Sedimentology of Lower Ordovician clastic shelf deposits, Montagne Noire (France)

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Etude sédimentologique des dépôts clastiques de plate-forme de l'Ordovicien inférieur, Montagne Noire (France)

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Mots-clés : Shale, Grès, Arenig, Lithofaciès, Sédimentation marge continentale, Tempestite, Hérault (Région Roquebrun), Montagne Noire.

Abstract

This study investigates the lowermost Arenigian siliciclastic deposits of the Roquebrun area, eastern Montagne Noire (France). The whole sequence consists of cyclically arranged shallow marine to peritidal shales and sandstones. Based on lithology and sedimentary textures, six lithofacies types are distinguished in this paper: A) sandy noduliferous shale, B) sandy shales with thin crossbedded sandstone beds, C) hummocky crossbedded sandstones with thin shale interbeds, D) amalgamated hummocky cross stratified quartzarenites, E) thin-bedded shale-/sandstone intercalations with wave ripples, linsen and flaser bedding, and F) shales and siltstones with sparse quartzarenite beds. Three alternative facies models are discussed: 1. offshore bar model: open shelf (Lithofacies A to C), with intercalated sequence of offshore bar deposits (D and E) surrounded by restricted marine interbar deposits (F); 2. tectonic rise model: clastic ramp-/ barrier shoreline facies sequence from open shelf mud (A) and distal tempestite facies (B) through proximal tempestite (C)/ shoreface (D) to shoreline (E) and lagoonal deposits (F). This second model implies a nearby emergent area which is assumed to represent a local tectonic uplift in this part of the lower Ordovician Gondwana shelf; 3. sequence stratigraphic model: continental margin / shelf break facies sequence with intercalated peritidal lowstand deposits. The depositional environments of lithofacies A to F, respectively, are interpreted in the same way as in the previous model, but the coastal deposits of lithofacies D to F are proposed to rim the exposed Gondwana shelf during sea level lowstand. The present field data do not allow to make a clear decision between these models. From a sedimentologic point of view, the first model seems to be the least probable. In any of these models, a short-term relative sea level fall during the time of deposition is indicated. Syndepositional tectonic activity is indicated by increased accumulation rates of the early Arenigian deposits and can be inferred from the abrupt cessation of sandy input near the top of the sequence.

Résumé

Dans les environs de Roquebrun (Hérault, Montagne Noire), on observe des grès et des schistes de l'Ordovicien inférieur, affectés par une forte déformation tectonique. Les dépôts les plus jeunes de cette série, objet de l'étude, ont une puissance d'environ 1 500 m. Cette série appartient à l'Arénigien inférieur et est recouverte en discordance par le Silurien et le Dévonien.

La présence de fossiles marins dans la série clastique du groupe de Roquebrun indique qu'il s'agit de dépôts de plate-forme. Six lithofaciès ont été distingués (A B C D E et F) :

Le Lithofaciès A comprend des schistes et des shales dépourvus de niveaux gréseux.

Le lithofaciès B est composé de schistes analogues dans lesquels sont intercalés de minces bancs de grès présentant souvent des traces de Phycodes.

Le lithofaciès C correspond à des bancs de grès où sont intercalés des schistes en fins niveaux comportant également des Phycodes.

Le lithofaciès D comprend des grès quartzeux sans intercalations de schistes. Ces grès sont constitués en

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bancs à stratification entrecroisée en mamelons formant des barres bien visibles de quartzites de plusieurs mètres de puissance. Des traces de Daedalus *et des coquilles de lingules représentent les fossiles les plus fréquents.*

Le lithofaciès E est formé par des séries finement stratifiées de schistes et de grès quartzeux à ripple marks et à stratifications obliques. Daedalus *est également présent.*

Enfin le lithofaciès F regroupe des schistes et des siltites au sein desquels sont parfois intercalés des bancs de grès quartzeux.

En ce qui concerne les traces fossiles, on rencontre Cruziana, *mais pas de* Phycodes.

Ces six lithofaciès forment des séries cycliques et régulières. La partie inférieure de la série est constituée de cycles du type A B C-A B C. Au-dessus viennent des cycles D E D E - F - D E D E, auxquels succèdent des cycles A B C puis l'ensemble se termine par des schistes monotones dépourvus de termes arénacés. Le passage brutal des cycles A B C aux cycles D E F indique une césure dans l'histoire sédimentaire. L'absence de termes arénacés dans la partie supérieure est un autre fait marquant dans la sédimentation.

Plusieurs indices montrent l'existence d'une activité tectonique synsédimentaire dans les zones proches du milieu de dépôt. Le taux d'accumulation est beaucoup plus élevé pendant l'Arénigien inférieur qu'au Cambro-Trémadocien. Ceci s'explique par une accélération de la subsidence à mettre en relation avec une tectonique en expansion. De même la disparition brutale du matériel arénacé dans la partie supérieure de la série a probablement une cause tectonique. Les sédiments clastiques de Roquebrun s'interprètent comme des dépôts de mer épicontinentale ouverte où prédominent les tempêtes. Les lithofaciès A à C y sont ainsi considérés comme des sédiments de plate-forme à caractère proximal subtidal croissant et les lithofaciès D à F assimilés à un complexe lagunaire à chenaux. Les lithofaciès D à F ont par ailleurs été interprétés par Eschard (in Courtesolle et al. *1985) comme des barres de tempête formées à proximité de la côte.*

Trois scénarios sont proposés pour l'ensemble de la série étudiée.

1. Dépôt de plate-forme externe avec formation intermittente de barres de tempête lors d'un niveau marin bas ; 2. Dépôt de talus clastique avec formation locale d'un faciès de plage sur haut fond tectonique lors d'un niveau marin bas ; 3. Modèle identique de talus clastique mais la formation du faciès de plage est alors la conséquence d'un niveau marin plus bas et correspond à une limite de séquence. D'après les données disponibles, aucun de ces modèles ne peut être mis en avant. En tout cas, le caractère cyclique du Groupe de Roquebrun est le résultat de variations régionales du niveau marin. Le plus bas niveau marin est indiqué par le début du cycle DEF (base de la cluse de l'Orb).

Biostratigraphiquement, ce niveau se situe dans la zone à Deflexus de l'Arénigien inférieur. Seule la comparaison avec d'autres régions permettra de dire s'il s'agit d'un événement local ou global.

Introduction

In early Paleozoic time, southwestern France was part of the Gondwana continent at its "northern" continental margin off the present African coast (Matte 1986, Paris and Robardet 1990). Paleogeographic reconstructions (van der Voo 1988, Scotese and McKerrow 1990) indicate Ordovician paleolatitudes of c. 60-70° S and thus a position adjacent to or within the southern subpolar low pressure belt. A high latitude position has also been suggested from pelagic trilobites (Cocks and Fortey 1990) and graptolites (Atlantic cool water graptolite province: Berry and Wilde 1990) as well as from neritic biota (North Gondwana Province: Paris and Robardet 1990, Cocks and Fortey 1990).

The Ordovician deposits of the Montagne Noire consist mainly of monotonous sandstone-shale alternations and some quartzitic sandstones (formerly known as "Grès à Lingules") in their upper portion. A panafrican basement source area has been inferred from petrography (Dabard and Chauvel 1991) as well as from radiometric ages of detrital mica and zircons (Gebauer and Grünenfelder 1974, 1977, Gebauer *et al.*, 1989). Early workers (Thoral 1935a, b, 1941, Geze 1949) proposed a shallow marine to littoral environment of deposition, especially for the quartzose deposits of the Grès à Lingules. Subsequent authors, however, classified the Lower Ordovician rocks as "flyschoid" depositional facies (Hupé 1959, Andrieux and Matte 1963). More recent studies (e.g., Eschard in Courtessole *et al.*, 1985, Dabard and Chauvel, 1991) recognized them as storm-dominated shelf deposits, thus returning to a shallow marine interpretation. The diverse brachiopod-trilobite assemblages throughout the succession also indicate shallow marine conditions (Dean 1966, Courtessole *et al.*, 1981, 1982, 1983, 1985).

Ordovician stratigraphy and paleogeographic reconstructions of this region suffer from limited outcrop areas and intense tectonic deformation. Much progress has been made by the recent biostratigraphic studies of Courtessole *et al.*, (1981, 1982, 1983, 1985), but, as in any biostratigraphic scheme, the relative importance of facies-dependent versus evolutionary control of the observed faunal changes has to be assessed carefully. Sedimentologic interpretation of the depositional facies may help to elucidade the depositional and environmental history recorded by this sedimentary pile. The main purpose of this study is to discuss three alternative facies models for the Lower Ordovician deposits of the Roquebrun area (eastern Montagne Noire), which have somewhat different consequences for the pre-Hercynian paleogeographic and tectonic evolution of this part of southern Europe.

Geologic setting

The study area is located southeast of Roquebrun (Hérault), where Ordovician rocks represent the central parts of a several kilometer wide synformal structure, the Synforme de Roquebrun. This structure is part of the inverted lower limb of the Mont Peyroux nappe, one of three southward-verging nappes of the eastern Montagne Noire (Mattauer and Proust 1963, Arthaud *et al.*, 1966, Arthaud 1970, Guérangé-Lozes and Burg 1990; Fig.1). Deformation and nappe emplacement took place during the mid-Carboniferous, when terranes of Gondwanan crust were accreted to the southern European continental margin in the course of the Hercynian orogeny (Gebauer and Grünenfelder 1974, Engel *et al.*, 1981, Vernay 1983, Matte 1986).

Stratigraphy

Ordovician deposits of the western Mont Peyroux nappe consist of siliciclastic sediments of Tremadocian and Lower Arenigian age, truncated by an angular unconformity and superseded by early Devonian clastics and carbonates (Thoral 1933, 1935a, 1941, Geze 1949, Dean 1966, Feist and Schönlaub 1974, Courtessole *et al.*, 1982; Fig.2). Within the study area, only the upper 1 500 m of this Lower Ordovician sediment pile is preserved, dated as lowermost Arenigian (*Didymograptus deflexus* -zone: Courtessole *et al.*, 1981, 1982, 1985).

A revised scheme of litho- and biostratigraphical subdivisions has been worked out by Courtessole *et al.*, (1982, 1985), who also published a preliminary map of this region based on fossil occurances. A tentative geological map of the study area has been worked out by Noffke (1992; Fig. 1 C is a simplified sketch of this map). Due to the rarity of fossils, this map is based primarily on lithologic and trace fossil evidence. The lithostratigraphic units used therein (and herein, Fig. 2) were defined after outcrop occurances and descriptions given by Courtessole *et al.*, (1982, 1985). The whole sequence is intensively folded and faulted throughout the study area, and logs of undisturbed sections of more than a few tens of meters are not available. In thicker sections, tectonically introduced gaps and repetitions have to be considered. All stratigraphic logs dealing with more than a few meters in vertical succession, therefore, are derived by compilation of data from different outcrops. Nevertheless, the order of lithologic (and hence facies) succession seems to be well-established (Courtessole *et al.*, 1981, 1982, 1985, Dabard and Chauvel

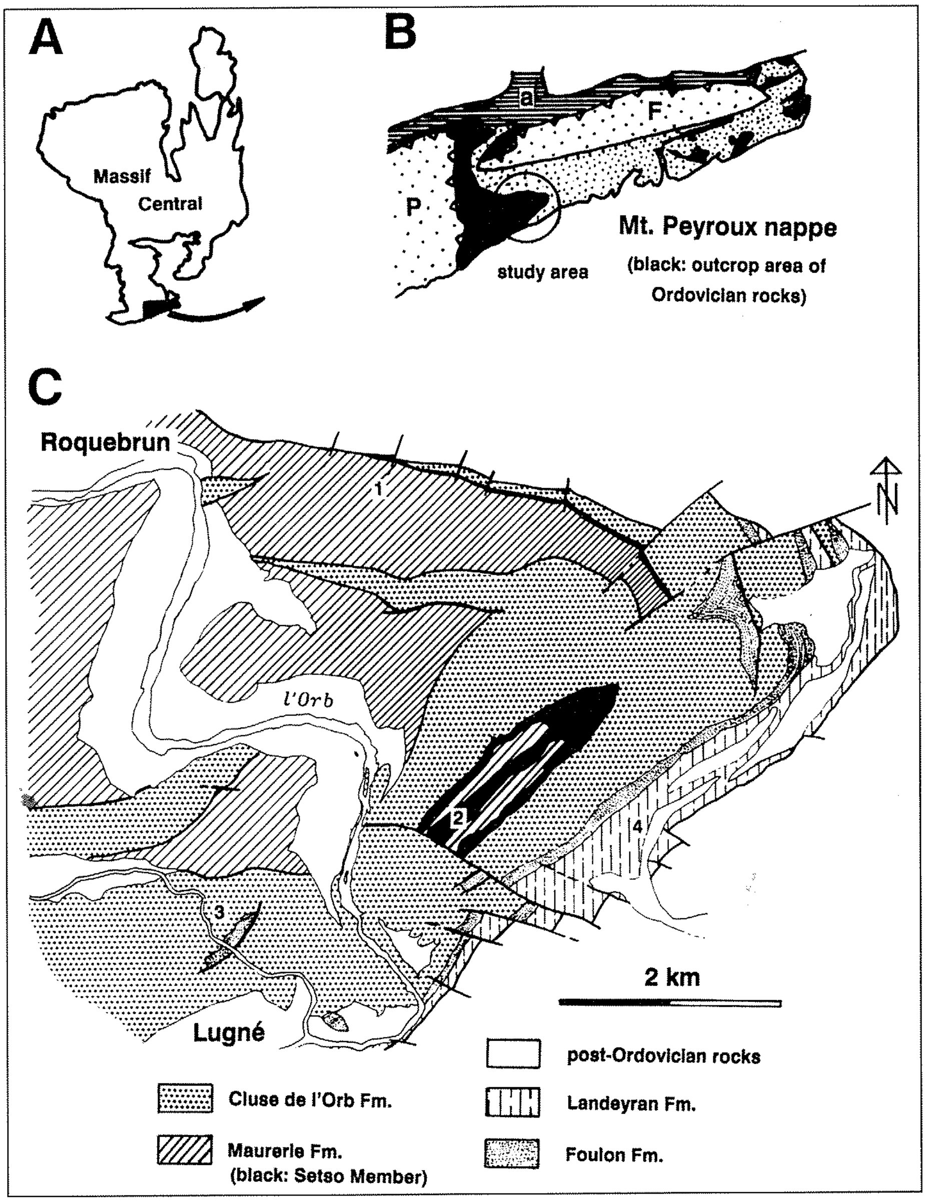

Fig 1. A,B. – Tectonic sketch map of eastern Montagne Noire and location of the study area; a: autochthon/parautochthon, F: Mts. de Faugères Nappe, P: Pardailhan Nappe (Arthaud, 1970; Engel *et al.*, 1981). C: Simplified geological map of the Ordovician rocks of the Roquebrun Synform (after Noffke 1992). The whole sequence is tectonically inverted. Numbers 1-4 refer to outcrops cited in Fig. 11.

Fig. 1 A, B. – Carte tectonique schématique de l'est de la Montagne Noire et localisation de la zone étudiée, A : autochtone/parautochtone, F. : Nappe des Mts de Faugères, P : Nappe de Pardailhan (Arthaud, 1970 ; Engel et al., *1981). C : Carte géologique simplifiée des roches de l'Ordovicien du synforme de Roquebrun (d'après Noffke 1992). La séquence dans son ensemble est tectoniquement inversée. Les numéros 1 à 4 renvoient aux affleurements cités à la figure 11.*

1991, Noffke 1992), though the given thickness data may have limited accuracy only.

The oldest deposits of the study area belong to the Maurerie Formation (Grès et Schistes de la Maurerie; Courtessole *et al.*, 1982). These are gray sandy shales with intercalated micaceous, medium-grained sandstones, which predominate in the upper parts of the formation. The uppermost 20m or so of the Maurerie Fm. consist of lithologically similar, but black-coloured sandstones and shales (Setso Member; Dean 1966). Thin-bedded sandstones, siltstones and shales alternating with 20-40m thick successions of medium grained micaceous quartzarenites represent the Cluse de l'Orb Formation (Grès de la Cluse de l'Orb; Courtessole *et al.*, 1982). The sandy shales and decimeter-thick sand-

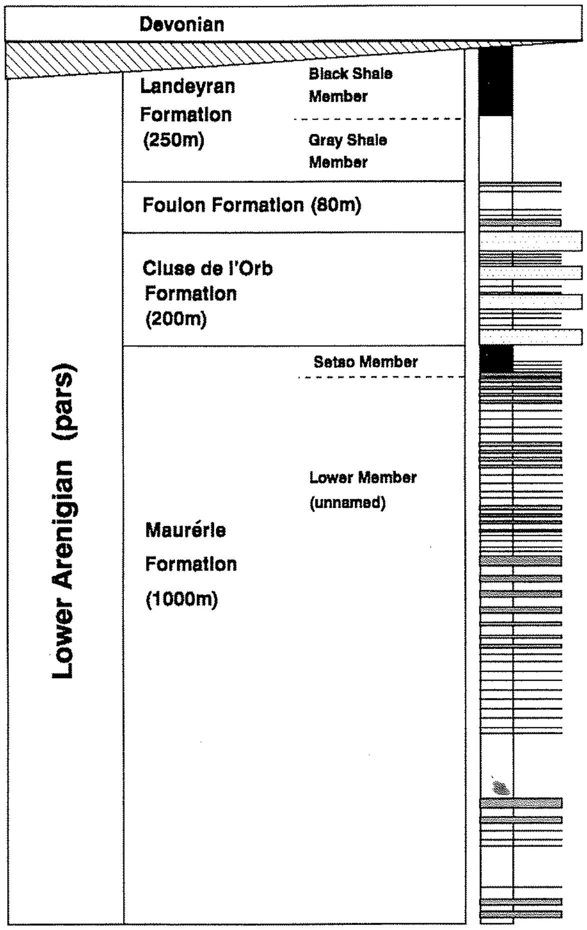

Fig. 2. – Lithostratigraphic summary column of the study area, adapted from Courtessole *et al.* (1982, 1985). Lowermost Ordovician deposits (Barroubio and St. Chinian Formations, respectively) crop out to the west and northwest of the study area. White: gray shales and sandy shales, black: black bituminous shales and sandy shales, dense stipple: micaceous sandstones (schematic), wide stipple: complex interstratifications of quartzose sandstones, siltstones and sandy shales (cf. Fig. 9). The Ordovician - Devonian unconformity cuts down to the Maurerie Fm. in the northern part of the study area.

Fig. 2. – Colonne lithostratigraphique d'ensemble de la zone étudiée, adaptée d'après Courtesole et al. *(1982, 1985). Les dépôts de la base de l'Ordovicien inférieur (formations respectives de Barroubio et St Chinian) affleurent à l'ouest et au nord-ouest de la zone étudiée. En blanc : shales gris et argilites sableuses ; en noir : schistes bitumineux noirs et argilites sableuses ; en pointillé dense : grès micacés (représentation schématique) ; en pointillé espacé : interstratifications complexes de grès quartzeux, de siltites et d'argilites sableuses (cf. fig. 9). La discordance Ordovicien-Dévonien coupe la formation de Maurerie au nord de la zone étudiée.*

stones of the succeeding Foulon Formation (Couche de Foulon; Dean 1966) lithologically resemble those of the Maurerie Fm. below. With a sharp break in lithology, the uppermost Foulon sandstones are followed by gray and black, sand-free shales of the Landeyran Formation (Schistes du Landeyran; Thoral 1941). Due to pre-Devonian erosion, this uppermost unit is only preserved in the southern district of the Roquebrun synform.

Lithofacies types

On the basis of lithological and textural characteristics, we distinguish six lithofacies types, referred to as Lithofacies (LF) A to F. They differ from each other in sand-to-mud ratios, sedimentary textures, and in their trace fossil assemblage. Shelly fossils were not subject of this study, and paleontologic data cited below are mainly quoted from the literature (Thoral 1933-1946, Dean 1966, Courtessole *et al.*, 1981-1985). Distinct body fossil assemblages have been attributed to the lithofacies types by combination of these literature data with only limited field data. Our remarks on body fossil occurances have to be regarded to as preliminary, therefore. We wish to make clear, that the relationships between body fossil assemblage and depositional facies, as supposed herein, are tentative and have to be confirmed (or rejected) by further studies.

Lithofacies A: Noduliferous shales and sandy shales (Pl.1a).

Description: Fissile sandy shales of the Maurerie and Foulon Formations commonly exhibit gray to greenish gray colours; black bitouminous sandy shales are restricted to the upper Setso Member of the Maurerie Fm. Stratification is indistinct to absent. Sand-size material, dominated by detrital mica flakes, makes up c.1-5 % of the sediment, the higher values are achieved near the facies transition to LF B. Fossiliferous concretions, 5 to 20 cm in diameter, can be found throughout the lithofacies. They are of variable composition: siliceous, calcareous and sideritic nodules have been reported. Sideritic concretions are the most common variety, though in outcrop most of them are weathered to red ochre yielding easily accessible but fragile shelly fossils (nodules limoniteux, Courtessole *et al.*, 1982). Chevron-like siliceous concretions resembling cone-in-cone structures can also be found (Bonte 1945, Becq-Giraudon 1990).

Though no specific trace fossils have been found, the lack of clear stratification may be related to intense bioturbation homogenizing the sediment. Shelly faunas are diverse and include both benthic (brachiopods, trilobites, echinoderms, bivalves) and planktic (graptolites, hyoliths, cephalopods) organisms. They are scarcely scattered throughout the sediment, only in few discrete horizons they are somewhat enriched compared to the bulk of the deposit. Within the shaley sediment, the fossils are typically damaged by the slaty cleavage, but in carbonate (or, at the surface, ochric) nodules real "fossil breccias" can be found.

The gray and black shales of the Landeyran Formation closely resemble this facies (no or weak bedding, sideritic concretions, diverse fauna of comparable composition), but differ by the absence of sandy material. The abrupt cessation of sandy input documented by the Foulon/Landeyran transition cannot easily be explained by simple facies shift to more distal environments and will be discussed separately below.

Interpretation: Occasional bedding planes bearing shell concentrations may indicate rare erosional events. No other evidence of strong bottom currents or of storm wave action has been observed. Compared to the other lithofacies types, sandy input is weak. This sandy shale facies probably reflects outer shelf conditions with water depths well below storm wave base.

Lithofacies B: Shales with thin crossbedded sandstone beds (Pl.1b).

Description: This facies includes sandy shales with intercalated centime-

Fig. 3. – *Phycodes* burrows at the base of a thin bioturbated sandstone bed (Lithofacies B); Setso Member (Maurerie Fm.), Roquebrun.

Fig. 3. – Terriers de Phycodes *à la base d'un mince lit de grès bioturbé (Lithofaciès B) ; Membre de Setso (Fm. de Maurerie), Roquebrun.*

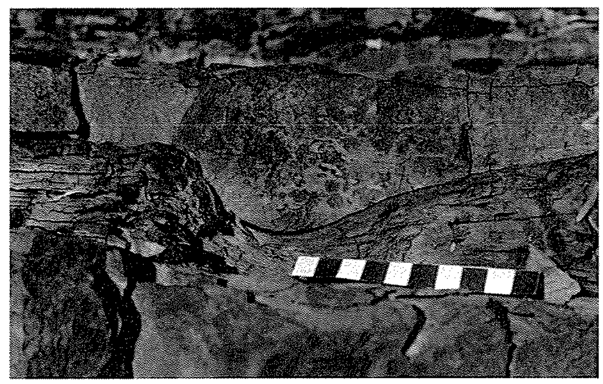

Fig. 4. – Gutter cast infilling small meandering channel in shale. The sandstone shows faint horizontal laminations within the channel and low-angle crossbedding (HCS?) in the middle of the bed (Lithofacies C); Foulon Fm., Rieuberliou Section; scale in cm.

Fig. 4. – Petit chenal décrivant des méandres dans le remplissage d'une rigole creusée dans les shales. Le grès présente un léger feuilletage horizontal à l'intérieur du chenal avec stratification entrecroisée d'angle faible (stratification entrecroisée à mamelons ?) au milieu du lit (Lithofaciès C) ; Fm. du Foulon, Section de Rieuberliou, échelle en cm.

ter-scale sandstone beds and is restricted to the Maurerie and Foulon Formations. The sandstones are medium to dark gray in colour; only within the Setso Member do black crossbedded sandstones occur. The frequency of sandstone intercalations ranges from 1-2/m near the transition to LF A to 10/m adjacent to LF C. The sandstone beds show diverse internal textures: plane lamination, unidirectional, small-scale plane and concave crossbed sets and climbing ripple lamination. Gradation from medium to fine sand is rarely visible. In places, graded concentrations of abraded shells can be found at the base of some of the sandstones.

Apart from undetermined simple burrows (*Planolites?*), bioturbation is dominated by *Phycodes circinnatum* Richter. Some of the sandstone beds are totally homogenized by bioturbation and their bases are densely covered by *Phycodes* traces (Fig.3). In one instance, a probable *Zoophycos* trace could be recognized on a weathered sandstone surface. Body fossils are less frequent than in LF A, though perhaps of comparable diversity. From our field observations we suggest that benthic fossils prevail in the sandstones but planktic and benthic forms can be found in the intermittent sandy shales.

Interpretation: The graded and crossbedded sandstones indicate combined suspension/traction transport. Basal scour or other predepositional erosion is rarely documented. Sandy input is sparse and sporadic, probably representing short depositional events punctuating long periods of muddy background sedimentation. The crossbedded sandstones may have formed when storm-generated turbidity currents transported sandy material from nearshore environments to the outer shelf, where it settled below storm wave base (Nelson 1982, Walker 1984).

Lithofacies C: Hummocky crossbedded sandstones with intermittent shales (Pl.1c).

Description: This facies consist of medium to coarse grained sandstone beds, 10-100 cm in thickness, that either alternate with sandy shales and thin, cm-scale sandstones, or are stacked upon each other with only thin shaley interbeds. It is well developed in the upper portion of the Maurerie lower Member, but it also occurs in the Foulon Formation. The frequency of the dm-scale sandstone beds is 10-50/10 m. Erosive bases (displaying gutter casts (Fig.4), small scours and prod marks) and hummocky cross stratification (HCS) are the most prominent feature of these sandstones. The tops of the hummocky cross stratified beds may be gradational or sharp, sometimes capped by asymmetric ripple marks. In some instances, however, internal textures have been obscured by soft sediment deformation processes (convolute bedding, load casts, ball-and pillow structures).

As in LF B, *Phycodes circinnatum* Richter is the most important trace fossil. Moreover, casts of *Cruziana rugosa* d'Orbigny can rarely be found at the bases of some beds (e.g., lowermost Setso Member). Shelly fossils are rare, and seem to be restricted to reworked bioclasts (e.g., echinoderm or mollusc debris). In the lowermost Foulon Fm. abraded lingulid shell fragments occur as graded shell bed at the base of few sandstone beds.

Interpretation: Predepositional erosion and HCS indicate that storm waves affected the sea floor and deposited the dm-scale sandstones in their waning stage. Post-depositional current reworking probably occurred (asymmetric ripples), but there is no evidence of fairweather wave activity. Muddy background sedimentation prevailed between individual storms, as documented by the shaley interbeds. The depositional environment of LF C can be regarded as sublittoral open shelf, but above storm wave base. This view is supported by the presence of *Cruziana* traces, which are thought to represent shallow marine subtidal environments (Seilacher 1964, 1967, Frey and Pemberton 1984). The rarity of records of these traces can be attributed to the difficulties of identifying them where no change in sediment material has occurred and their low preservation potential on pre-storm sedimentary surfaces.

Lithofacies D: Amalgamated micaceous quartzarenites (Pl.1d).

Description: Hummocky crossbedded quartzitic sandstones, arranged in 3 to 5 m thick units of amalgamated, deci-

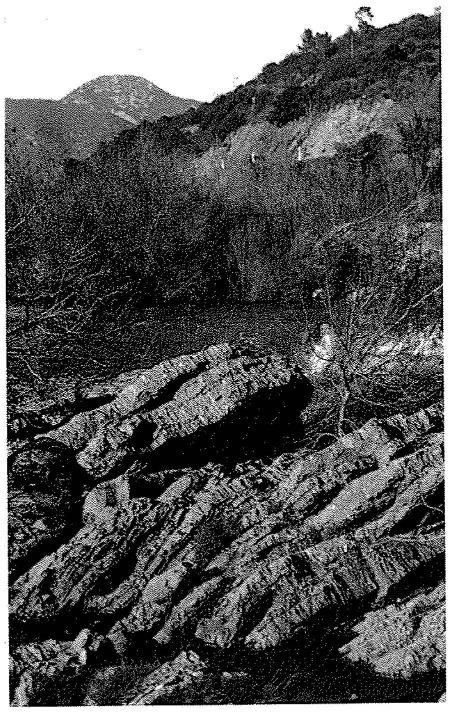

Fig. 5. – Thick-bedded quartzitic sandstone (Lithofacies D), intensively bioturbated by vertical *Daedalus* traces, which almost obliterate primary bedding textures; Cluse de l'Orb Fm., l'Orb valley near Maynard.

Fig. 5. – Grès quartzitique en lits épais (lithofaciès D), intensément bioturbé par des traces verticales de Daedalus, *oblitérant presque le litage primaire. Cluse de la Fm. de l'Orb, Vallée de l'Orb près de Maynard.*

meter-scale beds, represent the most spectacular facies of the Cluse de l'Orb Formation (detailed description given by Eschard *in* Courtessole *et al.*, 1985). Parallel lamination is seen at the bases of some individual beds and truncated by HCS. Rounded mudclasts can be found on bedding planes. Occasionally, small shallow channels intersect the hummocks.

Red concretions, up to 1m in diameter, occur in some beds. They are ellipsoidal in shape and somewhat flattened parallel to bedding. Adjacent bedding textures bend around their margins enclosing those laminae that can be traced right through the nodules in a less compacted state, and hence indicate an early diagenetic (i.e., pre-compactional) origin of these concretions. Cements within these concretions are partly siliceous (due to pressure-solution and reprecipitation processes) but mainly composed of Fe-bearing carbonate (siderite or Fe-calcite: J.-J. Chauvel, written comm. 1994).

The trace fossil assemblage sharply contrasts with those of the preceding lithofacies. *Daedalus halli* (Rouault) predominates, accompanied by less ubiquitous *Skolithos* burrows and few *Planolites*. The internal texture of beds up to 1m thick has been completely reorganized by bioturbation, displaying nothing else than vertically arranged *Daedalus* cones side by side (Fig.5). Coquinas of phosphatic lingulid shells are common in this lithofacies and gave rise to the name "Grès à Lingules", referring either to the quartzitic deposits or to the complete Cluse de l'Orb Fm. (Thoral 1941). They occur as graded shell beds at the base of some individual beds. Other fossils are restricted to rare fragments and abraded clasts.

Interpretation: The sudden increase in sandstone maturity from LF C to D probably reflects the transition from intermediate to high energy environments. Frequent reworking and resedimentation is also indicated by the replacement of the *Phycodes/Cruziana* trace fossil assemblage by vertically oriented *Daedalus* and *Skolithos* traces, indicative of depositional environments above normal wave base (Seilacher 1967, Frey and Pemberton 1984). The sedimentary record is dominated by proximal storm deposits (HCS, rip-current (?) channels). Apart from *Skolithos*-Facies bioturbation, little trace has been left of fairweather redeposition at the sedimentary surface. The common facies transition to, and interfingering with, wave-rippled deposits of LF E (see below), indicates a coastal, though probably sublittoral (shoreface) environment for LF D.

Lithofacies E: Rippled sandstones and sandy shales with flaser texture (Pl.1e).

Description: In LF E we include thin-bedded, variably rippled and cross-bedded sandstones and shales of the Cluse de l'Orb Fm. Two subfacies can be distinguished, which alternate with each other on a dm-scale:

E1: Thinbedded (2-5 cm) rippled sandstones with shale drapes (Pl.1e). Oscillation ripples, wavy lamination, flaser bedding and thin beds of parallel lamination can be seen. Rare decimeter-scale sets of planar to concave crossbedded sandstones (Eschard in Courtessole *et al.*, 1985: Pl. II), may also be included in this lithofacies.

E2: Shales and sandy shales, commonly dark gray to black, with cm-scale crossbedded sandstone lenses and load casted ripples (Fig.6). Polygonal shrinkage cracks occur in the shaley deposits. Occasionally interbedded sandstone beds (5-20 cm) bear dm-scale interference ripples on their tops.

Trace fossils are scattered throughout the sediment but are rarely dense enough to overprint primary bedding textures. *Daedalus*, *Skolithos* and *Planolites* seem to be the only recognizable traces. Body fossils are rare, mainly restricted to small fragments and bioclasts. In thin section, microscopic fragments of graptolites have been identified (Noffke and Ligouis, in prep.).

Interpretation: LF E is characterized by small-scale vertical changes in hydraulic conditions, predominance of wave-formed textures, frequent emersion and a low degree of bioturbation. Shrinkage cracks and megaripple bedding indicate some tidal influence, but the overall depositional pattern is wave-dominated. Deposition above fair weather wave base in a littoral environment (foreshore, back-barrier or lagoonal shoreline) seems probable. Some deposits of LF E1 may have been formed in a shallow sublittoral (upper shoreface) setting, either.

Lithofacies F: Sandy shales and siltstones with thin micaceous quartzarenite beds (Pl.1f).

Description: In the Cluse de l'Orb Fm., LF D and E alternate with shale/sandstone alternations up to 20-60 m thick. These shaley sequences consist mainly of thin bedded sandy shales and siltstones with interbedded dm-thick micaceous quartzarenites (5-10/10 m). Gutter casts and scours are common at the bases of these sandstone beds, which frequently exhibit HCS. This facies is rather similar to LF C in overall appearance. Nevertheless, clear differences can be seen in the conspicously lower frequency of massive sandstone beds and the occurrence of micaceous quartzarenites, which are absent from LF C. Rapid deposition of even meter-scale sandstones is indicated by soft sediment deformation textures (load balls, convolute bedding) and dish structures in some of these beds. Sediment liquefaction and load-casting, however, may also be due to periodic wave loading in shallow water during major storms (Walker 1984), a possibility supported by equal-distance ball-and-gap geometry of some load-casted sandstone beds (plate 1, f). An about 15 m thick pile of chaotic ball-and-pillow sandstones in a sandy shale matrix crop out at the Orb river 3 km southeast of Roquebrun (detailed description in Andrieux and Matte 1967).

Some of the sandstone beds reveal *Planolites* and *Cruziana* traces at their bases (Fig.7). Of the latter, three types have been identified: *Cruziana rugosa* d'Orbigny, *C. rouaulti* Lebesconte and *C. imbricata* Seilacher. Contrary to LF C, *Phycodes* is virtually absent from this lithofacies. Body fossils are dominated by trilobites, accompanied by inarticulate Brachiopods, molluscs and rare echinoderms (Courtessole *et al.*, 1982, 1985). Referring to these authors, however, the shelly fossil assemblage is less diverse than in the upper Maurerie Fm. (and therefore, supposingly, in LF C).

Interpretation: Compared to LF C, absence of *Phycodes* burrows and, probably, diminished diversity of marine body fossils indicate a somewhat restricted environment for LF F. Its stratigraphic position, surrounded by shoreface and littoral sediments, implies a lagoonal setting. Subtidal muddy background sedimentation prevailed during fair weather conditions, whereas sandy material may have been swept in by tidal currents or storm waves. Interbedded thick quartzose tempestites may represent washover fans spilled in from the barrier shoreline during major storms. Storm erosion and deposition of tempestites took place less frequent than in LF C, thus implying a comparatively protected site of deposition.

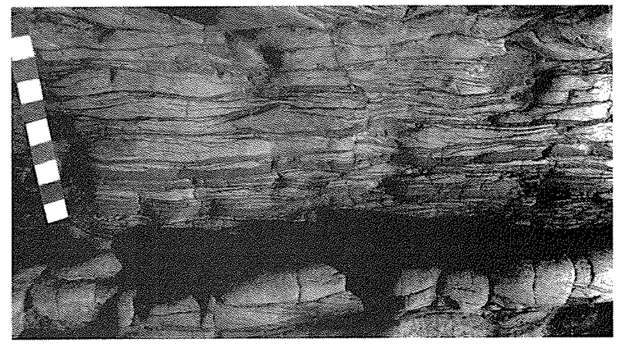

Fig. 6. – Flaser and linsen bedding in shaley sandstones (Lithofacies E); Cluse de l'Orb Fm., l'Orb valley near Maynard.

Fig. 6. – Stratification lenticulaire dans des grès argileux (Lithofaciès E) ; Cluse de la Fm. de l'Orb, Vallée de l'Orb près de Maynard

Fig. 7. – *Cruziana* traces at the base of a thin quartzitic sandstone bed intercalated in shale (Lithofacies F); Cluse de l'Orb Fm., l'Orb valley near Maynard.

Fig. 7. – Traces de Cruziana *à la base d'une mince couche de grès quartzitique intercalé dans les shales (Lithofaciès F) ; Cluse de la Fm. de l'Orb, Vallée de l'Orb près de Maynard.*

Fig. 8. – Tectonically inverted thinning-upward sequence of the basal Foulon Fm. Thick sandstone beds of Lithofacies C (to the left) grade to the right into thin-bedded sandstone-shale alternations (Lithofacies B) and finally into sandy shales (right, at hammer). Five smaller-scale subcycles of about 1m thickness are visible in this part of the section (Rieuberliou outcrop).

Fig. 8. – Séquence tectoniquement inversée vers le haut de la formation basale du Foulon. Couches de grès épais du Lithofaciès C (à gauche) passant aux alternances grès/shales en minces niveaux à droite (Lithofaciès B) et enfin aux argilites sableuses (à droite du marteau). Cinq sous-cycles de plus petite échelle, d'environ 1 m d'épaisseur sont visibles dans cette partie de la section (affleurement de Rieuberlou).

Facies successions

a) Maurerie and Foulon formations

The sedimentary successions of the Maurerie and Foulon formations are rather similar in that they consist of cyclic successions of lithofacies A, B and C. Several distinct thickening-upward cycles (each 60-100 m in thickness) can be recognized in the lower member of the Maurerie Fm. On the other hand, thinning-upward cycles can be seen in the lower Setso Member and in the basal parts of the Foulon Fm. The basal Foulon thinning-upward cycle is only c.5-6 m thick but is further subdivided by 0.5-1 m thick smaller scale subcycles (Fig. 8). Comparable high-frequency cycles have only been observed in the Foulon and (if the small-scale facies variations of the D-E-F association (see below) are referred to as cycles) in the Cluse de l'Orb Fm.

Though all facies boundaries within these cycles are rather indistinct, gradual facies shifts from LF A to LF B and from LF B to LF C (in thickening-upward cycles) are present. The first appearance of persistent sandstone beds as well as the onset of storm-induced erosion and redeposition (as indicated by scours and HCS) supports the view that different lithofacies indicate different depositional environments. These environments, however, clearly were juxta-

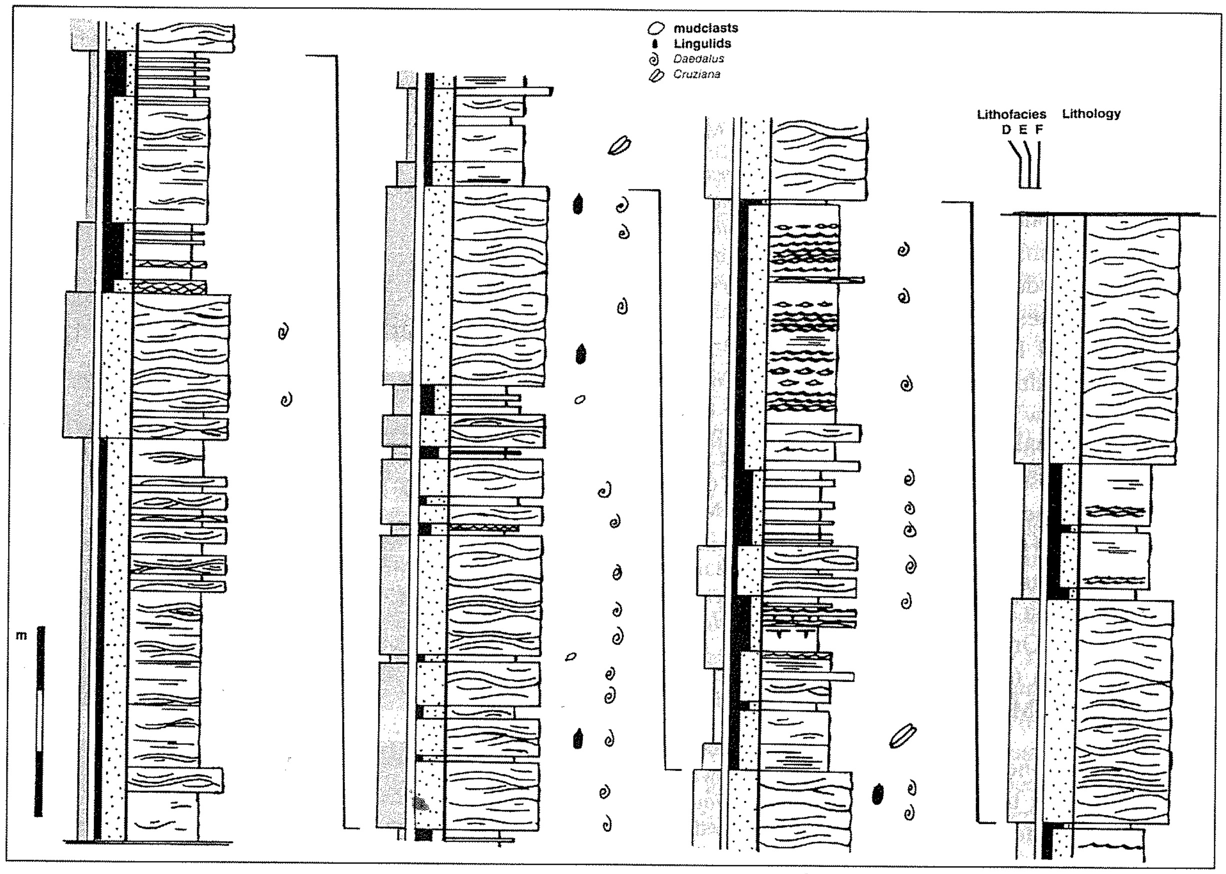

Fig. 9. – Measured section of the uppermost 40 m of the Cluse de l'Orb Fm., Rieuberliou section. The columns represent lithofacies succession (left), shale-to-sand-ratio (middle), and sedimentary structure (right). Only those sedimentary structures visible at the outcrop wall have been included in the drawing. Mudcracks are more common than depicted in this figure, as indicated by their presence in the footwall rubble, but hard to identify in cross section at the outcrop wall.

Fig. 9. – Section mesurée des 40 m supérieurs de la formation de la Cluse de l'Orb. Les colonnes représentent une série de lithofaciès (à gauche), le rapport grès/sable (au milieu) et la structure sédimentaire (à droite). Seules les structures sédimentaires visibles à l'affleurement sont représentées sur la figure. Les fissures de retrait sont plus fréquentes qu'il n'apparaît sur cette figure, comme l'indique leur présence dans l'éboulis au pied de la paroi, mais sont difficiles à identifier sur la coupe transversale de l'affleurement.

posed (more specifically, A next to B and B next to C), as would be expected from "Walther's law" — a geological bias not unequivocally verified in all parts of the sequence (see d, below). Contrary to the smooth facies transitions within each cycle, cycle (and subcycle) boundaries are clearly visible as abrupt changes in sandstone thicknesses and frequency and may represent either hiatuses or sudden shifts in depositional environment.

b) Cluse de l'Orb Formation

The Cluse de l'Orb Fm. is made up of lithofacies D, E and F. The transitions between these lithofacies are less gradual than those between LF A to C described above, and decimeter- to meter-scale interfingering of different facies is common (Fig. 9). As previously pointed out by Eschard (*in* Courtessole *et al.*, 1985), there is a pronounced large-scale cyclicity in the thickness range of 50-80 m (and hence comparable to the Maurerie cycles), produced by the alternation of two main facies associations:

1. 20-40 m thick units of thick-bedded micaceous quartzarenites with only minor intercalations of shale and sandstone (Facies R4 of Eschard; "Grès à Lingules" *sensu stricto*; Fig. 10a). These quartzitic units consist of meter-scale alternations (or subcycles) of LF D, E and F (Fig. 9);

2. 20-30 m thick units of sandy shales and siltstones with intercalated sandstones (Fig. 10b, foreground), predominantly of LF F (Facies R1 and R2 of Eschard); amalgamated hummocky cross stratified beds up to 1-2 m in thickness are occasionally intercalated (LF D; Facies R3 of Eschard). Locally, bedding is disturbed by soft sediment deformation textures (ball and pillow structures, minor slumps; Facies R7 of Eschard).

Since any one lithofacies may be present in either unit, the transition from one facies association to another is due to changes in relative lithofacies abundance within the unit. This implies that, in spite of the quite different environmental energy regimes documented, lithofacies D to F have to be ascribed to intimately linked environments which may have easily been converted into each other, though the probability of each to develop would have been dissimilar at different times.

c) Boundaries of the Cluse de l'Orb Fm.

There are sudden leaps in sandstone maturity from the uppermost Maurerie Fm. to the Cluse de l'Orb Fm. as well as from the uppermost Cluse de l'Orb Fm. to the basal Foulon Fm. These changes are mainly produced by the appearance and disappearance of micaceous quartzarenites, which are absent from preceding and later Ordovician deposits of the area. In Lithofacies E and F of the Cluse de l'Orb Fm., however, micaceous sandstones similar in composition to Maurerie and Foulon sandstones occur and mineralogical and geochemical studies have revealed no evidence for different sources of these two sandstone lithologies (Dabard and Chauvel 1991). It seems more likely that the advanced maturity of the micaceous quartzarenites may have been achieved by wave and storm reworking at or near their site of deposition, a view supported by the presence of wave and storm wave related sedimentary structures.

Apart from petrologic maturity, the step from uppermost Cluse de l'Orb hummocky crossbedded amalgamated sandstones (LF D) to lowermost Foulon hummocky crossbedded sandstones with shale interbeds (LF C) seems rather slight and compares to shoreface to nearshore shelf facies changes frequently described in the geologic literature (Reviews given by Elliott 1986, Pettijohn *et al.*, 1987, Einsele 1992). Little can be said about the significance of the lower boundary of the Cluse de l'Orb Fm., since the uppermost portion of the Setso Member is commonly disturbed by Hercynian faulting and part of the succession may have been lost in some outcrops. Immediate erosive contact of LF D on thickening-upward LF B seems probable, however.

d) Landeyran Formation

One of the most striking features of the Roquebrun series is the abrupt cessation of sand deposition at the base of the Landeyran Fm. Superficially, the shales of the Landeyran Fm. resemble lithofacies A in diagenetic facies (sideritic nodules) and faunal composition (Dean 1966, Courtessole *et al.*, 1981, 1982, 1983, 1985). An *ad hoc* interpretation, therefore, may be a shift to more distal and deeper-water environments from Foulon to Landeyran times, perhaps induced by rapid subsidence or by a sudden sea level rise. However, relative sea level rise alone cannot explain the complete absence of sandy material until the source area also subsided below sea level. Otherwise, at least small amounts of sand should be expected to be incorporated to the muddy outer shelf deposits due to storm-generated suspension clouds. It is indeed this minor proportion of sandy material that makes the difference between LF A proper and the facies of the Landeyran shales. There is indeed no clear evidence of deep-water conditions from benthic fossil assemblages, though a shift to more pelagic environments may be suggested. On a paleoecological basis, Dabard and Chauvel (1991) concluded that the depositio-

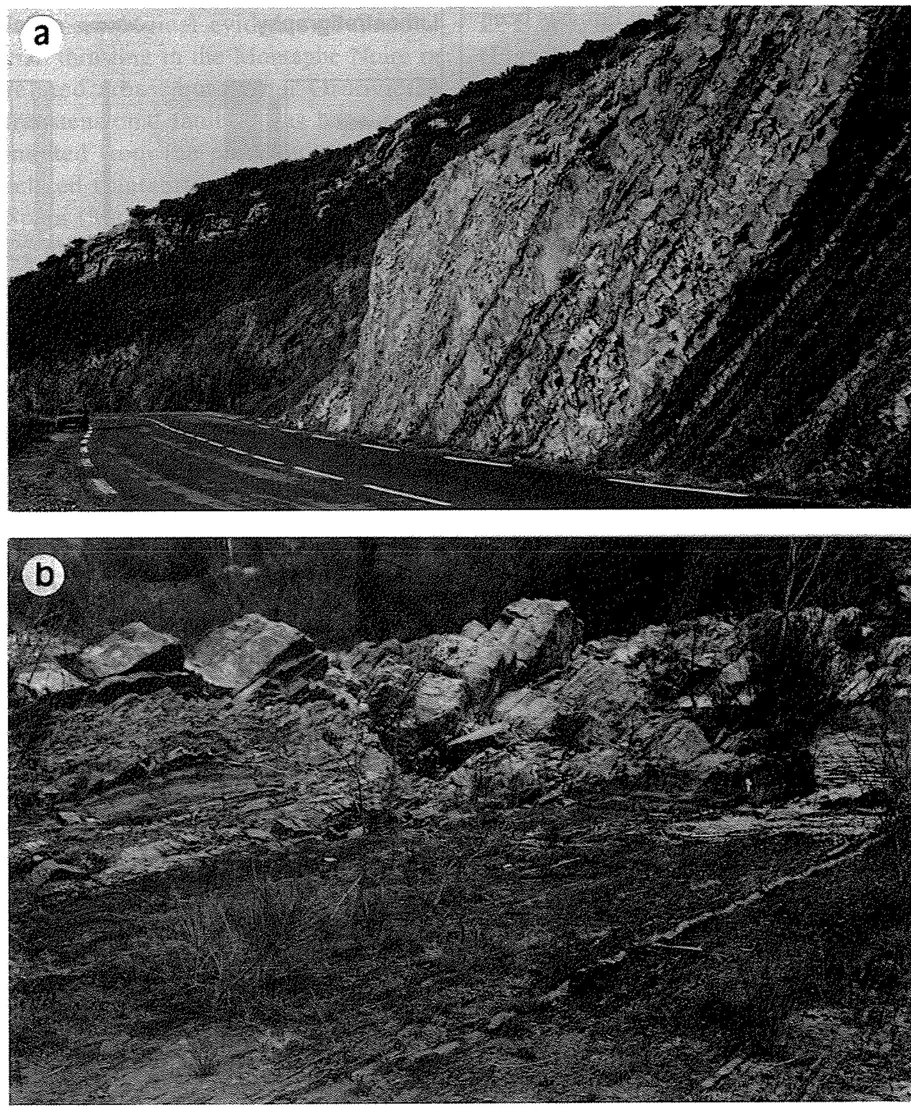

Fig. 10. – Alternations of Lithofacies D, E and F in the Cluse de L'Orb Formation. a) Quartzitic "bars" of 10-20m thickness (Lithofacies D and E, light colour), separated by sandy shales with tempestitic sandstones (Lithofacies F, 30-80 m); Rieuberliou section. b) Transition from Lithofacies D (thick beds, upper left) to Lithofacies E (light-coloured thin beds, left) and dark-coloured sandy shales of Lithofacies F (foreground); l'Orb river near Maynard. Both sections are tectonically inverted.

Fig. 10. – Altérations des lithofaciès D, E et F à la Cluse de la formation de l'Orb. a) "barres" quartzitiques de 10 à 20 m d'épaisseur (Lithofaciès D et E, en clair), séparées par des argilites sableuses avec tempestites gréseuses (Lithofaciès f, 30 à 80 m) ; section de Rieuberliou. b) Transition du lithofaciès D (lits épais, en haut à gauche) au lithofaciès E (lits minces et clairs, à gauche) et argilites sableuses de couleur sombre du lithofaciès F (au premier plan) ; rivière de l'Orb près de Maynard. Les deux sections sont tectoniquement inversées.

nal depth of the Landeyran Fm. has been less than 200 m.

The only distinctive property of the Landeyran shales compared to LF A of the Maurerie and Foulon formations seems to be the lack of sand proliferation from the former source area. Sandy material is transported subtidally even to pelagic shelf environments due to tidal and oceanic currents and storm surges (Sharma 1975, Nelson and Creager 1977, Walker 1984). Sand-free environments seem only to develop where sand-laden bottom surges are cut off from a given area, either by divertion to submarine channels or entrapment within intrashelf subbasins, or by the definite cease of sand proliferation to the shelf. From a theoretical point of view, three alternative causes can be proposed: 1. a very rapid and large relative rise in sea level (Dabard and Chauvel 1991, Chauvel, written comm. 1994) that drowned the former source area (from our point of view the least probable possibility), 2. channeling of the shelf edge and bypass of the sandy terrigeneous sediment into the deep sea during Landeyran time, and 3. tectonically-caused entrapment of sediment on its way to the Landeyran depositional sites. In the latter speculative model, deep troughs were generated by extensional or wrench tectonics to the south of the study area, separating the Montagne Noire area from its Gondwanan hinterland. (It should be noted that "separation" only refers to the pattern of sediment distribution and does not necessarily imply significant tectonic or biogeographical segregation). In this case, a sand-free, pelagic, but shallow-water environment may have formed without significant change in relative sea level.

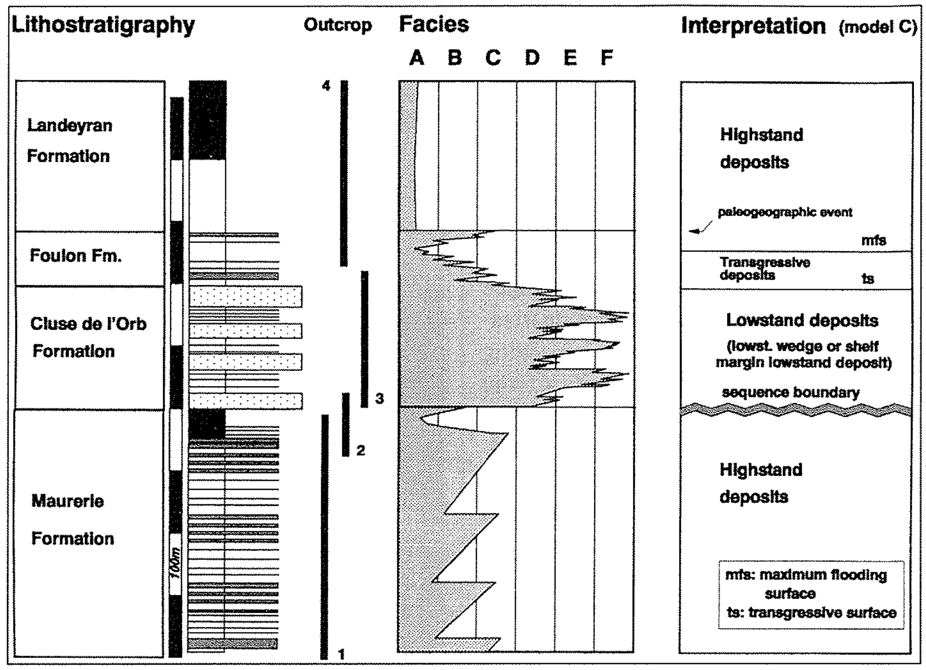

Fig. 11. – Composite log and facies distribution for the upper 900 m of the studied section. Lithofacies types range from A (open shelf, most distal) to F (lagoonal, most proximal). Quartzitic "Lingula-Sandstones" (wide stipple) display complex facies architecture predominantly of LF D and E (see Fig. 9). Note that the shale-sandstone alternations of the Cluse de l'Orb Fm. are composed of LF F (with minor portions of LF E) , but those of Maurerie and Foulon formations belong to LF A to C, respectively. Outcrop bars designate: 1. Route de Laurenque, 2. Setso Valley, 3. Rieuberliou Valley, 4. Landeyran Valley; (cf. Fig. 1). In a sequence stratigraphic interpretation (model C), the Cluse de l'Orb Fm. is proposed to represent a lowstand shelf margin deposit, superseded by transgressive (thinning upward) Foulon shelf deposits. The maximum flooding deposit is probably positioned within the Foulon Fm. (at the turning point from thinning upward to thickening upward architecture) but may alternatively be hidden within the monotonous, sand-free shales of the Landeyran Fm.

Fig. 11. – Distribution des logs composites et des faciès pour les 900 m supérieurs de la section étudiée. Les types de lithofaciès varient de A (plateau continental ouvert sur le large, le plus souvent distal) à F (lagunaire, le plus souvent proximal). Les grès à Lingula *quartztiques (pointillé espacé) témoignent de faciès complexes allant principalement des lithofaciès D à E (voir Fig. 9). On notera que les alternances de schiste et de grès de la Cluse de la formation de l'Orb se composent du lithofaciès F (avec de petites parties du lithofaciès E), mais que celles des formations de Maurerie et du Foulon appartiennent respectivement aux lithofaciès A et C. Les barres affleurantes désignent : 1. Route de Laurenque. 2. Vallée de Setso. 3. Vallée de Rieuberliou. 4. Vallée de Landeyran (cf. fig. 1). Dans l'interprétation d'une séquence stratigraphique (modèle C), nous proposons de considérer la formation de la Cluse de l'Orb comme un dépôt de marge continentale de niveau bas, recouverts par les dépôts de plate-forme transgressifs du Foulon (allant en s'amincissant vers le haut). Le dépôt de plus hautes eaux se situe probablement à l'intérieur de la formation du Foulon (au point de passage d'un amincissement à un épaississement vers le haut) mais peut aussi se trouver masqué à l'intérieur des schistes monotones exempt de matériel arénacé de la formation de Landeyran.*

e) Facies sequences

In summary, the succession studied can be subdivided into three distinct facies sequences characterized by different internal architecture (Fig. 11):

1. Maurerie Formation, built up of several 60-100 m thick depositional cycles consisting of lithofacies A to C;

2. Cluse de l'Orb and Foulon formations, constructed by two hierarchical orders of cycles, displaying LF D to F (Cluse de l'Orb Fm.) and A to C (Foulon Fm.), respectively: High frequency subcycles of one to a few meters are grouped into larger scale cycles of 6-10 m (Foulon Fm.) or 50-80 m (Cluse de l'Orb Fm.);

3. Landeyran Formation, consisting of homogeneously developed sand-free shales.

Whereas facies boundaries within these sequences can be ascribed to lateral shifts of adjacent depositional environments, the transition from one sequence to another is marked by a distinct break in facies succession. The Maurerie-/Cluse de l'Orb boundary, though poorly preserved due to tectonic effects, seems to include some stratigraphic hiatus, indicated by the superposition of LF D on LF B. This may possibly be due to a relative fall in sea level (e.g., tectonic uplift or eustatic sea level drop), but a sudden increase in sediment supply cannot be excluded until the fine stratigraphy of this boundary is better confirmed from undisturbed outcrop sections.

As outlined above, the cessation of sandy input at the Foulon/Landeyran-boundary is probably related to a change in sediment supply rather than to a change in depositional environment. This may have occurred either by topographic isolation from, or drowning of, the former source area.

Accumulation rates

According to Courtessole *et al.*, (1982), the sedimentary pile considered here has to be placed completely within the *Didymograptus deflexus* zone of the lower Arenigian, which starts near the base of the Maurerie Fm. and still continues during deposition of the upper Landeyran Fm. The duration of this graptolite zone may be proposed to be about 2-3Ma, depending on the time scale used (Harland *et al.*, 1982, 1989). If the total thickness estimate of c. 1 500 m is correct, surprisingly high accumulation rates of 200 to 500 m/Ma have to be inferred. These rates strongly contrast with earlier Ordovician deposits of the region: Tremadocian c. 40 m/Ma; *Tetragraptus* zone of lower Arenigian c. 100 m/Ma (thickness and biostratigraphic data from Courtessole *et al.*, 1982). The estimate of 2-3 Ma for the duration of the *deflexus*-zone may indeed be wrong, but even then the accumulation rates would have been much higher than during Tremadocian times: the accumulation of 1 500 m of sediment at 40 m/Ma would take more than 35 Ma, which is much more than the duration of the complete Arenigian stage.

Since the depositional surface did not aggrade above sea level, this implies accelerated subsidence of the Roquebrun area during the *deflexus*-zone. Subsidence rates of more than 200 m/Ma strongly imply synsedimentary tectonic activity, e.g. by thrust loading in orogenic foreland basins or extensional (rift / pull-apart) basin generation. There is, however, no unequivocal structural or sedimentological evidence of Ordovician thrusting in the Montagne Noire or related areas, but Upper Ordovician transtensional faulting has been documented from the paleogeographically related Cantabrian region of northern Spain (Martinez Catalan *et al.*, 1992). For the Montagne Noire, tectonic activity has not yet been documented prior to the Silurian, when the Lower Paleozoic rocks were gently tilted and eroded before they were unconformably overlain by Upper Silurian and Lower Devonian marine deposits (Feist and Schönlaub 1974). If this unconformity stems from compressive or extensional tectonic activity is still open to debate. The same is true for a local upper Cambrian disconformity, that may indeed be non-tectonic in origin (Boyer and Guiraud 1964). For the Lower Ordovician, however, we deduce from the high rates of subsidence cited above that some kind of tectonic activity has occurred.

Discussion

Facies model A: Open shelf and offshore bar deposits.

In his study of the Cluse de l'Orb Fm., Eschard (*in* Courtessole *et al.*, 1985) interpreted the muddy sequences of this formation as sublittoral open shelf deposit. In his model the micaceous quartzarenite units are thought to result from storm-induced accumulation of sand to lens-shaped offshore tempestite bars, accreting vertically up to fairweather wave base and capped by wave rippled littoral deposits. In this case, the Cluse de l'Orb Fm. may have been formed on the open shelf far from any exposed land surface.

There are, however, some hydrographic and paleoecological arguments against this model:

1. Eschard (*in* Courtessole *et al.*, 1985) considered the quartzitic bars of the Cluse de l'Orb Fm. to consist of relatively homogeneous, hummocky cross-bedded deposits 20-40 m in thickness. Detailed facies logging of these "bars", however, revealed complex interstratification of hummocky crossbedded, wave rippled, and muddy deposits, i.e., of LF D, E and, in minor proportions, of LF F (Fig. 9, lithofacies column on the left side of the log). Individual units of LF D rarely exceed 10 m or so in thickness, and only these HCS-dominated units may properly adressed as "tempestite bars" as proposed in Eschards model. Since most "bars" (LF D) are capped by wave rippled and partly mudcracked intertidal sediments (LF E; Fig. 9), most of their deeper part probably deposited in uppermost subtidal environments (less than 15 m, allowing for compaction), that is, above fairweather wave base. Therefore, the most important factors concerning sand reworking and redeposition may have been fairweather wave and tidal current activity. The sedimentary structures preserved in any particular deposit are not necessarily produced by the most frequent type of redeposition, however, but by the final event reworking this sediment. Where the depth of storm erosion exceeded the fairweather accumulation rate, only storm-generated sedimentary structures are preserved within the redeposited remnant sediment. Thus, a storm-dominated sedimentary record is indicative for intense storm wave action at the sea floor, but does not imply that storms were the main factor for sediment accumulation.

2. The possibility of spontaneous initiation and stationary accretion of offshore sand bars by storm wave action may indeed be doubted. Where open shelf sediment is redistributed by storm waves, dispersal and levelling to some equilibrium surface would rather be expected than accumulation of distinctly localized sandy bars surrounded by muddy spacings. Though offshore sand bars and ridges are common features on present shelves, most of them seem to be remnant beach barrier deposits drowned during the Early Holocene transgression (Field 1980, Nelson *et al.*, 1982). Storm reworking of these palimpsest sands tends to produce widespread continuous sheet sand bodies (Field 1980, Swift *et al.*, 1983) rather than isolated patches of amalgamated tempestites. Unfortunately, the Ordovician deposits of the study area are too heavily tectonized to map the original shape of the sandstone bodies in question. If, after all, an offshore bar geometry is suspected, one has to pro-

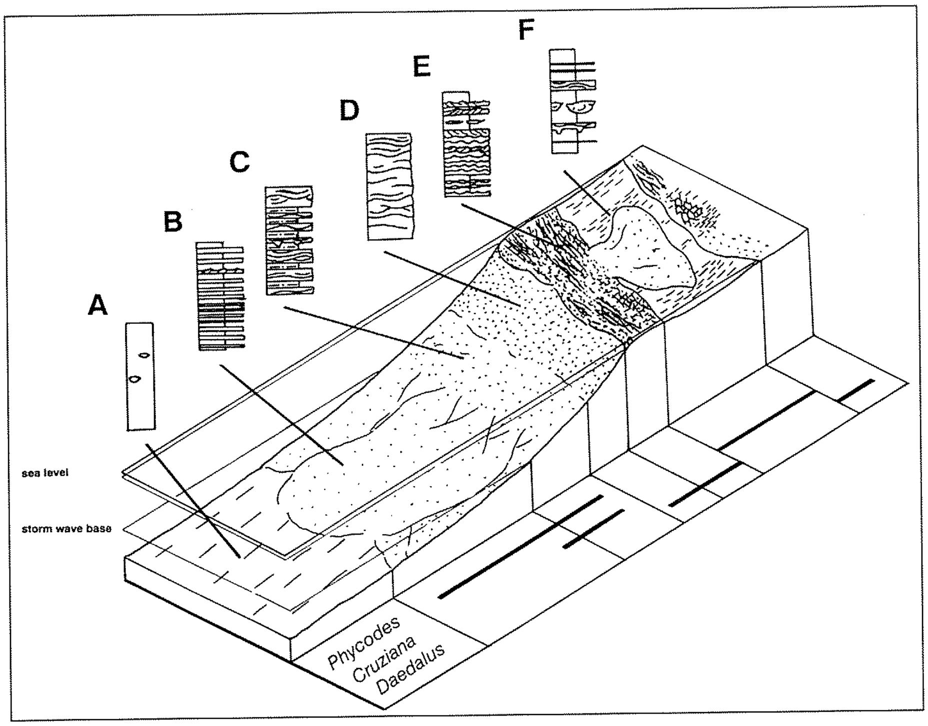

Fig. 12. – Proposed depositional environments of the Ordovician deposits of the Roquebrun area and distribution of selected trace fossils. A: outer shelf mud, B: distal tempestite facies (below storm wave base), C: proximal tempestite facies (above storm wave base), D: shoreface, E: littoral and lagoonal shoreline deposits (on both sides of F), F: lagoonal (sublittoral) with spillover lobes. Not to scale.

Fig. 12. – Milieux de dépôts proposés pour les dépôts ordoviciens de la zone de Roquebrun et distribution de certaines traces fossiles. A : boues du plateau extérieur ; B : faciès de tempestite distale (au-dessous des vagues de tempête) ; C : faciès de tempestite proximale (au-dessus de la base d'une vague de tempête) ; D : zone infratidale ; E : dépôts côtiers littoraux et lagunaires (de part et d'autre de F) ; F : lagunaire (sublittoral) avec lobes de déversement.
Echelle non respectée.

pose some other mechanism for sand accumulation (e.g., tidal or oceanic currents) and to claim intense storm wave reworking of these bars to explain their HCS-dominated internal architecture.

3. If adjacent Maurerie and Foulon Formations are taken into account, their lithological and ichnofaunal differences to LF F of the Cluse de l'Orb Fm. clearly indicate a different environment for the latter (cf. descriptions of LF C and F, respectively). Compared to the (inferred) open marine conditions of LF C, the Cluse de l'Orb deposits (of LF F) have to be ascribed to somewhat restricted conditions, as implied by the absence of *Phycodes* and diminished tempestite frequency. At the present state of information, this seems to be constrained by the restricted faunal diversity of the Cluse de l'Orb Fm. (compared to Maurerie and Foulon formations) reported by Courtessole *et al.*, (1982, 1985). In an offshore bar model, however, this may be achieved by the assumption of a period of extraordinary hydrodynamic conditions compared to the "normal" open shelf environment of the Maurerie and Foulon formations, perhaps induced by sea level lowstand during Cluse de l'Orb time.

Facies model B: Tectonic uplift island coastline.

Based on our field observations and regarding to the complete Lower Arenigian sequence, we recommend a clastic ramp model as an alternative interpretation of the Roquebrun series (Fig. 12). This model implies no significant break in depositional history at the boundaries of the Cluse de l'Orb Fm. apart from lateral shift of adjacent environments. Lithofacies A to F, respectively, are interpreted to represent different segments of a continuous shelf-to-shore profile, implying a "standard" barred beach depositional system (Elliot 1986, Reineck and Singh 1986; ichnofacies after Frey and Pemberton 1984):

A: muddy open shelf, well below storm wave base (sandy shale);

B: open shelf (upper *Zoophycos*-facies?), receiving minor sandy input from storm-induced suspension clouds, but not directly affected by storm surge bottom erosion (sandy shale with thin sandstones, *Phycodes*, *Planolites*);

C: open shelf (*Cruziana*-facies), more proximal than B and located above storm wave base, subjected to storm erosion and redeposition (hummocky cross-bedded sandstones with shale interbeds, *Phycodes*, *Cruziana*);

D: shoreface (nearshore sublittoral), site of frequent redeposition (*Skolithos*-facies), mainly by waves and storms (HCS-dominated quartzose sandstones, *Daedalus*);

E: littoral environment of foreshore and lagoonal shoreline (*Skolithos*-facies), dominated by fairweather redeposition by waves and currents (wave-rippled and partly mudcracked sandy shales and quartzose sandstones, *Daedalus*, *Planolites*);

F: lagoonal mud with spillover sands shed in from the beach barrier (LF D and E) by landward-directed storm surges, sublittoral (*Cruziana*-facies), but somewhat restricted faunistically from the open sea (sandy shales and siltstones with minor quartzose tempestites, *Cruziana*).

Possibly, part of LF E represents the coastline landward of these lagoons.

The appearent lack of backshore and dune deposits, thought to be characteristic of beach barrier depositional systems (Davidson-Arnott and Greenwood 1976, Reinson 1984, Eliott 1986), is probably due to intense storm and wave erosion. In Mesozoic to Cenozoic times, protective plant growth represents an important factor in the preservation potential of supralittoral deposits (Reineck and Singh, 1986). Due to the absence of land plants, supralittoral erosion may have taken place at higher rates in Ordovician times. This problem, however, is present in any facies model for the Cluse de l'Orb Fm., since tidally exposed sand flats accessible for eolian redeposition are proposed in any instance for lithofacies E.

A rapid fall in sea level can be inferred from the sharp and perhaps erosive base of the Cluse de l'Orb Fm., which can be interpreted in terms of a rapid seaward shift of shoreline sedimentation onto former shelf environments (Plint 1988). Yet even this interpretation cannot be followed without at least one speculative preassumption: because it involves shoreline sedimentation, one has to imply some nearby topographic high to act as a depositional "nucleus" to prograde from or transgress onto. (Note that this uplift is not implied to be localized at but adjacent to the depositional site). There is no petrographic evidence for a new sediment source at the base of the Cluse de l'Orb Fm. (Dabard and Chauvel, 1991). If a tectonic rise is invoked to explain the depositional pattern of this formation, this inferred rise has obiously not been eroded to its basement but only in its upper (sedimentary) cover. The resedimented material of this cover was, in its upper portions, the lateral equivalent of the Maurerie Fm. and thus of the same (Gondwanan) provenance. The lack of petrographically distinguishable sedimentary material, therefore, is not necessarily at variance with a local rise of significant topography. The need for some local rise becomes even more pronounced when the paleogeographic situation of the Early Ordovician Gondwana shelf is considered (e.g., Paris and Robardet 1990, Cocks and Fortey 1990): the "Gondwanaland"-shoreline was located well upon the Sahara Platform, far from the South European depositional realm near the shelf edge. Lower Ordovician tectonic activity, involving local uplift and neighbouring subsidence, has been reported from northern Spain (Martinez Catalan *et al.*, 1992), and highly evolved pre-Caradocian paleosols developed at the famous "Sardic Unconformity in Sardinia (Coccozza and Jacobacci, 1975). Sardinia is placed offshore relative to southern France in pre-Alpine tectonic reconstructions (Scotese and McKerrow 1990, Oczlon 1992). Hence, the possible existence of some Early Ordovician topographic rise near the Montagne Noire, though not yet independantly proven, may at least be held as a plausible assumption.

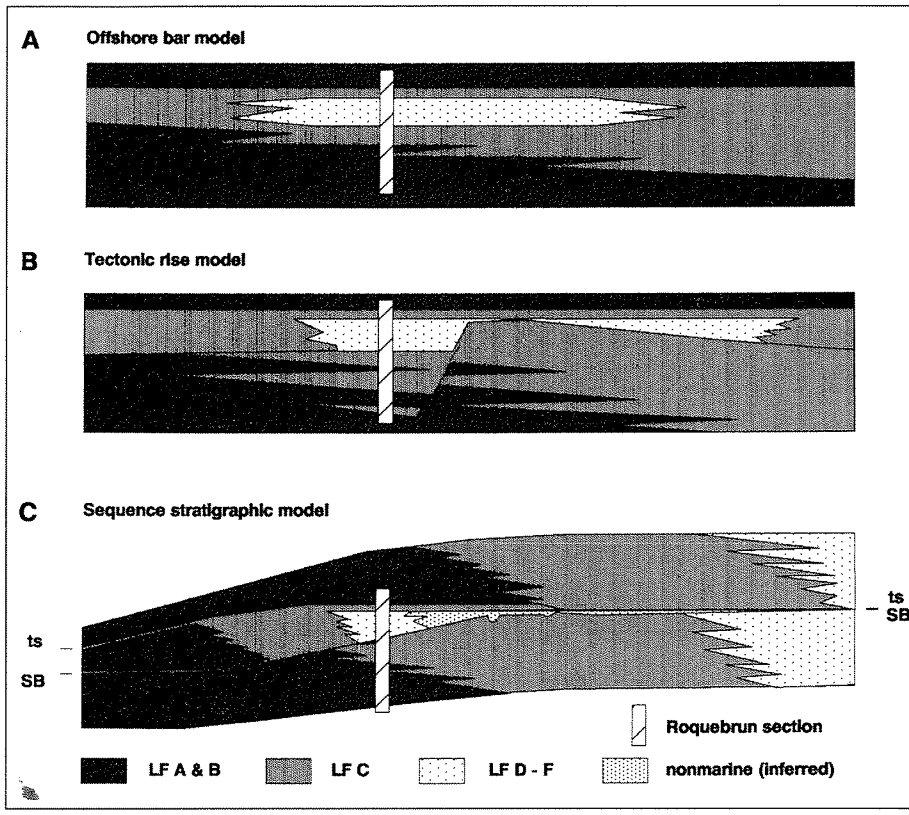

Fig. 13. – Diagrammatic comparison of the lithostratigraphic models for the Roquebrun series as discussed in the text. Note that the original geometry of the Cluse de l'Orb Fm. (LF D-F) is reconstructed different in either model. SB: sequence boundary, ts: transgressive surface. In the sequence stratigraphic model (C), nonmarine deposits or paleosols are inferred, as a working hypothesis, to the south of the Montagne Noire, e.g. on the Saharan platform.

Fig. 13. – Schéma comparatif des modèles lithostratigraphiques de la série de Roquebrun examinés dans le texte. On notera que la géométrie originale de la formation de la Cluse de l'Orb (lithofaciès D à F) est reconstituée différemment dans chaque modèle. SB : limite de la séquence, ts : surface de transgression. Dans le modèle de séquence stratigraphique (C), on infère la présence de dépôts non marins ou de paléosols, à titre d'hypothèse de travail, au sud de la Montagne Noire, par ex. sur la plate-forme saharienne.

Facies model C: Shelf break sequence stratigraphy.

A third interpretation can be proposed, however, on the basis of sequence stratigraphic models of continental margins (e.g., Van Wagoner *et al.*, 1988, Vail *et al.*, 1991). In this model, depositional environments of LF A to F are also interpreted in terms of a shelf-to-shoreline depositional system (Fig. 12), but it differs from facies model B in its paleogeographic setting. In this third model, the shales and sandstones of the Maurerie Fm. are interpreted to be highstand deposits laid down in an outer shelf or shelf edge environment, disconformably capped by a sequence boundary (erosive base of the Cluse de l'Orb Fm.). A relative fall in sea level shifted the bayline from its "normal" (highstand) position on the Saharan Platform to the shelf edge at or near the Roquebrun depositional site. The nearshore deposits of the Cluse de l'Orb Fm. represent the lowstand deposits of the next sequence, superseded by transgressive thinning-upward cycles of the Foulon Fm. The uppermost Foulon prograding sandstones and Landeyran Shales represent the succeeding highstand deposits. As outlined above ("Facies successions", d), the Foulon/Landeyran-boundary probably developed due to a change in paleogeography and sediment dispersal patterns rather than water depth.

A major advantage of this model is that there is no need to imply some hypothetical tectonic rise or anactualistic hydrodynamic conditions on the outer shelf. The main disadvantage, however, is that it is based only on a very small outcrop area and a theoretical stratigraphic model instead of a well-established two-dimensional stratigraphic profile. Further, the compatibility of sequence stratigraphic models derived from seismic lines with observable outcrop stratigraphy has yet to be improved (Miall 1991, Schlager 1991). The validity of facies model C, therefore, strongly depends on the validity of its main assumption, that is, how far the stratigraphic model used here for the Gondwana continental margin represents a plausible approximation to its former stratigraphic architecture.

Conclusions

The Lower Arenigian siliciclastic deposits of the Roquebrun area were laid down in a shallow marine shelf environment. The most characteristic feature of this sequence are cross-stratified sandstones dominated by storm-generated internal textures. In this respect, the Roquebrun deposits compare to Ordovician rocks in other parts of Southern Europe (Brenchley *et al.*, 1986, Durand 1985). This type of "storm-dominated" record of depositional processes is in accordance with paleogeographic reconstructions that place Southern Europe in a high-latitude position, that is, in a climatic zone near the subpolar convergence (cf. Introduction). Its situation may be compared to modern subarctic shelves, e.g. the Bering Sea, where, aside from oceanic and tidal currents, storm reworking and redeposition is one of the most important depositional processes (Sharma *et al.*, 1972, Sharma 1975, Nelson and Creager, 1977, Nelson 1982).

A clastic ramp - barrier shoreline facies model, as favored here, is consistent with the lithofacies characteristics and relationships, and avoids the difficulties associated with an open shelf - offshore bar model. In both models, the shale/sandstone-alternations of the Maurerie and Foulon formations are interpreted as shallow marine deposits of a graded shelf, ranging from a deep muddy distal facies to shallow sandy, storm-dominated proximal facies. Contrary to the offshore bar model of Eschard (*in* Courtessole *et al.*, 1985), however, the crossbedded quartzarenites and intercalated mudstones of the Cluse de l'Orb Fm. are proposed here to represent barrier-beach and lagoonal deposits. The depositional site of the Roquebrun deposits probably was situated at or near the shelf break of the continental margin (Paris and Robardet 1990, Cocks and Fortey, 1990). Two alternative stratigraphic settings can be proposed to explain shoreline deposition at the outer shelf. Some kind of tectonic uplift may be inferred as depositional *nucleus* for marginal marine deposition. This hypothetical rise, however, may have been uplifted slightly prior to Cluse de l'Orb time but became emergent only during this time interval due to a temporary sea level lowstand. Alternatively, the Cluse de l'Orb Fm. may represent a shelf margin lowstand deposit and form part of a "model" shelf edge sequence analogous to standard sequence stratigraphic models of modern continental margins. Yet there is too little known about the depositional architecture of the Ordovician continental margin of Northern Gondwana to decide between these models.

A sea level lowstand during Cluse de l'Orb time is indicated in either of these facies models, though the implied magnitude of relative sea level change is somewhat different. A comparatively minor change may hold for offshore bar generation or emersion of a pre-existing tectonic rise, but a large fall in sea level and exposed shelves have to be inferred, if the shelf margin facies model is adopted. This lowstand is followed by renewed transgression at the end of Cluse de l'Orb time, as indicated by the deepening-upward architecture of the Foulon Fm, and possibly by increased abundance of glaucony at the base of this Formation (Dabard and Chauvel, 1991). The formation of this mineral, which is also present near the base of the Cluse de l'Orb Fm. (Dabard and Chauvel, 1991), is not restricted to transgressive environments, however, and its occurrance may therefore represent other environmental changes not caused by sea level change (Reineck and Singh, 1986, Pettijohn *et al.,* 1987, Einsele 1992). Several short-term sea-level changes are superimposed onto this main regression - transgression cycle, documented by smaller-scale cyclicities throughout the sequence.

Syndepositional tectonic activity is indicated by drastically increased accumulation rates at the beginning of the Arenigian. A further hint of tectonic activity can be seen in the sudden cessation of sandy input at the base of the Landeyran Fm. ("Facies successions", d). This interpretation is, of course, even more speculative than those concerning depositional environment. Due to limited outcrop area and pre-Devonian erosion, these indications of Early Ordovician tectonic activity remain circumstantial. Nevertheless, southern France represents a "white spot" on Ordovician paleotectonic maps, and therefore we may hope that even these tentative clues will contribute to the deciphering of the early paleozoic tectonic evolution of the Hercynian Foldbelt.

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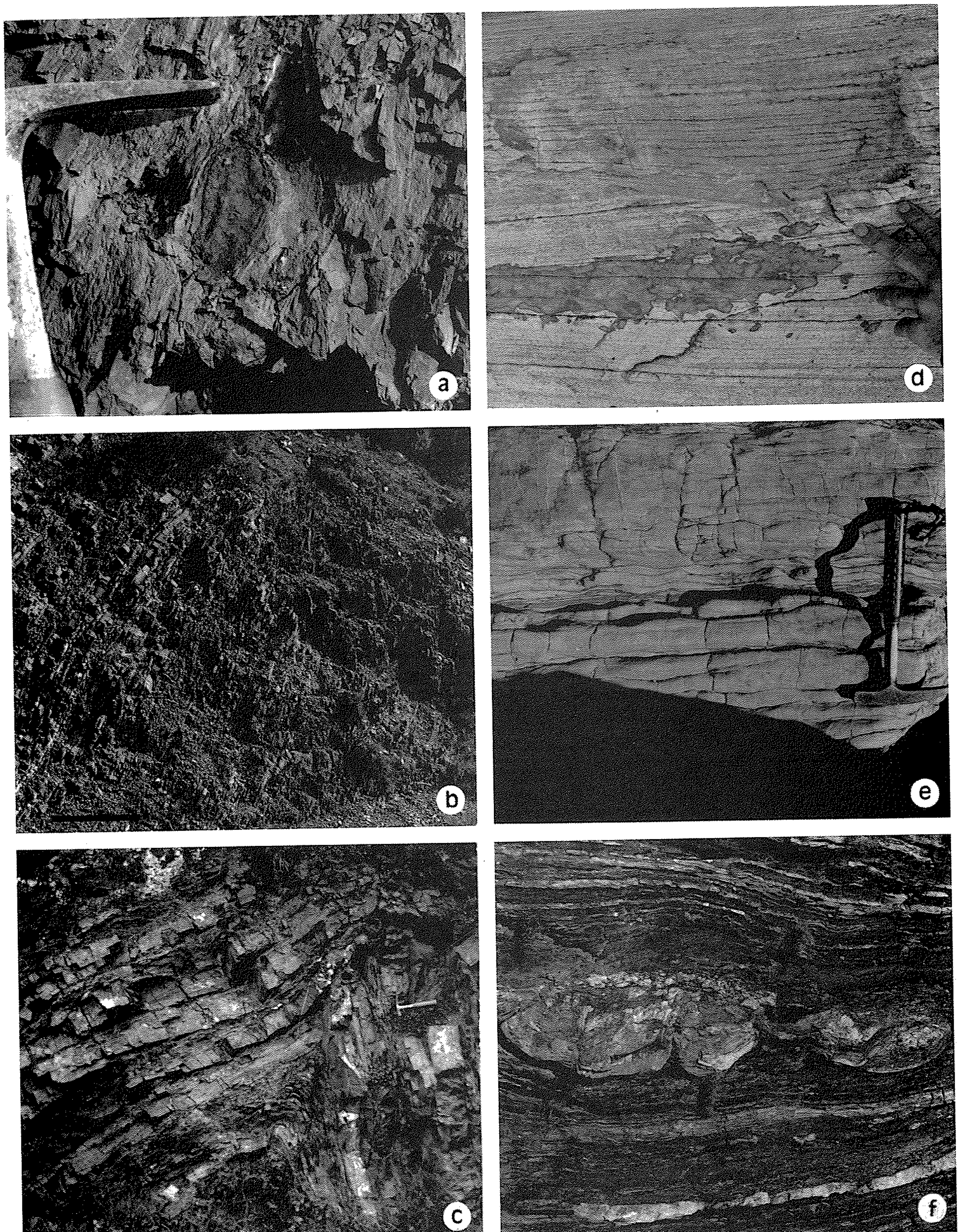

Plate 1. – Lithofacies types of the Ordovician rocks near Roquebrun.
a) Unstratified marine mudstone with limonitic nodule, Lithofacies A;
b) Thin-bedded shale-sandstone alternations, Lithofacies B (scale bar c.50 cm);
c) Decimeter-thick sandstone beds with shale intercalations, Lithofacies C;
d) Thick-bedded hummocky cross-stratified quartzitic sandstone, Lithofacies D;
e) Thin-bedded quartzitic sandstones displaying wavy and flaser bedding, Lithofacies E;
f) Sandy shales with intercalated thin quartzitic sandstone beds, Lithofacies F. Large load cast to the left is about 1m thick.

Planche 1. – Types de lithofaciès des roches de l'Ordovicien près de Roquebrun.
a) boues marines non stratifiées avec nodule limonitique. Lithofaciès A ;
b) alternances grès-shales en couches minces, Lithofaciès B (échelle c : 50 cm) ;
c) couches de grès d'épaisseur décimétrique avec intercalations de shales, Lithofaciès C ;
d) grès quartzitique à stratifications entrecroisées en mamelons, en bancs épais, Lithofaciès D ;
e) grès quartzitiques en lits minces à stratification lenticulaire et ondulée, Lithofaciès F ;
f) argilites sableuses avec intercalation de minces couches de grès quartzitique. Lithofaciès F : la grande figure de charge à gauche mesure environ 1 m d'épaisseur.