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GEOLOGICAL OUTLINE, COMMUNITY SEQUENCE AND PALEOECOLOGY OF THE SILURIAN OF SARDINIA

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Key-words: Silurian, Sardinia, communities.

Riassunto. I due distinti tipi di successioni siluriane affioranti in Sardegna (Italia) sono qui analizzati e confrontati tra loro. Particolare attenzione viene rivolta alla loro età, al loro contenuto faunistico ed al loro significato globale nel tentativo di fornire un ulteriore contributo all'interpretazione degli eventi verificatisi nel Siluriano.

Abstract. Two distinct types of Silurian successions from Sardinia (Italy) are described and compared each other. Their age, faunal content and significance are briefly summarized in the attempt of giving a contribution to the global view of Silurian events.

Introduction and geological outline.

Sardinia is the second largest Mediterranean island located just in the heart of the Thyrrenian Sea at equal distance between Italy, France and Spain. A rich Paleozoic fauna, already reported about 140 years ago (Meneghini, 1857) and which provided also the oldest Italian fossils, is there exposed.

Together with Corsica, Sardinia is a segment of the European Hercynian collisional Chain which was affected by strong deformation, metamorphism and intense magmatic activity. Paleontological and geological evidences locate these two regions almost adjacent to Spain and southern France until late Oligocene (Arthaud & Matte, 1966; Cherchi & Schroeder, 1973, 1976; Westphal et al., 1976). The suture between Armorica and Gondwana is expressed in the northern part of the island by a SE-NW tectonic contact ("Posada-Asinara Line"), regarded as a segment of the south European Hercynian Suture Zone. It separates the northern "High Grade Metamorphic Complex" (Corsica and northern Sardinia) from the "Medium to Low Grade Metamorphic Complex" (central and southern Sardinia) (Fig. 1). These units represent two terranes, fused together by Hercynian events, which geometrically acted as the overthrusting continental margin and the overthrust continental margin respectively (Carmignani et al., 1992). The sedimentary cover rocks of Cambrian-early Carboniferous age, belonging to the underlying margin, are detached from their basement and accumulated in a pile of allochthonous nappes exposed between the Posada-Asinara Suture Line and the autochthonous rocks of the External Zone of the chain in SW Sardinia. Stratigraphic and structural features allow to divide this allochthonous complex into Internal Nappes (from the Posada-Asinara Line to the overthrust External Nappes) and External Nappes (between Barbagia and Iglesiente) (Carmignani et al., 1992).

The geotectonic picture of the region has been widely discussed and different interpretations have been proposed (e.g. Vai, 1980a, 1980b, 1991; Vai & Cocozza, 1986; Carmignani et al., 1992). To these works we refer for further information.

South-central Europe is supposed to have been located in the Silurian at high latitudes in the southern hemisphere adjacent to the northern margin of Gondwana, being mostly populated by low-diversity temperate shelf faunas (Scotese & McKerrow, 1990).

The Silurian in Sardinia.

Silurian rocks are exposed, discontinuously, only in southern Sardinia. Two distinct and peculiar situations occur in the SW part (Iglesiente and Sulcis sub-regions) and in the SE part (Gerrei and Sarrabus sub-regions) of the island. They remind mainly to the Silurian sequences exposed in Bohemia and Thuringia respectively. Their mutual relation is still unclear and this justifies a separate treatment and the use of different correlation charts (Fig. 2). In addition, formal lithostratigraphic units were proposed for the Silurian-early Devonian of SW Sardinia (Gnoli et al., 1990) which are now commonly used (e. g. Siveter et al., 1991; Bechstädt, 1994). Still informal names are in use in SE Sardinia, directly adopted from Thuringia (Helmcke, 1973; Jaeger, 1976, 1977). Formal names are going to be proposed by Barca, Corradini, Ferretti & Serpagli (work in progress).

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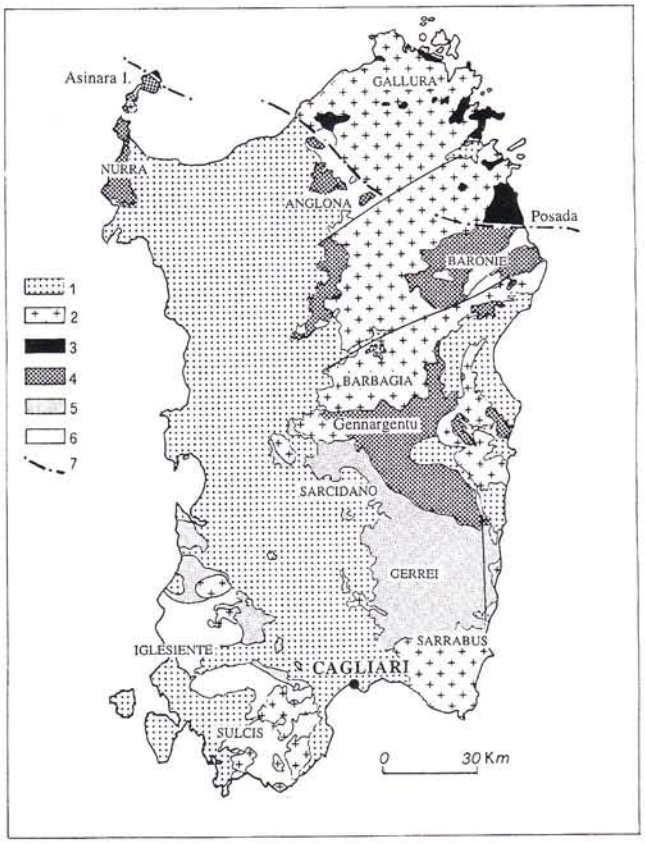

Fig. 1 - Primary structural elements of the Sardinian Basement. 1: Post-Hercynian cover; 2: Hercynian batholith; 3: High Grade Metamorphic Complex; 4: Internal Nappes; 5: External Nappes; 6: External Zone; 7: Posada-Asinara Line. Modified after Carmignani et al. (1992).

The strong tectonic activity which affected Sardinia during all the geological history of the island is mainly responsible for the fact that no continuous sections expose the full Silurian. This is reflected also in the definition of lithostratigraphic units, mostly derived from the study of several discontinuous outcrops. Furthermore, references both to graptolites and conodonts as zonal fossils are necessarily made, due to the peculiar lithology of the exposed formations. The left-band column reported in the 1995 issue of "Silurian Times" is here used, even if we believe that some of the modifications proposed in the conodont zonation and in the correlation with graptolites must be further tested.

The Silurian starts in Sardinia with graptolitic silica-argillaceous and siltitic shales, rich in carbon and pyrite especially in SE Sardinia ("alum slates"; Jaeger, 1977) and interbedded by lydites in the lower part. The Genna Muxerru Fm. of SW Sardinia (20-25 m; Fig. 2) provided the Llandovery graptolite *acuminatus, vesiculosus, cyphus, triangulatus-pectinatus, convolutus, turriculatus-crispus* and *griestoniensis-crenulata* biozones (Gnoli et al., 1990; Storch & Serpagli, 1993). The lower and upper boundaries of the formation are never clearly exposed but both appear gradational. The recovery in many sections of the *acuminatus* Biozone (Fig. 2) makes highly possible that this formation extends up to the base of the Silurian. The "Lower Graptolitic Shales" of SE Sardinia (30-40 m; Fig. 2 and 3) cover a longer time interval, revealing how shaly deposition persisted in this area also in Wenlock and early Ludlow times. No undisturbed lower contacts of the formation with Ordovician rocks are known. Lydites, very rare in SW Sardinia, are well developed here in the Llandovery up to the *turriculatus-crispus* Zone with thick individual beds, bearing frequent radiolarian lenses, separated by thin shaly layers. Phosphorites occur in the middle-upper part of the formation (Fig. 2) from the *lundgreni* to the *nilssoni* Zone as nodules, lenses or proper layers (Barca & Jaeger, 1990). Llandovery graptolites of the *vesiculosus, triangulatus-pectinatus* and *argenteus* (≈*gregarius*), *convolutus, turriculatus-crispus, griestoniensis-crenulata* and *spiralis* biozones are reported. This unit extends into the early Ludlow, at least up to the *nilssoni* Biozone (Barca & Jaeger, 1990) as also recently confirmed by the recovery at the base of the overlying calcareous formation of the *A. ploeckensis* conodont Zone (Barca et al., 1995), whose lower part seems to be equivalent to the uppermost part of the *scanicus* graptolite Biozone.

The Fluminimaggiore Fm. (Fig. 2) overlies the Genna Muxerru Fm. in SW Sardinia and roughly corresponds to the "calcari a *Orthoceras, Cardiola, Monograptus*, ecc." of the early authors. Its thickness, estimated only indirectly due to the strong tectonism, is 45-50 m. The formation spans from late Llandovery to earliest Lochkov. Black calcareous lenticular layers (Fig. 4) alternate with dark non calcareous pelites and shales. Plastic deformation and cleavage strongly alterated the shales while limestone blocks preserve fossils mostly in full three dimensions (Gnoli et al., 1980). The black colour and the peculiar bituminous smell reveal high content of organic matter. Fauna is dominated by cephalopods, associated with bivalves, pelagic ostracodes, graptolites, conodonts, forams, chitinozoans and muellerisphaerids whereas gastropods, brachiopods, trilobites, the problematic organism *Kolihaia* and eurypterid fragments are extremely rare. Graptolites are frequently found packed together in pseudo-lenticular calcareous bodies (Fig. 5). Bivalves are the only significant indicators of a benthic epifauna while almost no trilobites and brachiopods have been found, revealing the presence of anomalous oxygen conditions which could not be tolerated by these organisms. Phyllocarids and pelagic crinoids are occasionally present towards the top. The crinoid bioclastic packstone horizon associated with *Scyphocrinites* and spreading over many other regions of Gondwana caps the Fluminimaggiore Fm. The *P. amorphognathoides, O. sagitta sagitta, O. bohemica, A. ploeckensis, P. siluricus, O. remscheidensis, O. eosteinhornensis-O. e. detortus* and *I. woschmidti woschmidti* conodont biozones have been do-

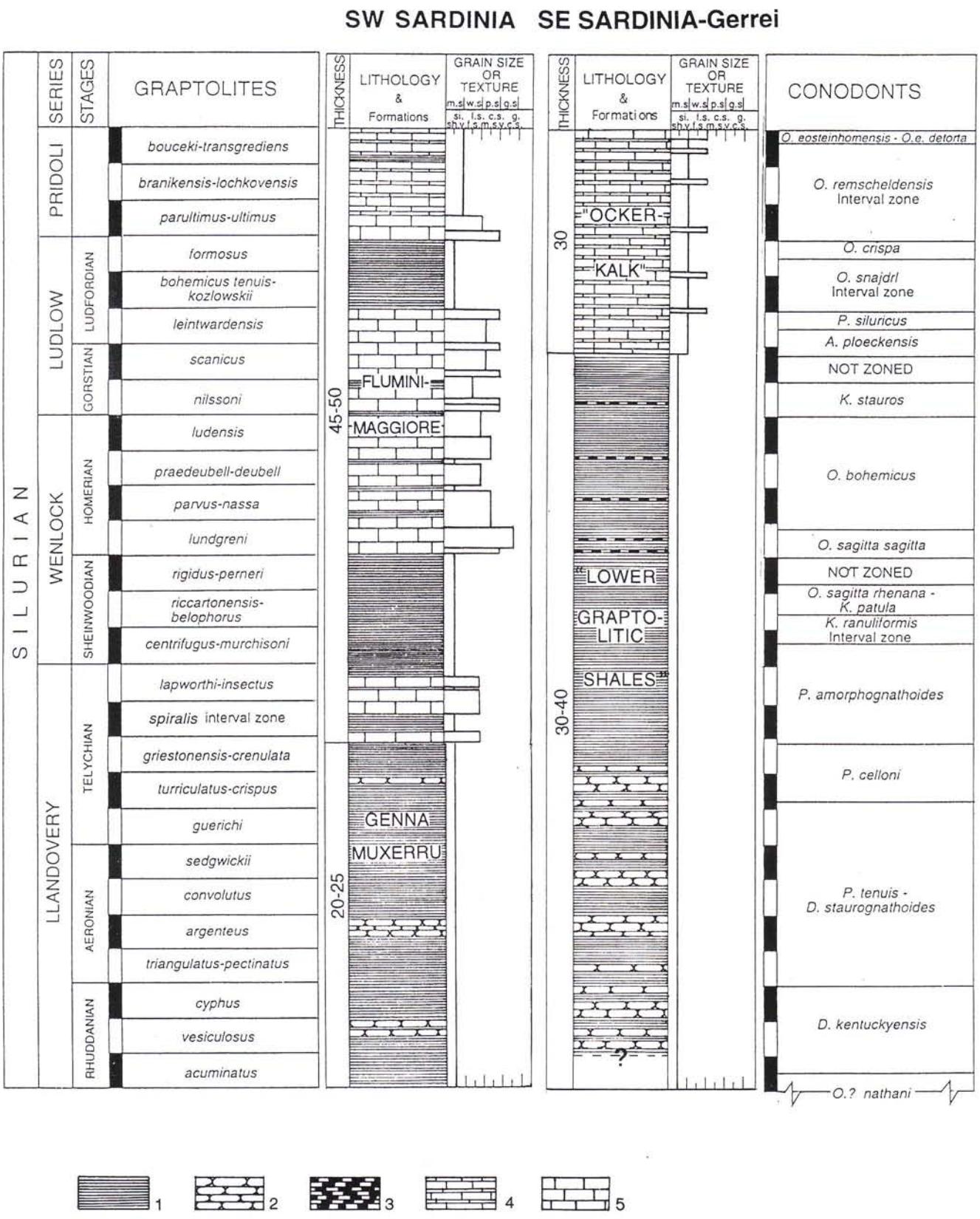

Fig. 2 - Stratigraphic column of the Silurian exposed in SW and SE Sardinia (Gerrei) respectively. 1=shales; 2=lydites; 3=phosphorites; 4=bedded limestone; 5=massive limestone. Stratigraphic scale used here is the one recently proposed by the Silurian Subcommission on Stratigraphy (1995), even if further testing is probably needed.
Dunham's classification: m.s=mudstone; w.s=wackestone; p.s=packstone; g.s=grainstone. Udden-Wentworth scale: sh.=clay; si.=silt; v.f.s.=very fine sand; f.s.=fine sand; m.s. medium sand; c.s.=coarse sand; v.c.s.=very coarse sand; g.=granules.

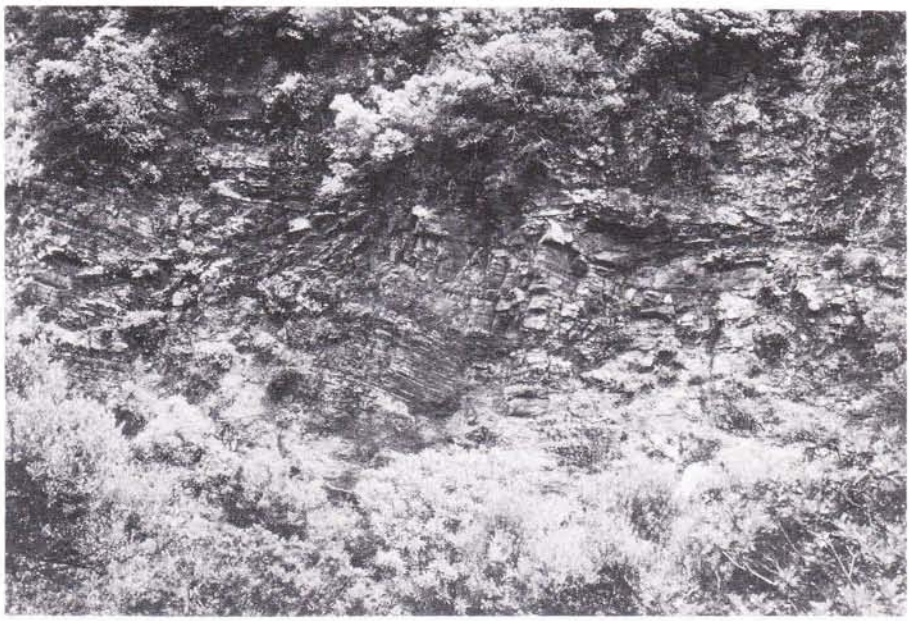

Fig. 3 - "Lower Graptolitic Shales" exposed in the Baccu Scottis section (SE Sardinia, Gerrei sub-region).

cumented (Gnoli et al., 1990). Late Ludlow is probably represented in SW Sardinia by dark shales as the *O. snajdri* Interval Zone and the *O. crispa* Biozone have never been found. Such biozones, however, occur in SE Sardinia (Barca et al., 1995). Graptolites from the calcareous bodies provided so far the *lundgreni, nilssoni, scanicus, leintwardensis, parultimus-ultimus* graptolite zones (H. Jaeger, comm. pers. 1987; Rickards et al., 1995). Carbonate deposition is characterised by dominant fossiliferous wackestone-packstones that pass to fossiliferous mudstones at the top of the formation.

The nautiloid limestones of SW Sardinia are mainly represented in SE Sardinia (Gerrei sub-region) by the uppermost part of the "Lower Graptolitic Shales", by a calcareous unit ("Ockerkalk") and probably by the lowermost part of another shaly unit, the "Upper Graptolitic Shales". The "Ockerkalk" (30 m thick; Fig. 2 and 6) is an argillaceous limestone with a blue-grey colour weathering to ochre (so the name) and having a typical irregular flaser texture. The poor fauna is mainly composed of few nautiloids (Gnoli, 1993), rare ostracodes, brachiopods, thin-shelled bivalves, trilobite fragments, gastropods, sponge spiculae, phyllocarids (mainly mandibles) and crinoids. Trace fossils and very small solitary corals were reported from the "Ockerkalk" by Jaeger (1977). All these organisms are scattered in a micritic limestone, only locally concentrated in thin wackestone bands of disarticulated debris. A rich conodont fauna spanning from the *A. ploeckensis* to the *O. remscheidensis-O. e. detortus* Biozone has been reported, documenting the *A. ploeckensis, P. siluricus, (Pe. latialata), O. snajdri, O. crispa, O. remscheidensis, O. eosteinhornensis-O. e. detortus* conodont biozones (Barca et al., 1995). The *O. snajdri* Interval Zone and the *O. crispa* Biozone have been therefore for the first time reported in Sardinia. The precise stratigraphic definition so achieved is in

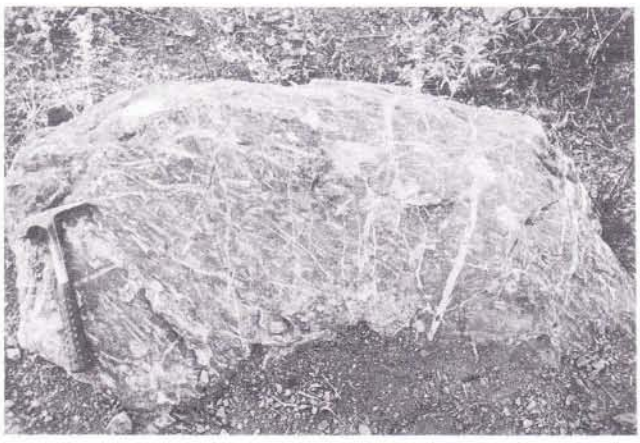

Fig. 4 - Black lens-shaped limestone rich in cephalopods of the Fluminimaggiore Fm. exposed at Fluminimaggiore-Galemmu (SW Sardinia).

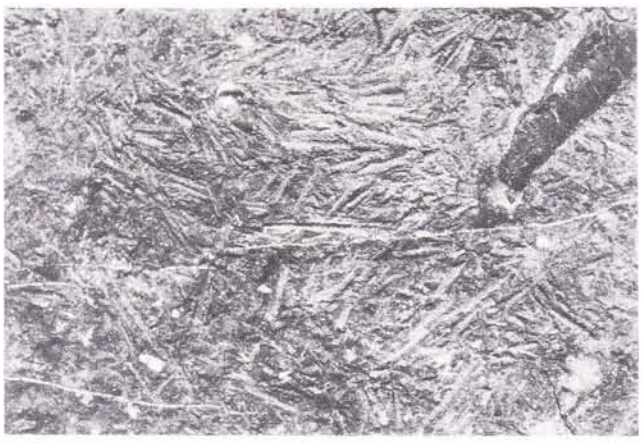

Fig. 5 - Graptolite limestone with beautifully preserved three-dimensional specimens at Fluminimaggiore-Perd'e Fogu (SW Sardinia); approximately 0.6x.

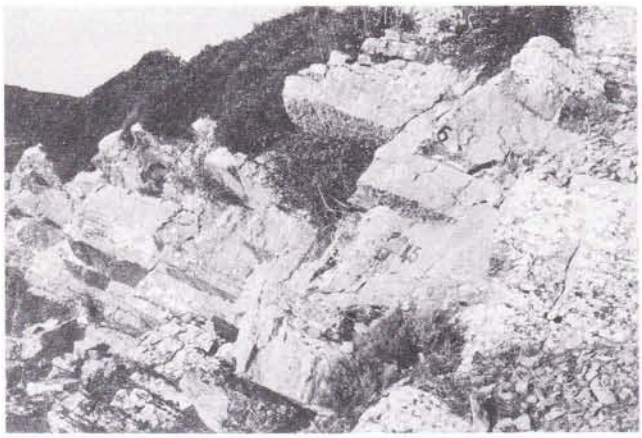

Fig. 6 - The "Ockerkalk" limestone exposed in the lower part of the SIL I° section (SE Sardinia, Gerrei sub-region). The interval represented here belongs to the *P. siluricus* Biozone. Stratigraphic distance between samples 5 and 6 is about 1 m.

good agreement with the graptolite data derived from the embedding shales at the base and the top of the formation (Jaeger, 1976). The lobolith-horizon with the giant pelagic crinoid *Scyphocrinites* well known along the northern Gondwana margin across the S/D boundary and already recorded in the early Devonian of SW Sardinia (Gnoli et al., 1988) extends also to the late Silurian of SE Sardinia (Gerrei sub-region; Helmcke, 1973; Jaeger, 1976, 1977; Barca & Jaeger, 1990; Barca et al., 1995). To point out that, at least in Sardinia, late Silurian loboliths are apparently smaller than those of early Devonian age. In the Sarrabus sub-region of SE Sardinia, Silurian olistolithes and olistostromes embedded in flysch-type silico-clastic sediments of probably early Carboniferous age were described (Barca, 1991; Barca & Olivieri, 1991). Graptolitic alum slates with interbedded lydites (like those described in Barca & Jaeger, 1990) as well as calcareous blocks (described in Barca et al., 1986; Barca & Olivieri, 1991) are part of this complex (S. Barca, comm. pers. 1996), deposited in a foredeep basin, with many analogies with the Culm-type Hercynian flysches of southern Europe (Spalletta & Vai, 1982; Vai & Cocozza, 1986).

The Silurian/Devonian boundary occurs in SW Sardinia still in the calcareous Fluminimaggiore Fm. (Gnoli et al., 1988), whereas it seems to develop in SE Sardinia (Gerrei sub-region) at the base of the "Upper Graptolitic Shales" whose first layers bear the index species *M. uniformis* (Jaeger, 1976). These are composed of alum slates without lydites or phosphorites. According to the composite section prepared by Barca & Jaeger (1990, fig. 9), *Scyphocrinites* occurs also in the lower part of this formation. These shales grade continuously to nodular limestones of late Lower to Middle Devonian age.

Paleoecological remarks.

As expressed by lithological columns (Fig. 2), the Silurian started in Sardinia with a more or less uniform diffusion of dark lyditic shales rich in graptolites. The same deposition occurs at the base of many other south-European sequences, indicating the establishment of a common circuit along northern Gondwana after the marked provincialism of the Upper Ordovician. The shaly deposition occurred in a reducing euxinic sapropelitic basin (Jaeger, 1977; Gnoli et al., 1990) and was interrupted diachronously by a calcareous sedimentation which started sporadically already in late Llandovery and more definitely in Wenlock times in SW Sardinia

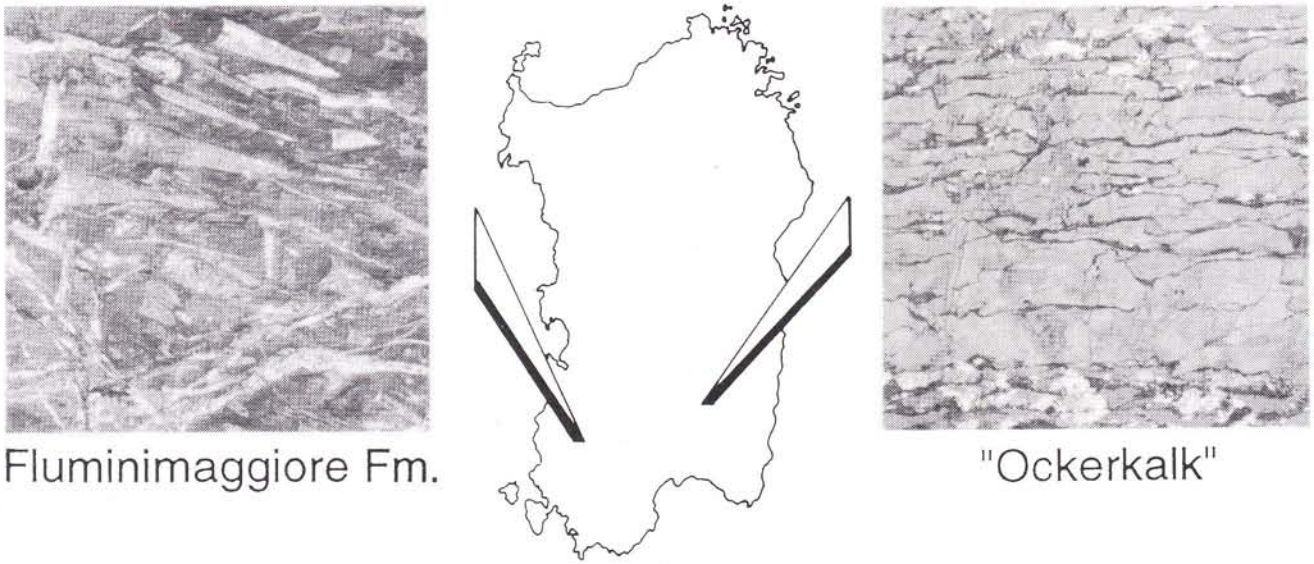

Fig. 7 - Calcareous deposition in the Silurian of Sardinia: the Fluminimaggiore Fm. occurs in SW Sardinia and the "Ockerkalk" in SE Sardinia.

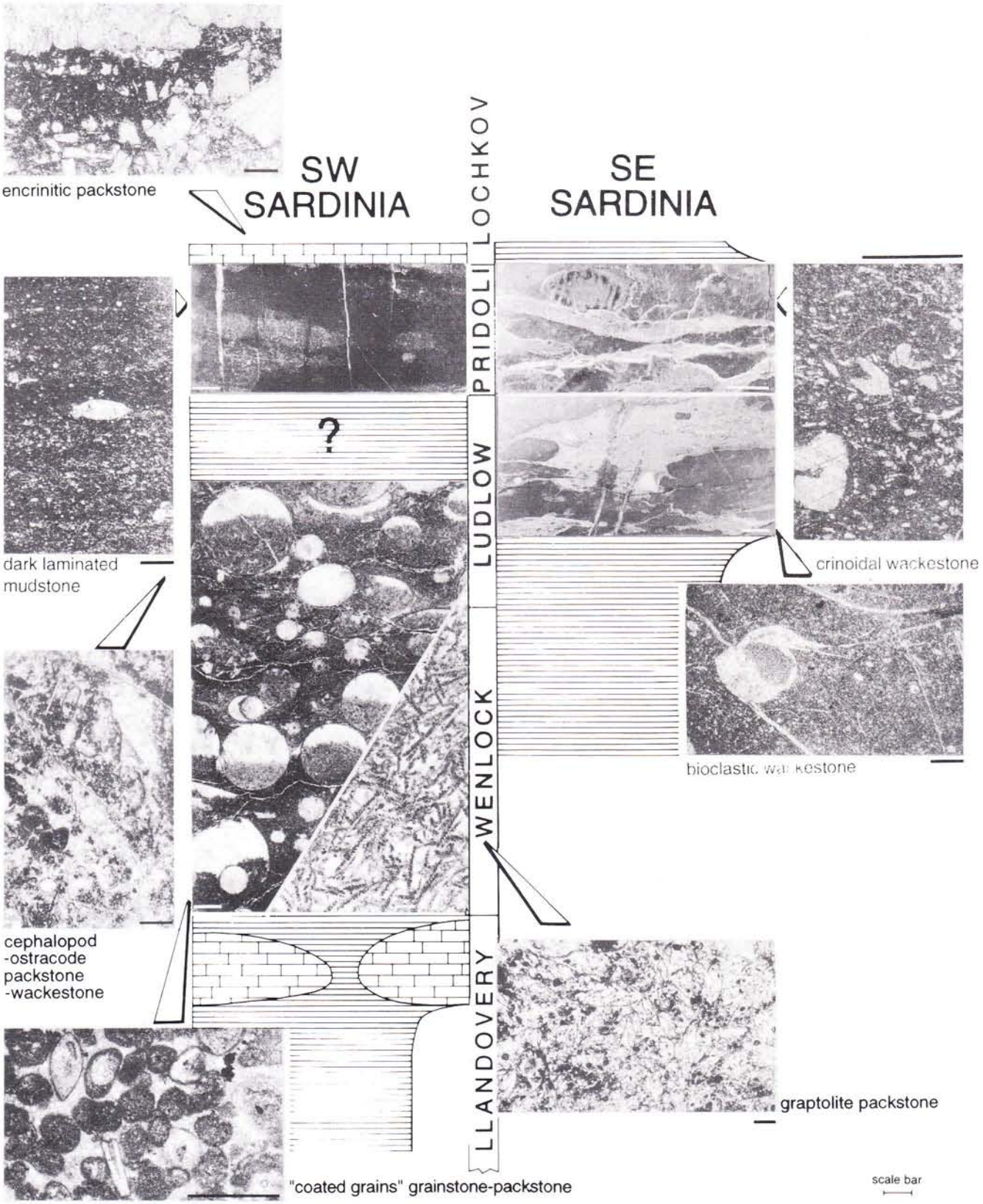

Fig. 8 - Comparison between the calcareous sedimentation and microfacies of SW Sardinia and SE Sardinia (Gerrei sub-region). Scale bar reference = 2x (for white bars) or 10x (for dark bars). Microfacies photographs partly from Ferretti (1989) and Barca et al. (1995).

and only in late Ludlow in SE Sardinia (Fig. 7). Cephalopod limestones from SW Sardinia are lens-shaped beds which always intercalate to shales. They probably represent short sedimentation events in the quiet depositional environment of the shales. A very pronounced double alignment of orthoconic shells, comparable to the crest and the trough of ripple marks and to the typical bimodal orientation pattern of wave accumulation, was revealed by examination of large cephalopod plates and blocks and by laboratory experiments (Gnoli et al., 1980). A constant SSE-NNW cephalopod orientation was recently described from a new upper Wenlock locality (Ferretti et al., 1995a), suggesting the existence of at least a connection with the global current carrying cephalopods over many parts of northern Gondwana. Even displaced blocks bearing random oriented orthocones were found.

Five different microfacies (Fig. 8) were recognised in the Wenlock-upper Ludlow limestones from SW Sardinia, indicative of two main different regimes: a shallow high-energy deposition for the cephalopod-ostracode packstone-wackestones (typical of the *Orthoceras* limestone), 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. The Pridoli sedimentation indicates a shift to deeper waters being represented by dark fossiliferous mudstones with occasional disarticulated winnowed shell lags of thin-shelled and convex-up bivalves and ostracodes, small orthocones and rare crinoid fragments (Ferretti, 1989).

Limestones from SE Sardinia are mostly represented by massive sequences of fine micritic limestones with millimetric shell-lags of disarticulated debris (Fig. 8). A quiet pelagic environment below wave-base was supposed (Barca et al., 1995).

As already noted, the transition to the Devonian occurs still in calcareous facies in SW Sardinia while in SE Sardinia it appears to correspond to the lithological change from the "Ockerkalk" limestone to the overlying "Upper Graptolitic Shales".

Community sequence.

Eight communities and assemblages, both benthic and pelagic owing to the peculiar nature of the fauna, were described from the Silurian of southern Sardinia (Ferretti et al., 1995b, in Boucot & Lawson, Eds.). That study was completed in 1989, when the latest information on the "Ockerkalk" and the new faunal discoveries from the Fluminimaggiore Fm. were not yet emerged. Subsequent investigations respectively of the nautiloid (Gnoli & Serpagli, 1991) and of the bivalve fauna (Kriz & Serpagli, 1993) from SW Sardinia provided a detailed intra-taxa community definition. The community sketch given here (Fig. 9) is an attempt of summarize all data nowadays available on the Silurian Communities of Sardinia. Many of them, like the *Orthoceras* lmst. and *Cardiola* Communities, have a widespread distribution in the circum-Mediterranean area.

The "Graptolitic Shale" Community covers most of the Llandovery, being only sporadically associated with the *P. amorphognathoides* Community reported in SW Sardinia. In Wenlock times, the *Orthoceras* lmst. and *Cardiola* Communities developed in SW Sardinia, being strongly related each other and interfingering and alternating to the "Graptolitic Shale" Community. The very rich *O. sagitta sagitta* Community and a first "Graptolitic Limestone" Community were also present at that time.

The ostracode *Entomis migrans* and *Bolbozoe bohemica* Communities flourished in Ludlow times; the *Orthoceras* lmst., *Cardiola*, "Graptolitic limestone" and "Graptolitic Shale" Communities were still present. The conodont *Kockelella-Ancyrodella-Polygnathoides* Community developed both in SW and in SE Sardinia. The *O. crispa-O. snajdri* Community from SE Sardinia is the only present at the end of the Ludlow. A further "Graptolitic limestone" and the *Orthoceras* lmst. Communities are reported in the early Pridoli of SW Sardinia, while the conodont *O. remscheidensis* Community was present on both sides of the island. The phyllocarid *Ceratiocaris* Community, a peculiar forams Community from SW Sardinia and the *Scyphocrinites* Community from both sides of Sardinia developed close (the former two) or crossed the Silurian/Devonian boundary.

Twelve Silurian-Lower Devonian Bivalvia-dominated communities were recognised at distinct stratigraphic levels inside the Fluminimaggiore Fm. (Kriz & Serpagli, 1993). The strong affinity of SW Sardinia and Bohemia was stressed once more by the occurrence of almost 80 common bivalve species. Four medium-diversity communities were described within the *Cardiola* Community Group of late Wenlock to late Ludlow age. Adaptation to the cephalopod limestone biofacies was achieved by these communities mainly composed of abundant epibyssate bivalves living on a substrate represented by cephalopod shells. Pridoli communities adjusted to the soft bottom conditions of the micritic facies with low-diversity infaunal and seminfaunal populations. Monospecific or almost monospecific communities developed at restricted living conditions (e. g. limited current activity and low oxygen content) while in the most favourable regions relatively higher diversity and lower population density communities still grew (Kriz & Serpagli, 1993).

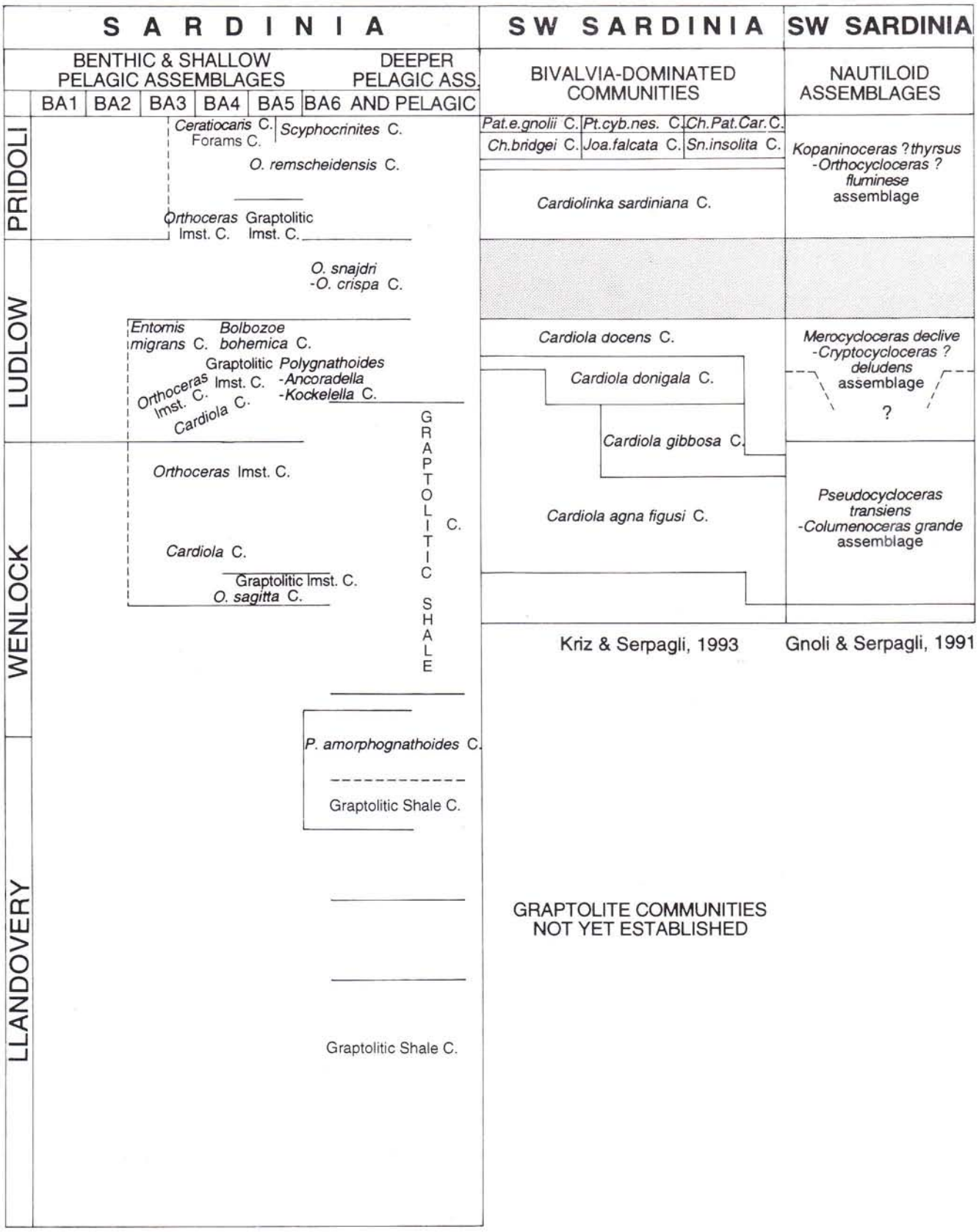

Fig. 9 - General sketch of Silurian Communities in Sardinia. Data of the left column are modified after Ferretti et al. (1995b).

Three nautiloid assemblages with potential stratigraphic value were recognised in the middle-late Silurian of SW Sardinia (Gnoli & Serpagli, 1991). The *Pseudocycloceras transiens-Columenoceras grande* assemblage occurred in the *O. sagitta sagitta-O. bohemica* Zones, the *Merocycloceras declive-Cryptocycloceras ? deludens* assemblage developed in the *A. ploeckensis-P. siluricus* Zones and the *Kopaninoceras ? thyrsus-Orthocycloceras ? fluminese* assemblage extended from the *O. eosteinhornensis* to the *I. w. woschmidti* Zone. Each of them has a widespread distribution and is closely linked again to the nautiloid fauna from the Prague Basin.

New data are still emerging from Sardinia and interesting projects are running on. Major attention has been recently paid towards "minor" fossil groups (i. e. chitinozoans or muellerisphaerids) or unusual facies like the graptolitic limestones of SW Sardinia; conodont evidences from additional "Ockerkalk" sequences are coming. So, the picture here drawn is just a preliminary synthesis based on previous studies and current researches on the Silurian of Sardinia. This region will certain provide in the near future new pieces of information to understand more clearly Silurian events.

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