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The Perd'e Fogu outcrop: a classical exposure of "*Orthoceras* limestone" in the Fluminimaggiore area (SW Sardinia)

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LOCALITY	About 600 m North-East of Fluminimaggiore at geographic coordinates 39°26'37"N, 8°30'02"E.
LITHOSTRATIGRAPHIC UNIT	Fluminimaggiore Formation.
AGE	Silurian (Wenlock-Ludlow): *sagitta* to *siluricus* conodont zones.
WHAT TO SEE	"*Orthoceras* limestone", Bivalvia dominated communities, graptolitic limestone.

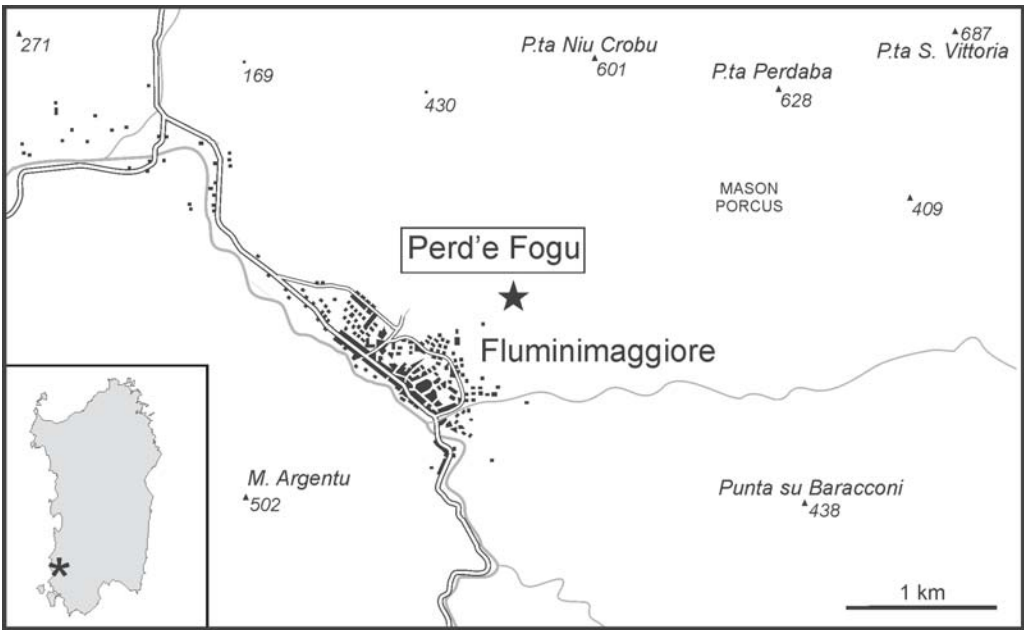


Fig. 1 - Location map of the Perd'e Fogu exposure.

Fig. 2 - General view of the Perd'e Fogu outcrop.

How to get there

The outcrop will be reached by a short walk starting from the old cemetery (Fig. 1). Displaced blocks of Silurian limestones of the Fluminimaggiore Fm. may be visible along the path.

Historical Outline

The Fluminimaggiore area has a special significance both for Sardinian palaeontology and Palaeozoic studies in Italy. Meneghini (1857) in fact just here illustrated nautiloids, bivalves and graptolites and Canavari (1899) reported ostracodes. The locality, discovered by General La Marmora in 1839, was originally named Cea Sant'Antonio (or Xea S. Antonio). The original outcrop was formed by displaced blocks of black limestone rolled downhill or collected and piled up by farm-workers in dry-stone walls along the paths close to the old cemetery of the village. The importance of Meneghini's paper (*Paléontologie de L'Ile de Sardaigne* - 548 pages and 4 plates all describing Palaeozoic fossils) was only lately appreciated probably because it was included in the larger three-volume monograph *Voyage en Sardaigne* edited by A. La Marmora.

Lithology

The Fluminimaggiore Fm. (Gnoli et al., 1990) is represented by black calcareous lenticular levels in non-calcareous pelites and shales. Peculiar concretions ("septaria") consisting of irregular polygonal systems of internal cracks almost always occupied by

Fig. 3 - Meneghini's original drawings (1857, Pl. C, figs. 3a, 15, 18 and 19) of two cephalopods, a bivalve and a piece of graptolitic limestone collected in the Fluminimaggiore area.

calcite, occur in one level probably belonging to the *sagitta* interval and may be occasionally found as loose blocks. The upper part of the Fluminimaggiore Fm., not exposed here, is characterized by more marly limestones and terminates with a crinoidal bioclastic packstone horizon.

The unit is exposed in the outcrop in form of discontinuous bodies (Figs. 2, 4). Each large body has been sampled in the last decades by specialists of diverse faunal groups,

Fig. 4 - Loose block of cephalopod limestone exposed in Perd'e Fogu. Coin for scale = 22 mm.

often in joint fieldworks, and dated by means of conodonts and, whenever possible, graptolites. In spite of the discouraging aspect at first-sight of the outcrop, just the Fluminimaggiore area has provided major information on the global Silurian faunas of Sardinia. Abundant cephalopods, associated with bivalves, pelagic ostracodes, conodonts, forams, graptolites, the problematic organism "*Kolihaia*", eurypterids, rare gastropods, brachiopods, trilobites, chitinozoans and muellerisphaerids were reported from these bituminous limestones.

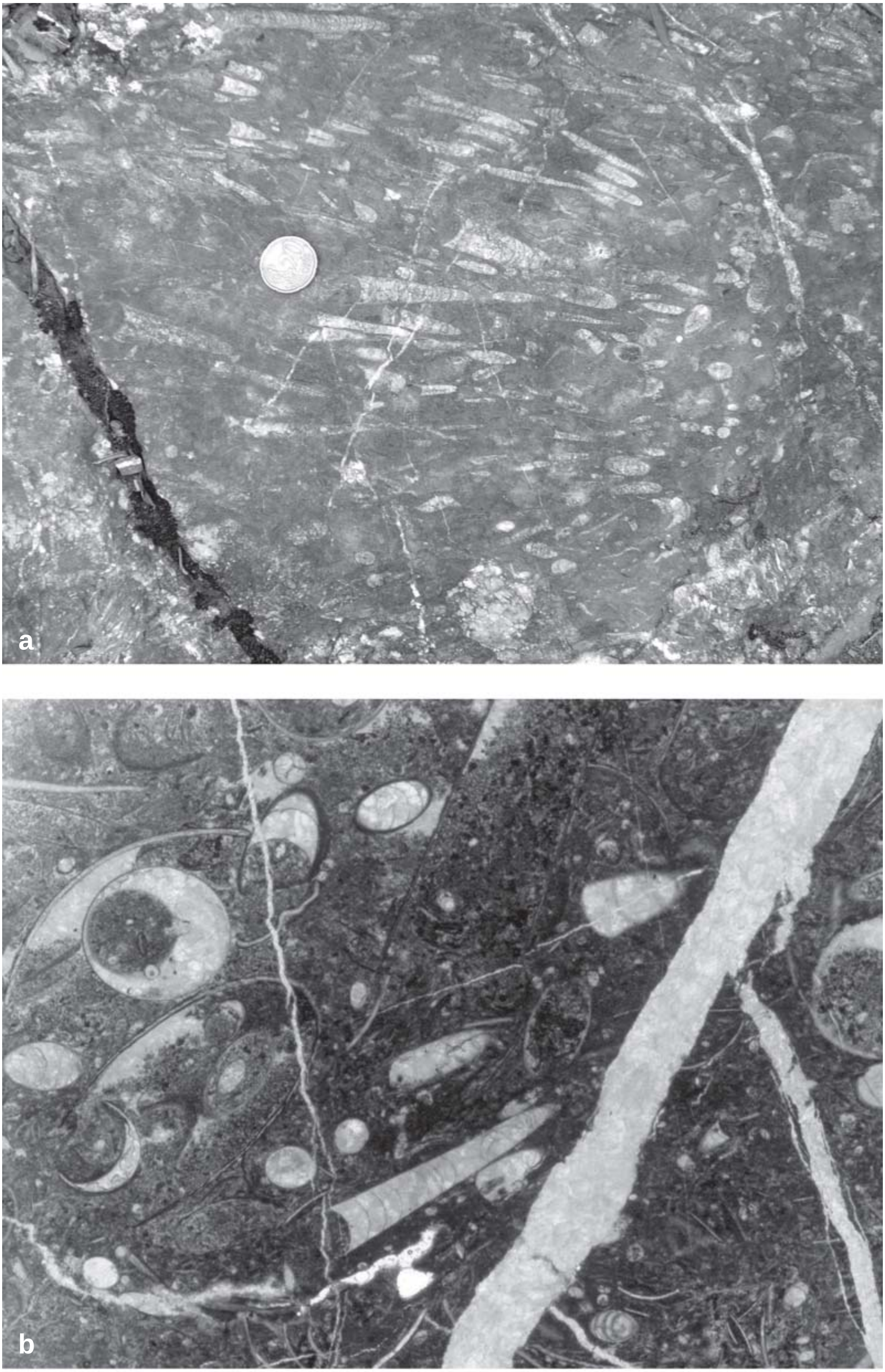
Fossil content of the Fluminimaggiore area

Meneghini (1857) described from this locality 4 bivalve and 20 cephalopod taxa (Fig. 3). This paper was re-evaluated more than a century later by Gnoli & Serpagli (1977), who paid a special attention to the cephalopods and reproduced one original plate. Further investigations revealed about 55 species of cephalopods (Serpagli & Gnoli, 1977; Gnoli, 1983, 1987, 1990; Gnoli & Serventi, 2009) and almost 80 species of bivalves (Kriz & Serpagli, 1993; Kriz, 2009). Bivalves, collected in the period 1982-1989 block by block, made possible detailed biostratigraphical correlation with other European peri-Gondwana regions, especially with the classic area of the Prague Basin, Bohemia, and environment analysis. Five graptolite taxa (from the limestones), four phyllocarid taxa (including mandibles; Gnoli and Serpagli, 1984), loboliths (Gnoli *et al*., 1988), eurypterid remains and problematic organisms (Gnoli, 1992a, b) were also reported. Conodonts allowed a precise biostratigraphic assignment of the displaced blocks, documenting six biozones spanning from the *sagitta* to the *siluricus* zones (Serpagli, 1967, 1971; Ferretti et al., 1998; Corriga et al., 2009). A large number of other microfossils include forams (Gnoli & Serpagli, 1985), chitinozoans (Dufka & Gnoli, 1996), ostracodes (Canavari, 1899; Palmer & Gnoli, 1985) and muellerisphaerids. Gastropods and trilobites are extremely rare being *Ampyx* sp. aff. *roualti* Barrande the sole trilobite species reported (Palmer & Gnoli, 1985). Microbiofacies were recognised and described in detail by Ferretti (1989) and summarized by Ferretti et al. (2009).

Cephalopods

Owing to the absence of a continuous section in the area, any general consideration derives from a block to block study of the outcrop. Nevertheless, the spot PF 1 allows further remarks because it is both the largest exposure and is particularly rich in cephalopods (Fig. 5a). There, the older cephalopod-limestone biofacies horizon which developed in the Silurian of Sardinia is present. It belongs to the *Pseudocycloceras transiens*-*Columenoceras grande* assemblage, which is one of the three nautiloid assemblages recognized in the south-western part of the island (Gnoli & Serpagli, 1991; Gnoli & Serventi, 2009). The assemblage consists of exclusive taxa, like *Phragmoceras broderipi subleve* (Barrande), *Columenoceras grande* (Meneghini), *Pseudocycloceras transiens* (Barrande), *Mericoceras* cf. *simois* (Barrande), *Plagiostomoceras* cf. *pleurotomum* (Barrande), *Michelinoceras* sp. 1 *sensu* Serpagli & Gnoli, *Oonoceras* sp. *sensu* Gnoli together with other ones spanning into the next assemblages such as *Arionoceras canonicum* (Meneghini), *A. submoniliforme* (Meneghini), *Orthocycloceras*? cf. *linx*

Fig. 5 - PF 1 exposure (*sagitta* Zone). a) Close view of oriented cephalopods; coin for scale = 22 mm. b) Cephalopod wackestone in thin-section analysis, x 3.5.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(Barrande), *Mericoceras* cf. *sericatum* (Barrande), *Plagiostomoceras gruenewaldti* (Barrande), *Sphooceras truncatum* (Barrande), *Geisonoceras*? cf. *socium* (Barrande), "*Sphaerorthoceras*" *curvum* Ristedt, *Parakionoceras originale* (Barrande), *Columenoceras*? *intermixtum* (Barrande), *Akrosphaerorthoceras gregale* Ristedt and *Michelinoceras michelini* (Barrande).

In this outcrop, however, the bulk of the nautiloid fauna is represented by *Arionoceras submoniliforme* (Meneghini), *A. canonicum* (Meneghini) and rare specimens of *Oonoceras* sp. (M. Gnoli, pers. comm., nov. 1997).

Bivalves

Twelve Bivalvia-dominated communities and subcommunities were recognized and described from the Silurian and lowermost Devonian Fluminimaggiore Fm. of Sardinia (Kriz & Serpagli, 1993). They represent useful tool in precise correlation of Sardinian upper Wenlock, Ludlow and Pridoli cephalopod limestone biofacies and micritic limestone facies with other European peri-Gondwana regions (Kriz, 1998).

Six of the Bohemian communities (*Cardiola gibbosa*, *Cardiola docens*, *Cardiolinka sardiniana*, *Snopyia insolita*, *Cheiopteria bridgei*, and *Patrocardia evolvens – Panenka*) were recognized in Sardinia. When compared with the Prague Basin, some of the Bivalvia

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Plate 1

Fig. 1 - *Ozarkodina confluens* (Branson & Mehl, 1933), Pa element IPUM 25884; sample PF 5 (*siluricus* Zone); lateral view, x90.

Fig. 2 - *Ozarkodina sagitta sagitta* (Walliser, 1964), Pa element IPUM 25873; sample PF 1 (*sagitta* Zone); lateral view, x 100.

Fig. 3 - *Ozarkodina sagitta rhenana* (Walliser, 1964), Pa element IPUM 25899; sample PF 1 (*sagitta* Zone); upper-lateral view, x 100.

Fig. 4 - *Polygnathoides siluricus* Branson & Mehl, 1933, Pa element IPUM 25892; sample PF 5 (*siluricus* Zone); upper-lateral view, x60.

Fig. 5 - *Kockelella absidata sardoa* Serpagli & Corradini, 1999, Pa element IPUM 25861; sample PF 11B (*hamata* Zone); lateral view, x80.

Fig. 6 - *Dapsilodus obliquicostatus* (Branson & Mehl, 1933), Sa element IPUM 25919; sample PF 1A (*crassa* Zone); lateral view, x100.

Fig. 7 - *Wurmiella hamata* (Walliser, 1964), Pa element IPUM 25903; sample PF 1D (*hamata* Zone); upper view, x100.

Fig. 8 - *Ancoradella ploeckensis* Walliser, 1964, Pa element IPUM 25922; sample 1Q (*ploeckensis* Zone); upper view, x85.

Fig. 9 - *Kockelella maenniki* Serpagli & Corradini, 1998; Pa element IPUM 25852; sample PF 1H (*siluricus* Zone); upper view, x80.

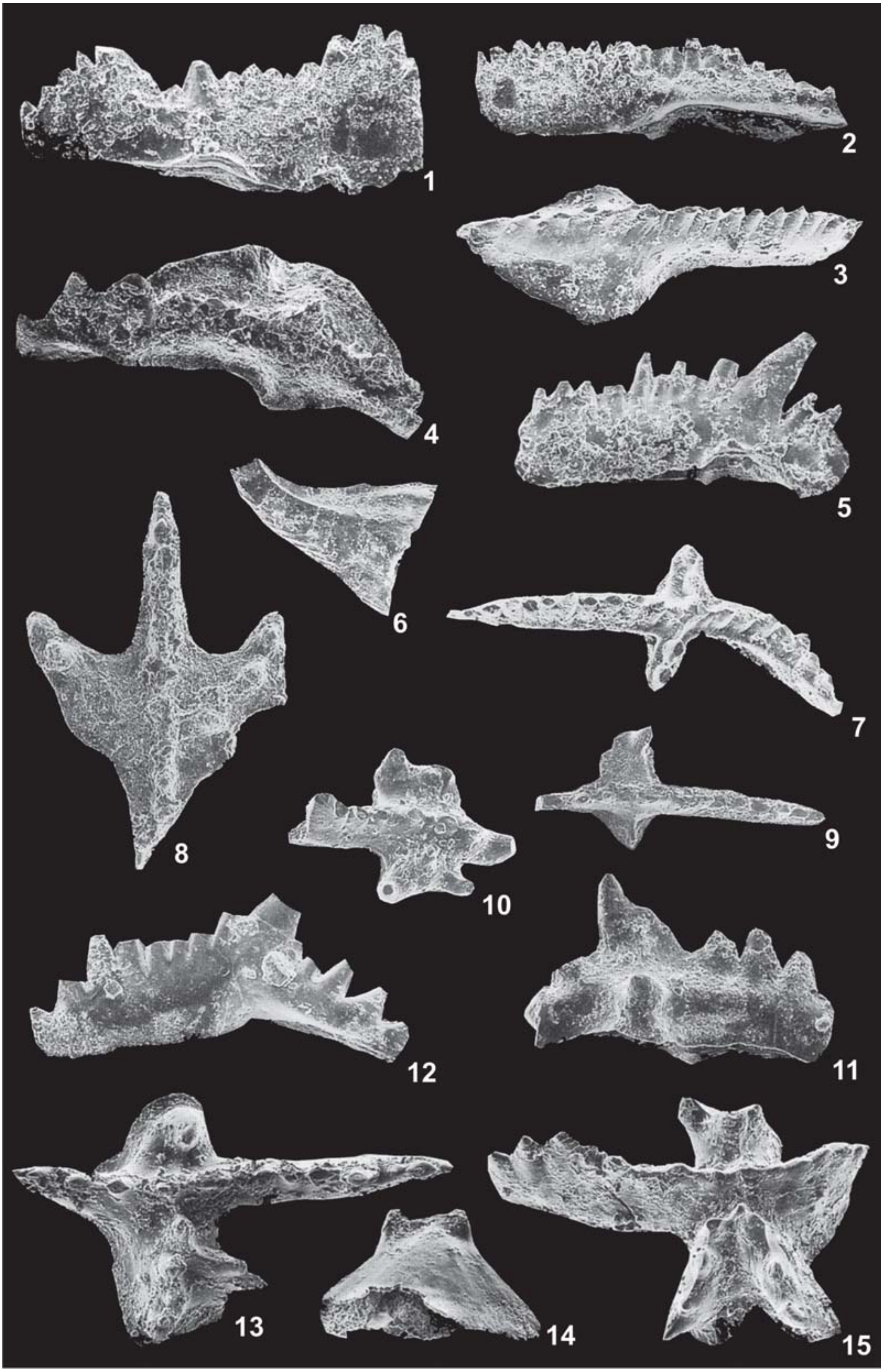
Figs. 10-11 - *Kockelella crassa* (Walliser, 1964).
10. Pa element IPUM 25844; sample PF 1A (*crassa* Zone); upper view, x80.
11. Pb element IPUM 25916; sample PF 1A (*crassa* Zone); lateral view, x85.

Fig. 12 - *Kockelella absidata absidata* Barrick & Klapper, 1976, Pa element IPUM 25860; sample PF 1Q (*ploeckensis* Zone); lateral view, x70.

Fig. 13 - *Kockelella variabilis ichnusae* Serpagli & Corradini, 1998, Pa element IPUM 25839; sample PF 11B (*hamata* Zone); upper view, x80.

Fig. 14 - *Pseudooneotodus bicornis bicornis* (Drygant, 1974), IPUM 25865; sample PF 6 (*sagitta* Zone); lateral view, x100.

Fig. 15 - *Kockelella variabilis variabilis* Walliser, 1957, Pa element IPUM 25855; sample PF 11B (*hamata* Zone); upper-lateral view, x60.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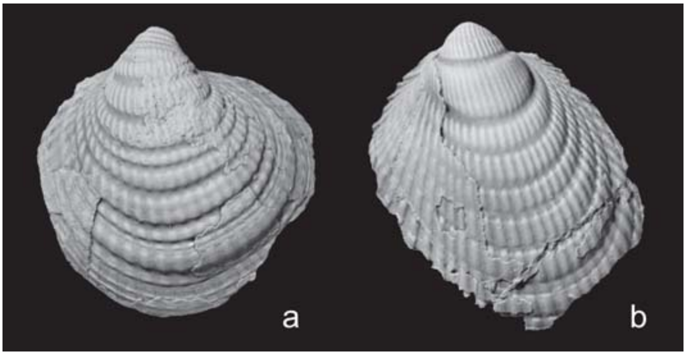

Fig. 6 - Some bivalves collected in the Fluminimaggiore area. a) *Isiola lyra* Kriz, Xea Sant'Antonio, block 11, the *Cardiola agna figusi* Community, Wenlock; IPUM 22659, right view, x1.7. b) *Cardiola agna figusi* Kriz, Xea Sant'Antonio, block 11, the *Cardiola agna figusi* Community, Wenlock; IPUM 22685, right view, x2.1.

dominated communities (Kriz, 1999) are in Sardinia characterized mostly by lower diversity and are developed as the high density subcommunities (*Cardiola agna figusi, Cardiola donigala, Cheiopteria – Patrocardia – Cardiolinka, Pterinopecten* (*P.*) *cybele nesiotes, Joachimia falcata,* and *Patrocardia evolvens gnolii*) closely related to the Bohemian homologous and analogous communities (Kriz, 2009). Characteristic for the Bivalvia dominated communities and especially subcommunities in Sardinia is the high population density of abundant epibyssate nepiomorphian bivalves (Kriz, 2007), especially representatives of the genus *Cardiola*, which developed a peculiar living strategy on the micritic substrate with abundant nektobenthic cephalopods. Shells are opisthocline, dorsoventrally elongated or subcircular (Fig. 6). The ventral end of elongated anterior margin together with the large umbones represented three major points of stability (distributed at the vertices of a triangle) enabling a stable byssal attachment to cylindrical cephalopod shells in any position (Kriz, 1979).

Conodonts

In an area where it is almost impossible to find continuous sections, biostratigraphic data are of basic importance for reconstructing depositional sequences. This is the reason why a huge number of different calcareous blocks have been tested for conodonts in the whole Fluminimaggiore area, where several biozones from Wenlock to Lower Devonian have been documented (Serpagli, 1967, 1971; Serpagli & Mastandrea, 1980; Olivieri & Serpagli, 1990; Ferretti et al., 1998; Corriga et al., 2009). In general, the fauna is quite abundant and in good state of preservation.

At Perd'e Fogu (Pl. 1) the conodont association includes twenty taxa of Wenlock and Ludlow age: *Ancoradella ploeckensis* Walliser, *Dapsilodus obliquicostatus* (Branson & Mehl), *Kockelella abs. absidata* Barrick & Klapper, *K. abs. sardoa* Serpagli & Corradini, *K. crassa* (Walliser), *K. maenniki* Serpagli & Corradini, *K. v. variabilis* Walliser, *K. v. ichnusae* Serpagli & Corradini, *Oulodus siluricus* (Branson & Mehl), *Ozarkodina bohemica* (Walliser), *Oz. confluens* (Branson & Mehl), *Oz. s. rhenana* (Walliser), *Oz. s. sagitta* (Walliser), *Polygnathoides siluricus* Branson & Mehl, *Pseudooneotodus beckmanni* Bischoff & Sannemann, *Ps. bic. bicornis* (Drygant), *Ps. bic. contiguus* Corradini, *Wurmiella excavata* (Branson & Mehl), *W. hamata* (Walliser), *W. inflata* (Walliser).

Graptolites

Silurian graptolites from Sardinia are commonly associated to black shale deposits, reported from classical localities both in southwestern and southeastern Sardinia. An

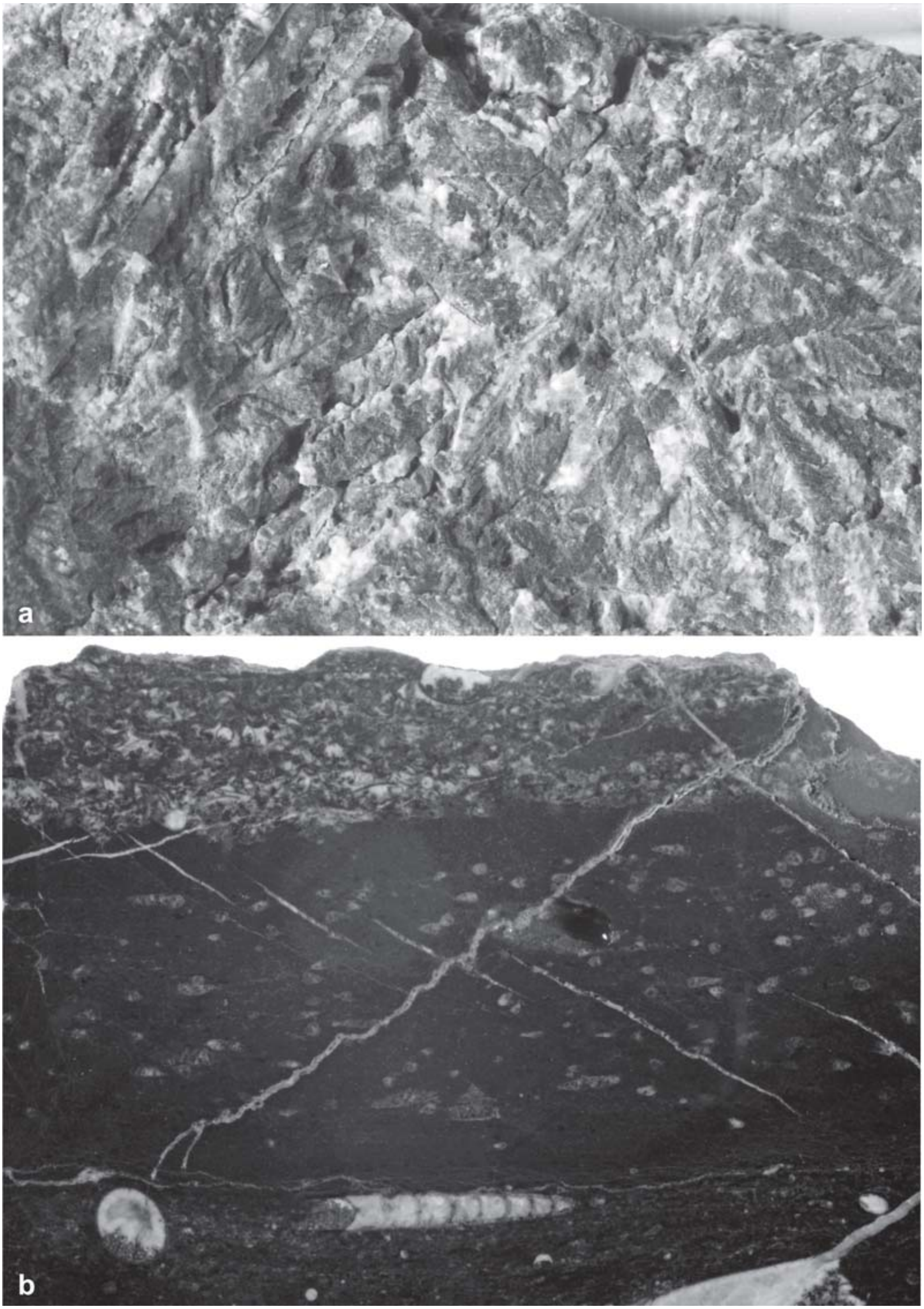

Fig. 7 - a) Graptolitic limestone with well preserved three-dimensional rhabdosomes, x3. b) Polished slab of a graptolitic/cephalopod limestone. A graptolite packstone level is deposited at the top of a wackestone with sparse graptolite fragments and cephalopods. Note geopetal infillings of cephalopods in the lower part of the slab, x2.

unusual type of limestone is exposed only in southwestern Sardinia associated with the cephalopod-limestone biofacies. Here in fact pseudolenticular dark calcareous bodies, up to 1 m in size, are literally crowded by three-dimensional graptolite rhabdosomes (Fig. 7a). The *lundgreni-testis*, *nilssoni-colonus*, *chimaera*, *linearis-leintwardinensis* biozones reported in the Perd'e Fogu graptolitic limestones document an upper Wenlock-Ludlow age, which is also confirmed by the conodonts co-occurring in the same blocks (Piras & Corradini, 2007). A single graptolite species, or a few at most, occur in each calcareous body. Wenlock-Ludlow graptolitic limestones are dominated by diverse species of *Monograptus*, *Colonograptus* and *Saetograptus*, accompanied by subordinate *Pristiograptus*. Lower Pridoli associations, documented elsewhere in the Fluminimaggiore area, are represented by *Monograptus parultimus* species (Rickards et al., 1995; Ferretti & Serpagli, 1996). Cross-sectioned bodies have shown that these limestones are constituted by centimetre 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 (Fig. 7b). Most cephalopods still preserve body chambers which are sometimes filled by graptolites. Orientation measurements on graptolite distribution (Ferretti & Serpagli, 1996) revealed how both random and current oriented concentrations are present, even for graptolites belonging to the same genus and having therefore similar hydrodynamic behaviour. These concentrations represent discrete event horizons of graptolites (Fig. 7b) which were living in an environment close to that of cephalopods and had possibly developed a sort of tolerance towards oxygen content and/or other palaeoecological features (Ferretti & Serpagli, 1996).

Biostratigraphy

In this locality conodont assemblages belonging to six zones have been recognized: *sagitta sagitta*, *crassus*, *variabilis variabilis*, *hamata*, *ploeckensis* and *siluricus*.

The graptolite biozones identified are: *Cy. lundgreni* - *T. testis*, *N. nilssoni* - *C. colonus*, *S. chimaera* and *S. linearis* - *S. leintwardinensis*.

A project with the goal of tying the conodont and graptolite zonation schemes on the basis of co-occurrences of these fossil groups in the graptolitic limestones is in progress.

Environment

Gnoli *et al.* (1980) attributed this cephalopod limestone to a normal oxygenated epicontinental sea of limited depth, rich in pelagic fauna in the upper part but definitely toxic towards the bottom. Furthermore, on the basis of new fauna, they suggested that the bottom was not constantly toxic, but that the Eh boundary was moving up and down. Examination of sufficiently extensive ortoceratid plates and blocks by Gnoli *et al.* (1980) together with laboratory experiments, revealed a very pronounced double alignment of orthoconic shells (similar to the crest and the trough of ripple marks) which is the typical bimodal orientation pattern of wave accumulation.

Ferretti (1989) identified three main microfacies in the cephalopod limestone of the Fluminimaggiore Fm., indicative of a shallow high energy deposition. A peloid-cephalopod-ostracod packstone to wackestone is typical for the "*Orthoceras* limestone" (Fig. 5b), associated with less common graptolitic packstones and "coated grains" grainstone to packstones. A deposition below normal wave-base but probably in areas within storm wave-base was suggested for rare Ludlow micritic mudstones with intercalated shell-lags and for dark laminated fossiliferous mudstones found respectively slightly eastwards and south-westwards.

The application of the bathymetric methods of Hewitt & Westermann (1988) on the Sardinian cephalopod fauna supposes (not yet confirmed) living depths between 100 and 500 m (Histon & Gnoli, 1994).

The analysis of the Bivalvia dominated communities characteristic for the cephalopod limestone biofacies of the Fluminimaggiore Fm. in Sardinia (Kriz & Serpagli, 1993; Kriz, 1999) shows very close relationships with the contemporaneous communities known from the Prague Basin of Bohemia and from other regions of the European peri-Gondwana. Prevailing epibyssate bivalves (59.4% in the *Cardiola agna figusi* Subcommunity, 82.61% in the *Cardiola docens* Community) indicate in Sardinia, together with high population density and relatively high diversity (16 to 13 species), favourable conditions at and above the sediment-water interface. Mostly current oriented cephalopods used as the firm substrate by epibyssate bivalves indicate contemporaneous surface current action important for the bottom ventilation. Presence of mostly disarticulated but not broken valves in the dark micritic and biomicritic limestone indicate not deep environment closely below the wave base. Locally abundant juvenile Bivalvia stages represent mass extinctions and indicate thus temporary deficit of oxygen and no current action.

The common orientation shared by the cephalopods in some of the main spots of the Perd'e Fogu outcrop (e.g. PF 1; Fig. 5a) suggests the existence of a surface global current carrying cephalopod shells and molluscs larvae, as already documented in other parts of northern Gondwana. Displaced blocks bearing random oriented cephalopods indicate that a current was not constantly present (Ferretti *et al.*, 1995).

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