Rendiconti della Società Paleontologica Italiana

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The Silurian of Sardinia

volume in honour of Enrico Serpagli

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Società Paleontologica Italiana
2009

The Silurian of Sardinia: facies development and palaeoecology

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Abstract - Main features of the Silurian sequences exposed in Sardinia (Italy) are here described. Oldest sediments are represented by black shales, rich in graptolites, grading into a calcareous facies throughout the middle Silurian; however, the sequences exposed in the southeast and in the southwest are different, even if some similitude is evident. The spectacular variety of invertebrate fossils is briefly outlined and their environmental settings are discussed in the attempt of giving a contribution to the global picture of Silurian events.

Key words - Silurian, Sardinia, Palaeoenvironment, Facies distribution.

Introduction

Silurian rocks of Sardinia contain abundant, diverse and well preserved marine faunas whose study has been continuous for about 150 years, starting from Meneghini pioneer paper of 1857 where the oldest Italian nautiloids, bivalves and graptolites were illustrated. However, descriptions of these faunas are spread across a large number of disparate monographs and shorter papers. The strong tectonic activity which repeatedly affected the region resulted in the absence of continuous sections spanning across the full system. The outcrops, although extensive, are mostly constituted of displaced blocks of tectonized - faulted, folded and cleaved rocks. This drawback often discouraged attempts to get a comprehensive vision of the Silurian scenario of Sardinia. The best known Silurian fossils from the region are the cephalopods and the graptolites, which represent the most significant pelagic elements of the fauna, and have the latter been used, to a greater or lesser extent, for biostratigraphical correlation. Later on, new information were added either on the benthic (e.g. Kriz & Serpagli, 1993) or pelagic (e.g. Palmer & Gnoli, 1985; Storch & Serpagli, 1993) fauna and a more precise stratigraphical assignment was finally achieved by means of conodonts (e.g. Serpagli, 1998).

Silurian life and depositional settings in the Sardinian sea

As described previously, fossiliferous Silurian rocks crop out almost exclusively in southern Sardinia, in two different areas of the island: in the southwestern sector with the Iglesiente and Sulcis sub-regions, and in the southeastern sector that involves the Gerrei and Sarrabus sub-regions. Silurian successions of the two parts of the island remind to coeval successions exposed in Bohemia and Thuringia respectively. However, their mutual relation is still unraveled.

Black-shale entrance

The Silurian Period spans about 27 million years (Ogg et al., 2008). The terminal Ordovician faunal extinction, triggered by a major glaciation on the southern supercontinent of Gondwana, produced a radical change-over of the marine biota. After the marked provincialism of the pre-glacial Late Ordovician, rather uniform facies of pelagic and hemipelagic black shales characterize post-glacial Silurian succession of northwestern Gondwana and close-by areas. Rapid late Hirnantian (terminal Ordovician) deglaciation of the Gondwana supercontinent lead to a dramatic rise of sea-level that, together with ocean stratification, triggered a wide-spread early Silurian post-glacial marine anoxia. Graptolite-rich black shales predominated in the Llandovery and Wenlock of the peri-Gondwanan Europe (Storch, 1998) with most spectacular sections exposed in Spain, Portugal, Sardinia, the Carnic Alps, Thuringia and Bohemia (Storch, 1998). Their rich and closely similar faunal content, in graptolite terms, has enabled a precise biostratigraphical correlation within the area. Rapid evolution of moderately to highly diversified graptolite faunas was punctuated by several extinction events assigned by Melchin et al. (1998) and Loydell (1998) to persisting glacioeustatic sea-level fluctuations. Graptolite faunas extended over wide shelves and basins along the northwestern margin of Gondwana, with local differences explained largely by different depositional depths and local environmental conditions expressed in three depth-/nutrient related graptolite sub-faunas recognized by Storch (1998): 1) a low diversity, oxygen tolerant sub-fauna in shallow-shelf environments; 2) a moderate diversity sub-fauna, associated with non-graptolite macrofossils (e.g., eurypterids, ceratiocarids, nautiloids, bivalves, brachiopods and crinoids) suggesting anoxic conditions at the sediment/water interface; 3) a sub-fauna of typical hemipelagic anoxic black shales, with particularly rich graptolite assemblages. The last named graptolite sub-

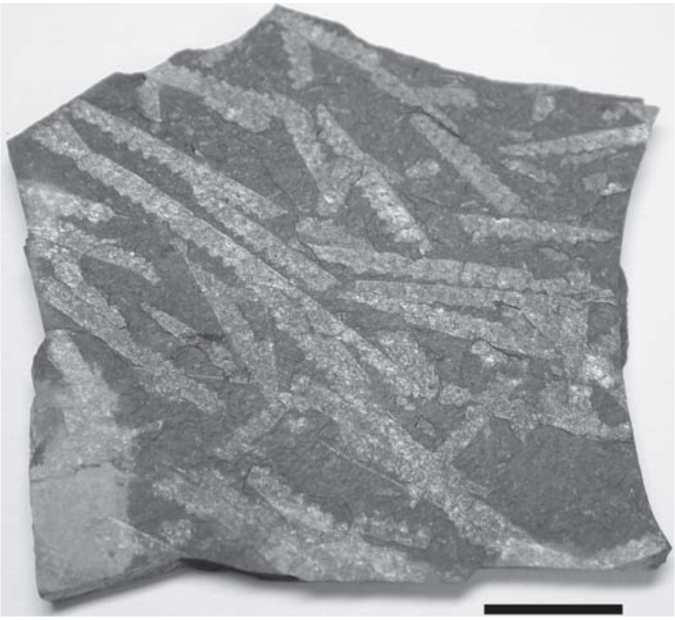


Fig. 1 - Lower Graptolitic Shales, Goni Section, level with *M. praedeubeli* (Wenlock, identified by H. Jaeger, 1987, pers. com.). Scale bar = 1 cm (refigured after Corradini *et al.*, 2002).

fauna has a wide distribution in the peri-Gondwanan Europe, reflecting presumably deep shelf to upper slope facies, or even a deeper, sediment starved depositional environment for the alum shales and silicites which occur in Thuringia and southeastern Sardinia (Storch, 1998).

Also in the territory of Sardinia, the lower Silurian is characterized with rather uniform graptolitic silica-argillaceous and siltitic black shales (Fig. 1). In southeastern Sardinia, graptolitic black shales (alum shales) are subordinate to lydites (black silicites) in the lower part of the succession. Phosphorites are present, but only in southeastern Sardinia, in the middle-upper part of the shales in form of nodules, lenses or proper layers (Barca & Jaeger, 1990).

In southwestern Sardinia, 20-25 m thick graptolitic shales assigned to the Genna Muxerru Formation have documented a Llandovery age (Storch & Serpagli, 1993; Storch et al., 2002). In southeastern Sardinia, the deposition of the 40 m thick Lower Graptolitic Shales spans over a longer time period, persisting in this area also through Wenlock to earliest Ludlow times. In both sectors of the island, graptolitic shales appear to have started just at the very beginning of the Silurian, as the *ascensus-acuminatus* graptolite Biozone is documented (Storch & Piras, 2009). Random orientation of the graptolite rhabdosomes was more commonly observed on bedding planes than alignment by currents. Apart from graptolites, radiolarians (Barca & Jaeger, 1990), chitinozoans (Pittau et al., 1998; Pittau & Del Rio, 2000) and muellerisphaerid spherulae (Pittau et al., 1998) have been reported from the graptolitic shales.

Limestone propagation

The shaley deposition was replaced diachronously by a calcareous sedimentation which started sporadically already in late Llandovery (Barca et al., 1992) and more definitely in late Wenlock times with lenticular limestone beds intercalated to shales in southwestern Sardinia. In the southeastern Sardinian sub-regions, the limestone deposits commenced in Ludlow times.

The calcareous unit of southwestern Sardinia belongs to the Fluminimaggiore Formation, a unit 45-50 m thick spanning from late Llandovery to earliest Lochkovian. Black calcareous lens-shaped beds alternate with dark non calcareous pelites and shales. These well known limestones, often referred to as “calcari a *Orthoceras*, *Cardiola*, *Monograptus*, ecc.”, are similar to other cephalopod-dominated limestones (Fig. 2) developed in other sectors of the northern Gondwana setting, having certainly in the Prague Basin the most typical exposures. Cephalopods are the most striking elements of the fauna, but at naked eyes also bivalves, pelagic ostracodes and graptolites may be easily recognized. Conodonts, forams, chitinozoans and muellerisphaerids are also present. Gastropods, brachiopods, trilobites and eurypterid fragments are, on the contrary, extremely rare. Phyllocarids and pelagic crinoids may be found towards the top of the formation.

The nautiloid fauna recovered in southwestern Sardinia is most closely related to that occurring in coeval levels of Bohemia. Gnoli et al. (1980), on the basis of measurements made on large cephalopod slabs and blocks and of laboratory experiments, reported a definite double alignment of orthoconic shells, similar to the crest and trough of ripple marks and to the distinctive bimodal orientation model of wave accumulation. A constant cephalopod orientation was reported from isolated spots in a late Wenlock-Ludlow locality of southwestern Sardinia by Ferretti et al. (1998). Displaced blocks, with random oriented orthocones, are also present (Ferretti et al., 1995).

Largely epibyssate bivalves of the *Cardiola* Community Group (Kriz, 1999) represent the only significant indicators of a benthic epifauna, as almost no trilobites and brachiopods

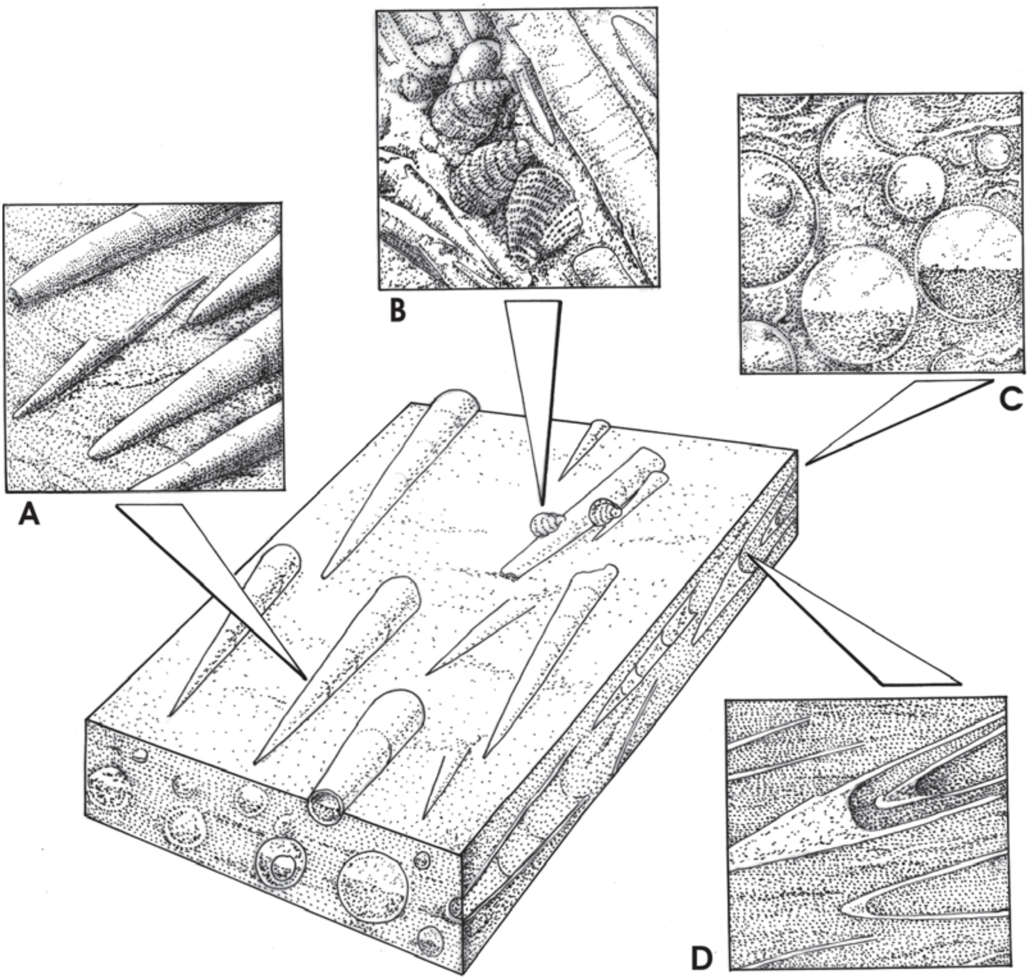


Fig. 2 - Cephalopod limestone main features: A) frequent isorientation of cephalopod shells; B) association between cephalopod shells and bivalve-dominated communities; C) concordant geopetal structures of cephalopod shells; D) “telescoping” (shell-in-shell structure) of cephalopod shells (modified after Ferretti & Kriz, 1995).

are present, possibly reflecting the existence of anomalous oxygen conditions which could not be tolerated by these organisms. Mass occurrences of shells were possibly resulting from regular mass mortalities caused by abiotic conditions (Kriz & Serpagli, 1993).

Flattened rhabdosomes of the Silurian graptolites have been described for a long time from the black shales of classical localities both in southwestern and southeastern Sardinia. Less known is the preservation of graptolites packed together in pseudolenticular limestone bodies, up to 1 m big, developed only in southwestern Sardinia in strict association with the typical cephalopod-dominated limestones. This unusual type of limestone is literally crowded by graptolite rhabdosomes preserved in full three-dimensions (Fig. 3). Graptolites from these bodies document a late Wenlock-early Pridoli age; the age was confirmed also by conodonts. Monospecific or oligospecific graptolite associations are present in each block. Wenlock-Ludlow graptolitic limestones are characterized by species of the straight robust *Monograptus*, *Colonograptus* or *Saetograptus* together with rare *Bohemograptus*. Early Pridoli associations are dominated by species of "*Monograptus*" (Ferretti & Serpagli, 1996b). Polished slabs obtained from cross-sectioned graptolite limestones revealed centimetric graptolite-packed layers, with sharp base, separated by fine grained calcareous mudstones where sparse graptolite fragments and small cephalopods, with common geopetal infills, are present. Most cephalopods still preserve body chambers which are sometimes filled by graptolites. These concentrations represent discrete event horizons of graptolites which were probably living in an environment close to that of cephalopods and had developed a similar sort of tolerance towards oxygen content and/or other palaeoecological constraints (Ferretti & Serpagli, 1996b). Orientation measurements on the graptolite distribution of some blocks revealed how both random and current oriented concentrations are present, even for graptolites belonging to the same genus or species and having therefore similar hydrodynamic behaviour.

Ferretti (1989) described five different microfacies (Fig. 4) in the Wenlock-upper Ludlow limestones of southwestern Sardinia, related to two main different regimes: a shallow-high energy deposition for the cephalopod-ostracode packstone-wackestones (typical of the "*Orthoceras* limestones"), the graptolitic packstones and the "coated-grains" grainstone-packstones, and a deposition below normal wave-base but probably in areas within storm wave-base for rare Ludlow pre-nodular mudstones with intercalated shell-lags and for dark laminated fossiliferous mudstones found locally. In Pridoli time, a shift to a deeper environment is suggested by dark fossiliferous mudstones, where winnowed shell lags of disarticulated thin-shelled and convex-up bivalves and ostracodes, small orthocones and rare crinoidal fragments are present (Ferretti, 1989).

A crinoidal bioclastic packstone, associated with *Scyphocrinites* loboliths, caps the Fluminimaggiore Fm. The same distinctive horizon is present in many other Gondwana

Fig. 3 - Graptolitic limestone exposed in southwestern Sardinia (Perd'e Fogu locality, Fluminimaggiore area). Coin for scale = 24 mm.

and extra-Gondwana (e.g. China and Arctic Canada) regions. The Silurian/Devonian boundary occurs in the calcareous Fluminimaggiore Fm. immediately below the lobolith-horizon (Gnoli *et al.*, 1990).

The Ockerkalk (25 m thick) is an argillaceous limestone developed in southeastern Sardinia above the Lower Graptolitic Shales, with a blue-grey colour weathering to ochre (so the name) and a peculiar irregular flaser texture. This unit is reported also in Thuringia, Spain, the Carnic Alps and northwestern Czech Republic. Crinoidal stems, all parallel to the bedding, and a few cephalopods (Gnoli, 1993) are the only macrofossils clearly visible in outcrop. Trace fossils and very small solitary corals were reported by Jaeger (1977); loboliths are present in a distinctive level (see below). The Ockerkalk unit is represented by massive sequences of fine micritic limestones with a scattered microscopic fauna of ostracodes, brachiopods, thin-shelled bivalves, trilobite fragments, gastropods, sponge spiculae, phyllocarids (mainly mandibles) and crinoids, sometimes concentrated in millimetric wackestone shell-lags of disarticulated debris. A quiet pelagic environment, below wave-base action, dominated by a fine-grain sedimentation and with bioclastic input variable in time and probably in space, especially in the crinoidal fraction, was proposed by Barca et al. (1995).

The lobolith horizon with the giant pelagic crinoid *Scyphocrinites*, already recorded in the Early Devonian (*woschmidti* conodont Zone) of southwestern Sardinia, extends also to the southeastern sector of Sardinia but with loboliths generally bigger (up to 20 cm compared to 12 cm of southwestern Sardinia) and occurring definitely earlier (*detortus* conodont Zone) (Corradini et al., 1998). The Silurian/Devonian boundary corresponds in southeastern Sardinia to the lithological change from the Ockerkalk limestone to the overlying graptolitic shales.

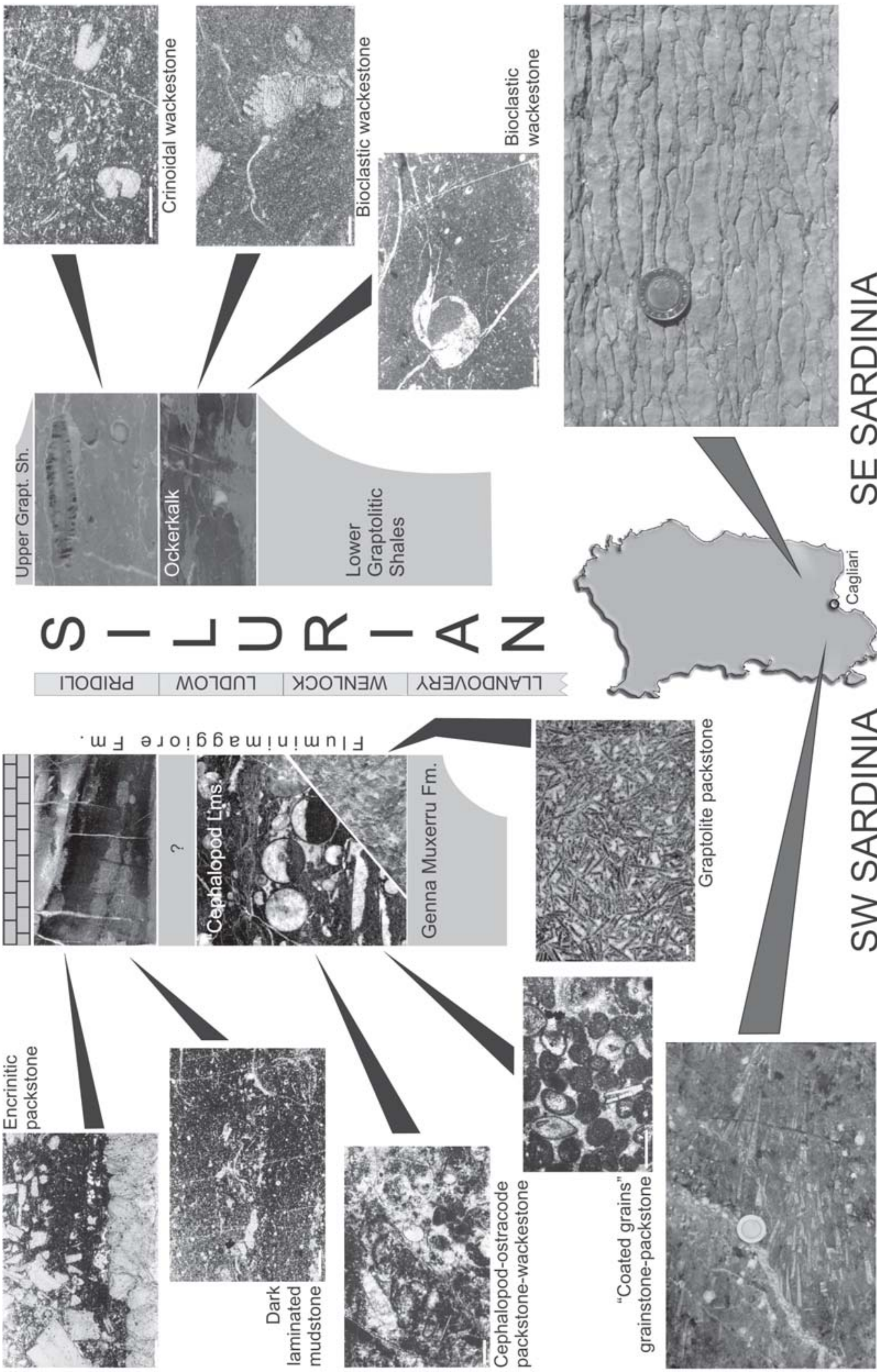
In a project on the Lau event (Jeppsson et al., 2002), $\delta^{13}C$ and $\delta^{18}O$ isotope samples have been collected from the Silius section. Researches are still in progress, but preliminary data, even if slightly weakened by metamorphism, appear useful for documenting variations in a deep water mid-latitude environment.

The explanation for a so different nature of the calcareous units exposed in southeastern and southwestern Sardinia has never been fully given, but certainly should consider also other South-European areas belonging (or close) to the northern Gondwana margin where the two limestone-types have also been reported. Similar facies differences, at least in the limestone development, occur in fact also in the Carnic Alps and in Bohemia and two distinct Silurian facies suites in the Iberian Peninsula were reported by Gutièrrez-Marco et al. (1998). The existence of a multivaried environmental setting in the Silurian appears therefore highly plausible.

Devonian cover

The Fluminimaggiore Fm. of southwestern Sardinia extends up to the earliest Devonian (earliest Lochkovian) and is covered by Devonian nodular and massive limestones, alternating with compact dark siltstones and shales, of the Mason Porcus Formation. In southeastern Sardinia, the calcareous Ockerkalk is followed by graptolitic shales, already

Fig. 4 - Generalized stratigraphical columns, outcrop view of the calcareous units and their main microbiofacies for the Silurian of southwestern and southeastern Sardinia. Microfacies scale bar = 1 mm (modified after Ferretti & Serpagli, 1996a).


SILURIAN
PRIDOLI
LUDLOW
WENLOCK
LLANDOVERY
Upper Grapt. Sh.
Ockerkalk
Lower Graptolitic Shales
Crinoidal wackestone
Bioclastic wackestone
Bioclastic wackestone
Fluminimaggiore Fm.
?
Cephalopod Lms.
Genna Muxerru Fm.
Graptolite packstone
Cagliari
SE SARDINIA
SW SARDINIA
Encrinitic packstone
Dark laminated mudstone
Cephalopod-ostracode packstone-wackestone
"Coated grains" grainstone-packstone

Devonian in age, known informally as Upper Graptolitic Shales, composed of alum slates only (Barca & Jaeger, 1990). The thickness of this unit is estimated in about 30 m (Jaeger, 1977). Planktonic graptolites are the only abundant fossils of the black shales, but rare *Ceriatocaris* (Jaeger, 1977) and a single specimen of pterineid bivalve (Barca & Jaeger, 1990) have also been reported from this unit. Crinoidal stems and calyces and possible loboliths (Barca & Jaeger, 1990, fig. 9; Piras et al., 2009) occur in the lower part of the Upper Graptolitic Shales.

Acknowledgements

Funding for this work was provided by MIUR-PRIN 2007 (*Analysis of stratigraphic, palaentological and structural features of the Hercynian basement and the Tertiary cover in Sardinia and Calabria, as a contribution to the geodynamic reconstruction of the central-western Mediterranean basin*).

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