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Facies and depositional setting of the Lower Cambrian archeocyath–bearing limestones of southern Montagne Noire (Massif Central, France)

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Key words. – Carbonate sedimentology, Bioconstructions, Depositional setting of archaeocyaths, Paleoecology, Paleogeography, Early Cambrian.

Abstract. – Archaeocyath-bearing limestones of the Lower Cambrian Pardailhan Formation of southern Montagne Noire are restricted to few intervals (H1, H2, H3) of the mixed carbonate-detrital succession exposed in several superposed tectonic units affected by severe deformation.

The comparative analysis of the archaeocyath assemblages together with a detailed sedimentological investigation leads to the understanding of the depositional settings and of the building style of the calcimicrobial-archaeocyath groups and to a better definition of the paleogeographic relationships of the different tectonic units.

Interval H1 : small, low-relief 'pioneer reefs' built by *Epiphyton* bushes and *Girvanella* crusts, associated with clusters of small stick-shaped archaeocyaths, colonized the detrital sand of the bottom. They are frequent in southern Minervois and more randomly distributed in northern Minervois and northern and southern Pardailhan and represent short-lived attempts of carbonate colonization on the sandy, mobile substrate of a wide continental shelf.

Interval H2 : Platy and bioclastic grainstones form the substrate and apron of small crust/cement reefs and associated clusters of ribbon-like and conical archaeocyaths in southern Minervois, or of mud-rich calcimicrobial mounds in southern Pardailhan. Displaced cups of stick-shaped archaeocyaths similar to those of Interval H1, occur in the granular facies, while in place saucer-like cups of *Anthomorpha margarita* are associated to the mud-rich mounds. This facies association records the repeated attempt at instauration and discrete development of a carbonate platform made of low-relief banks, the margins of which were colonized by *Girvanella* crust-buildups whereas in the more protected deeper zones *Epiphyton/Renalcis* mud-mounds dominated.

Interval H3 : *Epiphyton*/*Renalcis*, mud-rich mounds with solitary, large saucer-like cups of *Anthomorpha margarita*, represented by long, ribbon-like fragments, are dominant in the upper part of the platform. They rest on reduced lenses of grainstone and *Girvanella* crust boundstone and in southern Pardailhan are interbedded with nodular, marly mudstones containing bioclastic debris partly derived from the buildups. In this area they mark the transition from platform to shallow basin.

Faciès et conditions de dépôt des calcaires à archéocyathes du Cambrien inférieur de la Montagne Noire méridionale (Massif central, France)

Mots clés. – Sédimentologie des carbonates, Bioconstructions, Conditions d'installation des archéocyathes, Paléogéographie, Cambrien inférieur.

Résumé. – Les calcaires de la formation de Pardailhan (Cambrien inférieur du sud de la Montagne Noire) ne contiennent des faunes d'archéocyathes que dans quelques minces couches de la séquence carbonatée-détritique, dans chaque horizon (HI, H2, H3) exposée dans plusieurs unités tectoniques superposées qui sont affectées par de sévères déformations.

L'examen comparatif des assemblages d'archéocyathes associé à une investigation sédimentologique détaillée conduit à la compréhension des modes de dépôt et du style de construction des associations archéocyathes-calcimicrobes. Il permet également d'obtenir une meilleure définition des relations paléogéographiques entre les différentes unités tectoniques.

H1 : archéocyathes – calcimicrobes sont concentrés dans de petits récifs "pionniers", détritiques, avec de petits calices d'archéocyathes cylindriques (en bâtonnets), brisés et déplacés dans les dépôts interrécifaux; localement ils sont associés avec des boundstones en croûtes à *Epiphyton* et *Girvanella*. Les archéocyathes sont fréquents dans le Sud Minervois, plus irrégulièrement répartis dans le Nord Minervois, le Pardailhan nord et sud.

H2 : les archéocyathes sont en bâtonnets, isolés et fréquemment déplacés comme dans H1, mais on trouve aussi des calices en place, en forme de soucoupes; des grainstones, contenant du quartz diffus à grains fins à la base des bioconstructions en croûtes à *Girvanella*, témoignant d'une haute énergie, sont plus developpés dans le Sud Minervois, que dans le Nord Pardailhan; un boundstone à *Epiphyton* et *Renalcis* de basse énergie est trouvé dans le Minervois et le Nord Pardailhan.

H3 : les calices d'archéocyathes sont de grandes soucoupes, observées la plupart du temps sous forme de longs rubans ondulés, fragments de leur intervallum, dans un boundstone à *Epiphyton* et *Renalcis*. Dans le Nord Pardailhan, on trouve localement des faciès de tempête à la base des bioconstructions, tandis que dans le Sud Pardailhan, des faciès

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nodulaires, des mudstones, contenant des débris bioclastiques et quelques boundstones cryptalgaires et calcimicrobiens, sont le signe d'un environnement de basse énergie à la transition avec le bassin peu profond.

INTRODUCTION

Early studies regarded archaeocyaths as the main builders of early Cambrian reefs [Hyatt, 1885]. However, it has since been recognized that they are usually subordinate to calcimicrobes [Copper, 1974]. Research on reef composition and framework building styles has been intensively carried out on archaeocyath-bearing limestones in the course of sedimentological investigations firstly in non-tectonized provinces : Siberian Platform [Zhuravleva, 1960 ; Kruse *et al.*, 1995] ; Morocco [Debrenne, 1975] ; Canada [James and Kobluck, 1978 ; Debrenne and James, 1981 ; James and Klappa, 1983] ; China [Debrenne *et al.*, 1991 ; Gandin and Luchinina, 1993] ; Australia [Debrenne and Gravestock, 1990 ; James and Gravestock, 1990 ; Kruse, 1991], Anctartica [Rees *et al.*, 1989]. All the bioconstructions had the same basic building plan from their appearance (Tommotian) to their almost complete disappearance (Toyonian), and can be divided into component domains represented by archaeocyaths, calcimicrobes, lime mud and/or cement depending on external factors.

Such analysis has been extended to the tectonized provinces of Nevada [Rowland and Gangloff, 1988 ; Debrenne *et al.*, 1990] ; Mexico [Debrenne *et al.*, 1989] and Mongolia [Wood *et al.* 1993 ; Kruse *et al.*, 1996]. In western Europe, investigations on Cambrian buildups, locally affected by severe tectonic deformations, have been carried out in Spain [Zamarreno and Debrenne 1977 ; Moreno-Eiris, 1987] ; Sardinia [Gandin and Debrenne, 1984 ; Debrenne and Gandin, 1985 ; Debrenne *et al.*, 1989] and Germany [Elicki, 1999].

Since specific analyses of archaeocyath-bearing limestones of the strongly folded and sheared Lower Cambrian rocks of Montagne Noire are scarce [Debrenne and Courjault-Radé, 1986 ; Courjault-Radé, 1988a], this paper presents an attempt to match the present knowledge of the archaeocyath depositional settings, and an exhaustive sedimentological/ petrographic analysis of the associated limestones, which provides new data supporting and defining the paleogeographic reconstruction postulated by Courjault-Radé [1988b]) for southern Montagne Noire.

THE PARDAILHAN ARCHAEOCYATH-BEARING LIMESTONES

Geological setting

Montagne Noire, located at the southern end of the French Massif Central, represents a segment of the external zone of the French Variscan Belt, composed of superposed structural units resulting from polyphased orogenic events. In southern Montagne Noire the Cambrian suite is exposed in

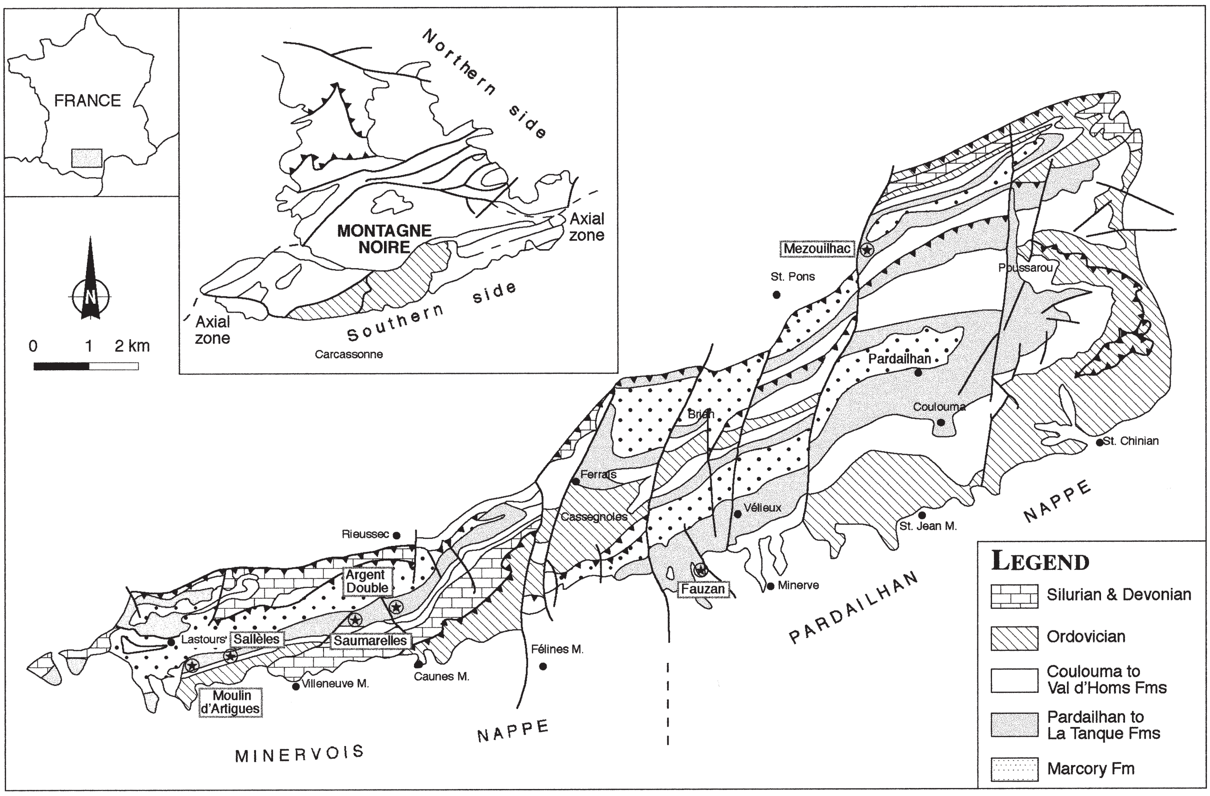


FIG. 1. – Regional structural framework of Montagne Noire and sampling localities (*). After Alvaro *et al.* [1998] modified.
FIG. 1. – *Cadre structural régional de la Montagne Noire. Localités d'échantillonage* (*). *D'après Alvaro* et al. *[1998] modifié.*

the Minervois and Pardailhan Nappes (fig. 1) which correspond to the reverse flanks of thrusted isoclinal folds. These folds, resulting from early-orogenic Variscan phases, were later thrusted southward, re-folded, and during the latest tensional phases, cross-cut by faults [Demange *et al*., 1986 ; Demange, 2001 and references herein]. In this area, the Cambrian lithosomes are affected by relatively weak deformations and epizonal metamorphism [Demange *et al*., 1986], which are more evident in the lower part of the succession, made up of mixed siliciclastic/carbonate facies. There, the repetition of the same sequential evolution and depositional characters within the carbonate and siliciclastic layers of each sequence of the middle part of the Pardailhan Formation, suggests that folding and tectonic boudinage, enhanced by the different competence of the two lithotypes [Deramond *et al*., 1981], may have resulted in multiplying the number of the limestone bodies, producing the apparent stratigraphic superimposition of numerous limestone beds [Etchler and Malavielle, 1990]. A similar tectonic pattern has recently been recognized in the coeval, mixed succession of SW Sardinia [Galassi and Gandin, 1992] where the effects of the Variscan tectonics produced the geometric repetition of the depositional carbonate bodies.

Lithostratigraphy and lateral distribution

In southern Montagne Noire, archaeocyath-bearing limestones are found only in some carbonate horizons of the Lower Cambrian Pardailhan Formation ("Alternances supérieures" *auct.* ; Upper Orbiel Formation : Courjault-Radé [1988]) which overlies a basal siliciclastic unit (Marcory Formation) and is followed by a carbonate unit (Lastours Formation, Alvaro *et al.* [1998]).

The Pardailhan mixed siliciclastic-carbonate succession consists of alternated sandstones, siltstone/shales and limestones (fig. 2), locally affected by late-diagenetic/tectonic dolomitization. In this unit, three intervals (H_1, H_2 H_3) corresponding to Boyer's [1962] "Alternances inférieures" "Alternances supérieures" and "La Masse" respectively, which are characterised by the gradual decrease of the siliciclastic components, the increase in thickness and lateral continuity of the carbonate intercalations, and the occurrence of archaeocyath assemblages, can be recognized.

In the whole region, except for southernmost Pardailhan, a thin siliciclastic layer ("Niveau d" : Boyer [1962]) at the top of Interval H3, marks the transition to the overlying Lastours Formation. This marker-bed, composed

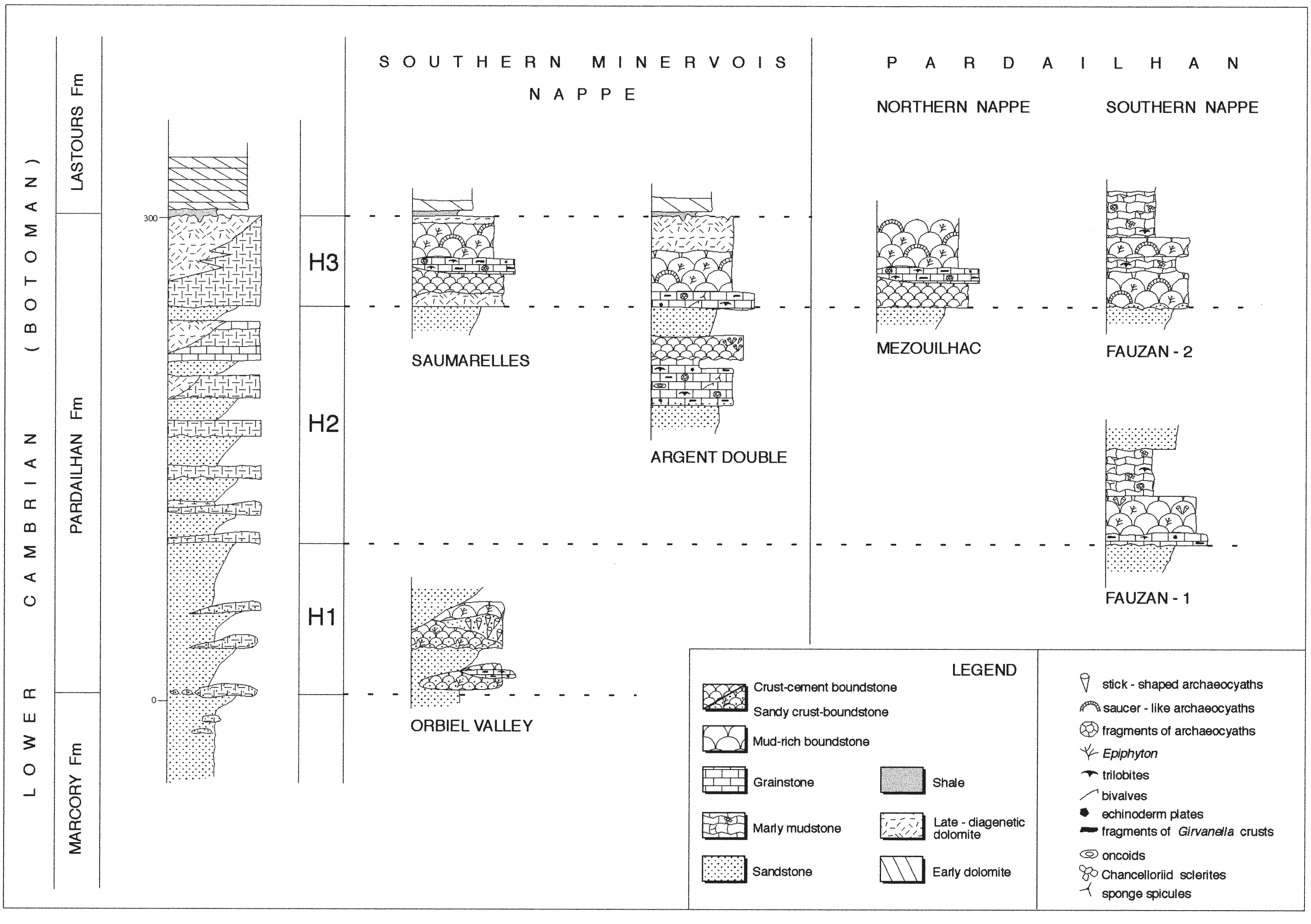
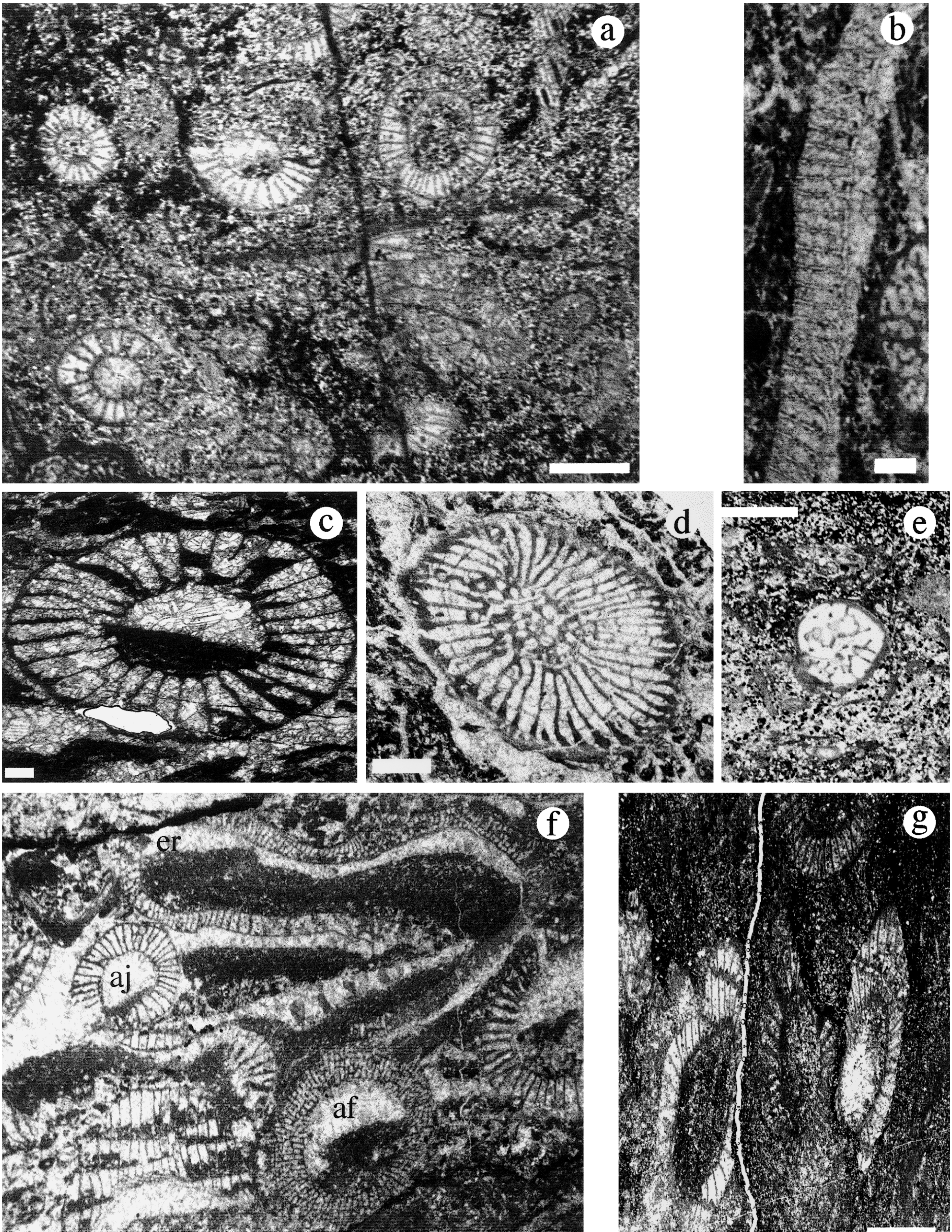


FIG. 2. – Pardailhan Fm : general stratigraphic log and regional distribution of the carbonate facies.
FIG. 2. – *Formation de Pardailhan : log stratigraphique général et répartition régionale des faciès carbonatés.*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of dark shale/siltstone or volcanoclastic material, seals underlying, poorly developed karst structures in southern Minervois [Courjault-Radé, 1988a].

H1 Interval **:** (up to 80 m) consists of grey-green, fine-grained sandstones with local low-angle cross-bedding, siltstones and irregularly interbedded, small carbonate lenses which gradually increase upwards in thickness and lateral extent. The small, convex carbonate lenses (up to 1 m thick and 2 m long) occurring at the very base of this unit are characterized by the abundance of fine quartz, mixed with the carbonate or concentrated in laminae and seams, and by the presence of archaeocyath clusters. In the upper part of the lenses the quartz content gradually decreases. Broken and corroded fragments (~1 to 2 cm large) of evidently displaced, small stick-shaped archaeocyaths, are often found concentrated within the calcareous nodules which form the tail of the lenses.

Upsection, the limestone bodies become larger and tabular. They consist of quartz-rich, pale-grey massive limestone, with small, often broken, stick-shaped cups of archaeocyaths, which upwards gradually evolve to pure, white-to-grey massive or finely laminated limestone, containing rare, scattered archaeocyaths.

The lowermost sandy lenses form a fairly continuous horizon only in the tectonic units of southern Minervois and northern Pardailhan, while they are lacking in southern Pardailhan [Boyer, 1962 ; Courjault-Radé, 1988a-b]. The upper ones are found irregularly interbedded within the siliciclastics in all the tectonic units. The archaeocyathan assemblages are more frequent in southern Minervois while in northern Minervois and northern Pardailhan they are randomly distributed.

The transition to the overlying H2 Interval is often cut by the Hercynian thrusts, and when not, it is marked by a thick (up to 100 m) exclusively detrital intercalation mostly composed of siltstone and fine-grained sandstone.

H2 Interval **:** (up to 100 m) consists of coarsening-upward sequences of shales, siltstone and fine-grained sandstone and quartzites, interbedded with increasingly thicker, tabular beds of pale-to-dark grey, massive pure limestone. In the lower part of this unit, cross-bedding is locally found in the sandstones. Relatively thick (up to 4 m, e.g. Argent-Double) bioclastic lenses or layers, occur at the base of the carbonate beds, still containing small amounts of fine-quartz. Upwards, finely laminated and massive facies prevail. The archaeocyaths, mostly concentrated as corroded fragments in the bioclastic facies, are found randomly scattered in the homogeneous ones.

This interval is thicker in the Minervois nappes; in the southern Pardailhan Nappe the basal, bioclastic layers are poorly developed.

H3 Interval **:** (up to 80 m) is a thick, laterally continuous limestone body, patchily affected by late diagenetic dolomitization. The archaeocyath-bearing facies occur in the upper part of the unit, 20-30 m below the top. The archaeocyaths are mainly represented by narrow ribbons of large and commonly well-preserved, saucer-like cups. The limestone lithofacies and the frequence and distribution of the archaeocyaths, vary in the different tectonic units :

– in northern Minervois, the pale-to-dark grey massive limestone contains in its lower part only rare isolated cups which however become more frequent towards the top;

– in southern Minervois, the massive carbonate body is often extensively dolomitized; only pale-to-dark grey lenses of pure limestone are preserved. They consist of homogeneous and bioclastic facies with few saucer-like cups;

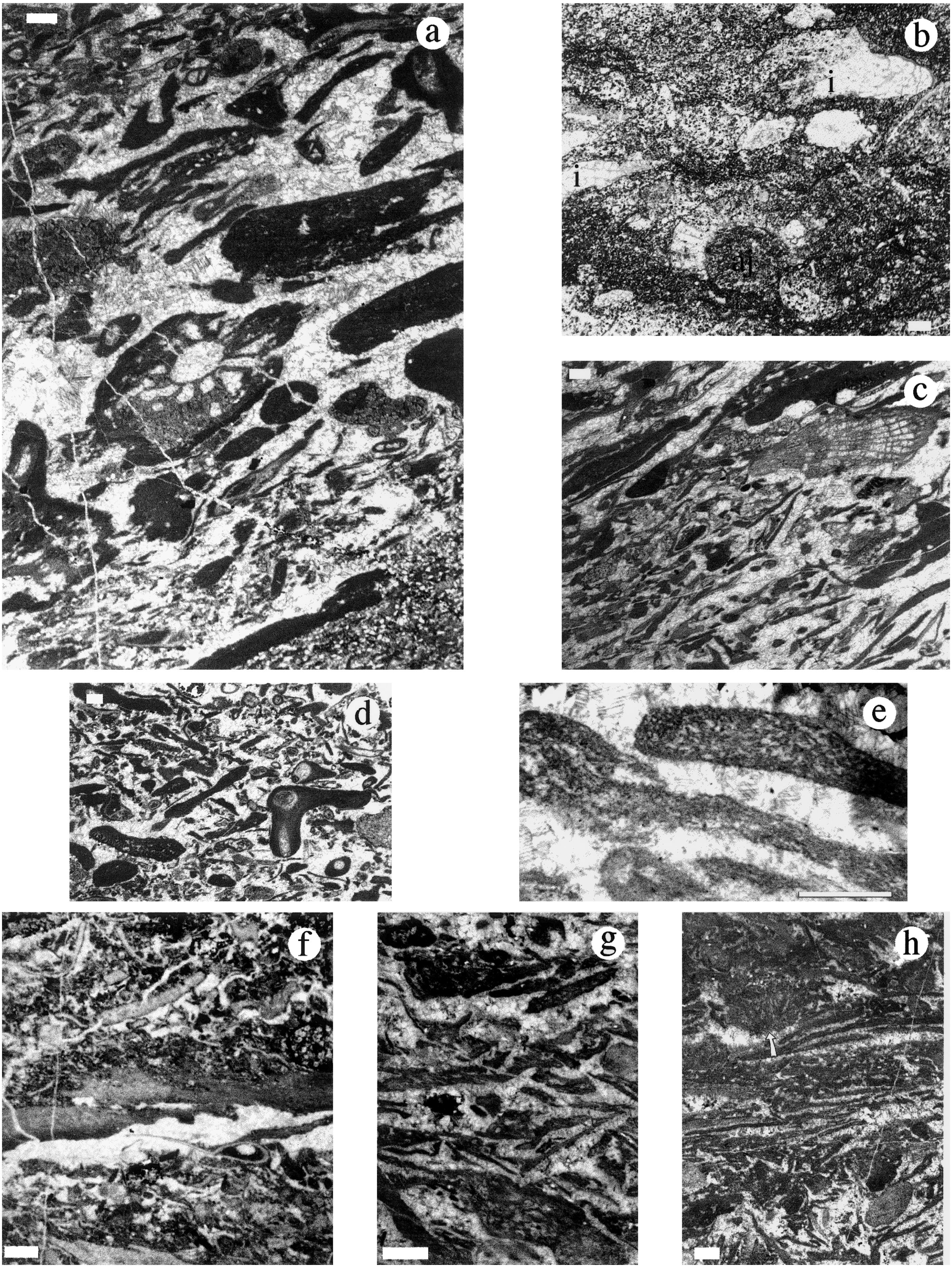
– in northern Pardailhan, the pale-grey massive limestone consisting of finely laminated and homogeneous facies, is associated with bioclastic lenses, and locally evolves to nodular facies. Archaeocyaths are commonly of small size and frequently broken ;

– in southern Pardailhan, marly, nodular limestones prevail and the massive, pure-limestone forms reduced interbeds. The fossiliferous facies occurs in the upper part of this interval only in the western part of the area. The archaeocyaths in the massive limestone are represented by large, isolated saucer-like cups, while in the nodular facies they are mostly bowl-shaped.

Microfacies description and interpretation

Detailed sedimentological/petrographic analyses have been carried out on the Pardailhan lithotypes, sampled in the

PLATE 1. – Repository of figured material : MNHN, Paris (Fr.)
Scale bar = 1 mm
Le matériel figuré est déposé au MNHN, Paris (Fr.)
Echelle = 1 mm
PL. 1a : cluster of *Inessocyathus* sp. in sandy matrix – Sallèles; H1;
1a : *groupe d'*Inessocyathus *sp. dans une matrice détritique – Sallèles; H1.* MNHM M84269, (MN12)
PL. 1b : fragment of ?*Anthomorpha* sp. in sandy matrix – Sallèles; H1.
1b : *fragment ? d'*Anthomorpha *sp. dans une matrice détritique – Sallèles; H1.* MNHN M 84270, (89-19)
PL. 1c : *Inessocyathus levis* DEBR. enclosed in calcimicrobial boundstone – Mézouilhac; H3.
1c : Inessocyathus levis *DEBR. inclus dans un boundstone calcimicrobien – Mézouilhac; H3.* MNHN M 84271, (89-88).
PL. 1d : basal part of *Anthomorpha margarita* BORN. with corroded walls – Argent-Double; H3.
1d : *partie basale d'*Anthomorpha margarita *BORN. avec murailles érodées – Argent-Double ; H3.* MNHN M 84272, (89-84).
PL. 1e : basal part of *Protopharetra* sp., with calcimicrobial coating – Moulin d'Artigues; H1.
1e : *partie basale de* Protopharetra *sp., avec enveloppe calcimicrobienne – Moulin d'Artigues; H1.* MNHN M 84273, (89-26).
PL. 1f : cluster of ribbon-like and conical cups of *Afiacyathus* cf. *alloiteaui* DEBR. (af), *Ajacicyathina* (aj) and *Erismacoscinina* (er); the cups are all oriented as shown by the geopetal infilling; the cements show faint traces of the original prismatic calcite – Argent-Double; H2.
1f : *groupe de calices en rubans et/ou coniques d'*Afiacyathus *cf.* alloiteaui *DEBR.* (af), *d'*Ajacicyathina (aj) *et d'*Erismacoscinina (er); l*es calices sont tous orientés dans le même sens comme le montre les remplissages géopétaux. Les ciments montrent de faibles traces de la calcite prismatique originelle; Argent-Double; H2.* MNHN M 84274, (89-77).
PL. 1g : cluster of *Retecoscinus boyeri* DEBR.; stretched cups in sandy matrix – Sallèles; H1.
1g : *groupe de* Retecoscinus boyeri *DEBR.*; *calices étirés dans une matrice détritique – Sallèles; H1.* MNHN M 84275, (89-02).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three statigraphic intervals and in the tectonic units (fig. 2) of :

– the southern Minervois Nappe – H1 at Moulin d'Artigues and Sallèles in the Orbiel Valley; H2 and H3 in Argent Double Valley; H3 at Saumarelles ;

– the southern Pardhailhan Nappe – H1 is not exposed; H2 (Fauzan 1) and H3 (Fauzan 2) on the western flank of the Cesse Gorge ;

– the northern Pardhailhan Nappe – H3 at Mézouillac.

The dominant carbonate facies are : sandy and pure limestones, mostly represented by calcimicrobial biolithites and bioclastic facies, and more or less nodular, marly limestones. Quartz-rich carbonates are found only in the lenticular bodies of the lower part of the H1 Interval and of the basal part of some of the tabular intercalations of Intervals H1, H2 and H3. The marly facies are exclusive of the H3 Interval in the Pardailhan Nappes.

General remarks

Since most of the studied sections of the Lower Cambrian successions are exposed either at the core of synforms or near the contact zone of nappes or faults, the dynamic inprint of the tectonic events on the lithotypes, is more evident in the massive, pure-carbonate facies.

The primary fabric of most of the carbonates under study is affected by recrystallization, selective or pervasive dolomitization and severe tectonic deformation. The interpretation of the protolith of the more deformed facies was achieved through the analysis of about 200 oriented thin-sections. Tectonic stress appears to be responsible for the general recrystallization of micrite into microsparite and/or pseudosparite, the deformation and twinning of the primary calcite cements, and extensive microfolding and shearing. Moreover, the tectonic boudinage of the thin calcareous layers included in the sandstones, often produced flake intraclasts, and microfolding resulted in calcite neoformation or selective dolomitizion in the fold cores which often mimic bioturbation, fenestrae or oncoids. A comparable deformational fabric has been observed in similar lithotypes of the Sardinian Lower Cambrian [Galassi and Gandin, 1992].

Grains and skeletons are often selectively or extensively replaced by idiotopic dolomite. Cements appear mostly as neomorphic mosaics of twinned blocky calcite, primary prismatic calcite is preserved only locally. The petrographic analysis of the calcite and dolomite mosaics suggest that dolomitization, pervasive recrystallization and twinning of the calcite, took place during or after the tectonic stress.

The skeletal remains show different kinds of preservation related to the primary fabric and mineralogy. The micritic skeletons of archaeocyaths, the finely prismatic exuviae of trilobites and the echinoderm plates mostly maintain their original texture but in some cases they also are replaced by neomorphic calcite or dolomite as commonly happens for the sponge spicules and the skeletal parts of chancelloriids. Moreover, the large skeletons of the archaeocyaths often appear stretched and deformed (pl. 1g) as a result of mechanical stress. Calcimicrobes also underwent processes of tectonic compaction, recrystallization and stretching (pl. 3e) so that their fabric is mostly represented by dense or clotted microsparite locally containing revealing ghosts of the original biogenic structures.

The quartz-rich facies

The microfacies include boundstone, clusters of archaeocyaths and wackestone/packstone. The detrital fraction consists of arkosic, fine-grained sand and silt the amount of which varies from 50 % of the volume of the matrix in the basal lenses, to a few scattered grains at the base of the tabular beds. Quartz grains are mostly angular but some of them are well rounded and often broken, suggesting a partial recycled derivation.

– *A-Sandy boundstone* consists of a calcimicrobial frame built by *Epiphyton* bushes and arched or straight *Girvanella* crusts (pl. 3a ; 4g). Archaeocyath cups are locally associated. The calcimicrobial crusts appear as dense microsparite in which sometimes it is possible to recognize ghosts of the primary fabric made of *Girvanella* filaments (pl. 2e). *Epiphyton* bushes (pl. 4g) are also found growing on the calcimicrobial crusts and on the archaeocyath cups, which are often encrusted by a microbial coating. Detrital material

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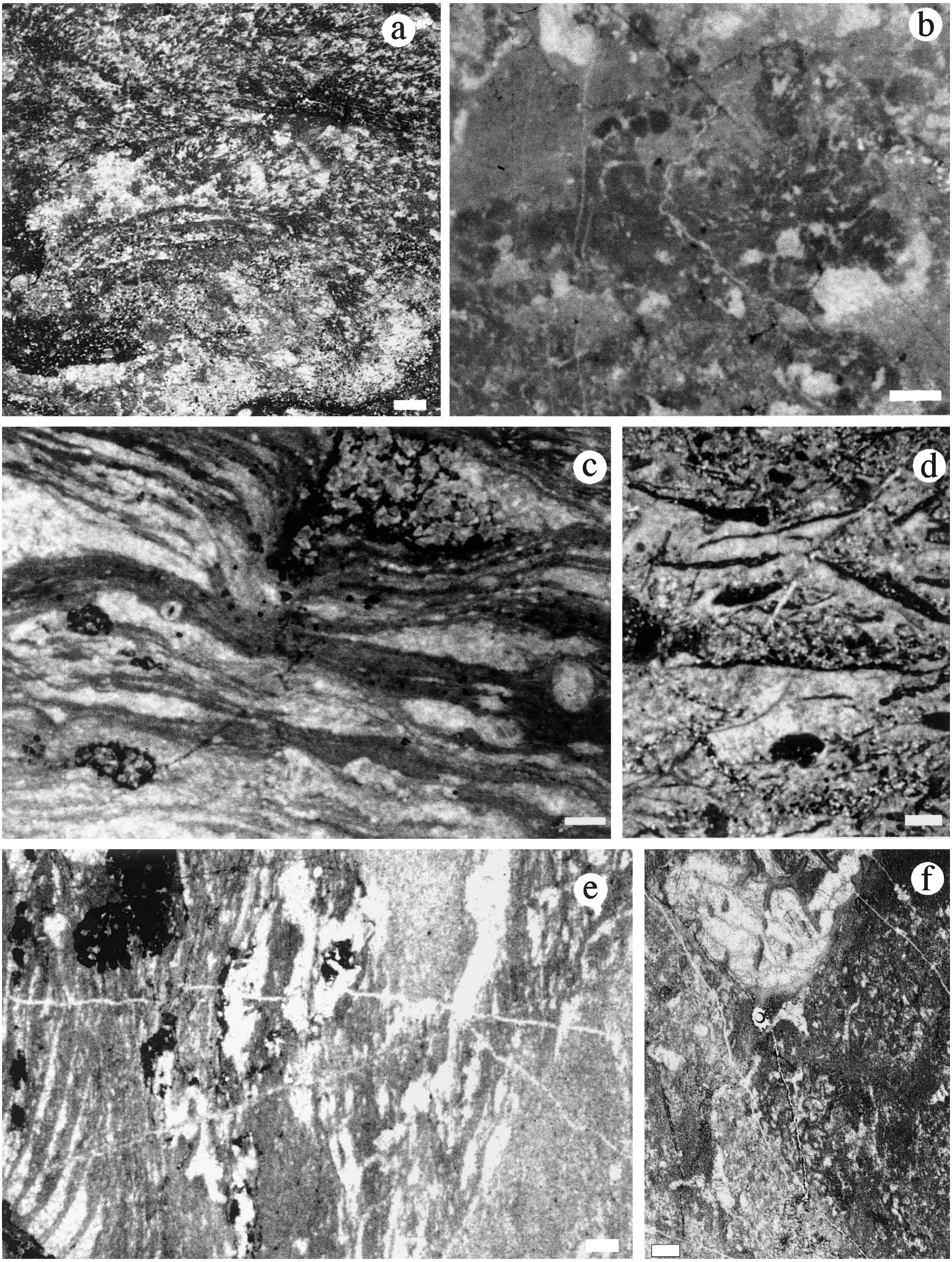
PLATE 2. – PL. 2a : unsorted crust grainstone, comprising archaeocyath debris and quartz grains, resting on sandy wackestone (lower right) – Argent-Double; H2.
2a : *grainstone en croûte mal trié, avec des débris d'archéocyathes et des grains de quartz, reposant sur un wackestone détritique (en bas, à droite) – Argent-Double; H2.* MNHN M 84276, (89-78).
PL. 2b : wackestone/floatstone with fragments of archaeocyath cups in sandy matrix. Longitudinal section of Irregulares (i) and transverse section of *Ajacicyathina* (aj) – Sallèles; H1.
2b : *wackestone/floatstone avec des fragments de calices d'archéocyathes dans une matrice détritique. Section longitudinale d'Irregulares (i) et section transversale d'*Ajacicyathina (aj) – *Sallèles; H1.* MNHN M 84277, (89-21).
PL. 2c : intraclast/bioclastic grainstone comprising coated bioclasts often infilled with brown-red mudstone and fragments of *Anthomorpha margarita* BORN. (basal longitudinal section); Fauzan 2; H3.
2c : *intraclaste/bioclastique grainstone avec bioclastes recouverts et souvent remplis de mudstone roux, et de fragments d'*Anthomorpha margarita *BORN. (section basale longitudinale); Fauzan 2*. H3; MNHN M 84278, (89-104).
PL. 2d : unsorted bioclastic grainstone with fragments of calcimicrobial crusts and coated bioclasts, and chancelloriid sclerites – Argent-Double; H2.
2d : *grainstone bioclastique non trié, avec des fragments de croûtes calcimicrobiennes, des bioclastes recouverts et des sclérites de chancelléridés – Argent-Double; H2.* MNHN M 84279, (89-76).
PL. 2e : well preserved *Girvanella* filaments in crust fragments; Moulin d'Artigues; H1.
2e : *filaments de* Girvanella *bien conservés dans les fragments de croûtes; Moulin d'Artigues; H1.* MNHN M 84280, (89-30).
PL. 2f : bioclastic grainstone stabilized by a calcimicrobial crust and associated shelter cement; Saumarelles; H3.
2f : *grainstone bioclastiques stabilisés par une croûte calcimicrobienne et par le ciment d'abri; Saumarelles; H3.* MNHN M 84281, (89-65A).
PL. 2g : unsorted grainstone consisting of fragments of *Girvanella* crusts; Moulin d'Artigues; H1.
2g : *grainstone non trié se composant de fragments de croûtes de Girvanella; Moulin d'Artigues; H1.* MNHN M 84282, (89-30).
PL. 2h : crust boundstone with Botomaella tufts (arrow), resting on bioclastic grainstone; Moulin d'Artigues; H1.
2h : *boundstone à croûtes avec des touffes de Botomaella (flèche), reposant sur le grainstone bioclastique; Moulin d'Artigues; H1.* MNHN M 84283, (89-35).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is always present entrapped in the calcimicrobial tissues or as a part of the matrix infilling the skeletal cavities. The poorly developed cements mostly occur in shelter- or flat-floored geopetal cavities.

– *B-Archaeocyath clusters* are composed of oriented, low-diversity assemblages of non modular, stick-shaped, small cups (diameter 2.5 mm ; mean size up to 6 mm), embedded in quartz-rich matrix. Regulares (pl. 1a) are dominant, represented by juveniles of *Ajacicyathina*, and by *Inessocyathus levis* (pl.1c), *Retecoscinus boyeri* (pl. 1g) or bowl shaped Erismacoscinina. Less frequent juvenile Irregulares (pl.1e), are associated with identifiable cups of *Dictyocyathus* sp., *Protopharetra circula*, rare, ribbon–like fragments of *Anthomorpha margarita* and some modular *Protopharetra* cf. *polymorpha*.

– *C-Wackestone/floatstone* consists of a terrigenous matrix containing carbonate grains represented by fragments of archaeocyaths (pl. 2b), calcimicrobial crusts, intraclasts and remains of trilobites, echinoderms, hyoliths, ?molluscs, ?lingulids. The assemblage of the displaced archaeocyaths reflects that of the clusters but with a lower number of individuals and diversity of taxa : small stick-like *Inessocyathus* sp., *Retecoscinus boyeri*, *Protopharetra circula*, *Anthomorpha* sp. (pl. 1b), bowl shaped Erismacoscinina, modular *Protopharetra* cf. *polymorpha* and rare ribbon-like forms.

– *Environmental conditions* – The small, low-relief biolithites made mainly by *Girvanella* and *Epiphyton* and low-diversity assemblages of small archaeocyaths, appear to represent the pioneer activity of organisms colonizing a detrital, mobile substrate. The small size of the calcimicrobial domes, the presence of in place clusters of archaeocyaths and the scarce occurrence of cements suggest a low-energy subtidal setting. The constant presence of detrital sand supports the proximity of an active fluvial system on land, implying a continuous supply of quartz sand during their growth. Similar *Girvanella*-archaeocyath assemblages have been reported from the Lower Cambrian of Sardinia [Debrenne *et al.*, 1989].

The pure-limestone biolithites

This facies includes two different types of calcimicrobial boundstone, and archaeocyath clusters :

– *D-Crust/cement boundstone* built by thin *Girvanella* crusts (pl. 3c) with sparse *Botomaella* tufts (pl. 2h), strengthened by well-developed marine cements. In the samples taken at the base of the tabular beds, quartz silt is frequently concentrated on the bottom of growth cavities (pl. 3d), or thin crusts are found resting on and stabilizing the grainstone facies (G-H ; pl. 2f).

– *E-Mud-rich boundstone* is built by dense frames of *Epiphyton*, and possible *Girvanella*, while *Renalcis* and archaeocyaths appear as minor contributors to the framework (pl. 3f ; 4c). It is commonly associated with the *I* mudstone which, together with poorly developed cements, also fills large shelter cavities, in part produced by saucer-like archaeocyaths (pl. 3b). The archaeocyaths are represented by frequent *Inessocyatus levis* (pl. 1c) and *Anthomorpha margarita* (pl. 1d, 4b). *Anthomorpha* is the dominant form, with non-modular, complete cups or large ribbon-like fragments, most of them affected by tectonic stretching. Smaller cups of Regulares and Irregulares, are

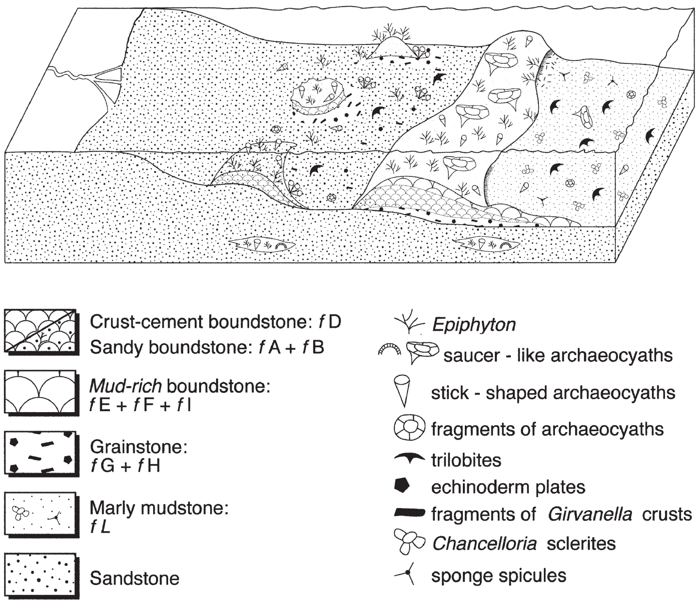
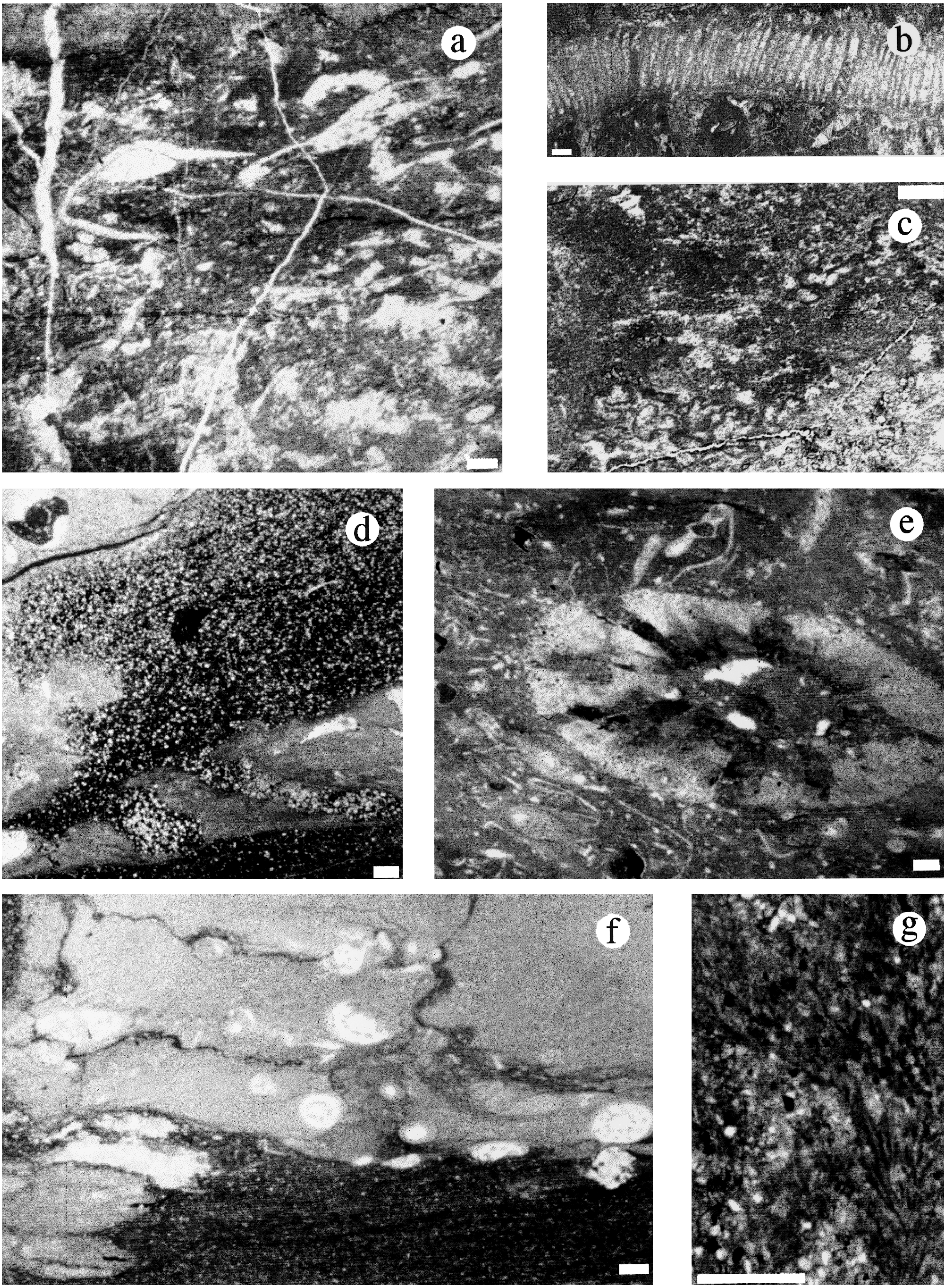


FIG. 3. – Reconstruction of the depositional setting of Pardailhan Fm, based on the sedimentary features of the carbonate facies.
FIG. 3. – *Reconstitution des environnements de dépôt de la formation de Pardailhan, basée sur les caractères sédimentaires des faciès carbonatés.*

PLATE 3. – PL. 3a : *Epiphyton* boundstone and associated arched, *Girvanella* crusts, form small lenticular bodies separated by quartz-rich seams; Sallèles; H1.
3a : Epiphyton *boundstone et croûtes arquées de* Girvanella *associées, formant de petits corps lenticulaires séparés par des pellicules riches en quartz; Sallèles; H1.* MNHN 84284, (89-01).
PL. 3b : *Epiphyton/Renalcis* boundstone with large cavities mostly filled by mudstone; cements are poorly developed; Argent-Double; H2.
3b : Epiphyton/Renalcis *boundstone avec de grandes cavités généralement remplies de mudstone; les ciments sont moins developpés; Argent-Double; H2.* MNHN M 84285, (MN11).
PL. 3c : crust boundstone with well developed cements; Sallèles; H1.
3c : *boundstone à croûtes avec ciments bien développés; Sallèles; H1.* MNHN M 84286, (89-16).
PL. 3d : crust boundstone with well developed cements and associated detrital silt; Moulin d'Artigues; H1.
3d : *boundstone à croûtes avec ciments bien développés et silt détritique associé; Moulin d'Artigues; H1.* MNHN M 84287, (89-33).
PL. 3e : deformed calcimicrobial boundstone with ghosts of *Epiphyton* and archaeocyath cup; Fauzan 1; H2.
3e : *boundstone à calcimicrobes déformé avec fantômes d'*Epiphyton *et calice d'archaeocyathe; Fauzan 1; H2.* MNHN M 84288, (89-41).
PL. 3f : *Renalcis* colony developed on a solitary archaeocyath cup; Fauzan 1; H2.
3f : *colonie de* Renalcis *croissant sur un calice d'archéocyathe solitaire; Fauzan 1; H2.* MNHN M 84289, (89e47).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often micritized and their identification is not possible. *Afiacyathus* is probably present with eroded outer walls.

– *F-Clusters of archaeocyaths* with geopetal infilling and well-developed cements which show traces of the primary prismatic structure (pl. 1f). The archaeocyath assemblage, composed of oriented, small cups (up to 50 mm in diameter) with generally micritized walls, is dominated by mushroom-shaped *Anthomorpha margarita* with long cylindrical cups evolving into larger cups with ribbon like intervallum (pl. 1f), associated to *Afiacyathus* cf. *alloiteaui*. This fauna is less diversified than that of the quartz-rich clusters and in this facies *Retecoscinus boyeri* is replaced by *Erismacoscinus* sp., and *Protopharetra circula* almost completely by *P. stipata.*

– *Environmental conditions* – The abundance of marine cements which reinforce the frail frame of the thin *Girvanella* crusts (D) and the archaeocyath clusters (F), indicates high energy conditions [James, 1981; Read and Pfeil, 1983]. The distribution of the archaeocyaths, seldom found in growth position, implies winnowing of the sediments by currents. Such conditions suggest that the builder organisms settled on and stabilized the loose substrate of a suitable topographic relief, either on top of the sandy buildups (A) or of small shoals made of bioclastic (G-H) or terrigenous sands. In contrast, the *Epiphyton*-dominated buildups, characterized by a high content of muddy internal sediments and by in-place, large *Anthomorpha* cups, are indicative of low-energy, deeper conditions [James and Gravestock, 1990]. Comparable mud-rich buildups occur in the Ceroide Limestone of Sardinia [Debrenne and Gandin, 1985].

The bioclastic facies

Two types of bioclastic grainstones can be distinguished on the ground of the nature and dominance of the allochems and the depositional characters of the associated sediments. Sorting is commonly poor and the allochem sizes vary from psammite to rudite (pl. 2a). The isopachous cements are rather well developed and preserved (pl. 2a ; c ; d ; e).

– *G-Platy grainstone* is almost exclusively made up of unsorted, angular fragments of *Girvanella* crusts (pl. 2e ; g) associated with rare fragments of *Epiphyton* bushes.

– *H-Bioclastic grainstone* consists of mixed grains deriving in part from the buildups, in part from the open sea. The former, commonly coated by micritic envelopes (pl. 2d), consists of abraded cups of archaeocyaths (pl. 1d ; 2a), flat *Girvanella* chips, *Epiphyton* bushes, and peloids, ooids and large oncoids often with archaeocyaths in the core. The sea-derived grains are chancelloriid sclerites, trilobites, echinoderms, hyoliths, probable molluscs, phosphatic lingulids, and mudstone intraclasts. The intraclasts are composed of the same reddish, marly mudstone which is also frequently found as the infilling of some bioclasts. A small amount of fine quartz grains (pl. 2a ; g) is locally enclosed in the fragments of calcimicrobial crusts or scattered among the allochems. Sometimes it is possible to observe the sharp transition from quartz-rich wackestone to well winnowed skeletal grainstone, locally showing normal or inverted grading (pl. 2a). The archaeocyaths are represented by the same forms found in the buildups : *Afiacyathus*, *Ajacicyathina, Erismacoscinina.* Irregulares are rarely observed except some *Protopharetra*-like forms and locally frequent fragments of ribbon-like *Anthomorpha*. The outer walls of the specimens are often missing, suggesting abrasion during transport.

– *Environmental conditions* – The platy-grainstone is the result of the accumulation of the products of the physiological breakup of the *Girvanella*-crust buildups (D), and their winnowing by waves or occasional storm currents. The association in facies H of bioclasts deriving from the buildups and of remains of organisms living on the muddy bottom of the open sea, suggests their transport and mixing by storm currents.

The lime-mudstones

The pure lime-mudstone is commonly associated with facies D. The marly facies are characteristic of well-bedded or nodular layers, interbedded with rusty-red dolomitic/silty marls or brown shales with few organic remains (pl. 4d ; f).

◄

PLATE 4. – PL. 4a : trilobite and sponge spicules wackestone associated with the mud-rich boundstone facies; Fauzan 1 ; H2.
4a : *wackestone à trilobite et spicules associés au faciès de boundstone riche en boue ; Fauzan 1 ; H2.* MNHN M 84290, (89-42).
PL. 4b : “ribbon” of *Anthomorpha margarita* BORN. enclosed in calcimicrobial boundstone; Fauzan 1 ; H2.
4b : *“ruban” d’*Anthomorpha margarita *BORN. inclus dans un boundstone calcimicrobien; Fauzan 1 ; H2.* MNHN M 84291, (89-59).
PL. 4c : *Renalcis* colony ; Fauzan 1 ; H2.
4c : *colonie de* Renalcis *; Fauzan 1 ; H2.* MNHN M 84289, (89-47).
PL. 4d : burrows filled with the overlying dolomitized shaly sediments, cross the marly mudstone containing small fragments of archaeocyaths ; Fauzan 2 ; H3.
4d : *les terriers remplis de sédiments argileux venant des dépôts dolomitisés sus-jacents, traversent les mudstones marneux contenant de petits fragments d’archéocyathes ; Fauzan 2 ; H3.* MNHN M 84292, (89-113).
PL. 4e : decorticated archaeocyath cup floated in marly wackestone containing sponge spicules, chancelloriid sclerites and hyolithids; Fauzan 2 ; H3.
4e : *calice flotté d’archéocyathe, dont la muraille externe est érodée, dans un wackestone marneux à spicules d’éponges, sclérites de chancelléridés et hyolithides; Fauzan 2.* H3 ; MNHN M 84293, (89-114).
PL. 4f : nodular marly mudstone with juvenile cups of archaeocyaths; Fauzan 2 ; H3.
4f : *mudstone marneux nodulaire avec des calices juvéniles d’archéocyathes ; Fauzan 2 ; H3.* MNHN M 84294, (89-111).
PL. 4g : *Epiphyton* bush and associated detrital fine sand; Sallèles ; H1.
4g : *buissons d’Epiphyton et sables détritiques fins ; Sallèles; H1.* MNHN M 84295, 89-01.

– *I-Pure mudstone/wackestone* contains sponge spicules, and sporadic, small fragments of lingulid phosphatic shells, trilobites, echinoderms and archaeocyaths (pl. 4a), sometimes coated with micritic envelopes.

– *L-Marly mudstone/wackestone/floatstone* contains variable amounts of silty quartz, mica flakes, pyrite, and brown pelitic intraclasts. The skeletal content is the same as in facies I, though sponge spicules and chancelloriid sclerites are more abundant. The intraskeletal cavities of chancelloriids and archaeocyaths (pl. 4e) are often filled with the same brown, pelitic sediment, different from the embedding one, which makes up pelitic interbeds and intraclasts. Bioturbation is frequent (pl.4d). Stylolites and pressure-solution seams parallel to the bedding, are marked by concentrations of iron oxides.

The archaeocyaths are often found in accumulations of juvenile forms (pl. 4f). The outer wall of the large cups of *Afiacyathus* is not preserved (pl. 4e) because of micritization, suggesting a prolonged lag of the cups in low-energy conditions, or because of erosion, suggesting dissolution, exhumation and abrasion during transport. Conversely the largest form (*Anthomorpha immanis*) is observed as a well preserved ribbon-like intervallum.

– *Environmental conditions* – the pure lime-mudstone facies represents carbonate muds deposited in a low energy, exclusively carbonate environment, adjacent to, or enclosed in the buildup system.

The marly facies (L), containing neritic faunas, represents open shelf, mixed carbonate/detritic muds, deposited below the fairweather wave base on a relatively well oxygenated bottom. The association of frequent remains of archaeocyaths and bioclasts coming from the buildups, and of intraclasts and often reworked, indigenous organisms, suggests that wave- or storm-induced currents, were responsible for the mixing of material ripped from the margins of the carbonate platform and from the muddy bottom of the shelf. The occurrence of the nodular fabric implies an early compaction of the sediments and rapid subsidence of the basin.

DISCUSSION

The mixed siliciclastic-carbonate succession of the Lower Cambrian, Pardailhan Formation exposed in the nappes of southern Montagne Noire, has been interpreted, on the ground of lithostratigraphic correlations, as deposited on a shallow shelf the proximal part of which corresponds to the Minervois Nappes and the more distal part to the southern Pardailhan Nappe [Courjault-Radé, 1988a,b]. The age of the whole archaeocyathan assemblage has been classically referred to the Botoman or possibly late Atdabanian-Botoman (Russian scale) by some authors and following the establishment of a western-Europe scale, to the terminal Ovetian [Alvaro *et al.*, 2001].

The results of the present sedimentological and paleontological investigation provide new data on the depositional conditions of the archaeocyath-bearing, carbonate intercalations of this unit. However, the lack of detailed correlations among the described outcrops, due to tectonic complexity and lack of biostratigraphic marker beds, prevents a wider paleogeographic interpretation.

The carbonate beds alternating with arkosic fine-grained sandstones (figs. 2 ; 3), record repeated attempts to establish a carbonate platform on a broad, gently sloping pericontinental shelf intermittently overrun by discharges of land-derived sands.

The quartz-rich, lenticular carbonate bodies, stratigraphically confined to H1 Interval, and diffused in all the tectonic units of southern Montagne Noire, represent the inception of the carbonate deposition on a broad, shallow shelf. Small domes built by *Girvanella/Epiphyton,* surrounded by small communities mainly composed of non-modular archaeocyaths, unsuccessfully tried to grow on the detrital bottom. The lateral extension of these bodies being rather reduced, and not always for tectonic reasons, it is likely that the pioneer activity of these organisms represents the stage of colonization of potential reefal communities that only later, when the detrital discharges became less frequent, found more favorable conditions for further development.

The carbonates of H2 Interval occurring in southern Minervois, and northern Pardailhan, and those of H3 Interval exposed in southern Minervois, represent increasingly lasting, carbonate deposition. The higher-energy buildups made by small domes of *Girvanella*-crusts and small clusters of archaeocyaths, settled at first on loose detrital sand, later prograded on their own aprons made of skeletal sands, forming small shoals on the margin of the incipient platforms. In the more protected deeper zones, mud-rich mounds built by *Epiphyton/Renalcis* communities and surrounded by lime mud, sheltered sparse saucer-like cups of *Anthomorpha margarita*.

H3 Interval records in southern Minervois the development of a thicker carbonate platform mostly built by the *Epiphyton/Renalcis* mud-rich mounds, which thinned out and prograded on the marly mudstones of the deeper basin of northern and southern Pardailhan. At the end of this interval the growth of the buildups suddendly ceased, probably as a consequence of emersion in the southern Minervois, proximal part of the platform [Courjault-Radé, 1988a,b] and of drowning in the more subsident northern and southern Pardailhan basin.

The archaeocyath fauna is characterized by two different, low diversity assemblages : the first one, found in the quartz-rich facies, is dominated by small, non modular, stick-shaped Regulares, often represented by juvenile forms, while the second one is represented by large, solitary saucer-like or bowl-shaped cups scattered within the pure, mud-rich mounds of the upper part of carbonate intercalations. Such ecologic features suggest stressed conditions that may have been caused in the first case, by the input of land-derived material – and possibly by the concomitant dilution of the sea water by the continental/meteoric fresh water – and in the second case by relatively deep, tranquil conditions [Wood *et al.*, 1993].

The installation, growth and progradation of the successive carbonate complexes was seemingly regulated by the duration of the breaks between the discharges, while their growth and progradation influenced the morphology of the platform which appears to have recurrently tried to evolve into a homoclinal ramp. Moreover, while the repeated input of clastics suggests a climatic component in the control of the discharges, their arkosic composition hints at a recently uplifted source terrain, hence at an active tensional tectonic regime which in the end may have been involved in the sudden demise of the buildups. An analogous depositional style appears to occur, though with slight diachronism, during the early Cambrian, throughout the tropical zone of the pericontinental shelf bounding western Gondwana [Courjault- Radé *et al*., 1992], as the result of the evolution of the continental rifting related to the Caledonian tectono-sedimentary cycle.

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