Sardinia were reported by Barca (1981; Sarrabus) and Barca & Argiolas (1985; Gerrei), whereas Barca & Salvadori (1974) and Barca et al. (1992a, b) referred on outcrops in the Arburese area (southwestern Sardinia).

Among other fossil groups from the Silurian of Sardinia, several papers refer to the occurrence of crinoids. Meneghini (1887) described *Actinocrinus* from the Sarrabus. The occurrence of the pelagic *Scyphocrinites* in southeastern Sardinia is reported by Helmcke (1973), Jaeger (1976, 1977) and Corradini et al. (1998). Serpagli & Mastandrea (1980) and Gnoli et al. (1988) encountered scyphocrinids in the southwestern part of the island. The claimed occurrence of Silurian crinoids near the Domusnovas village (Scarzella, 1915) and Corr'e Boi (Testa, 1922b) should be disregarded, the first being probably Ordovician, and the latter Devonian in age. It should be noted that Testa (1915, 1918, 1922a, c) is the author also of other unconfirmed occurrences of crinoids and "Silurian fossils" in several localities of southeastern Sardinia, and in the Iglesiente (Testa & Sartori, 1915).

A dozen of species of Silurian bivalves, mainly *Cardiola*, were described from the "*Orthoceras* limestone" of southern Sardinia by Meneghini (1857, 1880), Barrande (1881, in Serpagli 1982), Taricco (1922a, b), Gortani (1922) and Teichmüller (1931). More recently Kriz & Serpagli (1993) described and illustrated several Bohemian-type bivalve-dominated communities from southwestern Sardinia.

Gastropods are quite rare in Sardinia and only small specimens have been described from Silurian black limestones by Meneghini (1857) and Gortani (1922).

Trilobites are very rare in the Silurian of Sardinia. Fondi (1985) and Carosi et al. (1987) claimed the occurrence of Silurian trilobites (Harpidae and Phacopidae) close to the Ballao village (southeastern Sardinia), but their specimens likely come from the Lower Devonian. More sure is the occurrence of *Ampyx* sp. aff. *roualti* Barrande near Fluminimaggiore (Palmer & Gnoli, 1985).

Reports on other macrofauna are quite rare from the Silurian of Sardinia: phyllocarids (Gnoli & Serpagli, 1984; Gnoli & Serventi, 2005), eurypterids (Gnoli, 1992a) and the problematic *Kolihaia sardiniensis* (Gnoli, 1992b) were described from the southwestern areas; the occurrence of brachiopods (*Merista passa* and three doubtful specimens) is reported by Teichmüller (1931) from the southeastern Sardinia.

Starting from the sixties of the XX Century, investigation on microfossils largely increased the stratigraphical knowledge of the Palaeozoic of Sardinia. Most of these researches were carried on by the Palaeozoic research group of Modena University, led by Enrico Serpagli, and were mainly based on conodont associations from Silurian and Devonian calcareous rocks from southern Sardinia (Corradini, 1998). Studies on conodonts are still in progress, but several scientific papers have been already published. Furthermore, in connection with the "*Seventh International Conodont Symposium Held in Europe (ECOS VII)*" (June 1998) a field trip was organized in Sardinia and the guide book (Serpagli, 1998) includes many recent data on the Palaeozoic, especially Silurian, of Sardinia.

Serpagli (1967) firstly reported the occurrence of Silurian conodonts in Sardinia, collected from the "Calcari ad *Orthoceras*" of Fluminimaggiore area; slightly later the same author (Serpagli, 1971) described and illustrated the complete association. Thanks to these data, Serpagli better defined the Silurian sequence of the Iglesiente, previously defined by Taricco (1922a) and Novarese & Taricco (1923). More precisely Serpagli was able to confirm a Devonian age for the upper part of the sequence described by Taricco (1922a) as:

- upper Gotlandian - nodular limestones, calcareous shales with *Tentaculites* (partly Devonian?), shaley limestones and black shales;
- middle Gotlandian - Ampelitic limestones with *Monograptus priodon*, *Cardiola interrupta*, (a.o.).
- lower Gotlandian - Black shales with *Rastrites peregrinus*, *Diplograptus palmens*, (a.o.).

For several years researches were mainly focused on the Fluminimaggiore area. Serpagli & Mastandrea (1980) described a conodont association across the Silurian-Devonian boundary from Fluminimaggiore, and Serpagli (1983) described the apparatus of *Icriodus woschmidti woschmidti*. Gnoli et al. (1988) studied the Mason Porcus section as a reference section for the uppermost Silurian-Lower Devonian in southwestern Sardinia, Ferretti (1989) described the microbiofacies and Olivieri & Serpagli (1990) illustrated the rich conodont fauna. Gnoli et al. (1990) established formal lithostratigraphic units in the Silurian and Lower Devonian of southwestern Sardinia, while Barca et al. (1992a, b) provided stratigraphical and structural data in the Arburese unit.

Several papers on Silurian conodonts from southern Sardinia provided important contributions on biostratigraphy, palaeoecology and stratigraphic correlations: for a complete list refer to the appendix to Corriga et al. (2009, this volume).

The stratigraphical sequence and conodont associations from the Ockerkalk limestone of southeastern Sardinia are described in detail by Barca et al. (1994, 1995) and Corradini et al. (2000, 2001, 2002a, b). Recently, Gouwy & Corradini (2006) applied the graphic correlation method on eight sections from the Ockerkalk, and stressed important implications for conodont biostratigraphy.

Several papers and reports have been dealing also with other microfossil group from the Silurian of Sardinia since the second half of the XIX Century. Bornemann (1860, in Meneghini) reports the occurrence of Palaeozoic ostracods from the "Silurian shales", listing three species of *Berychia*; however, these findings should be referred to Ordovician sediments (Schallreuter et al, 2007). Canavari (1899, 1900) published two important studies on Silurian ostracods from the "dark limestones with *Cardiola* and *Orthoceras*"; more recently Palmer & Gnoli (1985) described myodocopid ostracods from southwestern Sardinia, providing a careful taxonomic and biostratigraphical revision of this fauna.

Micropalaeontological researches carried on by scientists of the Istitute di Geology and Palaeontology (now Earth Science Department) of Cagliari University since the seventies of the last century mainly dealt with Silurian acritarchs and chitinozoans discovered in several areas, both in southwestern (Del Rio et al., 1980) and in southeastern Sardinia (Pittau & Del Rio, 1998, 2002; Pittau et al., 1998). Silurian and Devonian chitinozoans from southwestern Sardinia were described also by Dufka & Gnoli (1996).

Rare Foraminifera were reported from the upper Silurian-Lower Devonian of Fluminimaggiore (Gnoli & Serpagli, 1985), whereas probable agglutinated foraminifers are described from the Wenlock of Goni, together with radiolarians (Pittau et al., 2002). The occurrence of radiolarians in southeastern Sardinia was underlined also by Greiling (1977, in Barca & Jaeger, 1990). Finally, Pittau et al. (2003) refer to the occurrence of Silurian silicispongia.

Conclusions

Present knowledge on the Silurian of Sardinia is backed by more that one and half century of researches. All the four Silurian series (Llandovery, Wenlock, Ludlow and Pridoli) are palaeontologically documented and a good biostratigraphic resolution has been achieved, mainly on the basis of graptolites and conodonts.

The sedimentary sequence is continuous in Sardinia from the base through to the top of the Silurian System. A prominent unconformity between the uppermost Ordovician and the lower Silurian, marked by a hiatus where Llandovery and part of the Wenlock would have been missing, claimed by a few authors (Cocozza et al., 1974) can be definitely excluded. Analogously, a continuos sedimentation occurs at the Silurian-Devonian boundary.

According to the present stratigraphical scheme, the Silurian of southwestern Sardinia is represented by two lithostratigraphical units (Gnoli et al., 1990): the lower Silurian Genna Muxerru Formation ("Scisti a graptoliti" Auct.), followed by the Fluminimaggiore Formation ("Calcari ad *Orthoceras*" Auct.). Faunal content has strong affinities with coeval associations from Bohemia (Gnoli, 1990; Kriz & Serpagli, 1993).

In southeastern Sardinia the sequence is similar to those cropping out in Thuringia (Jaeger, 1976, 1977; Barca & Jaeger, 1990). Two lithostratigraphical units, still not formalized, are called: the "Lower Graptolitic Shales" (Barca & Jaeger, 1990) ("Scisti a graptoliti" Auct.), including Llandovery to lower Wenlock shales (Gortani, 1923 a, b; Helmcke,1973; Barca & Jaeger, 1990; Jaeger, 1991), and the "Ockerkalk limestone" of Ludlow-Pridoli age.

Recent stratigraphical, structural and petrographic investigations in connection with a new detailed mapping project of southern Sardinia (Carmignani et al., 2001a, b; Barca et al., 2005 and references therein) allow to deny the presence of volcanics interbedded to Silurian metasediments in southeastern Sardinia, claimed by several authors of the XIX Century (Cavinato, 1948; Calvino, 1961; Pomesano Cherchi, 1962; Cocozza et al., 1974; Di Simplicio et al., 1974; Cocozza & Minzoni, 1977; Beccaluva et al., 1981). These volcanics actually are Middle Ordovician (rhyolites, "porfiroidi", etc.; Barca & Di Gregorio, 1979; Barca & Maxia, 1982; Carmignani et al., 2001a, b) or Upper Ordovician (basic volcanics; Lehmann, 1975; Memmi et al., 1982; Naud, 1982; Barca & Argiolas, 1985; Leone et al., 1991; Di Pisa et al., 1992; Carmignani et al., 2001a, b; and references therein). Their wrong stratigraphical placement came from the still unclear tectonic interpretation of the region, where tectonic contacts were often considered as stratigraphical boundaries.

Silurian sediments had also a strong importance in the history of mining exploitation of Sardinia. This is true mainly in the southeastern part of the island, where mesothermal mineralizations (mainly sphalerite, galena, chalcopyrite, fluorite and baryte, native silver, etc.) occur within a cataclastic-mylonitic belt (Traverso, 1890; De Castro, 1890; Cavinato, 1939; Vardabasso, 1948; Zuffardi, 1967; Valera, 1974; Marcello et al., 1978, 1994, 2004; Salvadori et al., 1982; Bakos et al., 1991; Stara et al., 1993; Carmignani et al., 2001a; Tocco et al., 2009; and references therein). In the Sarrabus sub-region, that level was historically known as "Filone Argentifero" (= "Silver belt").

Always in southeastern Sardinia, another cataclastic-mylonitic belt with antimony mineralization within Silurian shales occurs in connection with the "Villasalto overthrust", an important tectonic structure between the Gerrei and Sarrabus tectonic units (Carmignani et al., 2001a, b).

Finally, beside papers reported in this summary on the Silurian of Sardinia, further information can be obtained from bibliographical papers by Cartisano et al. (1922), Taricco & Sotgia (1922), Maxia (1941, 1973), Comaschi & Caria (1949), Segre (1964), Nicosia (1968), and Serpagli & Gnoli (1984).

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