Bollettino della Società Paleontologica Italiana	28 (1)	1989	87-100	3 pls.	Modena, Giugno 1989

Annalisa FERRETTI

Microbiofacies and constituent analysis of Upper Silurian - Lowermost Devonian limestones from Southwestern Sardinia

E.E.C.

SILURIAN
ECOSTRATIGRAPHY
IN IRELAND
AND SARDINIA

MUCCHI - MODENA

Bollettino della Società Paleontologica Italiana	28 (1)	1989	87-100	3 pls.	Modena, Giugno 1989

Microbiofacies and constituent analysis of Upper Silurian - Lowermost Devonian limestones from Southwestern Sardinia

Annalisa FERRETTI
Istituto di Paleontologia
Università di Modena

KEY WORDS — Microfacies analysis, Constituent analysis, Paleoenvironment, Silurian - Lower Devonian limestones, Southwestern Sardinia.

ABSTRACT — On the basis of their fossil content and sedimentological features, the Wenlockian, Ludlovian, Pridolian and Lower Lochkovian limestones of SW Sardinia can be subdivided into six main microfacies.

Paleontological and sedimentological data suggest deposition in shelf areas during Wenlockian - Ludlovian times and a deeper depositional environment in the following Pridolian - early Lochkovian. Biosedimentological data also evidenced environments characterized by normal salinity, high temperature and a generally low sedimentation rate.

RIASSUNTO — [Microbiofacies ed analisi modale quantitativa di calcari del Siluriano superiore - Devoniano inferiore della Sardegna sud-occidentale] — *Vengono analizzati livelli calcarei del Siluriano superiore e della parte basale del Devoniano inferiore (Lochkov inferiore) affioranti in alcune località della Sardegna sud-occidentale con età variabile dal Wenlock (zona a conodonti* sagitta sagitta) *al Lochkov inferiore (zona a conodonti* postwoschmidti = eurekaensis), *con la sola eccezione di un intervallo corrispondente alle zone* crispa + snajdri - latialata, *probabilmente non rappresentato da facies carbonatiche. Lo studio mediante sezioni sottili e l'applicazione a queste dell'analisi modale quantitativa, ha permesso di riconoscere 6 microfacies principali e di ipotizzare una ricostruzione dell'ambiente di deposizione. La sedimentazione sarebbe avvenuta nel Wenlock superiore-Ludlow prevalentemente in aree di piattaforma, mentre nella parte superiore del Pridoli e nel Lochkov basale si sarebbe verificato un deciso approfondimento verso un ambiente bacinale relativamente poco profondo, scosso da rideposizioni di materiale ad opera di correnti, probabilmente di tempesta. Indizi biosedimentologici indicherebbero poi condizioni di acque normal-saline e calde, ove il tasso di sedimentazione era piuttosto basso.*

INTRODUCTION

Silurian rocks exposed in Southwestern Sardinia are mostly represented by black graptolitic shales in the lower part of the succession (Llandovery) gradually interbedded until becoming dominant with cephalopod-black limestones (Wenlock-Ludlow and most of the Pridoli) and micritic-encrinitic limestone (late Pridoli). Tectonic stress, low grade metamorphism, magmatic intrusions and diagenetic changes, such as pressure solution, strongly affected these sediments. Consequently it is impossible to recognize continuous sequences of strata and correlate individual beds over long distances. Nevertheless, paleontological and sedimentological features allow to recognize and describe several microbiofacies and suggest a depositional model for the carbonate sedimentation in SW Sardinia during Silurian-early Devonian time. Modal quantitative analysis of the constituents (chiefly skeletal sand) was also taken into account during the study of the microfacies.

Samples were usually dated on the basis of conodonts (Serpagli *et al.*, in progress) and, when possible, of graptolites (courtesy of Dr. H. Jaeger).

The present paper is part of a larger project, headed by E. Serpagli, on the paleontology and biostratigraphy of the Sardinian Paleozoic; several papers have been published (for a detailed list, see Gnoli & Serpagli, 1985 b) or are in press.

GEOLOGICAL SETTING

Iglesiente and Sulcis (SW Sardinia) as well as Sarrabus and Gerrei (SE Sardinia) are the main areas of Silurian outcrops in the island.

Formal lithostratigraphic units for the Silurian - Lower Devonian succession of SW Sardinia were recently proposed by Gnoli *et al.* (1989), whereas the classic Thuringian triad seems to be present in SE Sardinia (Jaeger, 1977).

According to Gnoli *et al.* (text-fig. 2), the Silurian succession starts with 20-25 m thick black argillaceous

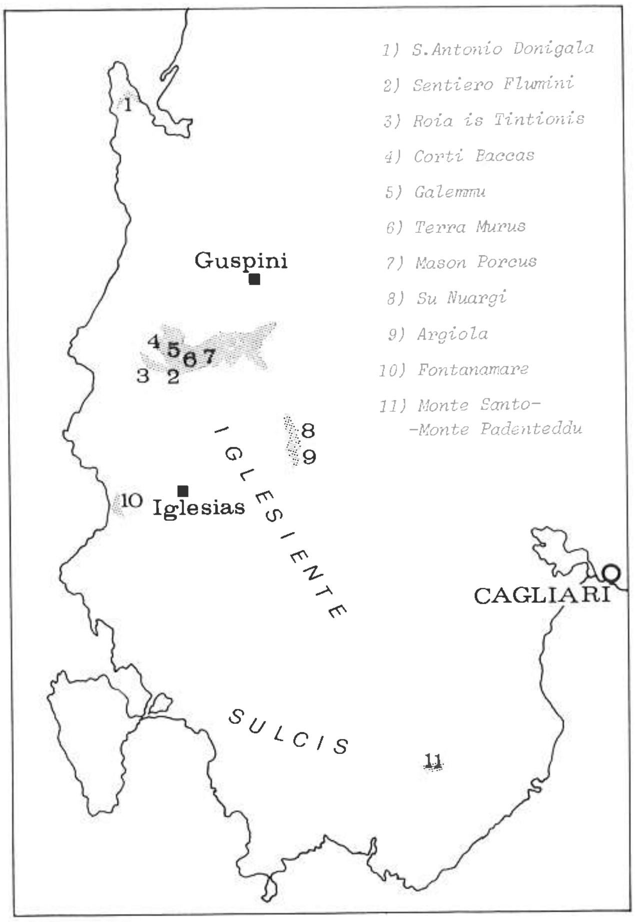
A contribution to project "Ecostratigraphy in Ireland and Sardinia".

shales with lidites; six Llandoverian graptolite zones (*acuminatus, vesiculosus, cyphus?, triangulatus, convolutus* and *turriculatus*) have been recognized. This formation, which roughly corresponds to the «Scisti neri a *Rastrites peregrinus, Climacograptus, Diplograptus*» of Taricco (1920-1921) has been named «Genna Muxerru Formation» after a hill not far from the Gonnosfanadiga village at the western border of the Campidano graben. This complex is followed by a 40-45 m thick unit («Fluminimaggiore Formation») consisting of an alternation of black calcareous layers and dark non calcareous pelites and shales (corresponding, more or less, to the «*Orthoceras* limestone» of the old authors). Toward the top of the formation the cephalopod limestone becomes more marly and is followed by a limestone rich in crinoidal bioclasts (Gnoli *et al.*, 1989). Paleontological studies on this unit (Meneghini, 1857, 1880; Canavari, 1899; Serpagli, 1967, 1971; Gnoli & Serpagli, 1977, 1985a, 1985b; Palmer & Gnoli, 1985; Serpagli & Gnoli, 1977; Gnoli, *et al.*, 1979) showed a great faunal richness both in number and in diversity, with nautiloids, graptolites, ostracodes, conodonts, foraminifera, phyllocarids, bivalves, gastropods and brachiopods as the most important elements of the varied assemblages.

Eight conodont zones from *amorphognathoides* to *postwoschmidti* (= *eurekaensis*), attributing an age from Wenlock to earliest Lochkow, have been identified in this formation (Serpagli *et al.*, in progress). Two apparently barren horizons corresponding to the conodont zones *patula* and *snajdri* / *latialata* + *crispa* can be probably related to highly tectonized shales (Gnoli *et al.*, 1989). This crinoidal unit is followed by a thick formation represented by nodular limestones, often thin bedded, and massive limestones alternating with compact dark siltstones and shales bearing numerous fragments of crinoidal stems. This last lithostratigraphic unit, early Devonian in age (conodont zones *delta* to *serotinus*), has been recently named «Mason Porcus Formation» (Gnoli *et al.*, 1989).

QUANTITATIVE ANALYSIS

Limestones were sampled from eleven localities (text-fig. 1) either in Iglesiente (S. Antonio Donigala,

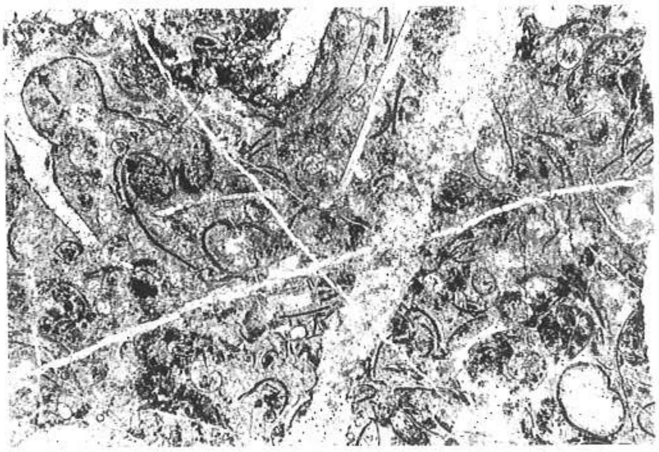


Text-fig. 1 - Map of the major outcrop-areas studied in this work.

Sentiero Flumini, Roia is Tintionis, Corti Baccas, Galemmu, Terra Murus, Mason Porcus, Su Nuargi, Argiola, Fontanamare) or in Sulcis (Monte Santo - Monte Padenteddu) but most sampling was restricted to the numerous exposures in the surroundings of Fluminimaggiore. However, most of these exposures can be better defined spot-outcrops (justifing the symbol BK as isolated blocks for many samples) because only the samples from Mason Porcus, Argiola and Monte Santo-Monte Padenteddu come from true sections. For convenience, the names of the above localities have been

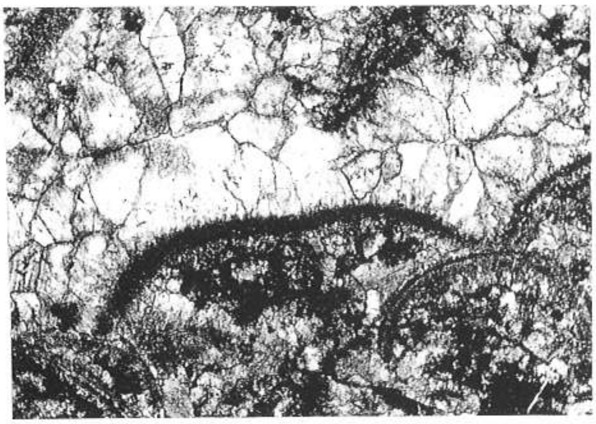
EXPLANATION OF PLATE 1

Fig. 1 - Microfacies 1, GALE-BK 3, cephalopod-ostracode packstone. Micritized shells of ostracodes are scattered in the section, × 11.
Fig. 2 - Microfacies 1, GALE-BK 15, peloid-cephalopod-ostracode packstone, «shelter micrite» inside ostracode shell, × 11.
Fig. 3 - Microfacies 1, SF-BK 5, cephalopod-ostracode packstone, SF-BK 5, note the fibrous acicular cement overgrowth on the shell of an ostracode and the drusy mosaic cement, × 28.
Fig. 4 - Microfacies 1, SN-BK1, cephalopod-ostracode wackestone with (a) telescoped orthocones, (b) ostracodes and (c) gastropods, × 11.
Fig. 5 - Microfacies 2, GALE-BK 13, graptolite packstone, × 4.
Fig. 6 - Microfacies 2, SF-BK 4, graptolite packstone, fragments of Graptoloids simulate a bryozoan-like colonial pattern, × 11.

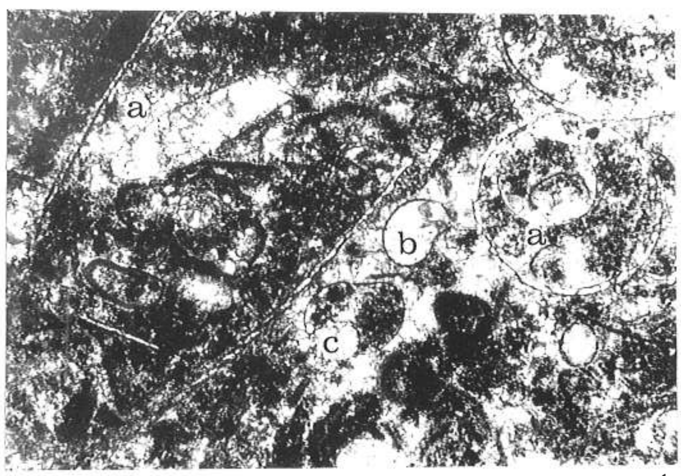


1

2

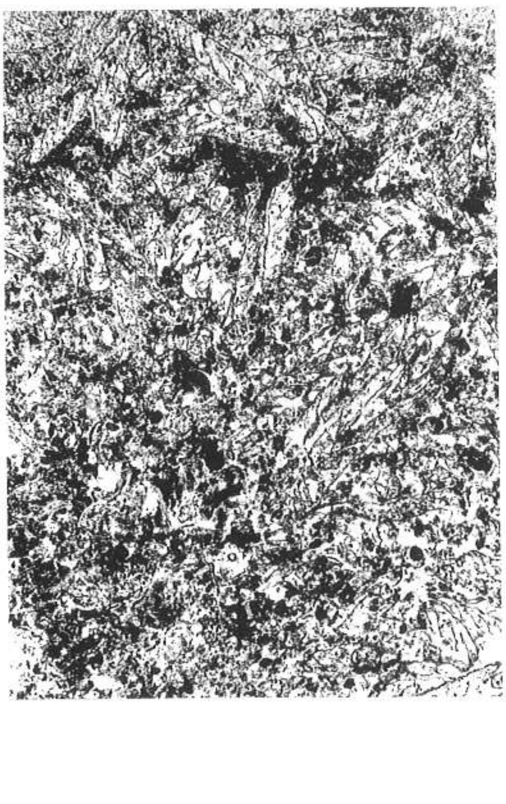


3

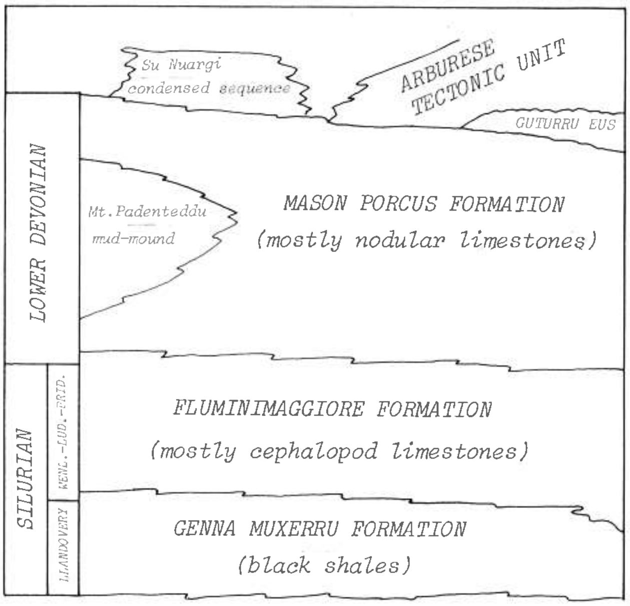


4

6



5



Text-fig. 2 - Schematic relationships of the Silurian- lower Devonian formations in Southwestern Sardinia (after Gnoli *et al.*, 1989).

abbreviated as follows: SAD for S. Antonio Donigala, SF for Sentiero Flumini, RT for Roia is Tintionis, CB for Corti Baccas, GALE for Galemmu, TM for Terra Murus, MP for Mason Porcus, SN for Su Nuargi, ARG for Argiola, FTM for Fontanamare, MS for Monte Santo-Monte Padenteddu.

Quantitative analysis of thin sections was done with the point-counting technique. The main constituents are matrix, cement, skeletal sand and opaque minerals. «Coated grains» and «bioturbation structures» were also counted for some samples. Skeletal sand was subdivided into the main taxa. The definition «grain solid» and not «grain bulk» (Dunham, 1962) was used in this analysis and so voids inside the organisms were counted as matrix or cement and not as skeletal grains (advantages and disadvantages of both definitions are discussed by Jaanusson, 1972). 0,10 mm was fixed as the maximum size of matrix grains. About 3.000 determinations were normally made for each thin section, using an optical microscope (25 or 63 ×) and a point-counting device. Data resulting from this technique, illustrated in text-figs. 3 and 4, will be discussed after the description of microfacies, to which they are strictly connected.

DESCRIPTION OF MICROFACIES

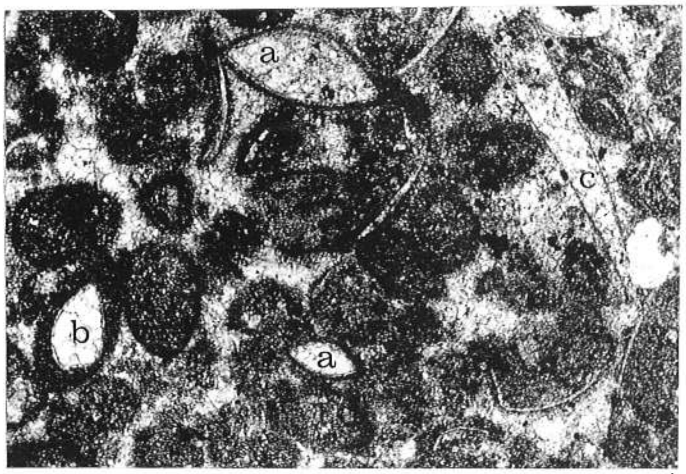
Six mains microfacies (MF 1 to MF 6) characterize the Silurian-Lowermost Devonian limestones of Southwestern Sardinia. They have been subdivided on the basis of fossil content, lithology and sedimentologic features.

MF 1) Peloid-cephalopod-ostracode packstone to wackestone

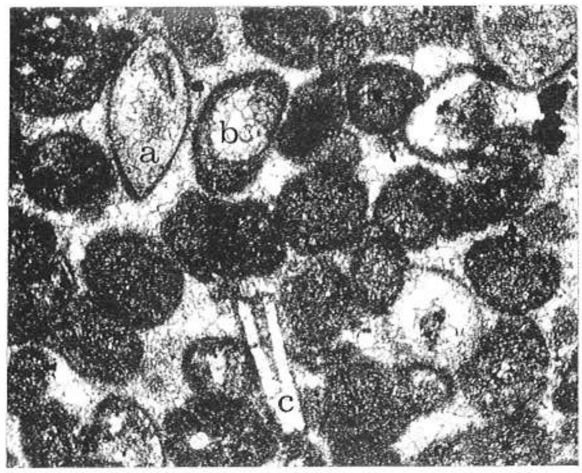
(Poorly washed biosparite; Pl. 1, figs. 1-4): this microfacies, very frequent in our samples of Wenlockian and Ludlovian age, is typical of the «*Orthoceras* limestone» , with sparitic and microsparitic cement (Galemmu, Su Nuargi, Sentiero Flumini, S. Antonio Donigala, Argiola, Corti Baccas). Geopetal structures and calcitic veins are quite common. Two cement generations can be clearly observed in many samples (Pl. 1, fig. 3): a fibrous acicular cement overgrowth on bioclasts (cement A, Flügel 1982) and a drusy mosaic cement (cement B, Flügel 1982). Ostracodes are highly fragmented and scattered throughout the samples, probably also because of bioturbation and current activity. Many of these fragments are only barely discernible from the matrix and some of these samples are referable to proper coquinas. Many ostracodes are impregnated with iron-oxides and micritized, indicative of marine, phreatic diagenesis (Shukla & Friedman, 1983; Pl. 1, fig. 1) sometimes showing clear algal borings. The fauna is very rich and consists of dominant orthocones together with graptolites, bivalves, gastropods, cono-

EXPLANATION OF PLATE 2

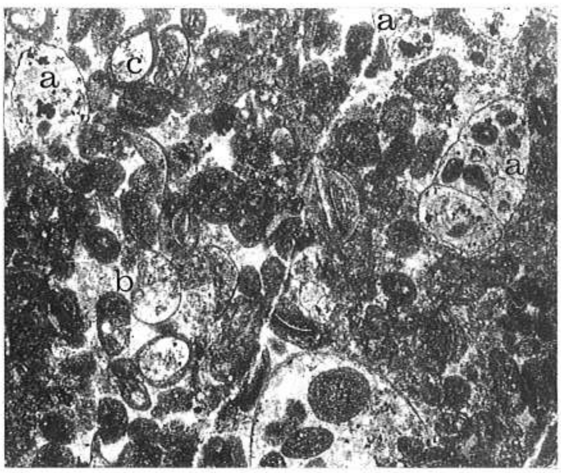
Fig. 1 - Microfacies 3, ARG-BK7, «coated-grains» grainstone with (a) ostracodes, (b) bivalves and (c) orthocones, × 28.
Fig. 2 - Microfacies 3, ARG-BK7, «coated-grains» grainstone, (a) ostracodes, (b) gastropods and (c) crinoidal fragments are present, × 28.
Fig. 3 - Microfacies 3, SF-BK 16, oolitic grainstone to packstone, (a) graptolite fragments together with (b) gastropods and (c) ostracodes are scattered in the section, × 11.
Fig. 4 - Microfacies 3, SF-BK 16, oolitic grainstone to packstone, micritic coating of a small orthocone, × 28.
Fig. 5 - Microfacies 4, MP 10b, pre-nodular mudstone, concentration of seams around a probable nautiloid fragment, crossed nicols, × 11.
Fig. 6 - Microfacies 4, MP 10c, pre-nodular mudstone with intercalated shell-lags consisting of (a) brachiopods, (b) trilobites or unrecognizable fragments, × 11.
Fig. 7 - Microfacies 4, MP 10b, intercalated shell lags with (a) crinoids, (b) trilobites and (c) nautiloids. Darker rims around bioclast concentrations consist of iron oxides, × 11.



1



2

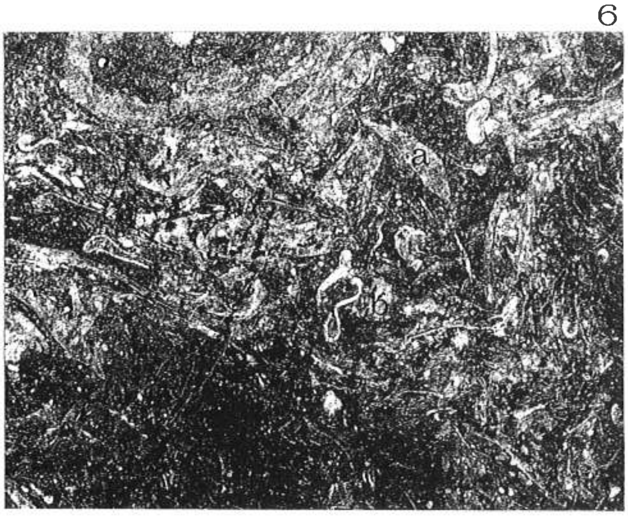


3

4

5

6



7

donts, crinoids, brachiopods... both shells and fragments, often with telescoped orthocones and shell-in-shell ostracodes and orthocones (Pl. 1, fig. 4). Peloids and among them fecal pellets are also present in some samples (i.e. GALE-BK 15). Examination of sufficiently extensive orthoceratid plates and blocks by Gnoli *et al.* (1979) together with laboratory experiments, reveals 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. Deposition in high energy water is also suggested by shelter porosity. The presence of micrite in sheltered areas (shelter micrite, Shukla & Friedman, 1983), such as the concavity of a shell, is the result of a selective removal of lime mud by high energy winnowing (Pl. 1, fig. 2). Sparitic and microsparitic texture is probably due to recrystallization of a very fine calcareous mud, in which fragments and shells of orthoceratids were deposited (Gnoli *et al.*, 1979).

MF 2) Graptolite packstone

(Graptolite-packed poorly washed biosparite; Pl. 1, figs. 5-6): graptolites, such as planktic animals, are also abundant in some limestones, even though typical of shales. Graptolite distribution is in fact the result of currents, with intense fragmentation in shelf areas (Cherns, 1988). Several samples from Galemmu, Sentiero Flumini and Argiola have graptolites covering most of the section and sometimes clearly visible tecae. Frequently, fragments of single rhabdosomes are so closely packed to simulate a bryozoan-like colonial pattern (Pl. 1, fig. 6).

This microfacies is strictly connected with the coeval MF 1, to which some samples grade and in which graptolite fragments can also rarely be found.

MF 3) «Coated grains» grainstone to packstone

(Biomicrite with «coated grains»; Pl. 2, figs. 1-4): this microfacies was found either at the levels of latest Wenlockian (Argiola) or Ludlovian (Sentiero Flumini, *ploeckensis* conodont-zone) age.

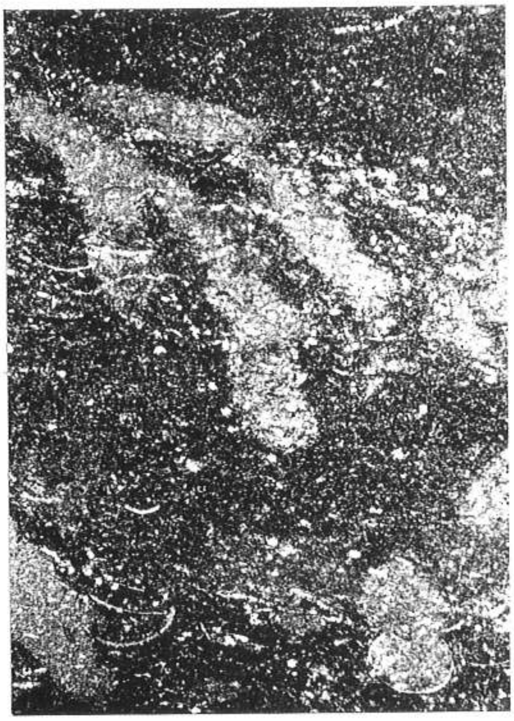
The latest Wenlockian deposition is represented by a typical grainstone (Pl. 2, figs. 1-2) characterized by thin micritic envelopes surrounding shells or skeletal fragments (mostly small bivalves but also ostracodes, gastropods and orthocones), as well as by well-rounded, fully micritic grains, both typical indicators of neritic environments (Wendt, Aigner & Neugebauer, 1984). The interparticle voids are filled with blocky cement (cement B, Flügel 1982). The average size of coated grains is 0.5 mm. In this depositional environment, usually regarded of high energy (Flügel, 1982), I also found scattered fossiliferous wackestone with articulated bivalves arranged in regular levels indicating, on the contrary, quiet and stagnant conditions, as also suggested by abundant opaque minerals. This could be related to a sudden change of sedimentation in areas producing coated grains or more probably to a transport of coated grains in a depositional area alternately agitated and calm. However the sorting of the grainstone favours the second hypothesis. A proper oolitic packstone to grainstone belongs to the same microfacies, but it occurs slightly later during Ludlovian times and seems to be restricted to the *ploeckensis* conodont zone (Pl. 2, figs. 3-4). Nuclei are mainly unrecognizable, but sometimes gastropod, orthocone or ostracode fragments may be distinguished. Ooids are generally found as veins inside graptolite rhabdosomes together with small graptolite fragments resulting from transport by wave motion or currents. As well known, modern ooid deposits characterize high energy environments, at or above the wave-base. Either coated grains grainstone or the proper oolitic grainstone to packstone were probably transported to their final resting place from a nearby coated grains generating and high-energetic, shallow water area. Unfortunately, restricted outcrops due to the peculiar tectonics of the region prevent a more detailed investigation of the source area.

MF 4) Pre-nodular mudstone

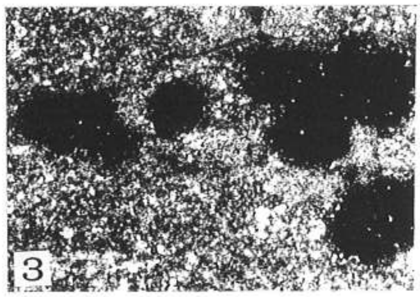
(Fossiliferous micrite; Pl. 2, figs. 5-7): this microfacies occurs in a few reddish argillaceous limestones of Ludlovian age (*crassa* to *siluricus* zones). Irregular ondulating iron oxide seams suggest a pre-nodular texture of these samples. Iron oxides often border the skeletal fragments and pigment the matrix. According to Wanless (1979), nodular limestone is the product of

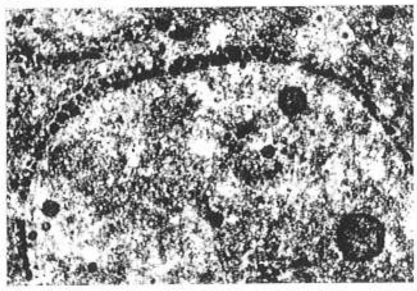
EXPLANATION OF PLATE 3

Fig. 1 - Microfacies 5, MP 10f, fossiliferous mudstone, bioturbation traces interrupt skeletal debris levels, × 11.
Fig. 2 - Microfacies 5, MP 5, fossiliferous mudstone, ? calcified radiolarians and disarticulated shells are well arranged in regular beds, × 11.
Fig. 3 - Microfacies 5, MP 10f, fossiliferous mudstone, darker spots consist of iron oxides, resulting from the oxidation of pyrite crystals, × 16.
Figs. 4,5 - Microfacies 6, ARG-BK 11, crinoidal bioclastic packstone, ostracode and phyllocarids in crinoidal limestone, crossed nicols, × 16 and × 8.
Fig. 6 - Microfacies 6, MP 6, crinoidal bioclastic packstone, × 11.
Fig. 7 - Microfacies 6, MS 1, crinoidal bioclastic packstone, × 11.

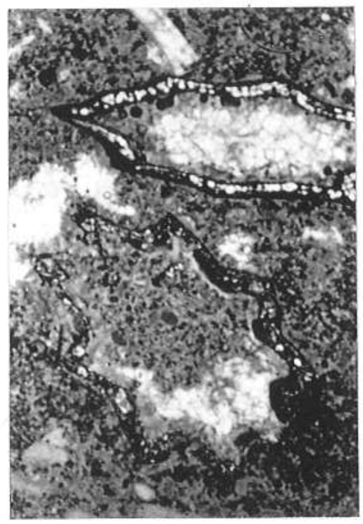


1

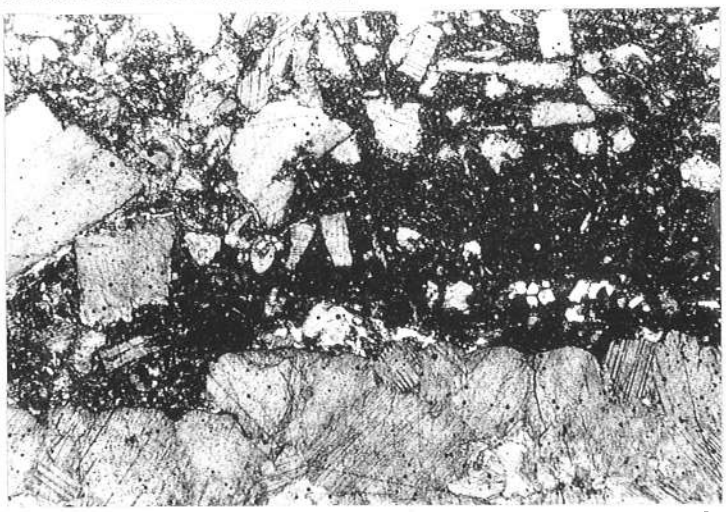




4



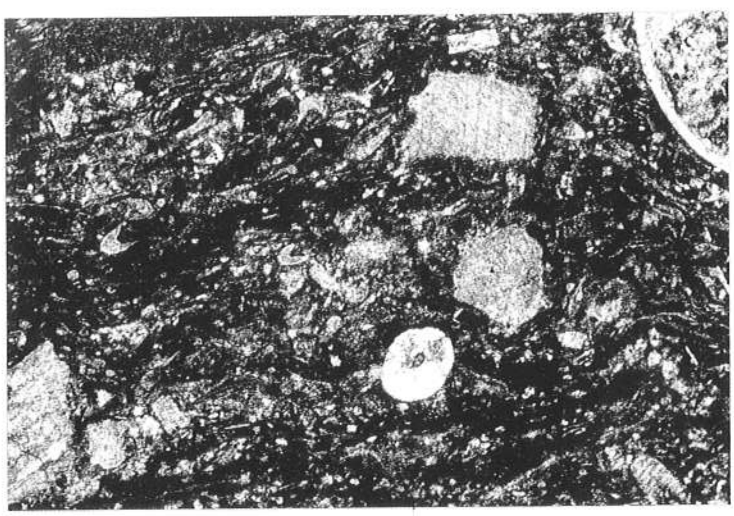
5

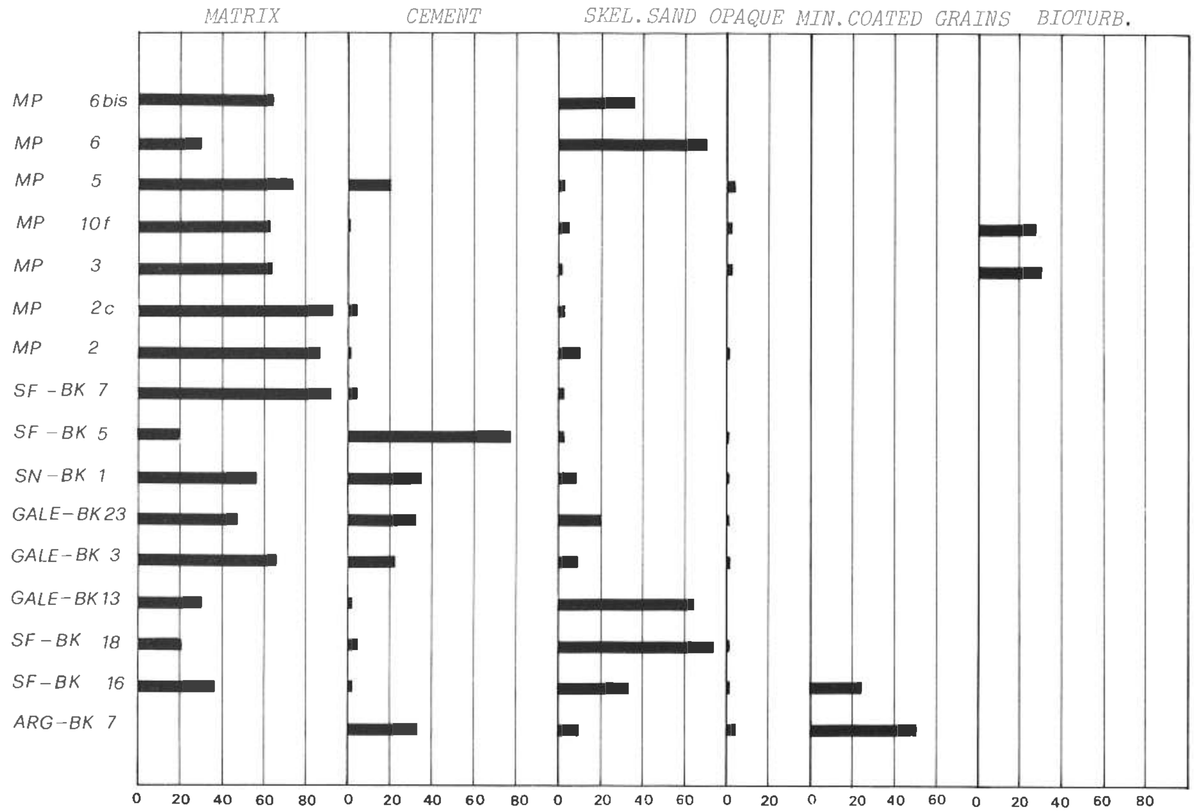


6

2

7





Text-fig. 3 - Constituent analysis of the main Upper Silurian-Lowermost Devonian Sardinian limestones.

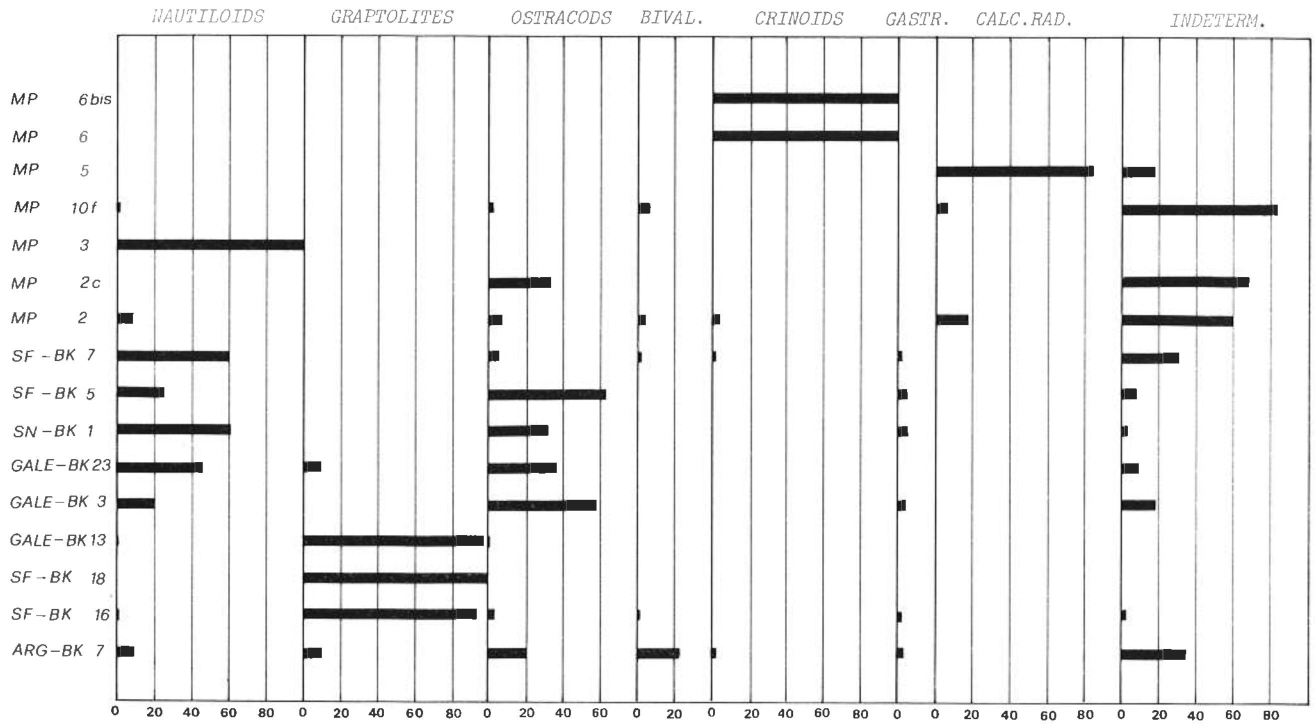
pressure solution («non sutured seam solution») in limestones with significant content of fine, platy insoluble material (such as clay, platy silt and carbonaceous material). The faunal content is very low and consists of echinoderm clasts together with large brachiopods, orthocones or unrecognizable fragments. Extremely rare quartz crystals occur as components of the matrix. Some bioclasts are structural resistant to pressure solution, in order to produce a concentration of seams all around (Pl. 2, fig. 5). The condensed nature of the limestone suggests a low sedimentation rate. Intercalated shell-lags, with sharp-basal contact and dissolution are quite common and are probably related to episodes of higher energy by storms.

They show a chaotic mixture of trilobites, ostracodes, small brachiopods, crinoids and skeletal debris. These accumulations are often bordered by iron-oxide crusts (Pl. 2, fig. 7).

Nodular limestones are generally considered as typical of shallow basinal areas (Wendt & Aigner, 1985), slopes (Tucker, 1974) or deeper ramps below fair-weather wave base (depth of 25-50 m; Dorobek & Read, 1986).

MF 5) Dark laminated fossiliferous bioturbated mudstone to wackestone

(Fossiliferous bioturbated micrite to sparse bioturbated biomicrite; Pl. 3, figs. 1-3): this microfacies occurs in Ludlovian (*crassa* to *siluricus* zone) and Pridolian (*eosteinhornensis* superzone) levels. Shells and bioclasts have been deposited in regular levels, indicating a typical quiet water environment. However the bioclasts are different in the two ages. The older deposits, cropping out in Fontanamare, show a rich fauna of ostracodes, bivalves, orthocones, trilobites and gastropods, highly variable in shape and size. Some structureless samples are probably the result of biogenic reworking, supporting that a rich endobenthic fauna was active inside the bottom. The fauna of the younger deposits, found at Mason Porcus, Galemmu, Sentiero Flumini, Roia is Tintionis and Argiola is poorer and consists of sparse pelagic small thin shelled bivalves, ostracodes, small orthocones, rare crinoid fragments and probably dispersed calcified radiolarians. Disarticulated shells are arranged with convex-up, indicating current orientation and lack of high bioturbation (Emery, 1968; Brenchley & Newall,



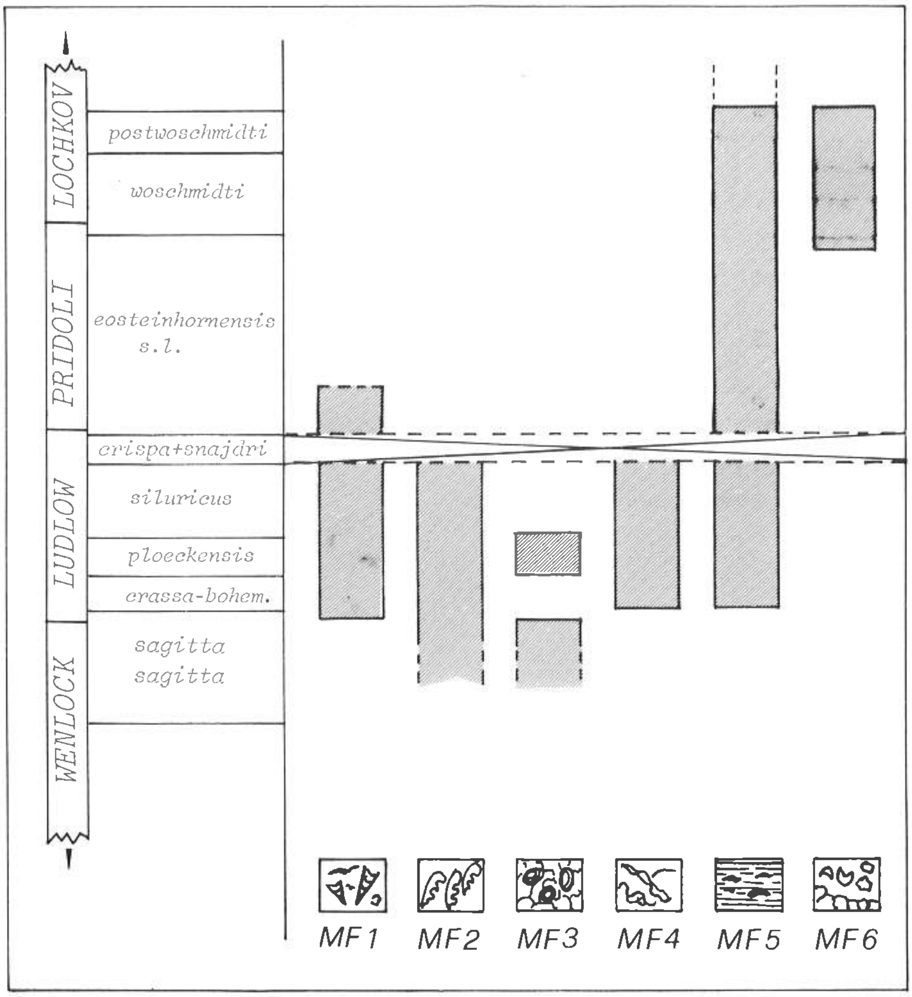
Text-fig. 4 - Composition of the skeletal sand in the main Upper Silurian-Lowermost Devonian Sardinian limestones.

1970). No compactional features, resulting from the full-bodied nature of organisms are present, revealing a low rate of sedimentation. Inside these sediments commonly laminated, bioturbation traces, penetrating to a maximum depth of about 10 cm in the sample, are also present. Generally, all these bioturbation structures are rich in iron oxides compared to the surrounding micrite, probably resulting from the oxidation of pyrite crystals, as suggested by the preservation of the typical habit in some. Sometimes, these oxides may be so concentrated to replicate the full shape of the bioturbation structure (Pl. 3, fig. 3). Current energy was only moderate. Enclosed within these limestones are allochtonous redeposited thin carbonatic levels, due to episodes of higher energy, probably related to storms. The older episodes are recognizable by thin biosparitic levels of shallow water origin, deriving from nearby shallow water platforms, while the younger ones are given by winnowed shell-lags constituted by regular shells with convex-up orientation (this hydrodynamically stable position would have resulted from waves or currents; Brenchley & Newall, 1970) («eventstone», Hüssner, 1985).

One of these events, located in the late Pridolian-early Lochkovian age, has been distinguished as MF 6.

MF 6) Crinoid bioclastic packstone

(Encrinitic biomicrite; Pl. 3 figs. 4-7): this microfacies characterizes sediments of Mason Porcus, Argiola, Monte Santo, Galemmu and Corti Baccas. Almost all of them belong to the conodont zones *Icriodus woschmidti* and *I.w.postwoschmidti* (latest Silurian-earliest Devonian) because of the presence of the markers-zone (Olivieri & Serpagli, 1989). Crinoids are completely disarticulated, with arms and stem plates showing a more or less pronounced gradational pattern. These fragments often reveal grain contact sutures (Pl. 3, fig. 6) and/or stylolites between areas of different crinoidal debris concentration («sutured-seam solution»; Wanless 1979). Lobolithes, buyont organs of planktic crinoids, such as *Scyphocrinites excavatus* (= *elegans*), are characteristic of Silurian-Devonian boundary beds, and constitute the upper part of this encrinitic sediment. They are generally associated with benthic crinoids (Stukalina, 1977), which probably populated shoals stirred by currents, while their fragments could be removed and transported to deeper areas (Wendt & Aigner, 1985). Crinoids are often the only organisms in the sample (e.g. MP 5a, MP 5b, MP 6, MP 6 bis), but they sometimes occur with ostracodes and phyllocarids (Pl. 3, figs. 4 and 5, Argiola), small brachiopods or orthocones



Text-fig. 5 - Stratigraphic distribution of the microfacies (not drawn to scale).

(Monte Santo-Monte Padenteddu). Some of these bioclasts have iron-oxide rims. Shelter void cement and intraclasts have been found in some samples of this resedimented debris facies, providing a good clue to periodic high energy events in a normally low energy environment (Kreisa, 1981; Brett, 1983).

Discussion of the data from quantitative analysis

To have a better evaluation of data from the «point-counting» analysis, I have preferred to discuss them after the description of the major microfacies recognized in our samples. Data are illustrated in text-figs. 3 and 4; samples are arranged in stratigraphic order, with the only exception of SF-BK 18, whose age is probably late Wenlock-Ludlow. The main constituents of the limestones are illustrated in text-fig. 3. The matrix content increases from the older samples (i.e. SF-BK 16 or SF-BK 5) to the younger (i.e. MP 2c, MP 5). In the former the matrix is mostly composed of more or less recrystallized micrite and skeletal fragments (in which ostracodes are important producers of skeletal debris in MF 1 and MF 2), in the latter (i.e. MP 2c, MP 2) pure micrite dominates. The reduction of the matrix content is coupled with the change of cement components and the decrease of interparticle cement. Infact, while it dominates in some samples (i.e. ARG-BK 7), only geopetal structures or veins are present in almost all Pridolian ones. Opaque minerals are ubiquitous and often concentrated in the proximity of decayed organisms (MP 5) or inside bioturbational traces (i.e. MP 10f).

As regards the skeletal fraction (text-fig. 4), it is clear that nautiloids and ostracodes are widespread in all samples, while crinoids can be quite abundant in some of them (i.e. MP 6 and MP 6 bis, corresponding to MF 6). Gastropods and bivalves (except ARG-BK 7) are scarse, whereas graptolites and crinoidal remains constitute the maximum faunal contents. This is certainly due or to the size of the fossils which in the case of graptolites are quite large, covering most of the thin section, or to the accumulation of a large amount of crinoidal debris.

Most of the indeterminable fragments in samples of Pridolian age (i.e. MP 2c, MP 5, MP 10f) are probably related to small thinned bivalves or ostracodes that have been broken and transported (as suggested by their sorting) and sometimes reworked by bioturbation (i.e. MP 10f).

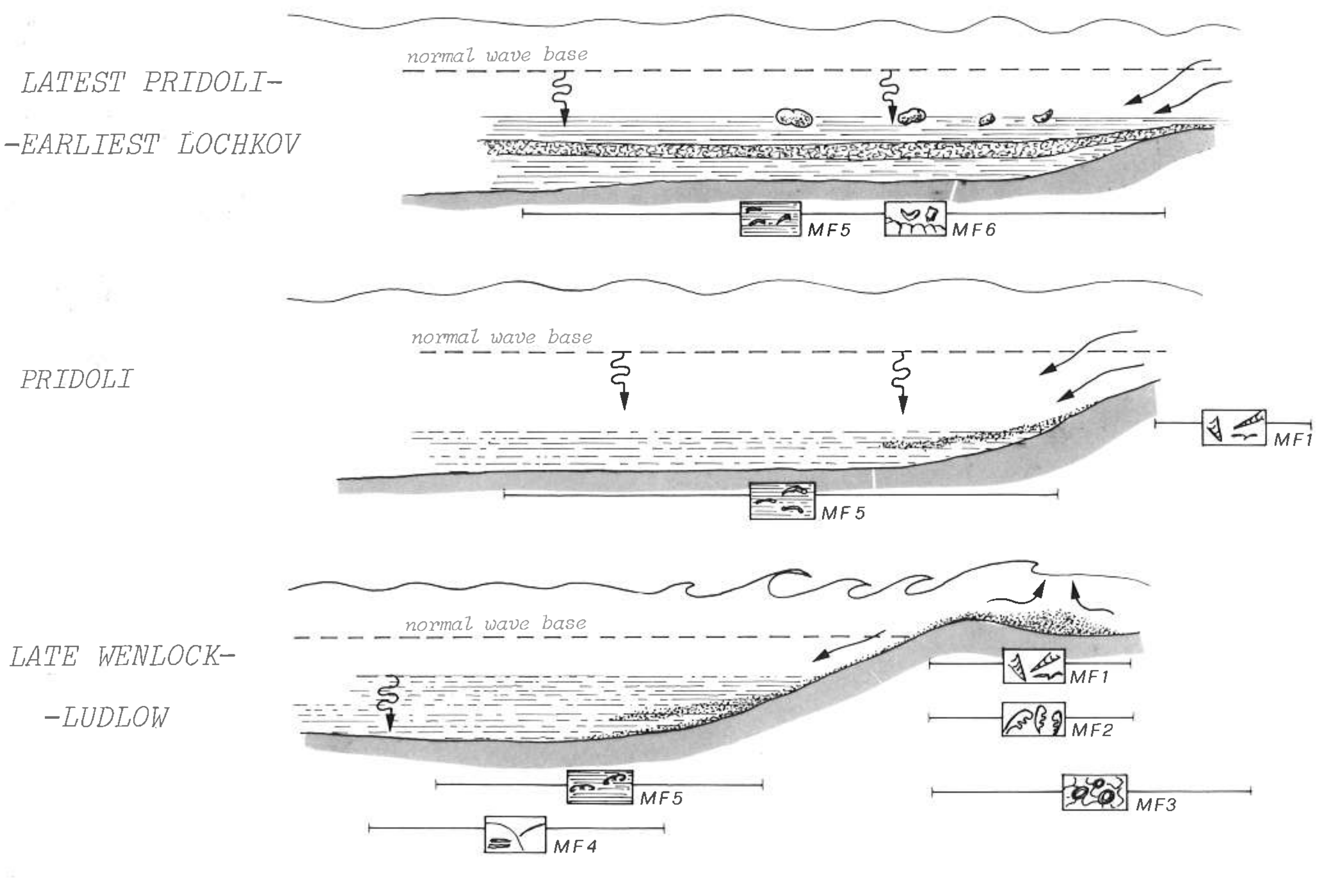
DEPOSITIONAL ENVIRONMENT

The environmental conditions of the Wenlock-Ludlow interval were studied in detail by Gnoli *et al.* (1979) who concluded that these sediments were deposited in a normally oxigenated epicontinental sea of limited depth, rich in exclusively pelagic fauna in the upper part but definitively toxic toward the bottom. More recently Gnoli & Serpagli (1985 a) suggested, on the basis of new data like the finding of large bivalves such as *Slava* (J. Kriz, paper in progress) in the upper part of the formation, that the bottom was not constantly toxic and that the Eh interface moved up and down.

One of the main goals of this research was to attempt to reconstruct the depositional environment of Upper Silurian - Lower Devonian limestones from Southwestern Sardinia, giving either more information for the late Wenlock - Ludlow interval or new data for the Pridolian - Lower Lochkovian limestones.

According to the paleontologic, petrographic, sedimentologic and stratigraphic data collected during this study, deposition occurred first in shallow and later in deep water. Transition from a neritic shelf environment to a shallow basin is illustrated schematically in text-fig. 6, where normal wave base is defined, according to Miller *et al.* (1988), as the «point of transition between skeletal grainstones, or coquinites, and the first distinct superimposed event layers with well-preserved smothered surfaces».

Three main stages of deposition can be inferred. During Late Wenlock - Ludlow (*sagitta* to *siluricus* zones), two areas with different energy were probably



Text-fig. 6 - Diagrammatic sketch showing depositional environments and characteristic microfacies for Upper Silurian-Lower Devonian limestones of Southwestern Sardinia. See the text for a full explanation.

present. MF 1, 2 and 3 were deposited in water depths near effective wave-base, as suggested by patterns of high energy (wave orthoconic ripples, telescoping, grain-support fabric, «shelter micrite», micritization,...). Oolitic grainstone then is interpreted as the result of waves and/or currents (Wilson, 1975) and, even if probably transported, it was generated in shallow water. More or less in the same time, together with these high energy carbonates, MF 4 and 5 were deposited below normal wave base but probably in areas within storm wave-base. The depositional environment was calm but with burst of high energy sedimentation, such as storms. Unfortunately, we do not yet have evidence of Upper Ludlovian sediments (*snajdri-latialatus* and *crispa* zones) to study the transition to the Pridoli and to MF 6, which clearly shows a progressive deeping. Furthermore, the upward grading from grainstones and packstones to mudstones is a strong indication of decreasing energy and deepening.

This interval has very poor fauna, composed by sparse small pelagic organisms. These sediments were laid down in a shallow stagnant basin, stirred by currents able to redeposit thin layers of shells or crinoid fragments.

Pelagic sedimentation need not involve great depths (Tucker, 1984). Furthermore, in very shallow water, minor changes in sea level or depositional topography can produce significant changes in the environment (Hallam, 1981). This deepening, infact, probably did not reach great depths, and a typical intraplatform basin can be imagined for these sediments. Accumulation of iron oxides along the rims of bioclasts or near the living chambers of nautiloids or the openings of other organisms as well as in the matrix and the presence of bioturbational structures give evidence of dysaerobic conditions on the bottom (Byers, 1977). All these sediments were certainly deposited in seas of normal salinity, as indicated by the widespread occurrence of stenohaline organisms (crinoids, nautiloids, trilobites, brachiopods). High temperature is evidenced by the presence of stenotherm organisms such as nautiloids, crinoids and some tropical bivalves, i.e. Cardiolidae (Pojeta, Kriz & Berdan, 1976; Kriz, 1979), as well as by micritization and the same genesis of coated grains. A low rate of sedimentation is suggested by micritization, boring, metal-oxide staining and uncrushed organisms.

ACKNOWLEDGMENTS

I am grateful to Profs. M. Gnoli and E. Serpagli (Pal. Inst., Modena University) for their special encouragement and helpful criticism during all stages of the work, as well as to Prof. A. Bosellini (Geol. Pal. Sc. Depart., Ferrara University), for his helpful suggestions and critical review of the manuscript and to Prof. J. L. Wilson for stimulating comments. Dr. S. Giberti provided help during many stages of the work and is deeply acknowledged. Thanks are also due to Prof. G.C. Parea (Geol. Inst., Modena University) and Prof. A. Rossi (Min. Petrol. Inst., Modena University) for valuable discussions and comments, and to Mr. G. Leonardi, the artist of the Institute of Paleontology, Modena University, who prepared the drawings.

This contribution was financially supported by the European Economic Community (EEC) in the context of the project "Silurian Ecostratigraphy in Ireland and Sardinia".

REFERENCES

Aigner, T., 1979, Schill-tempestite im oberen Muschelkalk (Trias, SW-Deutschland): N. Jb. Geol. Paläont. Abh., 157: 326-343, 7 text-figs.

Bandel, K., 1974, Deep water limestones from the Devonian-Carboniferous of the Carnic Alps, Austria: Spec. Publs Int. Ass. Sediment., 1: 93-115, 16, text-figs, Oxford.

Berry, W.B.N. & Wilde, P., 1978, Progressive ventilation of the oceans - an explanation for the distribution of the Lower Paleozoic black shales: Am. Jour. Sci., 278: 257-275.

Brenchley, P.J. & Newall, G., 1970, Flume experiments on the orientation and transport of models and shell valves: Palaeogeograpy, Palaeoclimatology, Palaeoecology, 7: 185-220, 12 text-figs, 1 tab.

Brett, C.E., 1983, Sedimentology, facies and depositional environments of the Rochester Shale (Silurian; Wenlockian) in Western New York and Ontario: Journ. Sed. Petrol., 53 (3): 947-971, 15 text-figs., 1 tab.

Byers, C.H., 1977, Biofacies patterns in euxinic basins: a general model. *In*: Deep-water carbonate enviroments, SEPM Spec. Pub. 25: 5-17, 8 text-figs.

Canavari, U., 1899, La fauna dei calcari nerastri con *Orthoceras* e *Cardiola* di Xea S. Antonio in Sardegna: Palaeontogr. Italica, 5: 187-210, 2 pls.

Carmignani, L., Cocozza, T., Gandin, A. & Pertusati, P.C, 1982, Lineamenti della geologia dell'Iglesiente-Sulcis. *In*: Guida alla Geologia del Paleozoico sardo, Guide Geologiche regionali, Soc. Geol. It.: 65-77, 3 text-figs, Cagliari.

—, —, — & —, 1986, The geology of Iglesiente. *In*: Guide-book to the excursion on the Paleozoic basement of Sardinia, IGCP project no. 5, Newsletter: 31-49, 4 text-figs. Pisa.

Cherns, L., 1988, Faunal and facies dynamics in the Upper Silurian of the Anglo-Welsh Basin: Paleontology, 31 (2): 451-502, 14 text-figs., 2 tab., 6 figs.

Dorobek, S.L. & Read, J.F., 1986, Sedimentology and basin evolution of the Siluro-Devonian Helderberg Group, Central Appalachians: Journ. Sed. Petrol., 56 (5): 601-613, 11 text-figs.

Dunham, R.J., 1962, Classification of carbonate rocks according to depositional texture: Mem. Amer. Ass. Petrol. Geol., 1: 108-121, 7 pls.

Emery, K.O., 1968, Positions of empty pelecypod valves on the continental shelf: Journ. Sed. Petrol., 38 (4): 1264-1269, 2 text-figs., 1 tab.

Flügel, E., 1982, Microfacies analysis of limestones: 1-633, 78 text-figs, 53 pls., 58 tab., Springer-Verlag, Berlin Heidelberg New York.

Folk, R.L., 1962, Petrography and origin of the Silurian Rochester and McKenzie shales, Morgan County, West Virginia: Journ. Sed. Petrol., 32 (3): 539-578, 12 text-figs., 5 pls.

GNOLI, M., 1984, Paleontological content, constituent analysis and microbiofacies of Early Devonian pelagic limestones from the Fluminimaggiore area (SW Sardinia): Boll. Soc. Paleont. Ital., 23 (2): 221-238, 5 pls.

—, LEONE, F., OLIVIERI, R. & SERPAGLI, E., 1988, The Mason Porcus Section as reference section for Uppermost Silurian-Lower Devonian in SW Sardinia: Boll. Soc. Paleont. Ital., 27 (3): 323-334, 2 pls.

—, KRIZ, J., LEONE, F., OLIVIERI, R., SERPAGLI, E. & STORCH, P., 1989, Lithostratigraphic units and biostratigraphy of Silurian and early Devonian of Southwest Sardinia: Boll. Soc. Paleont. Ital., (in press).

—, PAREA, G.C., RUSSO, F. & SERPAGLI, E., 1979, Paleoecological remarks on the «*Orthoceras* limestone» of Southwestern Sardinia (Middle-Upper Silurian): Mem. Soc. Geol. It., 20: 405-423, 9 text-figs, 4 tab.

— & SERPAGLI, E., 1977, Silurian cephalopods of the Meneghini collection (1857) with reproduction of the original plate: Boll. Soc. Paleont. Ital., 16 (2): 137-142, 2 text-figs., 1 tab.

— & —, 1984, Evidence of phyllocarid remains from Silurian-Devonian boundary beds in southwestern Sardinia: N. Jb. Geol. Paläont. Mh, 5: 257-268, 16 text-figs., 1 tab.

— & —, 1985a, Paleozoic of southwestern Sardinia. *In:* A. Cherchi (ed.) Guide book to the 19th E.M.C. 1985: 33-43, 1 text-figs, Cagliari.

— & —, 1985b, An unusually preserved foraminiferal association from the Upper Silurian-Lower Devonian beds in Southwestern Sardinia: Boll. Soc. Paleont. Ital., 23 (2), 1984: 211-220, 3 pls.

HALLAM, A., 1967, The depth significance of shales with bituminous laminae: Marine Geol., 5: 481-493, 4 text-figs.

—, 1981, Facies interpretation and the stratigraphic record: 90-101, W.H. Freeman & co. Ltd., Oxford - San Francisco.

HANDFORD, C.R., 1986, Facies and bedding sequences in shelf-storm-deposited carbonates-Fayetteville Shale and Pitkin Limestone (Mississippian), Arkansans: Journ. Sed. Petrol., 56 (1): 123-137, 15 text-figs.

HÜSSNER, H., 1985, Jurassic Carbonates of the Western High Atlas (Morocco): Microfacies analysis and plate tectonic framework: Facies, 12: 141-218, 17 text-figs., 10 pls.

JAANUSSON, V., 1972, Constituent analysis of an Ordovician limestone from Sweden: Lethaia, 5: 217-237, 11 text-figs., 2 tab.

JAEGER, H., 1977, The Silurian-Devonian boundary in Thuringia and Sardinia. *In:* The Silurian-Devonian boundary: IUGS Series A, 5: 117-125, 4 text-figs., Stuttgart.

KEITH, B.D. & FRIEDMAN, G.M., A slope-fan-basin-plain model, Taconic Sequence, New York and Vermont: Journ. Sed. Petrol., 47 (3): 1220-1241, 24, text-figs.

KING, D.T., 1986, Waulsortian-type buildups and resedimented (carbonate-turbidite) facies, Early Mississippian Burlingtone Shelf, Central Missouri: Journ. Sed. Petrol., 56 (4): 471-479, 12 text-figs.

KREISA, R.D., 1981, Storm-generated sedimentary structures in subtidal marine facies with examples from the Middle and Upper Ordovician of Southwestern Virginia: Journ. Sed. Petrol., 51 (3): 823-848, 16 text-figs., tab. 1.

KRIZ, J., 1979, Silurian Cardiolidae (Bivalvia): J. Geol. Sci., Paleontology, 22: 5-157, 42 text-figs., 40 pls., Praha.

MARTINSSON, A. (ed.), 1977, The Silurian-Devonian Boundary within IUGS Commission on stratigraphy and a state of the art report for Project Ecostratigraphy, International Union of Geological Science, 111 text-figs., Stuttgart.

MENEGHINI, G., 1857, Paleontologie de l'Ile de Sardaigne. *In:* Lamarmora, A., Voyage en Sardaigne, pp. 1-584, A-H, Imprimerie Royal Turin.

—, 1880, Nuovi fossili siluriani di Sardegna: Reale Acc. Lincei, Serie 3° Mem. Classe sc. fis. mat. e naturali, 5: 1-13, 1 tab, Roma.

MEYERS, W.J., 1980, Compaction in Mississippian skeletal limestones, Southwestern New Mexico: Journ. Sed. Petrol., 50 (2): 457-474, 8 text-figs.

MILLER, K.B., BRETT, C.E. & PARSONS, K.M., 1988, The paleontologic significance of storm-generated disturbance within a Middle Devonian muddy epeiric sea: Palaios, 3: 35-52, 14 text-figs.

MOSHIER, S.O., 1986, Carbonate platform sedimentology, Upper Cambrian Richland Formation, Lebanon Valley, Pennsylvania: Journ. Sed. Petrol., 56 (2): 204-216, 15 text-figs. 1 tab.

NELSON, C.H., 1982, Modern shallow-water graded sand land layers from storm surges, Bering shelf: a mimic of Bouma sequences and turbidite systems: Journ. Sed. Petrol., 52 (2): 537-545, 5 text-figs.

NELSON, C.S., HANCOCK, G.E. & KAMP, P.J., 1981, Shelf to basin, temperate skeletal carbonate sediments, Three Kings Plateau, New Zealand: Journ. Sed. Petrol., 52 (3): 717-732, 10 text-figs., 2 tab.

NOVARESE, V. & TARICCO, M., 1922, Cenni sommari sul Paleozoico dell'Iglesiente: Boll. Soc. Geol. It., 41: 316-325.

OLIVIERI, R. & SERPAGLI, E., 1989, Latest Silurian-Early Devonian conodonts from Mason Porcus section near Fluminimaggiore in Southwestern Sardinia: Boll. Soc. Paleont. Ital. (in press).

PALMER, D. & GNOLI, M., 1985, A preliminary report on new micropaleontological discoveries in the Silurian of Southwestern Sardinia: Boll. Soc. Paleont. Ital., 23 (2), 1984: 205-209.

POJETA, J.Jr., KRIZ, J. & BERDAN, J.M., 1976, Silurian-Devonian Pelecypods and Palaeozoic stratigraphy of Subsurface Rocks in Florida and Georgia and Related Silurian Pelecypods From Bolivia and Turkey, Prof. Pap. U.S. Geol. Surv., 879: 1-32, 8 text-figs., 2 tab.

SERPAGLI, E., 1967, Prima segnalazione di Conodonti nel Siluriano della Sardegna e relative osservazioni stratigrafiche: Acc. Naz. Lincei, Rend. Cl. Sc. fis. mat. nat., ser. 8, 42 (6): 856-858.

—, 1971, Uppermost Wenlockian-Upper Ludlovian (Silurian) conodonts from Western Sardinia: Boll. Soc. Paleont. Ital., 9 (1), 1970: 76-96, 1 text-figs. 4 pls., 1 Tab.

— & GNOLI, M., 1977, Upper Silurian cephalopods from Southwestern Sardinia: Boll. Soc. Paleont. Ital., 16 (2): 153-196, 13 text-figs., 9 pls., 3 tab.

— & —, 1984, Palaeozoic Palaeontology in Sardinia: a review (1857-1983): Boll. Mus. reg. Sci. Nat. Torino, 2 (1): 163-180.

SHUKLA, V., FRIEDMAN, G.M., 1983, Dolomitization and diagenesis in a shallowing-upward sequence: the Lockport Formation (Middle Silurian), New York State: Journ. Sed. Petrol., 53 (3): 703-717, 14 text-figs.

SIMPSON, J., 1987, Mud-dominated storm deposits from a lower Carboniferous ramp: Geological Journal, 22: 191-205, 10 text-figs.

SMITH, D.L., 1977, Transition from deep to shallow water carbonates, Paine Member, Lodgepole formation, Central Montana: SEPM Special Publication, n. 25: 187-201, 16 text-figs.

STUKALINA, G.A., 1977, Crinoids. *In:* The Silurian-Devonian boundary: IUGS Series A, 5: 333-336, 2 text-figs, Stuttgart.

TARICCO, M., 1920-1921, Sul Paleozoico del Fluminese: Boll. R. Com. Geol. Italia, 48 (6): 1-22.

TUCKER, M.E., 1974, Sedimentology of Palaeozoic pelagic limestones: the Devonian Griotte (Southern France) and Cephalopodenkalk (Germany): Spec. Publs Int. Ass. Sediment., 1: 71-92, 18 text-figs.

WANLESS, H.R., 1979, Limestone response to stress: pressure solution and dolomitization: Journ. Sed. Petrol., 49 (2): 437-462, 15 text-figs.

WENDT, J. & AIGNER, T., 1985, Facies patterns and depositional environments of Palaeozoic cephalopod limestones: Sedimentary Geology, 44: 263-300, 23 text-figs., 2 tab.

—, AIGNER, T. & NEUGEBAUER, J., 1984, Cephalopod limestone deposition on a shallow pelagic ridge: the Tafilalt Platform (Upper Devonian, eastern Anti-Atlas, Morocco): Sedimentology, 31: 601-625, 16 text-figs.

WILSON, J.L., 1975, Carbonate facies in geologic history: 1-471, 183 text-figs., 30 pls., Springer - Verlag, Berlin Heidelberg New York.

(manuscript received February 10, 1989
accepted April 8, 1989)

Annalisa FERRETTI

Istituto di Paleontologia
Via Università 4, I - 41100 Modena