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# A general view on the post-Sardic Ordovician sequence from SW Sardinia

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Ordovician rocks are quite widespread in South-western Sardinia and belong either to autochthonous or to allochthonous and/or parautochthonous structural units. These units are affected by a weak deformation and low-grade metamorphism (greenschist facies: Di Simplicio *et al.*, 1974).

The autochthonous Ordovician rocks include two main sequences, which are separated by an angular unconformity:

A) a lower sequence, which is formed by the uppermost part of the "Cambrian" Cabitza Formation (Cocozza, 1967) which has been regarded as Tremadocian on the basis of *Rhabdinopora flabelliformis* (Eichwald, 1848) and acritarchs (Barca *et al.,* 1987; Pillola & Gutierrez-Marco, 1988).

B) an upper, thick sequence, which starts with the "Puddinga" (Monte Argentu Formation) and ends, without any apparent disconformity, with early Silurian rocks.

The angular unconformity, which separates the weakly folded and faulted lower Cambrian to Tremadocian sediments from the overlying younger Ordovician strata is related to the so-called "Sardic Phase" of Stille (1939), whose age lies between the Tremadocian and Caradocian. The geodynamic processes, which gave rise to the Sardic deformation are still a matter of debate (Vai & Cocozza, 1986; Bechstädt & Boni, 1989, Carmignani *et al.,* 1991, for instance). Due to its stratigraphic position the Sardic Phase belongs to the group of early Ordovician "Taconic events" (*sensu* Ziegler, 1988). Owing to the moderate deformation and the relatively low depth of subsequent erosion it is obvious that the Sardic Phase was not a very important orogenetic phase and did not lead to a crustal consolidation of South-west Sardinia.

The deformational act was followed by uplift and erosion and finally by transgression of the post-sardic Ordovician sequence. Within South-western Sardinia the new sedimentary cycle did not start everywhere at the same time.

The most important post-sardic Ordovician autochthonous sequence of south-western Sardinia is the Iglesiente-Sulcis sequence. For a long time the only available stratigraphic references were papers by old authors (Novarese, 1914; Taricco, 1922). Several papers on specific taxonomic groups have been produced since Meneghini (1857). At present there are descriptions of the following fossil groups: brachiopods (Meneghini, 1857; 1880, Vinassa De Regny, 1910, 1927; Giovannoni & Zanfrà, 1979; Havlicek *et al.,* 1987; Leone *et al.,* 1991; Villas *et al.*, 2002), bryozoans (Vinassa De Regny, 1942; Conti &

Serpagli, 1984, 1987, 1988; Conti, 1990), cystoids (Vinassa De Regny, 1942; Maccagno, 1965), trilobites and other arthropods (Vinassa De Regny, 1927; Hammann *et al.,* 1990; Leone *et al.,* 1991; Hammann & Leone, 1997 and in press), conularids (Meneghini, 1880; Serpagli, 1970), cornulitids (Meneghini, 1857; Vinassa De Regny, 1942; Spano, 1974), graptolites (Leone *et al.,* 1993), conodonts (Ferretti & Serpagli, 1991), algae (Ferretti *et al.*, 2000; Hammann & Serpagli, in press).

Five formations and nine members were formally described (Leone *et al.,* 1991, Laske *et al*., 1994) (Figs 1, 2). More sedimentological and environmental data have been recently reported by Leone *et al.* (1995).

## The Monte Argentu Formation

The autochthonous succession starts with a mainly red coloured sequence of conglomerates, siltstones and sandstones ("Puddinga" *Auct.).*

The Monte Argentu Formation (Laske *et al.,* 1994) was lithologically subdivided into three units: Punta sa Broccia, Riu is Arrus and Medau Murtas Members (Laske *et al.,* 1994). In the Sulcis region and also in some places of the Iglesiente only the Medau Murtas Member is present.

*The Punta sa Broccia Member*. In most areas of the Iglesiente the Monte Argentu Formation starts with a 30-150 meter thick sequence of mainly red-purple, largely unfossiliferous, locally block-bearing cobble to small pebble and granule conglomerates with interbeds of siltstones and sandstones in variable amounts. This member forms a marked fining upward megasequence.

At several places of the Iglesiente (particularly in the area of Nebida and Bacu Abis) intercalations of limestone breccias (in part dolomitized) are interbedded within the coarse grained basal conglomerates or immediately overlie the Sardic unconformity.

*The Riu is Arrus Member* . The conglomerate dominated Punta sa Broccia Member is conformably overlain by 20-90 meter thick, locally fossiliferous, gray coloured siltstones and shales containing some intercalations of sandstones, usually in their lower and upper parts. At the base some fine grained conglomerate layers may also be present. Because of its widespread occurrence and its marked gray colour this unit can be taken as a marker horizon in the Iglesiente region. In former times these gray sediments were already mentioned by Taricco (1922) and Mascia (1976).

*The Medau Murtas Member*. The gray siltstones and shales are followed by an up to 150 meter thick sequence of again predominantly red, but partly also green coloured siltstones and sandstones. Fine grained conglomerate beds may be present too, but they always occur in subordinate amounts. Thicker beds of pebble to granule conglomerates may be present locally at the base of the Medau Murtas Member in places where they form the first sediment cover over eroded slates of the Cabitza Formation or the "Ceroid Limestone" of the Gonnesa Group (Pillola, 1990), as in the Sulcis region and in certain places of the Iglesiente region.

In the Sulcis region the siltstones of the Medau Murtas Member locally also contain some intercalations of limestones, mostly in the form of thin layers or lenses, for instance in the area of Narcao and Rosas (see also Poll, 1966; Fiori, 1977).

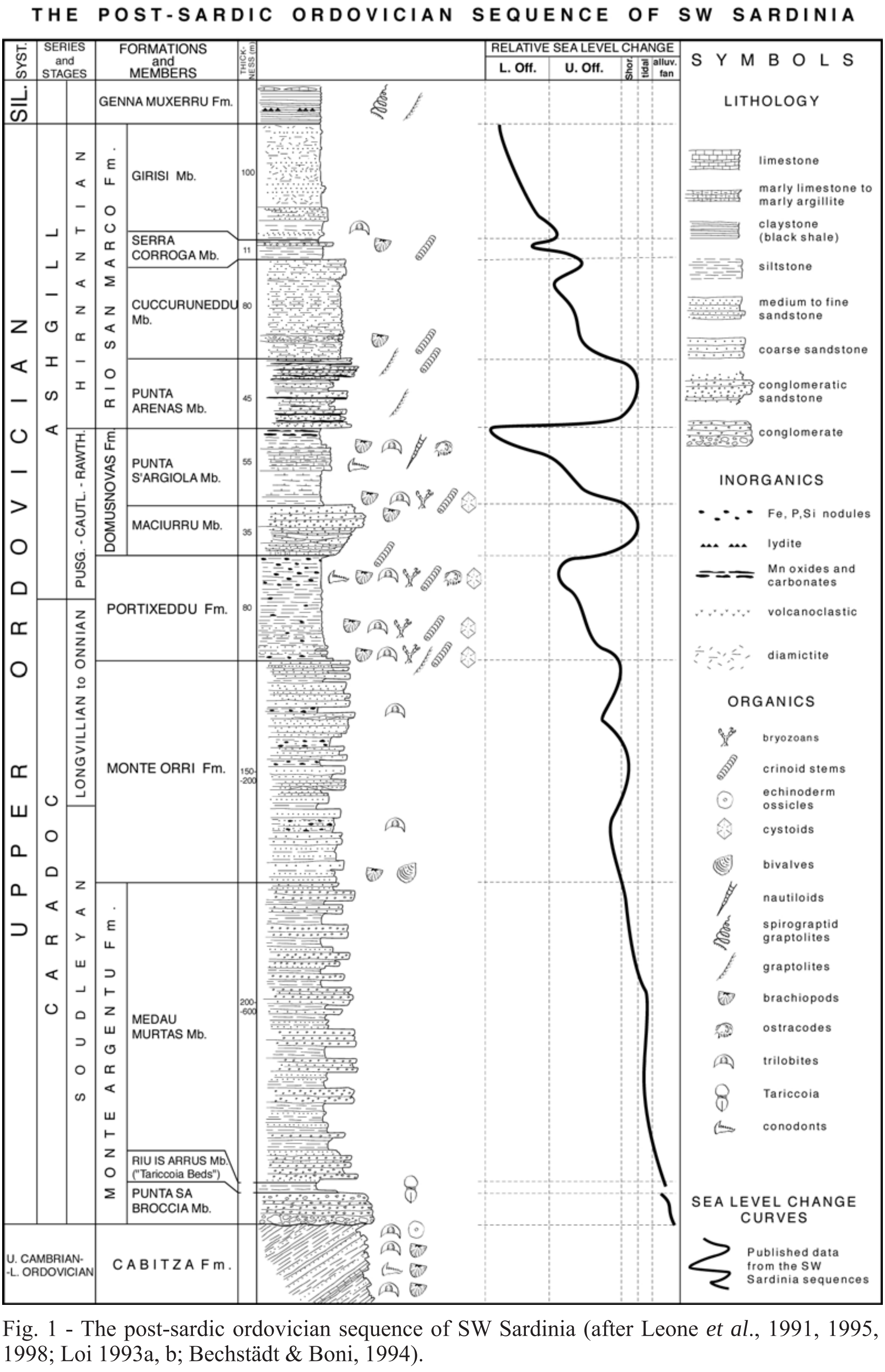



Fig. 1 - The post-sardic ordovician sequence of SW Sardinia (after Leone *et al.*, 1991, 1995, 1998; Loi 1993a, b; Bechstädt & Boni, 1994).

Sedimentology

The conglomerates of the Monte Argentu Formation are mainly composed of subrounded to occasionally well rounded clasts of slates, sandy slates and sandstones, which are derived from the Cabitza Formation. In some places (particularly at Nebida and Fluminimaggiore) also limestone clasts derived from the "Ceroid Limestone" of the Lower Cambrian Gonnesa Group are present. However, dolomite clasts from the lower Gonnesa Group as well as sandstone clasts from the Lower Cambrian Nebida Group are missing in the Monte Argentu Formation. In addition, small amounts of quartz vein and hematite particles are present. In the Sulcis region locally some conglomerate beds contain an unusually high content of quartz pebbles (Poll, 1966).

The matrix of the conglomerates ranges between granule-sized grains and fine sand, the silt and clay content is generally low. Both matrix particles and framework clasts are intensely stained red or are even sometimes completely substituted by hematite.

The limestone breccias are almost exclusively composed of "Ceroid Limestone" clasts. The breccias are usually cemented by carbonate, though locally a red silt matrix can be observed, too.

The sandstones of the Punta sa Broccia Member are mostly lithic arenites, although some of them must be classified as graywackes. Lithic grains are also an important constituent of the Monte Argentu Formation sandstones.

The limestones locally occurring in the Medau Murtas Member of the Sulcis region are predominantly micritic, exhibiting sometimes a fenestral fabric.

Apart from rare trace fossils, which were observed in the Bacu Abis area (Pillola, 1981; Loi *et al*., 1995), no other fossils have been found in the sediments of the Punta sa Broccia Member up to now. The only macrofossils, arthropod and possible algal remains, found within the sequence, occur in the gray siltstone/shale unit which separates the Punta sa Broccia from the Medau Murtas Member. They were already observed, however, but not figured by Taricco (1922).

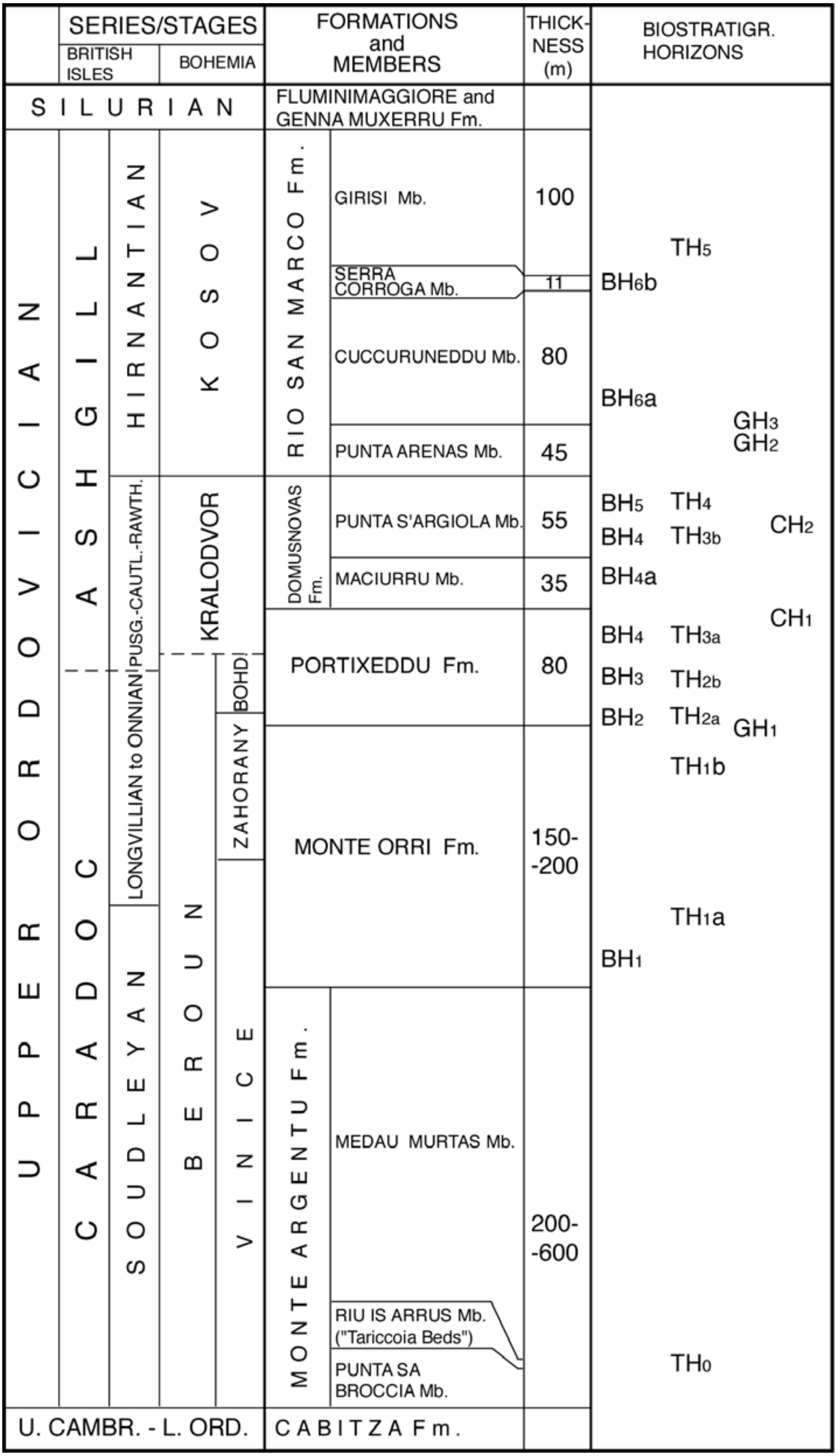
Rediscovered localities of Taricco and revision of fossils revealed the presence of only one species of a soft bodied new nectaspide trilobite, *Tariccoia arrusensis* (Hammann *et al.,* 1990). Biostratigraphically (TH0) this fossil is not significant because its occurrence is restricted to the Fluminimaggiore area.

Apart from rare trace fossils observed in some red siltstones and limestones no other fossils have been found in the sediments of the Medau Murtas Member.

Because of the lack of biostratigraphically useful fossils the Monte Argentu sequence cannot be dated directly. However, according to the stratigraphical context, its deposition is most probably strongly diachronous and took place mainly during the early Caradocian. Diachronism of the lower boundary of the Monte Argentu Formation is indicated by the fact that the lowest two members are missing in certain areas, which obviously is the result of a gradual transgression over an existing palaeorelief. The upper boundary of the Monte Argentu Formation is diachronous as well because it is both overlain by the Monte Orri Formation (Fluminimaggiore, Domusnovas and Monte Orri areas) and by the basal Portixeddu Formation (Bacu Abis area). In some places east of Buggerru the deposition of conglomerate (Monte Argentu Formation ?) may even reach higher up.

The beginning of the sedimentation of the Monte Argentu Formation cannot be dated precisely at all. Accumulation of alluvial sediments theoretically could have started at any time after uplift, which probably took place at the end of the Arenig. More probably,

Fig. 2 - Lithostratigraphic units and biostratigraphic horizons in the post-Sardic Ordovician sequence of SW Sardinia.


SERIES/STAGES
BRITISH ISLES
BOHEMIA
FORMATIONS and MEMBERS
THICK-NESS (m)
BIOSTRATIGR. HORIZONS
SILURIAN
FLUMINIMAGGIORE and GENNA MUXERRU Fm.
UPPER ORDOVICIAN
ASHGILL
CARADOC
HIRNANTIAN
PUSG.-CAUTL.-RAWTH.
LONGVILLIAN to ONNIAN
SOUDLEYAN
KOSOV
KRALODVOR
BOHD.
ZAHORANY
BEROUN
VINICE
RIO SAN MARCO Fm.
GIRISI Mb.
100
SERRA CORROGA Mb.
11
CUCCURUNEDDU Mb.
80
PUNTA ARENAS Mb.
45
DOMUSNOVAS Fm.
PUNTA S'ARGIOLA Mb.
55
MACIURRU Mb.
35
PORTIXEDDU Fm.
80
MONTE ORRI Fm.
150--200
MONTE ARGENTU Fm.
MEDAU MURTAS Mb.
200--600
RIU IS ARRUS Mb. ("Tariccoia Beds")
PUNTA SA BROCCIA Mb.
U. CAMBR. - L. ORD.
CABITZA Fm.
TH5
BH6b
BH6a
GH3
GH2
BH5 TH4
BH4 TH3b CH2
BH4a
CH1
BH4 TH3a
BH3 TH2b
BH2 TH2a GH1
TH1b
TH1a
BH1
TH0

however, it may coincide more or less with a marine transgressive cycle, which is very widespread in the west-Mediterranean region, starting over a small gap with a sedimentary iron ore at the beginning of the Vinice (Iberian Peninsula, Armorican Massif, Bohemia). A transgression of similar age and absence of Llanvirnian-Llandeilian marine sediments ("Tristani beds") is also known in the Pyrenees, the Montagne Noire, the Carnic Alps (Schönlaub, 1979) and in SE-Turkey (Dean & Monod, 1990) and this occurrence has been newly interpreted by Hammann (1992).

### Depositional environment

The conglomerates and associated sediments of the Punta sa Broccia Member are interpreted as deposits of alluvial fans, interfingering at least locally with lacustrine or marginal marine water bodies (local occurrence of trace fossils).

The sediments of the gray siltstone/shale unit with *Tariccoia* are interpreted as marginal marine deposits (sheltered bay or lagoon). This can be concluded from sedimentological observations, from the absence of clearly marine organisms and from the extremely low diversity of the fauna (Hammann *et al.,* 1990).

The siltstones and sandstones of the Medau Murtas Member are interpreted as deposits of coastal floodplains crossed by shallow, ? meandering river channels (sandstone units) (Oggiano *et al.,* 1986; Laske & Bechstädt, 1987, 1989). The rarely observed trace fossils and limestone beds indicate the local influence of marine or brackish waters.

Tidal laminites characterise some silty beds of the Medau Murtas Member (Loi, 1993b); the sandy beds show flat lamination and low angle cross lamination, ripple marks and thin levels of heavy minerals.

### The Monte Orri Formation

The lithology of the Monte Orri Formation consists of an exclusively siliciclastic sequence of olive-green, gray siltstones, claystones and fine to coarse silty sandstones. Some nodules, pyritic or phosphatic, occur at various levels.

The base of the Monte Orri Formation shows a gradual contact with the upper member of the Monte Argentu Formation. The boundary is placed in correspondence with a colour change from a facies with prevailing red beds (upper beds of Monte Argentu Formation) to a facies where the beds are constantly gray or green-gray in colour (Leone, 1973; Cocozza & Leone, 1977). In the Bacu Abis area the Monte Orri Formation is strongly reduced in thickness and represented by only 10 m of unfossiliferous coarse-grained sandstones with hummocky cross stratifications (HCS) ripples, which are overlain by transgressive basal sandstone and sandy shales with the fauna of the TH2a and BH2 of the Portixeddu Formation. This suggests that the lower boundary is strongly asynchronous as it obviously reflects the decreasing influence of a morphologically structured hinterland during a period of transgression. In the area of Fluminimaggiore the upper boundary with the Portixeddu Formation is arbitrary and gradational (Cocozza & Leone, 1977) and it is drawn where one can observe a change from prevalent greenish to prevailing gray colours, and where the siltstones and silty clays (with less common fine sandstones) start to bear frequent fossils, especially crinoids and bryozoan. In the eastern Iglesiente the boundary can lithologically be placed just in correspondence of the highest set of medium to coarse grained conglomeratic sandstone beds.

In the Fluminimaggiore area the Monte Orri Formation contains the first undoubtedly marine fossils of the post-sardic sequence. Here, north of the Monte Argentu, 15 m above the base, BH1 contains undeterminable articulate brachiopods, and bivalves (? *Modiolopsis*). First poorly preserved trilobites (*Huemacaspis* ? sp., *Prionocheilus* sp. indet.) occur together with lingulids at a distinct horizon (TH1a) with small phosphatic nodules about 35 m above the base. In the upper part of the formation, about 100-150 m above the base the fauna becomes more abundant and diverse (TH1b), comprising predominantly trilobites (*Deanaspis goldfussii fluminensis* Hammann & Leone, 1997, *Nobiliasaphus* aff. *nobilis* (Barrande 1846), *Dalmanitina* n. sp., *Eudolatites* n. sp., *Zetillaenus* cf. *ibericus* Hammann 1976, *Lichas* sp., *Dicranurus* n. sp.) as well as rare lingulids, strophomenids, orthocone cephalopods, bivalves, gastropods and hyolithids. The sediment is strongly bioturbated and arenitic horizons may contain *Skolithos*-like trace fossils. In Bohemia *Deanaspis goldfussi* (Barrande 1846) ranges from Letnà to Vinice Stages. The TH1b fauna of the Monte Orri Formation can also be well compared with that of the Lower Shale Member of the Bedinan Formation, SE-Turkey, which has been described and correlated by Dean (Dean, 1967, 1983) with the Bohemian Vinice Formation and possibly also with the Zahorany Formation. A fossiliferous outcrop with a graptolite assemblage (GH1) of Caradocian age has been discovered near Fluminimaggiore (Leone *et al.*, 1993). This level can be stratigraphically assigned to the uppermost part of the Monte Orri Formation (or to the lower part of the Portixeddu Formation?). The graptolites recovered are: *Glyptograptus* cf. *tenuissimus, Amplexograptus* sp., *Orthograptus* sp., (ex gr. *amplexicaulis), "Dictyonema"* sp., *Callograptus* sp. (aff. *elegans*), ?*Desmograptus* sp., *Thallograptus* sp., *Dendrograptus* sp., *Ptilograptus* cf. *delicatulus,*?*Mastigograptus* sp.

### Depositional environment

Hummocky cross stratification (HCS) and 2D and 3D ripples are widely present. The different types of HCS indicates a storm-dominated environment that is littoral in the basal part of the sequence and slightly deeper (shoreface-offshore transition) in the upper part.

The very irregular sedimentation of prevailing sandy material with *"Skolithos"*- bearing horizons reflects shallow, rapidly changing coastal conditions. The concentration of fully marine fauna in only some levels and the abundance of lingulids in others, may indicate some variation of salinity (compare Havlicek *et al.,* 1987).

The sediment and fauna reflect a marine transgression over a relief, that was almost completely levelled out. While in the areas of Fluminimaggiore and Domusnovas, as well as in the Sulcis region, littoral sediments were laid down, in the Bacu Abis region a shoal with reduced sedimentation existed.

### The Portixeddu Formation

The formation consists mainly of richly fossiliferous dark-gray fine sandstones, siltstones and shales, sometimes bearing pyritic, phosphatic or siliceous nodules quite abundant in the upper part (Leone *et al.*, 1991; Loi & Dabard, 1999, 2000, 2002). Towards the top siltstones and shales prevail. The fossils are generally concentrated in storm layers with pavements and channels.

The sediments of the Portixeddu Formation show typical characteristics of the inner shelf environment not far below the normal wave base, being more littoral in the basal part and more offshore in the uppermost part.

The formation is well developed throughout the whole Iglesiente-Sulcis region. In the area of Portixeddu and Fluminimaggiore the estimated thickness is more than 70 meters; in the Domusnovas area the thickness seems to increase slightly to about 90 meters and at the same time the lithofacies becomes slightly more pelitic with storm layers intercalated less often, indicating a slightly increasing water depth towards the east. In the Bacu Abis area, the thickness is reduced and the lithofacies shows indications of rather shallow water in the basal part that deepens fairly fast towards the top.

The Portixeddu Formation is highly fossiliferous, especially in its upper-median part, and it has yielded almost all of the formerly described Ordovician faunas. The fossiliferous locality of Portixeddu has been well known since Meneghini (1880). In this classical locality, the uppermost beds of the unit with their typical fauna are exposed. The rich and diverse fauna of the formation consists of brachiopods, bryozoans, cystoids, crinoids, and subordinately, of gastropods, bivalves, ostracodes, trilobites, cornulites, conularids and solitary rugose corals.

According to Leone *et al.* (1991) and Hammann & Leone (1997), three brachiopod (BH 2-3-4) and three trilobite horizons (TH 2a-2b-3), can be distinguished:

- BH2 and TH2a coincide in the lower part of the formation and contain a fauna with brachiopods: *Svobodaina havliceki* Villas 1985, *Rafinesquina lignani* Villas 1985, *Aegiromena aquila* (Barrande 1848), *Iberomena sardoa* (Vinassa 1927), *Rafinesquina pseudoloricata* (Barrande 1848), *Rostricellula termieri* Havlicek 1971; trilobites: *Dreyfussina exophtalma* (Dreyfuss 1948), *Calymenella* sp. ind. (?= *Homalonotus sardous* Vinassa 1927); fragments of bryozoans and echinoderms.

Comparisons with similar faunas from NE Spain (Fombuena Formation), central Pyrenees (Cava and Estana Formations), central Spain (“Bancos mixtos”), southern France (Glauzy Formation) and Bohemia indicate that for this horizon an upper Berounian (late Zahorany to early Bohdalec) age can be inferred.

- BH3 and TH2b: This horizon bears abundant *Aegiromena meneghiniana* (Vinassa 1927) together with scarce *Svobodaina* sp. (“cf. *ellipsoides*”) and *Rafinesquina* cf. *pseudoloricata* (Barrande 1848). The upper part of this BH3 horizon has also been detected at the classical locality of Portixeddu, where it also occurs just below the BH4 and yields *Svobodaina* sp., *Drabovia* sp., and *Aegiromena meneghiniana;* trilobites: *Dreyfussina exophtalma* (Dreyfuss 1948), *Klouceckia* cf. *phillipsi, Deanaspis goldfussii fluminensis* Hammann & Leone 1997 and *Eudolatites* n. sp.

In Bohemia *R. pseudoloricata* (Barrande 1848) exists in the upper Beroun (Zahorany and Bohdalec) Series (Havlicek & Vanèk, 1966), and as the *havliceki*-Zone ranges up into the Bohdalec Formation, the latter age is inferred for BH3.

- BH4 and TH3a, placed in the upper half of the formation contains brachiopods *Nicolella actoniae* (Sowerby 1839), *Dolerorthis maxima* (Vinassa 1927), *Dolerorthis intermedia* (Meneghini 1857), *Eridorthis angustisulcata* Havlicek 1981, *Saukrodyctia reticula* (Vinassa 1927), *Leangella anaclyta* Havlicek 1981, *Eoplectodonta* (*Kozlowskites*) *ichnusae* (Vinassa 1927), *Longvillia mediterranea* Havlicek 1981, *Iberomena sardoa* (Vinassa 1927), *Porambonites* (*Porambonites*) *magnus* Meneghini 1880 and *Eonastrophia pentamera* Meneghini 1857; trilobites: *Deanaspis* ? *novaresei* Hammann & Leone 1997, *Deanaspis* aff. *vysocanensis* (Pribyl & Vanék 1980), *Dalmanitina* (*Thuringaspis*) *lamarmorai* (Meneghini 1880), *Neseuretinus turcicus* Dean 1967, *Prionocheilus inermis* (Kolobova in Sokolov & Yolkin 1978), *Eccoptochile* n. sp., *Nobiliasaphus* aff. *nobilis* (Barrande 1946), *Ulugtella mediterranea* Hammann & Leone 1997, *Ulugtella angelini* (Holm 1882), *Zetillaenus wahlenbergianus* (Barrande 1852), *Zetillaenus* cf. *ibericus* Hammann 1976, “*Illaenus*” *creber* (Hammann 1992), *Thaleops (Amphoriops) inflata* Hammann 1992, *Thaleops (Amphoriops) zoppii* Hammann & Leone 1997, *Isbergia lenis* (Owens & Hammann 1990), *Radnoria simplex* Kolobova *in* Sokolov & Yolkin 1978, *Lichas* n. sp., *Dicranopeltis* n. sp., *Whittingtonia* sp., *Selenopeltis* ? sp., *Ceratocephala* sp., *Hispaniaspis dereimsi* Hammann 1992, *Calipernus* ? cf. *immanis* Hammann 1992, *Radiaspis* sp., *Diacanthaspis* (*Diacanthaspis*) n. sp.

The brachiopod association has been described from several Mediterranean regions, e.g. the Montagne Noire (Havlicek, 1981), Iberian Chains (Villas, 1985) and from Sardinia and the Carnic Alps (Havlicek *et al.,* 1987). Its exact stratigraphic correlation, however, with the late Berounian and Kralodvorian according to the Bohemian scale or with the late Caradoc and Ashgill according to the British scale is still open to discussion. A direct correlation with Bohemia is not possible, because the *Nicolella* Community is lacking there, and a correlation on the genus level with the British scale (Havlicek *et al.,* 1987) seems to be difficult as well. Havlicek's correlation of the fauna with the upper Berounian was mainly based on the presence of *S. ellipsoides*. This species, however, seems to be restricted to Bohemia (Villas *et al*., 1995).

In Bucaco and Crozon the highest occurrences of *S. havliceki,* dated on the basis of acritarchs and chitinozoans, range into the Pusgillian and coincide there with the first appearance of the *Nicolella* fauna. In Celtiberia the *Nicolella* fauna of the Cystoid Limestone is associated with *Leangella (Leptestiina) prantli* (Havlicek 1952), a typical Kralodvorian form, as well as with trilobites of Kralodvorian age (Hammann, *in* Hafenrichter, 1980; Owens & Hammann, 1990; Hammann, 1992). On the basis of these arguments and because several of these trilobites also occur in the BH4-TH3a horizon of the Portixeddu Formation, it has been placed in the Kralodvorian and Ashgillian, respectively (Leone *et al*., 1991).

On the other hand Vanek & Vokac (1997) recently suggested a correlation of TH3a with the Bohemian Bohdalec Substage (Berounian Series). This is also supported by the fact that the faunal association with brachiopods, trilobites (characterized by the genus *Neseuretinus*) and echinoderms of the BH4-TH3a of the Portixeddu Formation shows remarkable agreement even on the specific level with some Middle to Southeast Asian ocurrences, especially with that of the Obikalon Member of the Shakhriomon Formation of the Zeravshan-Pamir Zone of Uzbekistan (Sokolov & Yolkin, 1978). Being situated below the occurrence of *Parorthograptus pacificus*, the Obikalon fauna has been considered Caradocian in age and a late Caradocian age has also been suggested for other occurrences of *Neseuretinus* (Turkey, Afghanistan, Burma, South China, which suggests a clear palaeogeographical relationship of Sardinia with the Asian Cimmerian terranes).

The associations of BH2 and BH3 cannot be clearly assigned to any of the brachiopod communities defined in Bohemia (Havlicek, 1982). However the genera *Svobodaina, Drabovia, Aegiromena, Rafinesquina* and *Rostricellula* occurring in BH2 and/or BH3, are frequently recorded associated in several Berounian sandy horizons ("*Svobodaina* fauna"). Boucot (1975) Benthic Assemblages 3-4 suggest a similar ecology (Havlicek, 1982). The *Svobodaina* fauna developed on the cold water shallow shelves bordering Gondwana (Havlicek, 1976, 1986).

The brachiopod association of BH4 (*Nicolella* Community), is also assigned to the benthic communities 3-4 (Pickerill & Brenchley, 1979). Therefore, no significant change of depth should have happened during the changeover from the Mediterranean coldwater *Svobodaina* to the North European warm water *Nicolella* fauna, which can be interpreted as clearly climatic (Havlicek *et al.,* 1987).

### The Domusnovas Formation

The Domusnovas Formation (Leone *et al.,* 1991) has been subdivided into two lithological subunits: a mostly arenaceous lower one, ("Maciurru Member") and a shaly-marly upper one ("Punta S'Argiola Member").

*The Maciurru Member*. The Maciurru Member consists of alternating beds of quartz arenites and microconglomerates with rare lithic fragments and feldspars. Very abundant and thick placers are locally present (heavy minerals up to 24% of volume).

The member is conformably underlain by fossiliferous and nodular siltstones and shales of the Portixeddu Formation. It is conformably overlain by the slightly calcareous shales of the Punta S'Argiola Member.

The Maciurru Member is widespread in the Domusnovas area. South of Cixerri valley this member is hardly recognizable because of its extremely reduced thickness (1-15 cm). In the western region of the Iglesiente it is totally lacking. In the Fluminese, however, some quartzites near Acqua is Prunas belong to this member.

Rare and badly preserved fossils occur at different levels. A gastropod-bryozoan scattered brachiopod association occurs in the lowermost part of the type section; bryozoans, crinoid ossicles and brachiopods are abundant in the remaining part, even if dispersed. Frequent small pebbles are made of reworked bryozoan colonies or crinoidal thecae, or phosphatic nodules from the Portixeddu Formation.

Near the Domusnovas village (Ponte Riu S'Acqua Frisca) the sandstones are medium to fine in character and the brachiopod assemblage (Havlicek *et al.,* 1987) is formed by *Nicolella actoniae* (Sowerby, 1839), *Dolerorthis intermedia* (Meneghini, 1857), *Onniella novaresei* (Vinassa, 1927), *Reuschella* sp., *Drabovia* sp.*, Leptestiina meloui* (Havlicek, 1981)*, Iberomena sardoa* (Vinassa, 1927). This assemblage is assigned to the *Nicolella* Community of Pickerill & Brenchley (1979) of the Benthic Assemblages 3-4.

In the same area 2 km north of Perda Muzza section, a monospecific association of a new genus of Rhynchotrematidae (BH4a) has been found. This brachiopod assemblage is very similar to the Silurian *Rhynchonella* Community of Boucot (1975), typical of Benthic Assemblage 1 (littoral environment).

The *Nicolella* Community indicates a (? late Caradocian or) early Ashgillian age of this member (see also discussion of age of the Portixeddu Formation).

Depositional environment

Cocozza & Leone (1977) suggested a regressive sedimentation of this member related to the upper Ordovician glaciation. In fact, sedimentological evidence suggests a regressive trend and high energy conditions.

The Portixeddu Formation gradually and rapidly passes to the Maciurru Member. The thin transitional interval shows flaser bedding and wave ripples. Upwards the sedimentary structures (placers, horizontal lamination, planar dipping lamination, megaripples, 2D ripples) and the presence of *Skolithos (Monocraterion)* ichnofacies testify a littoral environment (shoreface) in full agreement with the Rhynchotrematidae association.

The extreme reduction (few centimeters) of the Maciurru Member in some localities and its absence in others can be regarded as resulting from a very strict paleogeographical control of the beach deposits. Thus, some characteristics of the Maciurru Member reflect an eustatic regressive event (Loi, 1993a, b) close to the Caradoc-Ashgill boundary, which fits the general curve of sea level changes established in the stable cratonic areas of Europe, America, Australia (Leggett *et al.,* 1981; Ross & Ross, 1992) and North Africa (Attou, 1992).

*The Punta S'Argiola Member*. The general lithology consists of red, fossiliferous siltstones/claystones, with a variable content of calcium carbonate.

In the type area of Punta S'Argiola a sequence 55 meters thick starts with a few meters of gray to light green massive siltstone, barren of fossils in the lower part but with scattered brachiopods and bryozoans in the upper one, followed by slightly calcareous siltstones, gray to light green in colour, with abundant bryozoans and brachiopods and rare trilobites.

The lower-middle part consists of more or less calcareous red shales, very rich in bryozoans, brachiopods (BH4) and echinoderms particularly in the first 15-20 meters.

Towards the top barren horizons of variable thickness alternate with fossiliferous ones. Bioturbation occurs in several levels.

The following part consists of a thin-bedded sequence of weak red marly shales alternating with dusky red calcareous shales, which yield a fairly abundant fauna of orthoconic cephalopods, small brachiopods, bryozoans and crinoids.

At the top of this bedded sequence a dark reddish gray, slightly calcareous silty shale, very rich in fossils is present; the fauna is characterised by trilobites ("Cyclopygid Bed", TH4), small brachiopods (BH5), ostracodes and rare cephalopods

The uppermost part consists mostly of unfossiliferous, dusky red to very dusky red shales. Towards the top of the sequence, narrow horizons or nodules, very rich in Fe and Mn oxides, mark the gradual transition to the overlying Punta Arenas Member of the Rio San Marco Formation.

The lower-middle part of the member bears the most abundant and variable amount of fossils, among which bryozoans, crinoids, cystoids *(Corylocrinus* sp.), articulate brachiopods, very rare trilobites and rare inarticulate brachiopods are the most important. More than 20 species of bryozoa were described by Conti (1990). The brachiopod fauna (BH4) consists of elements of the *Nicolella* Community, of the Benthic Assemblages 3-4. Only two trilobites has been found in the basal part (TH3b): *Eccoptochile* n. sp., *Illaenus* ? *creber* (Hammann 1992).

In the section near Domusnovas the "Cyclopygid Bed", bears at its base several orthoconic remains, usually preserved as siphuncles with wide endosiphuncular deposits typical of Actinoceratida and Endoceratida, as well as a small specimen of *Lituites*. The overlying part (about 1 metre thick) is characterized by deep-water brachiopod and trilobite assemblages (BH5 and TH4); besides, ostracodes are fairly common.

The trilobite fauna is dominated by *Cyclopyge (Phylacops) marginata* Hawle & Corda, 1847, but also contains many other typical Ashgillian species, e.g. *Symphysops armata* (Barrande, 1852), *Ovalocephalus tetrasulcatus* Kielan, 1960, *Arthrorhachis tarda* (Barrande, 1846), *Ulugtella angelini* (Holm, 1882), *Shumardia extensa* Weir, 1959, *Nankinolithus granulatus* (Wahlenberg, 1818), *Paraphillipsinella* aff. *nanjiangensis* Lu, (*in* Lu & Chang, 1974), *Stubblefieldia* sp., *Staurocephalus clavifrons* Angelin, 1854, *Deloites maiderensis* Destombes, 1972, *Dreyfussina struvei* (Destombes, 1963), *Dicranopeltis* cf. *polytoma* (Angelin, 1854), *Calipernus* cf. *immanis* Hammann, 1992. The exact age of the fauna within the Ashgill remains uncertain.

The brachiopod assemblage contains members of the cosmopolite *Foliomena* Fauna and the Bohemian *Proboscisambon* Community (Villas *et al.*, 2002). The *Foliomena* Fauna is known from Pusgillian to middle Rawtheyan, even if a few older records are from late Caradoc. The occurrence of members of the *Proboscisambon* Community, present in Bohemia in the uppermost part of the Kralùv Dvur Formation, may allow the attribution of a more detailed age to this horizon.

In the Riu Cannamenda section this level shows a different lithology (encrinitic and micritic limestones) and composition of the trilobite association with rare *Cyclopyge* and prevalence of the species of *Ovalocephalus, Nankinolithus, Dreyfussina* and *Stubblefieldia* suggesting relatively shallower conditions. Here this level has yielded a rich conodont fauna (CH2) documenting the *ordovicicus* Zone (Ferretti & Serpagli, 1991). New recent sampling (Ferretti & Serpagli, 1999) allowed a better definition of this conodont association, composed by *Amorphognathus ordovicicus* Branson & Mehl, 1933, *A. lindstroemi* (Serpagli, 1967), *Ansella* cf. *pseudorobusta* (Serpagli, 1967), *Dichodella* cf. *exilis* Serpagli, 1967, *Cornuodus bergstroemi* Serpagli, 1967, *Dapsilodus mutatus* (Branson & Mehl, 1933), *Hamarodus europaeus* (Serpagli, 1967), *Icriodella* cf. *superba* Rhodes 1953, *Istorinus erectus* Knüpfer, 1967, *Panderodus gracilis* (Branson & Mehl, 1933), *Plectodina* cf. *alpina* (Serpagli, 1967), *Sagittodontina robusta* Knüpfer, 1967, *Scabbardella altipes* (Henningsmoen, 1948), *Walliserodus* sp., “carniodiform” element *sensu* Ferretti & Barnes, 1997. This fauna falls in the HDS *(Hamarodus europeus-Dapsilodus mutatus-Scabbardella altipes*) biofacies of Sweet & Bergström (1984) which has been recovered in several European localities (Baltoscandia, England, Wales, Carnic Alps). The conodont fauna from Sardinia has mixed character. Together with the Carnic Alps, Sardinia probably occuped an outer position of lower latitudes (compared to the typical north-gondwanian regions of the circumpolar belt) (Ferretti & Serpagli, 1999).

### The Rio San Marco Formation

The Rio San Marco Formation (Leone *et al*., 1991) is exclusively built up of clastic deposits and has been subdivided into four members, which are in ascending order: Punta Arenas, Cuccuruneddu, Serra Corroga and Girisi Members (Leone *et al.,* 1991).

*The Punta Arenas Member*. This member is mostly made up of thin (5-10 cm) “brecciated” and conglomeratic layers, green in colour, the dominant clasts of which are of mainly heterometric and unsorted basic volcanitic rocks (Beccaluva *et al.,* 1981), alternating with Mn bearing carbonates and oxides, black siltstones and shales. Towards the base of the sequence some beds, which can reach 50 cm in thickness, bear clasts up to 3-4 cm in diameter.

The Punta Arenas Member shows strong lateral variations both in the partial thickness and in the distribution of the different lithologies and in the total thickness (0-50 meters).

A conformable contact exits with the overlying Cuccuruneddu Member, which starts where the sandy horizons do not bear any more volcanic material.

Very rare reworked fragments of bryozoa bave been discovered at several levels in the shales. Up to now only in one place two fragmentary specimens of graptolites (GH2), previous assigned to to *Glyptograptus* sp. and *Glyptograptus* sp. ex gr. *persculptus* (?), have been found. A new graptolite bearing-level (GH3) was recently found in the uppermost beds of the Punta Arenas Member; the presence of *Persculptograptus ojsuensis* (Koren & Michaylova, 1973) indicates the lower part of the Hirnantian (Storch, in prep.).

### Depositional environment

Nearshore environment characteristics have been established by Loi (1993 b) on the basis of manganese geochemistry. The deposition of manganese is strictly controlled by the eustatic and climatic variations and these processes are particularly important during glacioeustatic transgressions and regressions (Frakes & Bolton, 1984, Frakes & Bolton 1992). The most important sedimentary ores of Mn in the world (Nikopol, Chiatura, Vama, Imini, Urucum, Abuzemina e Polounotch) occur in littoral or tidal environment.

In Sardinia, Mn-bearing sediments are only present during the glaciation (Loi, 1993a, b; Ghienne *et al*., 2000). Physiographic modifications on the platform can thus be supposed, such as the individualisation of small isolated sub-basins after a rapid glacio-eustatic fall. During a global low glacio-eustatic sea level episode, glacioeustatically-driven fluctuations control the basinal redox dynamic. During very low sea-levels, large supply of fresh water is responsible for oxydizing conditions and Mn-oxide concretions can form. During relatively higher sea-levels, sea water inflows result in water stratification and reducing conditions. Mn-carbonate can form by the reduction of Mn-oxydes and dissolved Mn in water can concentrate in sea water.

The levels of manganese oxides and of manganesiferous carbonates developed from direct precipitation as indicated by bioturbation *(Skolithos* facies) which crosses those levels; the important manganese supply being derived from contemporaneous volcanic activity. The location of the source area of the volcanic materials is, at present, uncertain.

The transition from the Punta S'Argiola Member (outer shelf) to the Punta Arenas Member (nearshore) thus corresponds to an important marine regression.

However, the variation of the sea-level (more than 200 meters) seems too important to be regarded as resulting exclusively from eustatic processes.

*The Cuccuruneddu Member*. The general lithology consists of a rhythmical repetition of gray to light gray arenaceous-pelitic beds.

The member is conformable with the underlying Punta Arenas Member and with the overlying Serra Corroga Member. The lower boundary is below the first level of micaceous sandstone barren of volcanoclastic material.

The unit is apparently barren of macrofossils. Several kinds of ichnofossils are preserved on bedding planes but they are practically unstudied. Poorly preserved acritarchs and chitinozoans have been found in several pelitic horizons (Del Rio *et al*., 1979).

South of the Cixerri valley, more or less 15 meters above the base of the unit, a laterally irregular level, a few meters thick, of green, slightly carbonatic conglomerate with volcanic elements contains *Hindella crassa incipiens* (Williams, 1951) and other indeterminable articulate brachiopods (BH6a). The occurrence of this typical Hirnantian species supports the Hirnantian age of this member.

Sedimentology and depositional environment

The Cuccuruneddu Member is characterized by typical rhythmic deposits of sandy-clayey heterolithic sequences, constituting offshore storm facies frequently of turbidite-like type (Loi, 1993b). The main sedimentary structures are HCS, 2D and 3D ripples, placers, flute-casts, prod-marks and tool-marks (Leone *et al.,* 1991; Loi, 1993b). The various associations of structures observed indicate several distinct offshore environments and a new transgressive pulse. The level that has yielded *Hindella* gives evidence (unsorted pebbles of various lithologies within an abundant pelitic matrix) of a sedimentation influenced in some way by processes most probably related with the late Ordovician glaciation.

*The Serra Corroga Member*. The most typical lithology consists of a dark-gray and dark-green very fine siltstone with an extremely thin and closely-spaced parallel, varve-like lamination; rare small starved ripples are locally present. This lithology follows gray-greenish siltstones with narrow levels of fine sandstones and gray-greenish siltstones with well out-distanced parallel laminae.

A graded coarse siltstone and sandstone fossiliferous horizon is constantly present in all localities of the Domusnovas area between 26.50 and 50 cm below the top of the member.

This fossiliferous horizon (BH6b) has yielded mainly bryozoans and crinoid ossicles and brachiopods such as *Dalmanella* sp., *Mirorthis* cf. *mira* (Zheng, 1983), *Hirnantia* sp., *Kinnella kielanae* (Temple, 1965) and *Plectothyrella crassicosta* (Dalman, 1828), typical elements of the widely spread *Hirnantia* fauna, that occurred in a fairly wide range of depth in the shelf (Brenchley & Cocks, 1982 ), during the Hirnantian Stage.

The thickness of the Serra Corroga Member ranges from 4.50 to 11.50 meters (whereas the typical lithology varies between 3.40 and 7.00 meters).

Sedimentology and depositional environment

The typical varve-like sediments of the Serra Corroga Member consist of an alternation of light and dark coloured laminae of inframillimetric thickness (about 50 laminae in 1 centimeter). They consist of sequences made of (a) a fine grained silt level (average grain size 40 μm, with some rutile, zircon, tourmaline), (b) a thin film of clay minerals, and (c) a film of spheroidal pyrite (25 sequences per centimeter) (Loi, 1993b). These sediments are regarded as storm generated distal deposits.

In the distal upper offshore and in the proximal lower offshore the erosive character of storms disappears; the deposits show a laminar aspect with graded sequences separated by non deposition hiatuses, with characteristics similar to those of the distal turbiditic facies. The fine grained sandy beds and graded coarse sandstones that constitute intercalations in the typical facies might be related either with bathymetric variations or with exceptional storm events. The typical facies of this member can be interpreted as a turbidite-like storm facies deposited in the distal upper offshore and the proximal lower offshore, meanwhile the coarser intercalations have more affinities with the deposits of the middle part of the upper offshore.

*The Girisi Member*. In the Salto di San Marco area the lower part (about 40 meters) consists of dark gray siltstones and claystones with interbedded thin levels of fine and very-fine sandstones with horizontal and crossed lamination. Bioturbated horizons with horizontal trails are present in the lower part whereas in the upper part a 3 m thick rhythmical repetition of pelites and fine sandstones occurs in very thin beds.

The upper part (about 60 meters) consists of highly micaceous and mostly massive siltstones and claystones, dark-gray to green-gray in colour with occasionally intercalated thin beds of fine sandstones. Scattered quartz grains dispersed inside the micaceous siltstone have been observed at several levels. A single specimen of the trilobite *Mucronaspis mucronata mucronata* (Brongniart, 1922) has been found a few meters above the base.

For this member, even if not directly measurable, a thickness of 70-100 meters is inferred because in all localities it is strongly influenced tectonically by overthrust of the Arburese Unit.

In the member only one discontinuous level, occurring about 15 m above the base, bears a poorly preserved reworked fauna consisting of small and fragmentary moulds of articulate brachiopods, fragments and ossicles of crinoids, all surrounded by a blackish pelitic matrix. Therefore, no specific determinations are possible.

In several pelitic levels interbedded in the first 50 meters of the Salto di San Marco Section acritarchs of the *Neoveryhachium carninae* Assemblage have been found (Del Rio *et al.,* 1979). The late Llandovery-early Wenlock age of this acritarch assemblage proposed by these authors is in disagreement with the early Llandovery age, including *P. acuminatus* biozone, of the overlying black shales of the Genna Muxerru Formation stated on the base of well preserved graptolites (Gnoli *et al.,* 1990; Storch & Serpagli,1993). The most reliable age of the member is, therefore, late Hirnantian.

Depositional environment

Horizons bearing clasts uniformly dispersed within the rich micaceous-pelitic matrix are more common between 40 and 80 meters above the base, in the Serra Giomaria hills south of the Cixerri Valley. The largest clasts, visible in the field, are mostly well rounded quartz grains ranging from 0,4 to 3.0 mm in diameter and mica lamellae up to 1.5 mm. Such clasts occur on the rock surface as 2-3 in number per square centimeter. Very rare clasts of siltstone and micaceous shale up to 1 cm of diameter also occur. In thin section the grain percentage is higher (from 7 to 15 %), their size is extremely variable and degrees of rounding range from well rounded to very angular. These sediments have many features in common with the well-known glaciomarine facies of the uppermost part of the European Ordovician succession, (the “pèlites grèseuses” of Normandy and

Spain, the "microconglomeratic argillites" of North Africa or "diamictites" of the Prague Basin). Consequently the sediments of this member are interpreted as glaciomarine deposits. Because many clasts are well rounded, we suppose that they were dropstones included in the ice starting from almost contemporaneous littoral sediments. The glaciomarine origin inferred for such deposits is in full agreement with the late Hirnantian age of the Girisi Member.

## Sea-level fluctuations

The structures and compositions of the Ordovician sedimentary assemblages suggest various sedimentary settings, but always correspond to coastal and platform facies environments.

Bathymetrycal fluctuations are evidenced by the study of sedimentary facies (Loi, 1993a, b). Several transgressive-regressive sedimentary cycles have been identified (Fig. 1). The main three sea-level fluctuations can be interpreted as glacio-eustatic changes. The other less important sea-level changes could be linked to various phenomena such as subsidence increase, tectonic and probably minor glacio eustatic pulsations. The periods of tectonic activity and of increasing subsidence rate have controlled the deposition of thick sedimentary successions in alluvial fans and tidal flat facies of the Monte Argentu and Monte Orri Formations. In these formations, the increase in deposit rates without important environmental changes is related to the opening of Ordovician basins.

For the Iglesiente-Sulcis succession it is possible to establish a consistent and detailed sea level curve based on the variation of sedimentary facies and on biochronostratigraphic data (right side of Fig. 1). The main glacio-eustatic phenomena took place during early Hirnantian times, and the lesser important ones during early Ashgillian and infra-Hirnantian times.

The sea level fluctuations during early Ashgill times in Sardinia can be related to the sedimentary hiatus extending from upper Caradoc through upper (?) Ashgill in some parts of the world such as Spain (Perez-Estaun *et al.,* 1990) and Morocco (Destombes *et al.,* 1985). The lack of gaps in the Iglesiente-Sulcis area results from the higher depth of the Ordovician basin in Sardinia, which allows the recording of sea level variations.

The sea level curves, obtained for the Sardinian succession, are in good agreement with the curve (Leggett *et al.*, 1981; Ross & Ross, 1992) available for the Ordovician successions in North America and Europe.

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