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GROWTH AND DIAGENESIS OF CRYPTALGAL-BRYOZOAN BUILDUPS WITHIN A MID-VISEAN (DINANTIAN) CYCLIC SEQUENCE, BELGIUM[1]

by

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(18 figures, 1 table and 1 appendix)

ABSTRACT.- Cryptalgal-bryozoan carbonate buildups are reported from the Middle Viséan (Upper Dinantian) near Namur, Belgium. They occur in a 20 m-thick, upward-shallowing, carbonate rhythm - the thickest in a succession of such rhythms.

The rhythm comprises three phases; from bottom to top: (1) packstones-grainstones with rich and diverse biota, indicating open, shallow marine conditions; grading to (2) wackestones, with a poorer and more restricted biota, passing upwards to cryptalgal boundstones; and (3) mudstones with highly restricted and reduced biota.

Small- to medium- sized mounds (2-11 m thick) occur at the top of Phase 2 where they established on coral thickets. The buildups consist of a meshwork of bryozoans encrusted by finely laminated cryptalgal coatings and encrusting bryozoans. Brachiopods, sponges and vermetid gastropods are also present. Voids were filled by internal sediments and early marine cements. The growth of the buildups was probably interrupted by a short-lived sea-level drop, recorded laterally as what seems to be a karstic surface. Vadose internal sedimentation and minor leaching by meteoric water occurred in the ?exposed buildups. Marine conditions were then restored and, at the beginning of Phase 3 deposition, coral thickets (with cryptalgal coatings) colonized the top of the largest buildup. Most remaining pore space was filled by burial cements. Other minor diagenetic processes include neomorphism, dolomitization, precipitation of Ca-sulphates and silicification.

KEY-WORDS.- Dinantian, Belgium, limestones, buildups, sedimentology, diagenesis, petrography, model.

RESUME.- Des constructions carbonatées («récifs») à matériau cryptalgaire et bryozoaires sont décrits dans le Viséen moyen (Dinantien supérieur) près de Namur, Belgique. Elles se sont développées au sein d'un rythme carbonaté puissant de 20 m, le plus épais de la série rythmique dans laquelle il s'observe.

Le rythme comprend trois phases; de bas en haut: (1) des *packstones-grainstones* avec un contenu biotique riche et diversifié, indicateur d'un milieu marin ouvert, peu profond; passant à (2) des *wackestones,* avec faune et flore plus pauvres et typiques de milieux plus restreints, passant vers le haut à des *boundstones* cryptalgaires; et (3) des *mudstones* avec un contenu biotique réduit et indicateur de conditions très restreintes.

Des monticules de taille petite à moyenne (2-11 m d'épaisseur) s'observent au sommet de la Phase 2 où ils se sont développés sur des buissons de coraux. Ces «récifs» sont constitués d'un réseau de bryozoaires entourés d'un manchon laminé de nature cryptalgaire et incrustés de bryozoaires encroûtants. Des brachiopodes, éponges et gastéropodes vermétiformes complètent cet assemblage. Les cavités résiduelles furent comblées de sédiments internes et de ciments marins précoces. La croissance des «récifs» fut probablement interrompue par une baisse temporaire du niveau de la mer, comme le suggère une surface

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interprétée comme d'origine karstique. Une sédimentation interne vadose et une légère dissolution par des eaux météoriques se produisit alors dans les «récifs» ?émergés. Après restauration des conditions marines, au début du dépôt de la Phase 3, des buissons de coraux (avec manchons cryptalgaires) colonisèrent le sommet du plus grand «récif». Durant l'enfouissement subséquent, la majeure partie des pores résiduels fut remplie par des ciments tardifs. D'autres aspects de l'évolution diagénétique des carbonates décrits sont le néomorphisme, la dolomitisation, la précipitation de sulfates calciques et la silicification.

MOTS-CLES.- Dinantien, Belgique, calcaires, «récifs», sédimentologie, diagenèse, pétrographie, modèle.

1.- INTRODUCTION

Cryptalgal-bryozoan buildups are rare in the Middle Viséan (Upper Dinantian) of Belgium and have never been previously recorded. Those described here occur at Namur on the northern limb of the Namur Syncline (Fig.1). They lie within a 20 m-thick carbonate «rhythm» (= cyclic sequence or cyclothem) included in a succession of pure limestones characterized by a well-developed minor cyclicity (Gérards & Michot, 1963; Hoyez, 1972; Paproth *et al.*, 1983, pp.199, 209 and 218).

Three main sections have been studied (Fig.1 and Appendix): (1) old quarries at Bomel; (2) recently abandoned quarries at St-Servais, some 700 m west of Bomel; and (3) river-side crags at Lives-sur-Meuse (subsequently referred to as Lives), 4.4 km east of Bomel. Two other sections were also examined briefly: (4) the old quarry of Fond d'Arquet, between St-Servais and Bomel; and (5) Vedrin, 2.6 km north of Bomel: a section described by Hennebert & Hance (1980). The buildups only occur at Bomel: the other sections expose lateral equivalents.

The present study concentrates on the sedimentology and faunal content of the buildups and the limestones in which they lie.

2.- RESEARCH METHODS

Conventional sedimentological analyses were performed on 394 standard thin sections (all stained with an acidified Alizarin red-S solution),

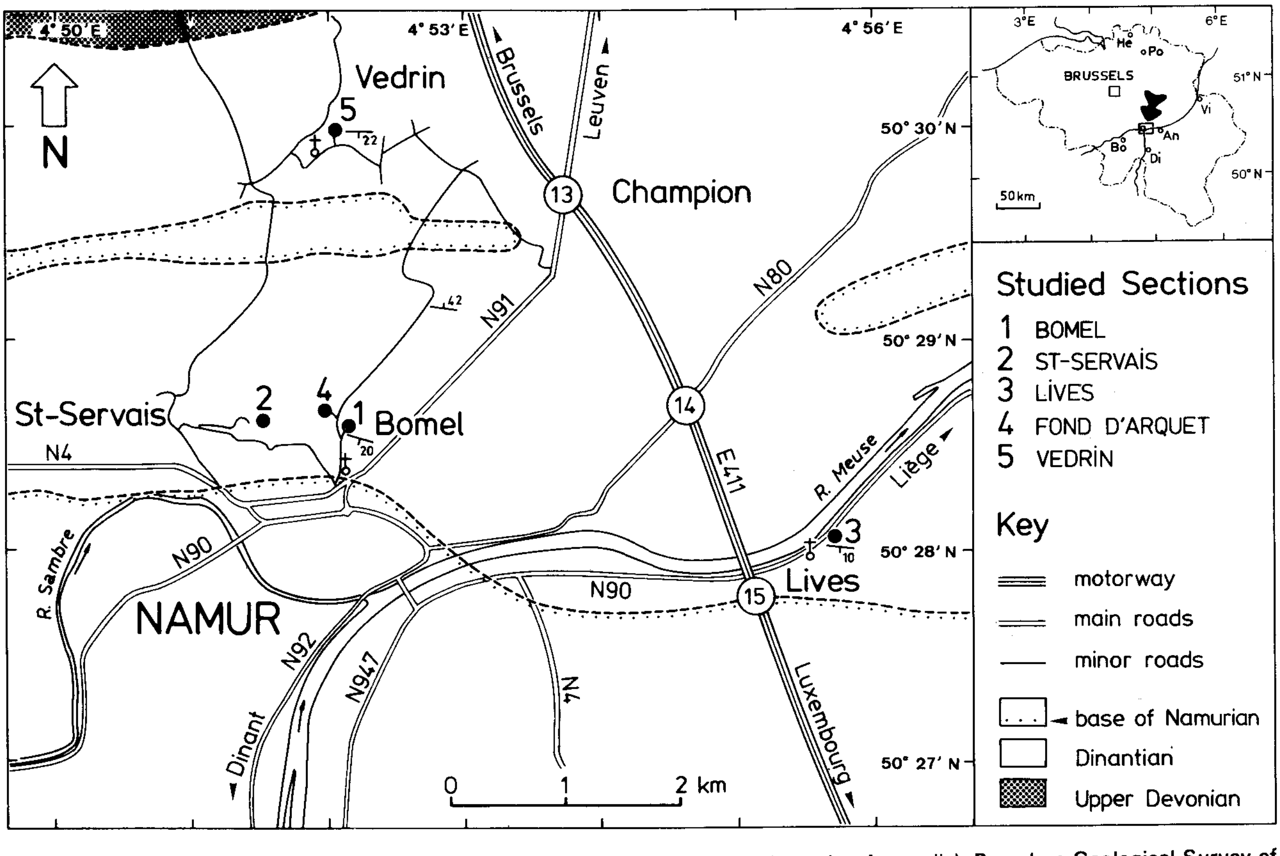


Fig. 1.- Geology of the Namur area with location of the five studied sections (see also Appendix). Based on Geological Survey of Belgium 1/40,000 maps, Sheets 144 and 155 (1901). Key to inset localities: An = Andenne, Bo = Bouffioulx, Di = Dinant, He = Heibaart, Po = Poederlee, Vi = Visé.

60 polished slabs and 16 acetate peels. Additionnaly, samples were selected for (1) cathodoluminescence (CL) microscopy; and (2) microanalysis, principally of the calcite cements, by electron microprobe.

Luminescent petrography was performed on 52 unstained, polished thin sections using a Technosyn Model 8200 Mk II cold cathode instrument mounted on a Nikon Optiphot research microscope with Microflex UFX photomicrographic attachment. Operating conditions were: 0.06-0.09 Torr (?) vacuum, 12-14 kV voltage, 600-700 μA beam current and 4 mm beam diameter.

Concentrations of Ca, Mg, Fe and Mn in calcite were determined on a Cameca Camebax Microbeam electron microprobe with four vertical spectrometers (Centre d'analyse par microsonde pour les Sciences de la Terre, Louvain-la-Neuve; Analyst: J. Wautier). For this purpose 12 polished thin sections were prepared and coated with a carbon film. Operating conditions included: 15 kV accelerating potential, 20-21 nA beam current and 10 s counting time. Electron-beam-induced decomposition of carbonates was reduced by microscanning each spot to be analyzed (spot size = 12.5 μm square; see Fig.15B). The standards employed were natural carbonate minerals: calcite, magnesite, siderite and rhodochrosite. For the Fe and Mn concentrations, only trends should be considered because several results showed values below detection limit. Presumably, the mean values reported here for these elements are slightly under-estimated.

3.- STRATIGRAPHIC SETTING

The buildups occur within the V2b (*sensu* Demanet, 1958), that is, in the lower part of the Livian stage of the Belgian Dinantian as defined by Conil, Groessens & Pirlet (1977). The V2b was divided into five stratigraphical units (V2bα-ε) by Gérards & Michot (1963) who also numbered each minor rhythm relative to the thickest one (V2bβ; 20 m) which was called Rhythm 0 (Fig.2). The buildups started to grow about half way through Rhythm 0.

4.- SEDIMENTARY EVOLUTION OF RHYTHM 0

4.1.- Field relationships

Like the other well-developed minor rhythms of the V2b, Rhythm 0 is characterized by two parts, a lower «zoogenic» part (Pirlet, 1968; Hoyez, 1972) and an upper «phytogenic» one. The former comprises dark, blue-grey, bioclastic calcarenites while the latter, which commonly starts with cryptalgal limestones, consists principally of dark, blue-grey calcilutites. These two components of V2b rhythms are easily recognized in the field because the bioclastic limestones weather dull grey while the calcilutites (often thinly bedded) weather pale. The contact between adjacent rhythms is always abrupt but the change from the «zoogenic» to the «phytogenic» part of a rhythm is often gradational and may occur in the same bed. The thickness of most rhythms ranges from one to several metres: the 20 m of Rhythm 0 is thus exceptional. A significant feature of the rhythms is their lateral extent. For example, Rhythm 0 has been traced from the Aachen region of western Germany through the Namur Syncline to the Boulonnais (northern France) and perhaps even to the Bristol area of southwest England (Hoyez, 1972; Conil & Naum, 1977). Over that distance, of at least 300 km, the rhythm apparently maintains most of its characters.

In the Namur area, Rhythm 0 (Fig.3) comprises about 10 m of platy, mainly micritic beds, 5-20 cm thick, overlying and sharply contrasting with a similar thickness of more massive bioclastic limestones in which bed thickness averages about 1 m but ranges up to 2 m.

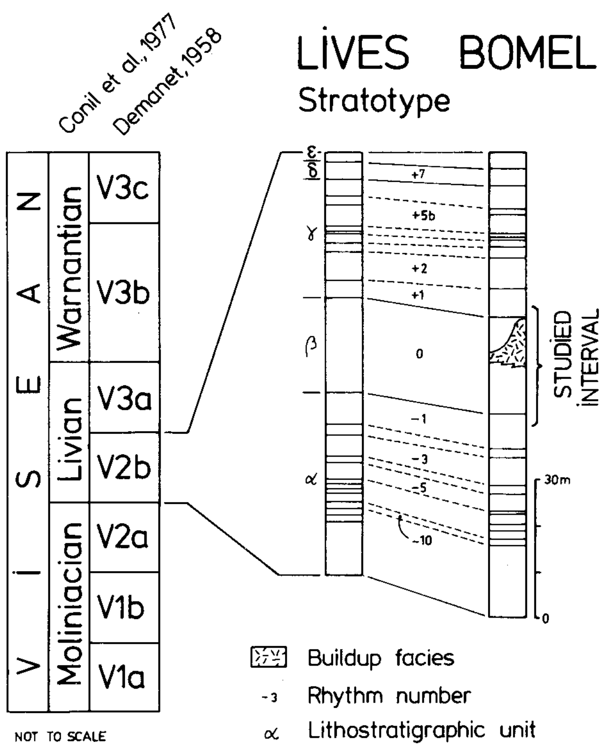


Fig. 2.- Stratigraphic setting of the studied interval. The Lives and Bomel sections correspond to Locations 3 and 1 in Fig.1, respectively. Note for comparison that the British Holkerian stage (George *et al.*, 1976) has the same stratigraphic range as the Belgian Livian.

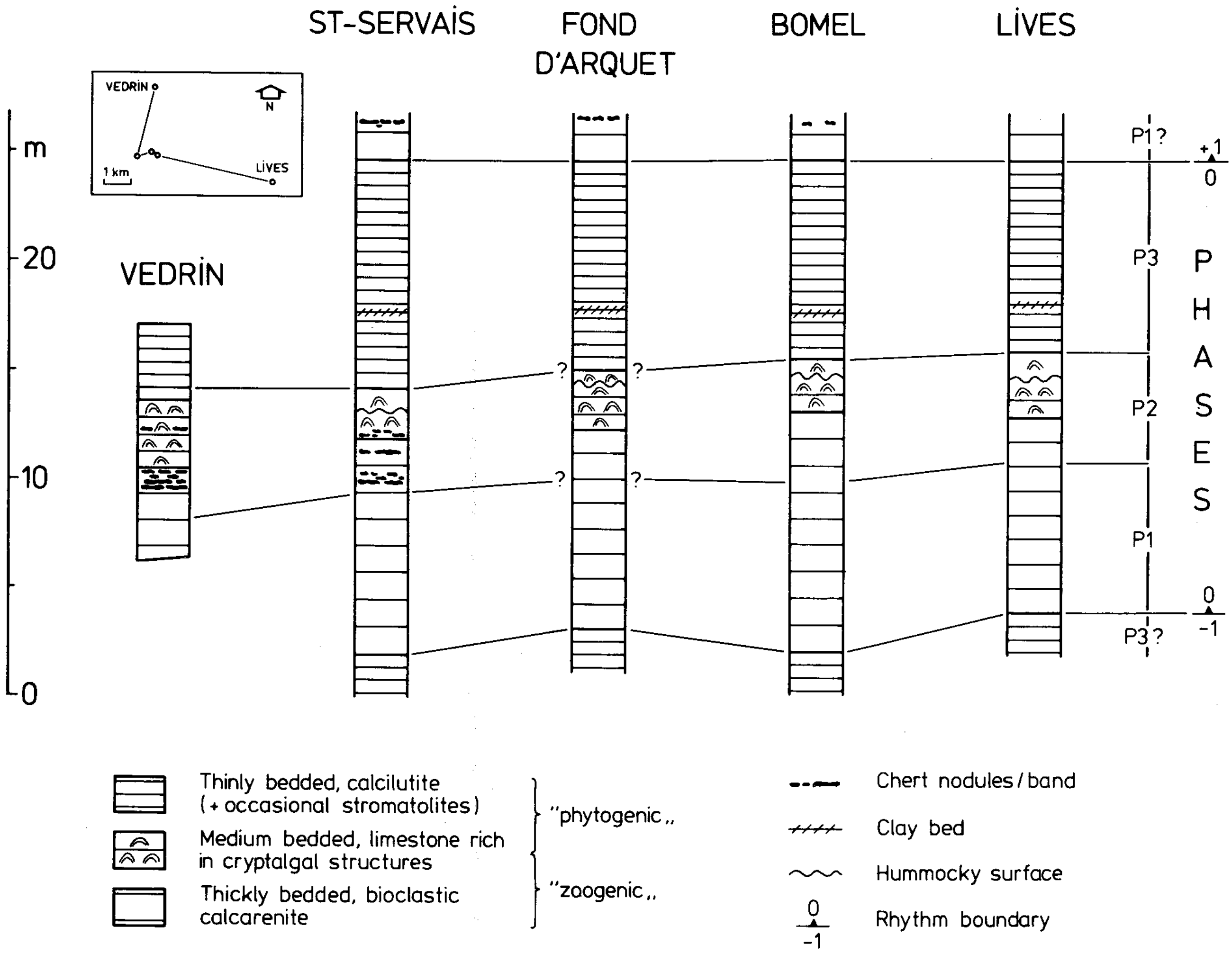


Fig. 3.- Simplified lithological sections through the studied interval. The Bomel section is taken at a point where there are no buildups. The Vedrin section is based on Hennebert & Hance (1980) and personal examination of their samples. The question marks in the Fond d'Arquet section result from lack of samples. See Fig.1 for location of sections.

There are two sharp breaks in the succession. The first of these is a *hummocky surface* (Fig.3) lying in the middle of the rhythm. The undulations have a mean wavelength of 10-15 cm and an amplitude of 2-8 cm (Fig.4). Although somewhat modified by stylolites, this surface does not seem to be exclusively of pressure solution origin, as evidenced by its smooth undulating form and its large lateral extent at constant stratigraphic level. The second interruption is a *clay bed,* 8-15 cm thick (Fig.3), with a very distinctive ochre colour. This bed has a heavy mineral association characterized by apatite and euhedral zircon which, together with the clay mineralogy as revealed by XRD (ordered mixed-layer illite-smectite) indicates a volcanic origin (Weaver, 1953, 1963; Thorez & Pirlet, 1979; Delcambre, 1983). These two interruptions can be traced the 5 km, from Lives to St-Servais, with only minor variation in character. The clay bed has been reported to have the same extension as Rhythm 0 (Hoyez, 1972; Conil & Naum, 1977; Thorez & Pirlet, 1979).

Black chert nodules (and rare thin bands) have been recorded in Rhythm 0 but only at St-Servais and Vedrin (Fig.3) where they are restricted to the lateral equivalents of the base of the buildups.

4.2.- Petrography

Compositional variation of Rhythm 0 in the neighbourhood of the buildups at Bomel is shown on Fig.5. The successions at Lives, St-Servais and Vedrin (Hennebert & Hance, 1980) have also been studied in detail and are very similar, although the last two sections do show some minor though significant differences from Bomel and Lives.

General evolution

Three phases (P1 to P3) have been distinguished within Rhythm 0 (Fig.5). They probably exist in the other rhythms because limited sampling has shown that the top of Rhythm -1 and the base of Rhythm +1 are very similar to P3 and P1 respectively.

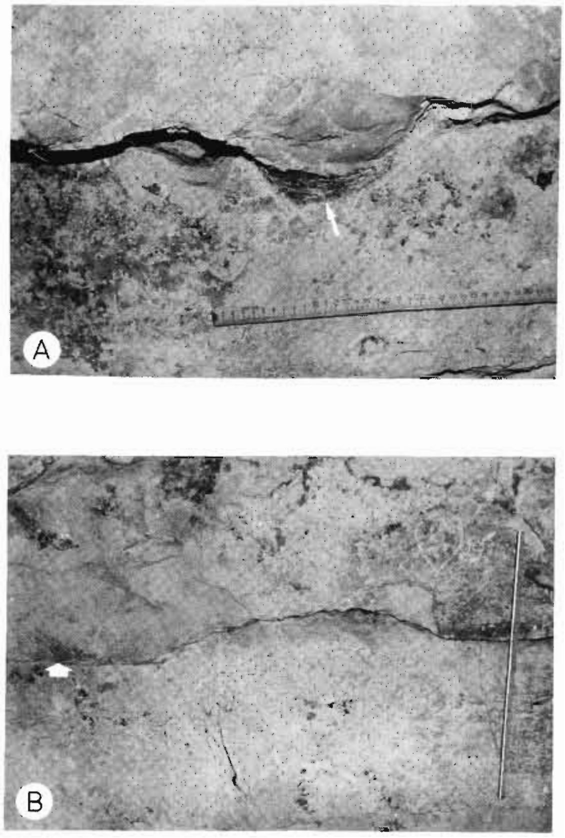


Fig. 4.- Vertical cross-sections through the hummocky surface at Lives. Note the mottled appearance of the cryptalgal limestone underlying the surface.
(A) Most common habit: small-scale undulation with dark shale filling the troughs (arrow). Scale in cm.
(B) Occasional habit: larger-scale undulation along which the small-scale undulations, like in (A), occur. Scale is 1 m long.

Phase 1 is characterized by packstones, and more rarely grainstones, rich in debris from a diversified marine fauna (Fig.5) in which moravamminids (organisms of uncertain affinity; see Fig.5 caption) dominate and echinoderms are important. The flora is much less developed. It is dominated by the assumed dasyclad *Koninckopora* (Wood, 1942; Deloffre, 1988), always fragmented, which is restricted to P1. Other indications of algal/bacterial activity are quite common in the form of «cryptalgal supra- and circum- crusts» and numerous bored grains. Small peloids commonly occur in P1.

Phase 2 is marked by a progressive decrease in skeletal debris accompanied by a shift from packstone-wackestone to wackestone. The moravamminids decline sharply in importance and molluscan debris becomes the dominant skeletal constituent. This phase also shows the successive upward disappearance of corals and echinoderms. Peloids are an important constituent in P2 whereas large peloids only become important in the upper part of this phase. *Koninckopora* disappears after the few first centimetres of P2 but cryptalgal structures, scarce in P1, become important in P2 and are very well developed in the upper half of the phase. «Stromatolites» and the unlaminated «cryptalgal pseudostromata» clearly dominate while «cryptalgal circumcrusts» are common. The cryptalgal facies are very heterogeneous : the amount in skeletal debris varies widely and the texture ranges from mudstone to grainstone and (commonly) to boundstone, even within a single sample. Associated with cryptalgal boundstones are numerous fenestrae, mostly irregularly shaped. The cryptalgal-bryozoan buildups occur in the upper part of P2.

Two thin but distinctive intervals are closely associated with the buildups. The first, 3-8 cm thick, immediately overlies the shaly fillings of the previously mentioned hummocky surface (Fig.4; HS in Fig.5). It is a packstone, with black shaly seams, characterized by the reappearance of a diversified and abundant fauna comprising tetracorals, tabulates, brachiopods, moravamminids, foraminifera, bryozoans, crinoids and trilobites as well as (crypt)algal structures (Fig.5). The second interval (CO in Fig.5), 4-6 cm thick, occurs at the top of P2 (capping Bed 22 in Bomel and its lateral equivalents in Fond d'Arquet and Lives) about 1 m above the hummocky surface. It is a coral packstone with foraminifera, shells and echinoids, all with (crypt)algal coats.

Phase 3 is much more micritic than the other phases and is dominated by mudstones. Most of the faunal components of the underlying phases have disappeared with the exception of ostracods which become the dominant biotic constituent. Isolated sponge spicules are quite commonly observed. In the field, about ten levels of bioclastic (echinoids and brachiopods) packstones-wackestones were recorded within P3 (not all shown on Fig.5 because not all were sampled). Peloids, large peloids and «other intraclasts» (see Fig.5 caption) are locally important and may even form very thin packstone to grainstone levels. Common, ovoid to rod-shaped large peloids, presumably of faecal origin, are particularly characteristic of P3 (and upper P2). Rare cryptalgal laminites have also been noted. Tubular fenestrae and predominantly horizontal burrows (*Chondrites*) are also very common.

Significantly, the passage from one phase to the next within the rhythm is always gradational: transitional zones often correspond to a single bed.

Figure 6, integrating the field and petrographic observations from the four sections studied in detail, shows the vertical trends for the major and/or more significant parameters in Rhythm 0.

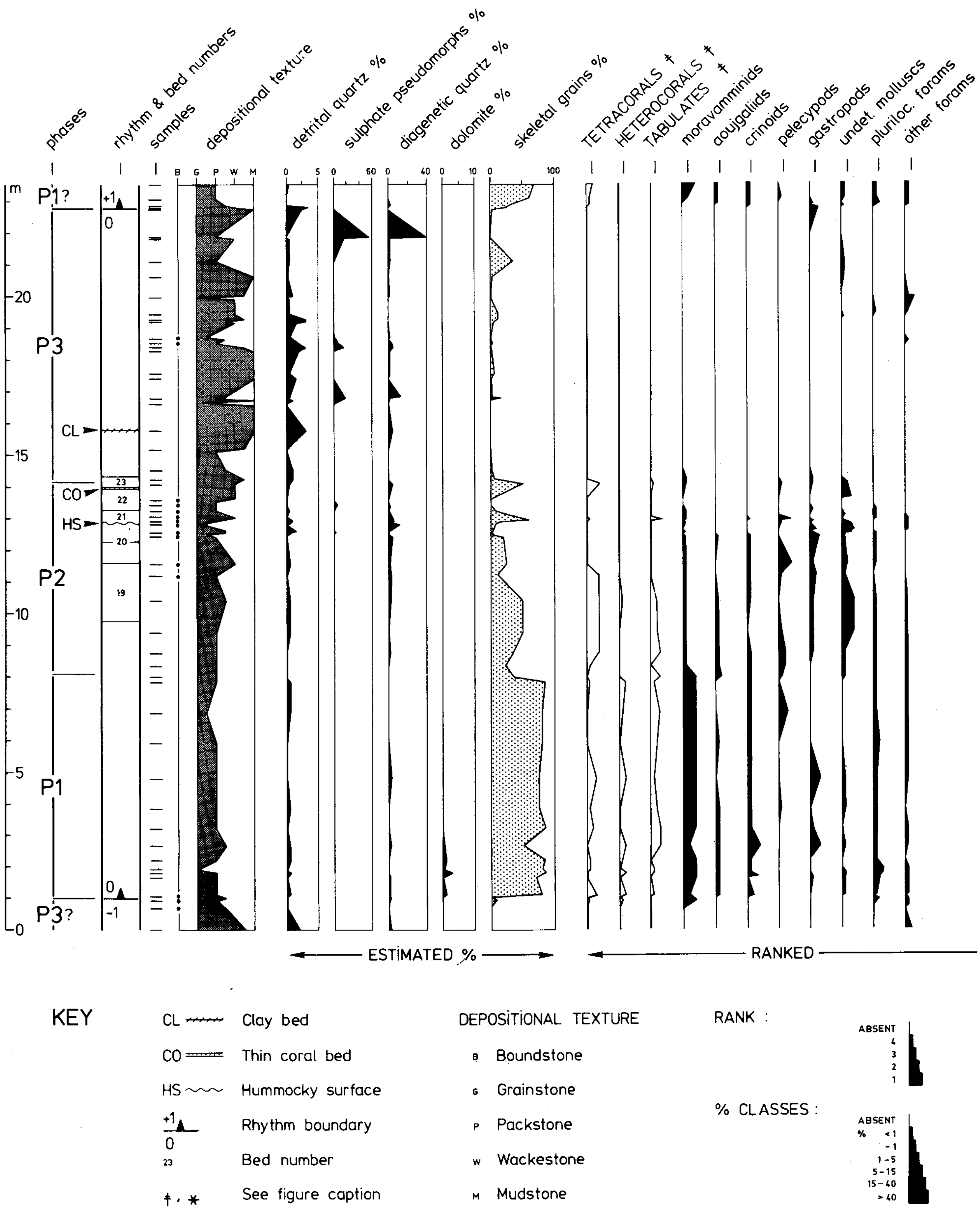
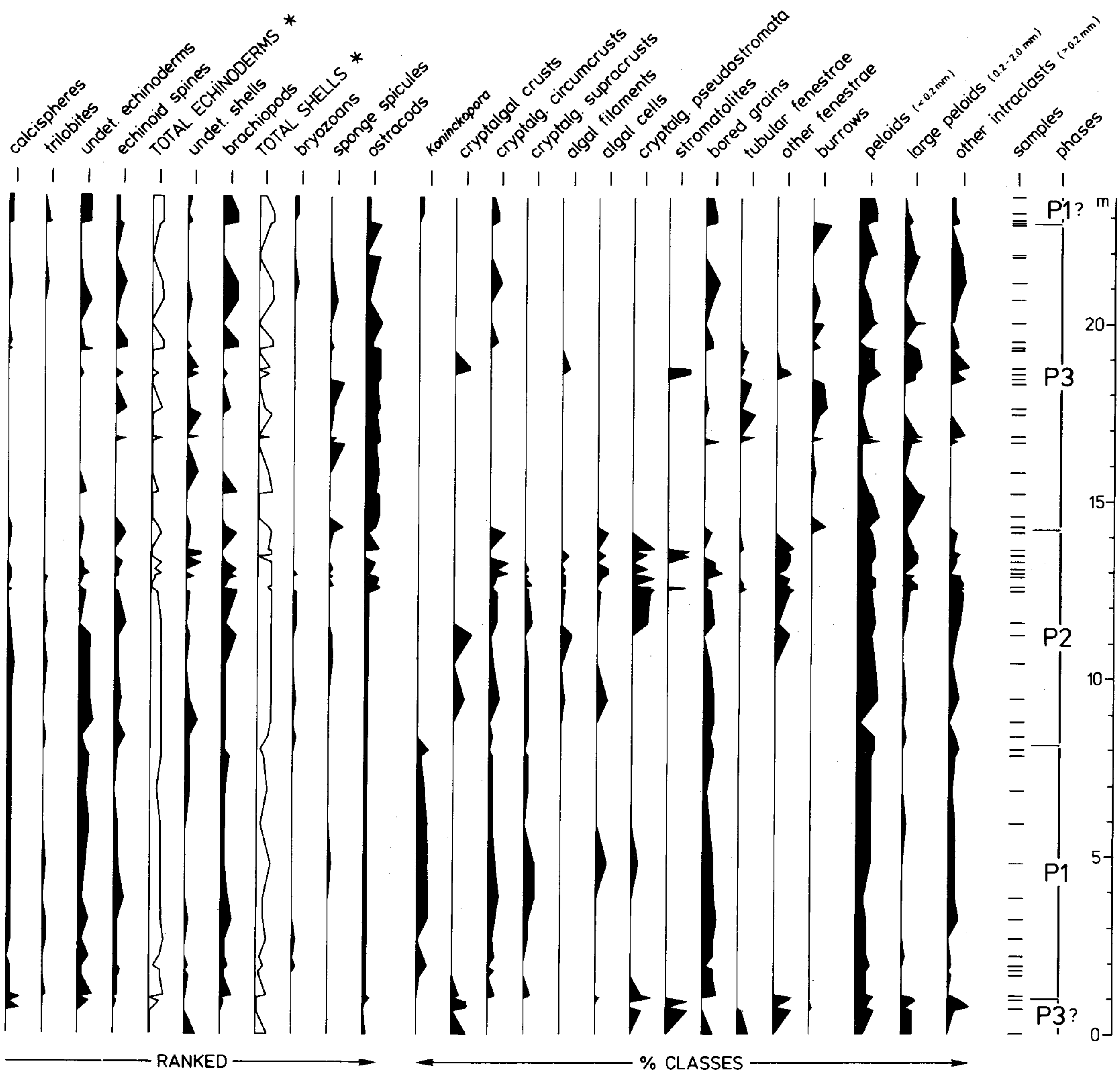


Fig. 5.- Petrographic log of the limestones in Bomel quarry, based on 68 thin sections from 60 samples.

Data are derived from visual estimates of the area occupied by the «component» in thin section (= volume in the rock). Three **systems of quantification** were used depending on the type of component; from left to right on the figure: (1) estimated % of total rock; (2) ranking scale; and (3) percentage class of total rock. Only the second method needs comment. It was used to estimate the relative importance of skeletal grains (excluding *Koninckopora*) disregarding the amount of matrix or cement. Following Lees & Hennebert (1982, p.28), the dominant component was coded as «1», the second most important as «2», etc. Rank 4 includes all other grains present but of lower rank than 3. All the components of the ranking system were ranked ignoring components labelled ǂ and *. During a second examination of the slides, the 3 coral groups (ǂ) were ranked relative to those previously assessed but, because of their large size (and therefore their possible poor representativity in thin section) the rank of the other components was not modified. Finally, the



slides were again examined and the component groups «Total echinoderm» and «Total shell» (labelled * on figure) were ranked taking into account neither the corals nor the grain types that they group. The columns labelled ‡ or * are left in outline to distinguish them from «normally» ranked components.

Only a few of the logged characters require commentary.

(1) The *depositional texture* is modified after Dunham (1962) in the sense that a composite texture has been assigned to rocks with small-scale heterogeneity: e.g. wackestone-packstone.

(2) *Skeletal grains* groups all the faunal skeletal components plus the dasyclad *Koninckopora.*

(3) *Moravamminids* and *aoujgaliids* are calcareous micro-organisms of uncertain affinity. Some authors (Termier, Termier & Vachard, 1977) considered them as hypercalcified sponges whereas others ranged them as dasyclad algae (see reviews by Roux, 1985 and Deloffre, 1988).

(4) *Other forams* includes all simple and tubular foraminifera without septa but excludes calcispheres which are logged separately.

(5) The term «*shell*» is restricted to brachiopod and mollusc grains.

(6) *(Crypt)algal structures* were named following Wolf (1965) except for the term «cryptalgal supracrusts». The latter has been coined for single micritic layers occurring only on the upper surface of loose grains. It is worth noting that following Wolf's definition, «cryptalgal circumcrusts» also includes surficially micritized grains.

(7) *Other fenestrae* groups irregular and laminoid fenestrae (Grover & Read, 1978).

(8) *Other intraclasts* refers to all intraclasts *sensu* Folk (1962) not classified as «large peloids».

Order of columns. Because many components occur throughout Rhythm 0, the columns could not be classed following a strict order of appearance within the rhythm. Rather, they were arranged from left to right approximately according to the degree of upward development or persistence in the rhythm.

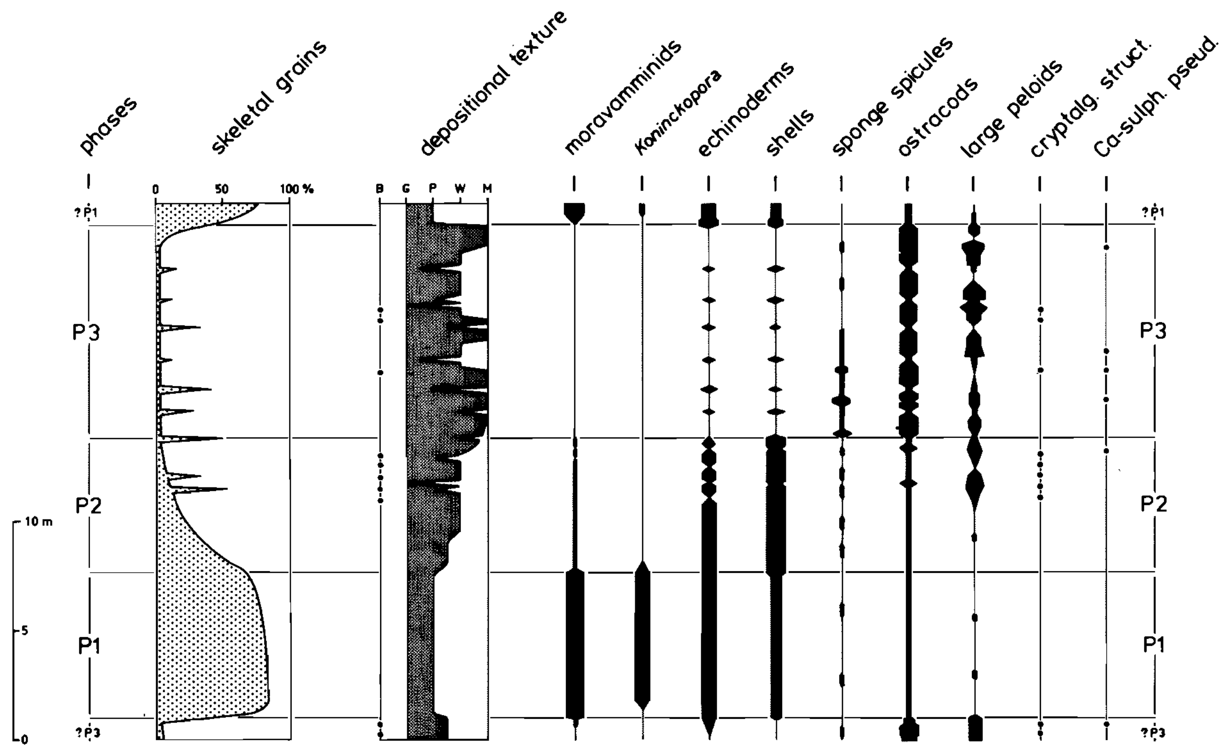


Fig. 6.- Summary petrographic log of the limestones from the studied interval. This general scheme, in which only the more characteristic components are figured, uses the data from Bomel (Fig.5) together with the results of similar analyses of the St-Servais, Lives, and Vedrin sections. «Components», quantification systems and scales are identical to those of Fig.5 though symmetric lay-out adopted here. Black dots indicate common occurrence of that parameter.

Phase correlations versus macroscopic ones

Despite some minor disagreement, correlations based on macroscopic lithological and paleontological criteria are similar to those based on the phases described above. The lower and upper limits of Rhythm 0 as defined by Gérards & Michot (1963) and Hoyez (1972) correspond exactly with the base of P1 and top of P3 respectively. However, the boundary between the «zoogenic» and «phytogenic» parts of Rhythm 0, defined by the same authors, does not correspond to any limit between phases based on petrographic criteria : it lies in the upper part of P2 (in the middle of Bed 20 at Bomel) i.e. 40-50 cm below the hummocky surface, where it is marked by a change in rock weathering colour from dark to light upwards.

5.- SETTING AND STRUCTURE OF THE BUILDUPS

Buildups have only been observed in Bomel quarries (Fig.7). Four or five coalescent *small buildups* occur in the middle of the west facing wall, and a *large buildup* is partially exposed on the eastern side of the road leading to the quarry (Fig.8). Stratigraphically, the buildups lie in the

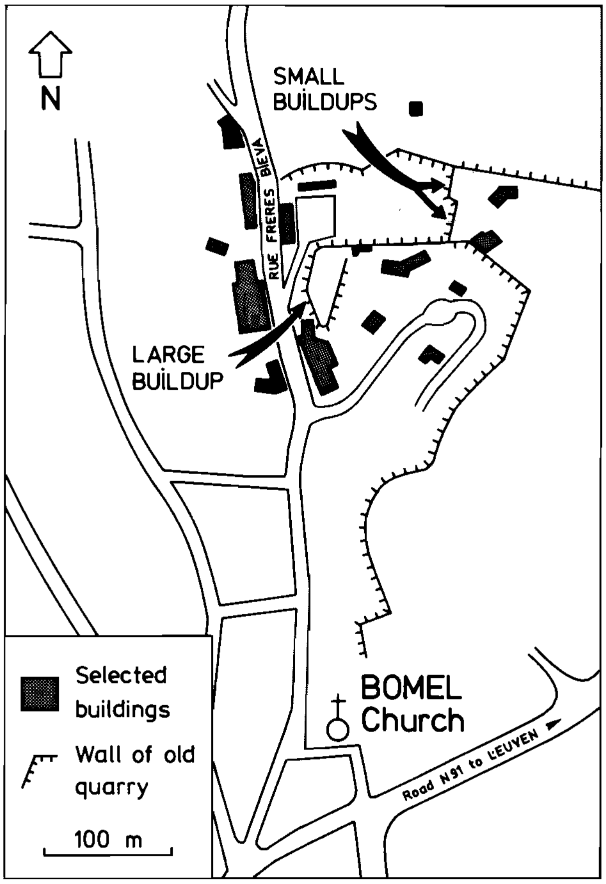


Fig. 7.- Map showing precise location of the studied buildups, north of Namur city centre (Fig.1).

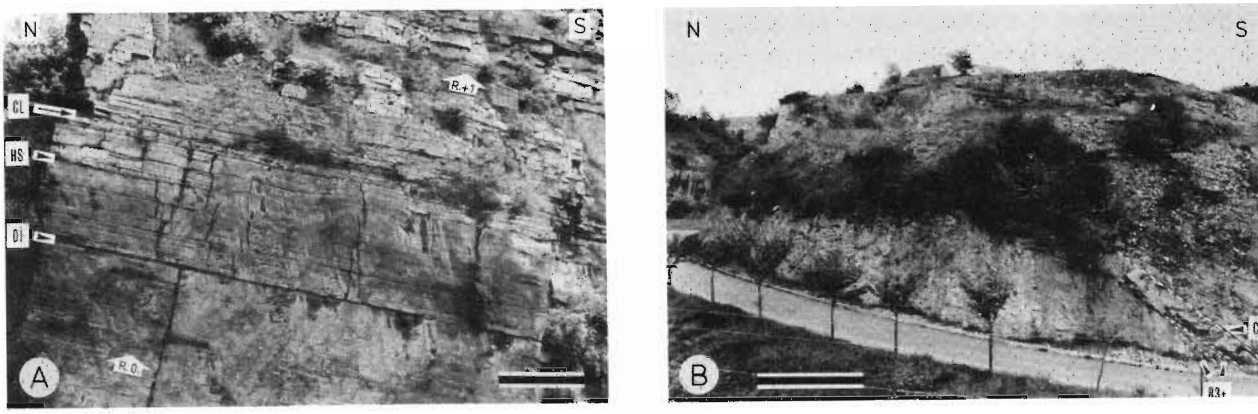
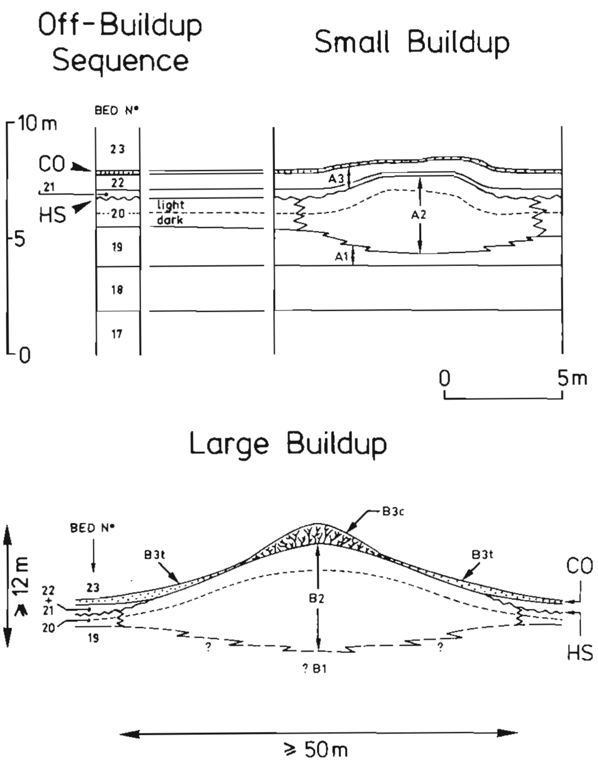


Fig. 8.- North-south cross-sections of the Bomel buildups. Scale bars = 5 m.

(A) East wall of old quarry showing small buildups in the middle of Rhythm 0 (large arrows indicate onset of Rhythms 0 and +1). The distinctive difference in weathering colour (see text) between the medium to thickly bedded calcarenites (lower half of rhythms) and the thinly bedded calcilutites (upper half of rhythms) is obvious. The contact between these two units in Rhythm 0 occurs in the middle of Bed 20, the lateral equivalent of the buildup cores. Two useful markers are indicated: the hummocky surface (HS) at the top of Bed 20 and the clay bed (CL) outlined by the vegetation. The prominent bedding plane - labelled DI- is a recent, laterally impersistent, dissolution feature.

(B) Recent road cut into the western side of the large buildup showing its massive core and talus of coral debris (B3t; outlined for clarity). CL indicates the clay marker bed already mentioned in (A). Note that upper left corner of (A) is visible in the background of this photograph (upper left).



A3	B3	Buildup cover (prior to deposition of Phase 3 muds) - c = coral cap; t = talus
A2	B2	Buildup core
A1	B1	Buildup foundation (inferred for B1)
CO		Coral debris bed
HS		Hummocky surface

Fig. 9.- General structure of the Bomel buildups as seen in cross-section (units defined in text). In the diagram of the large buildup, the thickness of the bioclastic talus and its lateral equivalents have been exaggerated for clarity. Otherwise there is no vertical exaggeration.

middle of Rhythm 0 near the top of Phase 2, i.e. in the transition zone between the «zoogenic» and «phytogenic» parts.

All the small buildups started growth in the same 1.80 m-thick bed (number 19, = A1 on Fig.9). Each one comprises a massive core (A2), dark coloured in the lower part and paler above, overlain by a 60 cm-thick stromatolitic cover (A3) which thickens to 1.20 m off the buildups. This is generally capped by a thin (4-6 cm) bed rich in broken corals (*Siphonodendron martini*; CO in Figs 5 and 9).

The base of the large buildup is not exposed, but field relations suggest that it started at a level similar, if not identical to the smaller ones (B1 on Fig.9). The massive core (B2) is overlain by coral (*S. martini*) thickets (B3c). The talus (B3t) observed on the southern flank of the large buildup was apparently derived from these thickets. It thins laterally and passes into the thin bed of broken corals mentioned above (CO in Figs 5 and 9). Detailed logging shows that the cores of the small buildups (A2) lie at the same stratigraphic level as that of the large one (B2). However, A3 must wedge out towards the large buildup as it has never been found at the top of B2.

The dimensions of the cores of the small buildups range from 4 to 8 m across and from 2 to 3 m high. In the large buildup, the core is more than 50 m across and at least 8 m thick. The thickness ratio of buildup (core) to its lateral equivalents (Bed 20 in Bomel = 1.20 m) ranges from 1.5 : 1 to 2.5 : 1 for the small buildups and up to 7 : 1 for the large buildup. The size of the buildups shows a marked increase from north to south, suggesting the existence of a small buildup complex. If the total thickness of the large buildup is considered (B2 + B3c = 10-11 m), its top appears to lie at the level of the base of Rhythm +1. The whole of Phase 3 must therefore wedge out against the buildup.

The north-south cross-sections show that the buildups are mound-shaped and have gentle slopes. Assuming no differential compaction, and taking into account the regional tectonic tilting, a paleoslope of 20° has been calculated for the southern flank of the large buildup. The only west-east section available tends to indicate that the buildups are domes rather than ridges.

6.- SEDIMENTOLOGY OF THE BUILDUPS AND ASSOCIATED UNITS

6.1.- The foundation of the buildups (A1 and ?B1)

The limestones immediately below the buildups are medium bedded calcarenites-calcirudites, with a packstone to wackestone texture. They have a rich brachiopod and coral macrofauna at the base and increasing amounts of laminated (presumably algal) encrustations upwards. The corals, mainly *S. martini*, occur either as thick accumulations of debris or, immediately under the buildups, as clustered colonies, about 35 cm high, with flat tops.

Away from the buildups, at St-Servais and Lives, the lateral equivalents of A1 contain scarce coral debris at the base and an increasing amount of cryptalgal material towards the top. At St-Servais, columnar thrombolites (Aitken, 1967) and numerous black chert nodules have also been noted at this level (Fig.3).

6.2.- The core of the buildups (A2 and B2)

6.2.1.- General description

Because of the difficulty of sampling the small buildups (high up on a vertical quarry face), the following description is based mainly on data from the large buildup (B2). The cores of the small buildups and the large buildup have about the same composition but pecularities of the former will be given after the general description.

The rock is composed of fenestellid and ramose bryozoans encrusted by laminated micritic cryptalgal coats (readily visible on polished slabs, Fig.10). These encrusted organisms formed a network within which bioclastic peloidal or micritic sediment accumulated. Remaining cavities (from several millimetres to 4-5 cm across) were filled by cements and internal sediments.

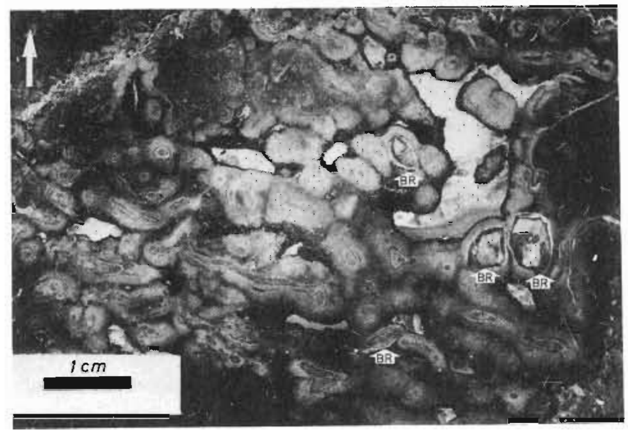


Fig. 10.- The core facies of the Bomel large buildup, showing ramose bryozoans with cryptalgal coatings (medium to light grey). Some brachiopods (BR) are also bound into the framework. Cavity fillings display the major diagenetic phases, namely an early layer of fibrous calcite (dark rim), overlain in some cases by a ?vadose crystal silt (Internal sediment B; light grey) and a final filling of coarse blocky calcite (white). Polished slab in specimen N°AL124. Large arrow points to stratigraphic top.

Numerous complete brachiopods occur in the buildup core (Fig.10): their genus is unknown but a typical feature is their tiny size (diameter rarely exceeding 10 mm and commonly around 5 mm). Towards the top of the large buildup (B2), there are scarce solitary and tabulate corals.

Nature of the biolithite network. The main skeletal meshwork comprises ramose rhabdomesid bryozoans (Fig.11A) or fenestellid bryozoan fronds (probably in growth position; Fig.11B) encrusted by ?algae, by encrusting bryozoans or sometimes by both alternately. Vermetid gastropods, generally prostrate but sometimes erect, are commonly attached to the bryozoan or the cryptalgal encrustations. The whole assemblage may be encrusted by another cryptalgal coat. Other encrusted organisms include very common, small brachiopods, quite common non-vermetid gastropods, and rare moravamminids, solitary tetracorals and colonial tabulates. Clusters of sponge spicules occur, probably representing individuals living or caught in the meshwork. The faunal constituents of the buildups are constant in character and low in diversity and, with the notable exception of the bryozoans, are rather similar to those of the lateral equivalents (top of Phase 2; Fig.5).

Volumetrically, the buildup-rock is dominated by cryptalgal encrustations (Fig.12). Cryptalgal structures increase in importance relative to other organisms upwards through the large buildup. The algal/bacterial communities clearly played an important rôle in stabilizing the buildups. This is most evident in the small buildups where whole organisms, especially bryozoans, are scarcer than in the large buildup. Recognizable algal filaments

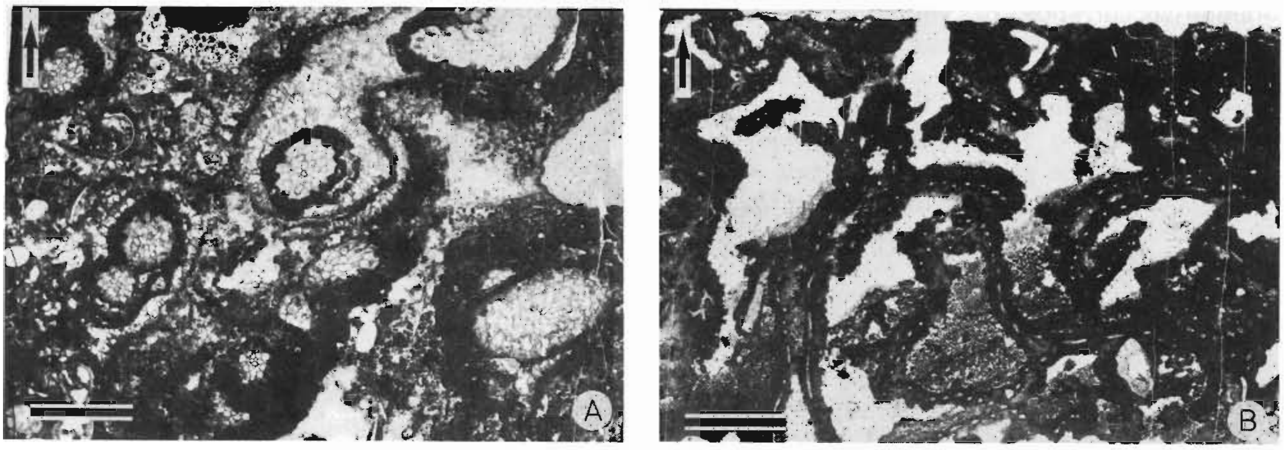


Fig. 11.- Photomicrographs showing two aspects of the core facies in the Bomel large buildup. Large arrows point to stratigraphic top. Plane light.

(A) Detail of sample shown in Fig.10, showing ramose bryozoans alternately coated by encrusting bryozoans and dark, micritic, cryptalgal layers. Note peloidal nature (with some bioclasts) of the internal sediment filling most of remaining voids within the boundstone. Scale bar = 200 μm. Thin section in specimen N°AL124.

(B) Boundstone showing a network of fenestellid bryozoans with cryptalgal coatings. Note numerous irregular fenestrae mostly filled with Internal sediments A (dark, with peloidal texture) and B (light grey), and late blocky calcite (white). Scale bar = 500 μm. Thin section in specimen N°AL237B.

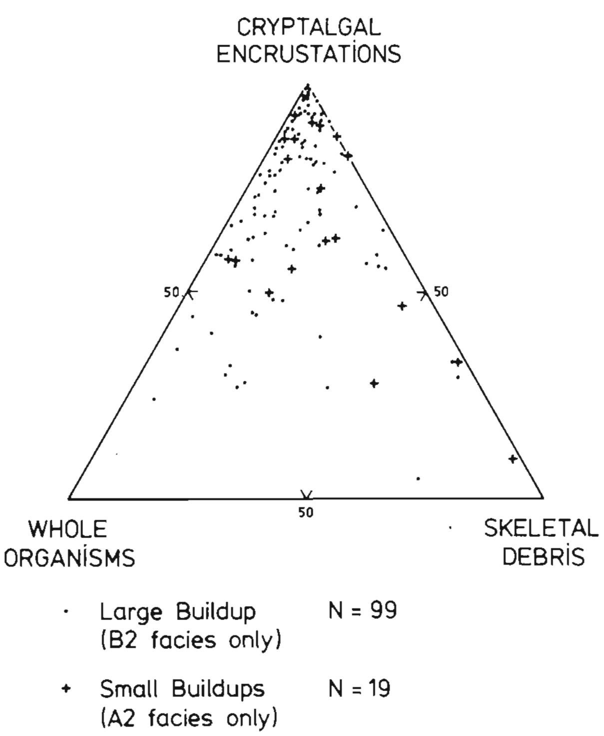


Fig. 12.- Compositional spectrum of the core facies of the Bomel buildups. Most of the «whole organisms» are inferred to be in growth position. Method. Percentage estimates by visual inspection of thin section. Seven parameters estimated; % recalculated on α 100% basis for the three -generally dominant- figured parameters. N refers to the number of thin sections studied.

or cells are uncommon in the «cryptalgal encrustations», so an algal origin is inferred mainly from the nature of the structures which rarely have a peloidal texture. The delicacy of the encrustations suggests microbial/bacterial communities may also have contributed (perhaps to a large extent) to the accretion. The encrustations comprise micritic laminae from 20 to 200 μm or even 400 μm thick. They are arranged concentrically around the encrusted organism to form a «casing» with a mean diameter of 3 to 10 mm and an observed maximum of 3 cm (Figs 10 and 11A). Individual laminae are often delimited by thin, dark micritic layers and, occasionally, by limonitic films. Dark tubules in the laminae are interpreted as algal filament molds, without any generic identification. Widespread (but minor in volume) «algal cells» within the laminae are attributed to *Sphaeroporella* which Mamet & Roux (1975) assigned to the green algae (?) *incertae sedis* (A. Roux, written comm., 1986).

A clear, microsparitic texture commonly occurs within the cryptalgal laminae. This is interpreted as a probable «microbial spar» in the sense of Monty (1982) who reported sparry cements that developed in close association with microbial, bacterial and blue-green algal communities of Devonian to Recent age. Some laminae also display a fibrous texture, brownish in colour, which may be a cement of similar origin (see also Van Laer & Monty, 1984). There are two reasons for believing that these textures are early-formed precipitates (cements) or possibly their recrystallization products rather than neomorphosed micrite: (1) thin micritic laminae (average = 40 μm) alternate with layers of microfibrous spar with the fibres normal to the laminae; and (2) fenestellid fronds, ramose bryozoans and more rarely brachiopods and crinoids, are often coated by a microsparitic layer which is itself encrusted. These textures are always separated from the true early fibrous cements (see below) by a micritic layer. The presence of these cements, together with the common occurrence of vermetid gastropods attached to the laminated coats, suggests that the cryptalgal structures were at least firm and cohesive if not lithified during sedimentation (Burchette & Riding, 1977). The ?algae must thus have played a rôle of prime importance in the building and stabilizing of the mounds. This would help to explain the absence of talus derived from the buildup cores.

Other cryptalgal encrustations present are more typical stromatolites, commonly stratiform (sometimes vertical -? coating fissures) with occasional hemispherical masses about 10 cm across. Small nodules and crusts of *Ortonella* have also been observed.

Synsedimentary filling of the voids. During the formation of the buildups, most voids were filled by muddy sediment (generally packstones, more rarely grainstones or wackestones) often rich in skeletal debris, intraclasts and peloids. Most of the skeletal material is broken shell (mainly brachiopods, some molluscs) and echinoderm debris (abundant echinoids and scarcer small crinoids). Ostracods and sponge spicules also occur but corals, aoujgaliids, *Koninckopora* and foraminifera are rare, and trilobites absent.

6.2.2.- Special features of the small buildups

The small buildups differ somewhat from their large neighbour by the abundance and type of cryptalgal structures. The former are richer in stromatolitic macrostructures (often of aberrant type with massive cores and finely laminated walls; cf. Pratt & James, 1982) than the latter where small, laminated encrustations predominate. Microscopic observations of samples from the small buildups (Fig.12) show less faunal elements inferred in growth position than in the large buildup.

6.2.3.- Lateral equivalents of the buildup cores

The passage from the small buildup core to the lateral equivalents is gradational. Close to the small buildups, the top of Bed 20 contains thickets of aberrant digitate stromatolites described by Gérards & Michot (1963) as «*Collenia* en bouffées de pipe».

Further away from the buildups, at St-Servais and particularly at Lives, the lateral equivalents of Bomel Bed 20 show very well developed cryptalgal structures. Oncoids are dominant at St-Servais whereas domal stromatolites and cryptalgal laminites occur at Lives.

6.3.- The buildup cover (A3 and B3)

Stromatolitic cover of the small buildups (Beds 21 and 22 = A3 in Fig.9).

Bed 21 is a wackestone characterized by numerous encrusted brachiopods and abundant oncoids some of which grade upwards into columnar stromatolites. Immediately above the small buildups the bed contains numerous columnar stromatolites.

Between the small buildups, Bed 22 consists of irregular, often undulose cryptalgal laminites containing rare pseudomorphs after gypsum. Immediately above the buildups, this bed thins markedly and, as in the underlying bed, columnar stromatolites occur in profusion and grade upwards into planar and undulose cryptalgal laminites.

Strikingly similar stromatolitic structures have been noted at the same levels at Lives. At St-Servais and Fond d'Arquet, however, the equivalent interval consists mainly of mudstones with very few planar cryptalgal laminites.

Large buildup cover and its talus (B3 in Fig.9).

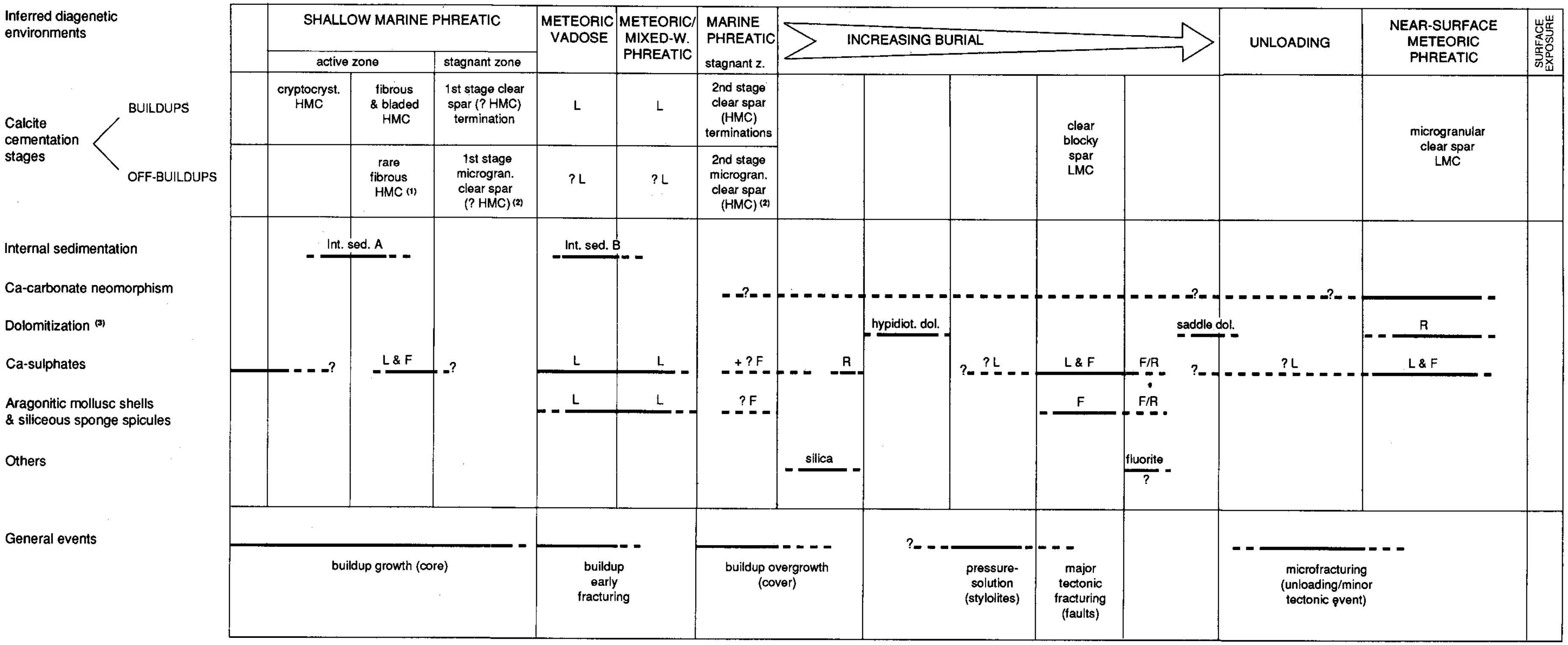
Beds 21 and 22 wedge out low on the flanks of the large buildup (Fig.9), so the capping of the large buildup is different from that of the small ones: it comprises flat-topped coral thickets (*S. martini*) in growth position. All corallites have thick stromatolitic coats and their columella show marked preferred orientation (about N 80° E) typical of a fairly agitated environment (Poty, 1981, pp.28-29). Centimetre-sized debris from these colonies contributed to the coral-echinoid packstones forming a talus low on the flanks of the large buildup. Laterally, away from the buildups, this talus grades to the already mentioned coral bed (CO in Figs 5 and 9).

On the southern flank of the large buildup, the talus is overlain by a 1 m-thick, mainly micritic, bed with some corals, cryptalgal laminites and small cryptalgal encrustations. The previously described clay bed (CL in Fig.5) occurs at the top of this bed, and is followed by platy calcilutites of Phase 3.

7.- DIAGENESIS

The sequence of diagenetic events which affected the buildups is summarized in Table 1. Those of the whole of Rhythm 0 (off-buildup facies) are also indicated although they will only be briefly discussed.

The main diagenetic features recognized in the buildups are the cements and internal sediments



(1) Only in cryptalgal boundstones (Phase 2).

(2) In Phases 1 and 2.

(3) Virtually absent in the buildups (except for microdolomites in echinoderm debris and late blocky spar).

Table 1. Tentative reconstruction of diagenetic history of the Rhythm O limestones. For each mineral phase, an horizontal line indicates precipitation unless L, R or F is specified. L implies leaching, R, replacement, and F, the filling of the voids resulting from leaching of the indicated mineral.

in primary interskeletal cavities, in empty brachiopod and vermetid gastropod shells, and in (? sponge) borings. Most of the studied limestones, especially those in the buildups, show some effects of neomorphism, dolomitization, Ca-sulphate crystallization and silicification, but they are generally slight.

7.1.- Internal sediments and cementation phases

In the buildups, the walls of some cavities are locally affected by tiny erosional scallops (Fig.13) which cut through cryptalgal laminae. They are very similar to the sponge borings figured by Johnson, Cuff & Rhodes (1984, p.521) but they could also be explained by early dissolution. Postdating these scallops, the following cavity-filling sequence has been established (Table 1; Fig.13):

1) a thin micritic coat;
2) the Internal sediment A, often multi-generation, penecontemporaneous with;
3) brownish, inclusion-rich fibrous/bladed cements «terminated» by;
4) a clear spar layer;
5) the muddy or silty carbonate Internal sediment B;
6) a mosaic of coarse blocky calcite; and
7) a mosaic of clear microgranular calcite.

In any given cavity, some of these stages may be absent. Even early cements may be missing, because they were scoured prior to later fillings (see origin of Internal sediment B, below).

(1) Micritic coat. A thin micritic layer about 10 μm thick is often present around cavities in the buildups (Fig.13). Dark in transmitted light, it shows a medium-dull yellow-orange colour under cathodoluminescence (CL).

Although now low-Mg calcite (LMC), this fabric is very similar in character to the «micrite Mg-calcite cement» described in the shallow Belize reefs by James *et al.* (1976). These authors (and many others: e.g. Lighty, 1985; Pierson & Shinn, 1985) showed that this cement is the first to appear and is the commonest of the early subsea cements usually recognized.

Because our «micritic coat» developed at the earliest stage of diagenesis, we interpret it as a marine phreatic cryptocrystalline cement, possibly with an original high-Mg calcite (HMC) mineralogy. There is only one occurrence of algal tubules closely associated with the micritic coat which may suggest that it may (at least in part) result from micritization.

(2) Internal sediment A. This geopetal sediment mainly comprises peloids and small bioclasts (mostly brachiopod and echinoid debris) which are sometimes coated by a thin micritic crust (Fig.11B). This internal sediment has almost the same CL characters as the sedimentary substrate, namely yellow-orange with a dull intensity. Pore space is generally filled by brownish fibrous calcite cements with a darker CL signature (see below). The sediment frequently exhibits an upward decrease in packing so that in the upper part of a layer, the peloids «float» in cement. The bioclasts are nevertheless restricted to the lower part of the layer.

This last texture could be explained in at least three ways: (1) deposition of the peloids during cementation; (2) displacement of already deposited peloids by growing fibrous cements; or preferably, (3) the peloids may be a type of cement, namely HMC (see reviews by MacIntyre, 1985; Lighty, 1985; and Chafetz, 1986).

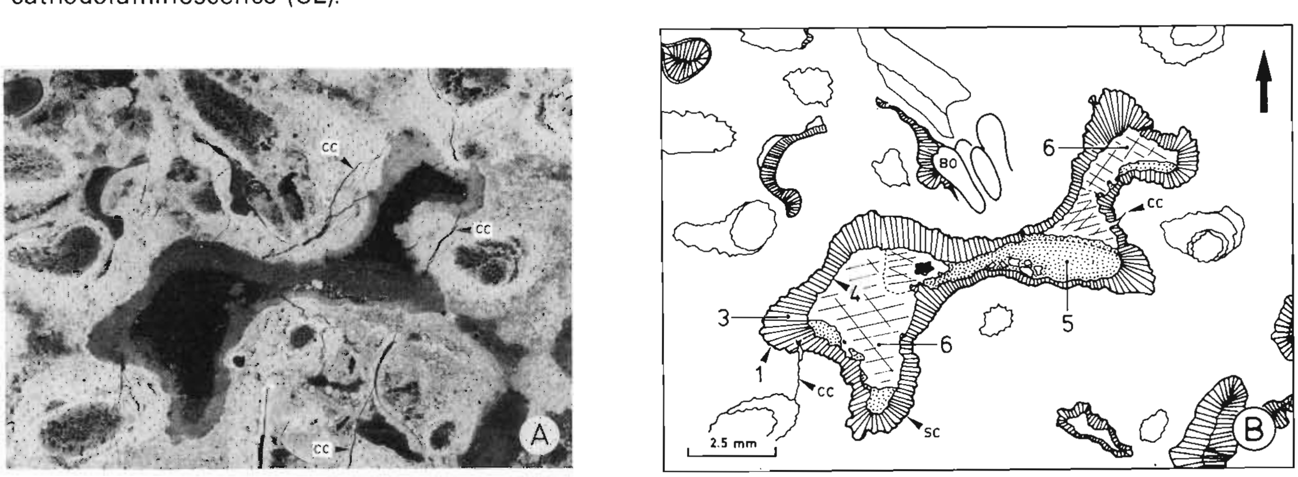


Fig. 13.- Negative print of plane-light photomicrograph (A) and diagram (B) showing diagenetic stages within an «open» (see text) cavity from the core facies of the Bomel large buildup. Locally affected by tiny scallops (SC), the cavity wall was first coated by a thin micritic layer (1). The cavity was subsequently filled by brownish fibrous cements (3) terminated by a thin, clear spar layer (4) which was overlain by the silty carbonate Internal sediment B (5) containing small lithoclasts, and finally a mosaic of clear blocky spar (6). CC indicates early compaction cracks predating late spar (6) but postdating the early fibrous cements (3). Some borings (BO) occur within the cryptalgal boundstone. It is worth noting the absence of Internal sediment A («Stage 2» in the above sequence) in the figured cavity. Large arrow points to stratigraphic top. Thin section in specimen N°AL124.

(3) Inclusion-rich fibrous and bladed cements. This generation of early cements has two distinct habits, fibrous and bladed, occurring respectively in «open» cavities (= voids with greater permeability) and «closed» cavities (= more confined voids). Rich in inclusions, cements of both habits are typically brownish in transmitted light. Under CL they are dull to very dull yellowish orange, generally darker than the micritic coat and the surrounding sedimentary framework. The CL signature is typically unzoned and sometimes blotchy (Fig.15). Mean microprobe analyses indicate 0.59 wt% MgO for the inclusion-rich fibrous and bladed cements (undifferentiated; N=33) -with one analysis up to 1.82 wt%- versus 0.43 wt% MgO for the substrate (N=15). Iron and manganese are extremely low with mean values of respectively 100 ppm FeO and 310 ppm MnO versus 240 ppm FeO and 250 ppm MnO for the substrate.

Fibrous cements in «open» cavities (Figs 13, 14A and 15A). This cement forms a layer generally ranging from 0.1 to 2 mm (maximum 5 mm) thick. It is generally isopachous but in some cases is thicker on the roof of the cavities than elsewhere. It is composed of many fibrous bundles nucleated at point centres 50 to 100 μm apart (radial fibrous cement). In some cavities the fibrous layer is fascicular-optic calcite (Kendall, 1977) with the fast vibration direction of individual fibres

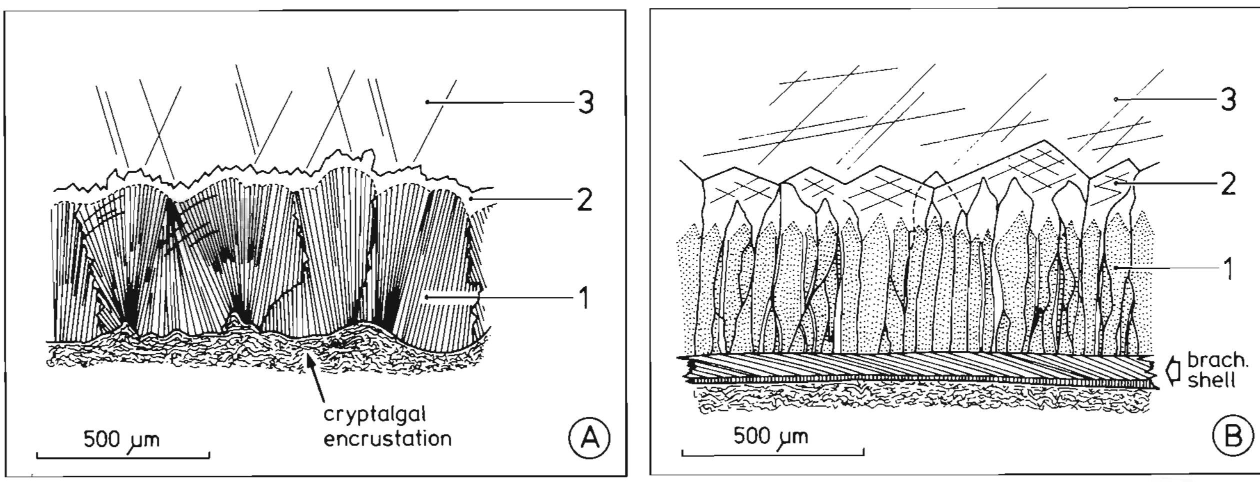


Fig. 14.- Diagrams showing main cementation phases in «open» (A) and «closed» (B) cavities in the core facies of the Bomel buildups. The cavity is first rimmed by a layer of brownish fibrous/bladed calcite (1, A/B) with clear spar terminations (2) and it is finally filled by clear blocky calcite (3).

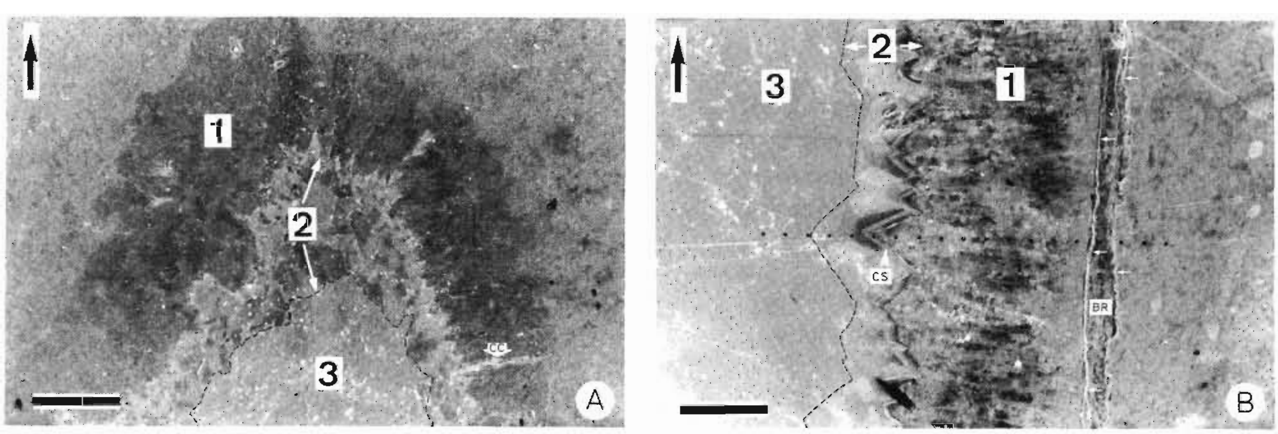


Fig. 15.- Thin section photomicrographs showing CL features of the main cementation phases in the core facies of the Bomel large buildup. The figures refer to the same calcitic phases as in Fig.14 diagrams (see text for CL description). The boundary between cements 2 and 3 has been outlined for clarity. Large arrows point to stratigraphic top. Scale bars = *200 μm*.

(A) Sequence in an *open cavity*. CL petrography reveals the scalenohedral terminations of the fibrous layer (1). Note the poorly developed CL zonation in the clear termination phase (2), which fills an early compaction crack (CC). The numerous bright specks in the coarse blocky calcite (3) correspond to calcitic (latest phase) or dolomitic microinclusions. Thin section in specimen N°AL124.

(B) Sequence in a *closed cavity*, namely a brachiopod shell (BR). The bladed layer (1) shows a blotchy dull CL signature. Note the minor corrosion surface (CS) locally present between the first (with well-developed CL zonation) and the second (with dull CL) stage of the clear terminations (2). As in (A) bright specks occur in the late blocky calcite (3). The youngest, bright luminescent, calcite fills thin veinlets (small white arrows) in the brachiopod shell. The 19, horizontally aligned, black spots represent a microprobe traverse through the cement sequence. Thin section in specimen N°AL123.

diverging away from cavity walls and curved cleavage traces concave to the wall. However, when devoid of that character, this layer generally exhibits a sweeping extinction under crossed polars. A vague zonation is occasionally seen at the base of the layer, suggesting at least two generations. Under CL, the inclusion-rich fibrous cement sometimes shows either scalenohedral terminations (similar to those of the bladed cement; Fig.15A) or botryoidal ones (Fig.14A). These fibrous cements are much better developed in the large buildup than in the small ones.

Bladed cements in «closed» cavities (Figs 14B and 15B). In the «closed» cavities of brachiopod shells the equivalent of the fibrous cement is one with bladed texture. It is isopachous and commonly comprises up to three generations, the first of which is generally very thin (20-30 μm) and predates Internal sediment A. The inclusion-rich bladed cement commonly shows scalenohedral terminations but never rounded ones.

The observed textures and the interlayering of the marine Internal sediment A within the fibrous and bladed cements point to their marine phreatic origin. Elongation of the crystals along their c-axes and abundance of inclusions indicate rapid precipitation near the sediment/water interface («active marine phreatic zone» of Longman, 1980). The original mineralogy is thought to be mainly HMC as suggested by the scalenohedral terminations, the very good state of preservation (no obvious neomorphism), the occurrence of fascicular-optic calcite (Sandberg, 1985) and a certain magnesium «memory» relative to adjacent substrate and cements (Benson & Matthews, 1971; Prezbindowski, 1985). It is worth noting, however, the general absence of microdolomite crystals in these cements.

(4) Clear termination of the fibrous/bladed cements. There is always a zone of inclusion-free, colourless spar in optical continuity with the brownish crystalline fibrous or bladed substrate (Fig.14). CL petrography reveals two distinct stages of growth; in order of formation: (1) at least one thin zone of non-luminescent calcite, and commonly four (rarely up to ten) thin zones alternately with bright (yellowish brown) and dull (yellow-orange) to non-luminescent signature; and (2) a thicker stage with a dull yellow-orange CL similar to that of the late blocky calcite (Fig.15). The first stage generally mimics the scalenohedral terminations -if present- of the fibrous/bladed inclusion-rich precursor, whereas the second stage often shows larger rhombic terminations. A minor *corrosion surface* is locally present between the two stages (Fig.15B). The two only available microprobe analyses show that the first stage of this cement has notably low magnesium content (0.07 wt% MgO; N=2) relative to adjacent cements, including the second stage of the clear terminations (0.43 wt% MgO; N=10). In the first stage the iron was undetected and the manganese showed very low values not exceeding 100 ppm MnO. The second stage is slightly enriched in iron and manganese relative to adjacent cements (210 ppm FeO and 380 ppm MnO).

The clear termination is generally much thicker (up to 250 μm) in «closed» cavities (overlying bladed cements) than in the «open» cavities (on fibrous cements) where it is typically only 20-30 μm thick (Fig.14). In some instances, the clear termination in brachiopod shell cavities is thicker than the brownish bladed cement itself. The clear spar termination is contemporaneous with or immediately subsequent to a phase of fracturing which clearly predates the late blocky cements. The microfractures, interpreted as early compaction cracks (see later discussion), are filled with a clear, microgranular calcite corresponding to either the first or the second stage of the clear termination (Fig.15A). Position in the diagenetic sequence (Table 1) and CL zoning allow the tentative correlation of the clear spar termination with three distinct clear cements noted in the packstones in the lower part of Rhythm 0 (Phases 1 and 2): (1) precompactional, microgranular isopachous calcite rims; (2) syntaxial calcite overgrowths on echinoderm fragments; and (3) scalenohedral «dog-tooth» isopachous rims restricted to intraskeletal pores in tetracorals (*S. martini*).

The clear and isopachous characters of the terminations (both stages) point to a slow precipitation under phreatic conditions, presumably in the stagnant marine phreatic zone, as defined by Longman (1980). The terminations are thought to have grown as HMC. With a low magnesium content (to be confirmed by further analyses) the first stage would record a depletion of the magnesium content in the precipitating fluids during early diagenesis, as described by Pierson & Shinn (1985).

Multiple zoning of the first stage of the clear terminations indicate rapidly fluctuating Eh/pH conditions. Such conditions are expected to prevail in biogenic carbonate sediments slightly and recently buried under the sea-bottom (decay of organic matter, periodic influx of well-oxygenated waters related to high-energy events like storms,...). The corroded surface between the two stages suggests that the rock was affected by fluids undersaturated with respect to calcite, after the growth of the first stage. As this corrosion surface can be shown to be penecontemporaneous with Internal sediment B (interpreted as vadose; see below), the dissolution event is suspected to have taken place under meteoric vadose or freshwater/ mixed-water phreatic conditions, depending on position in the buildups. Lack of zoning during the second stage indicates stable precipitation conditions during shallow, increasing burial.

Obviously some characters of the clear terminations together with the nature of the associated clear cements fit with a freshwater phreatic origin (Longman, 1980; and Pierson & Shinn, 1985, among others) but the first interpretation is preferred here (see later discussion).

(5) Internal sediment B. Two main types have been noted: «silt» and «micrite».

The «*silt*» type is dominant. It is composed of angular fragments of spar crystals with a mean diameter of 10-20 μm and a maximum of 50 μm (Fig. 13). It sometimes contains silt-sized, detrital quartz grains. Common buildup-rock lithoclasts and occasional micritic grains, peloids and even small bioclasts occur «floating» in the silt. This sediment shows a speckled CL (dull to dark, yellow-orange; generally brighter than Internal sediment A) resulting from a mixed composition of several cement phases (earlier and later) and varied sedimentary components. The lithoclasts show sharply cut fibrous/bladed cements with their clear termination limited to the first, finely zoned, CL stage. In character and occurrence, this type of internal sediment resembles the «vadose crystal silt» of Dunham (1969). In some instances, peloids with a mean diameter ranging from 30 to 60 μm are so numerous that the sediment fits the definition of «vadose pellet silt» (Dunham, *op. cit.*).

The «*micrite*» type is nearly opaque in transmitted light. It has a medium-dull yellow-orange CL more homogeneous than its silty counterpart. The micrite is often associated with quartz silt (10-30 μm) and is sometimes cross-laminated. The filling of the cavities by this type or the «silt» type seems to have been highly selective as the two types have never been observed in the same cavity.

As revealed by CL petrography, Internal sediment B immediately postdates the first stage of the fibrous/bladed cement clear terminations, as does the corroded surface within the clear spar terminations. Internal sediment B is also penecontemporaneous with the fracture phase already mentioned. The distribution of this generation of internal sediment is far from being random: it is rare or absent in the upper and outer parts of the large buildup but it is ubiquitous and sometimes abundant towards the base (Fig.16). In the small

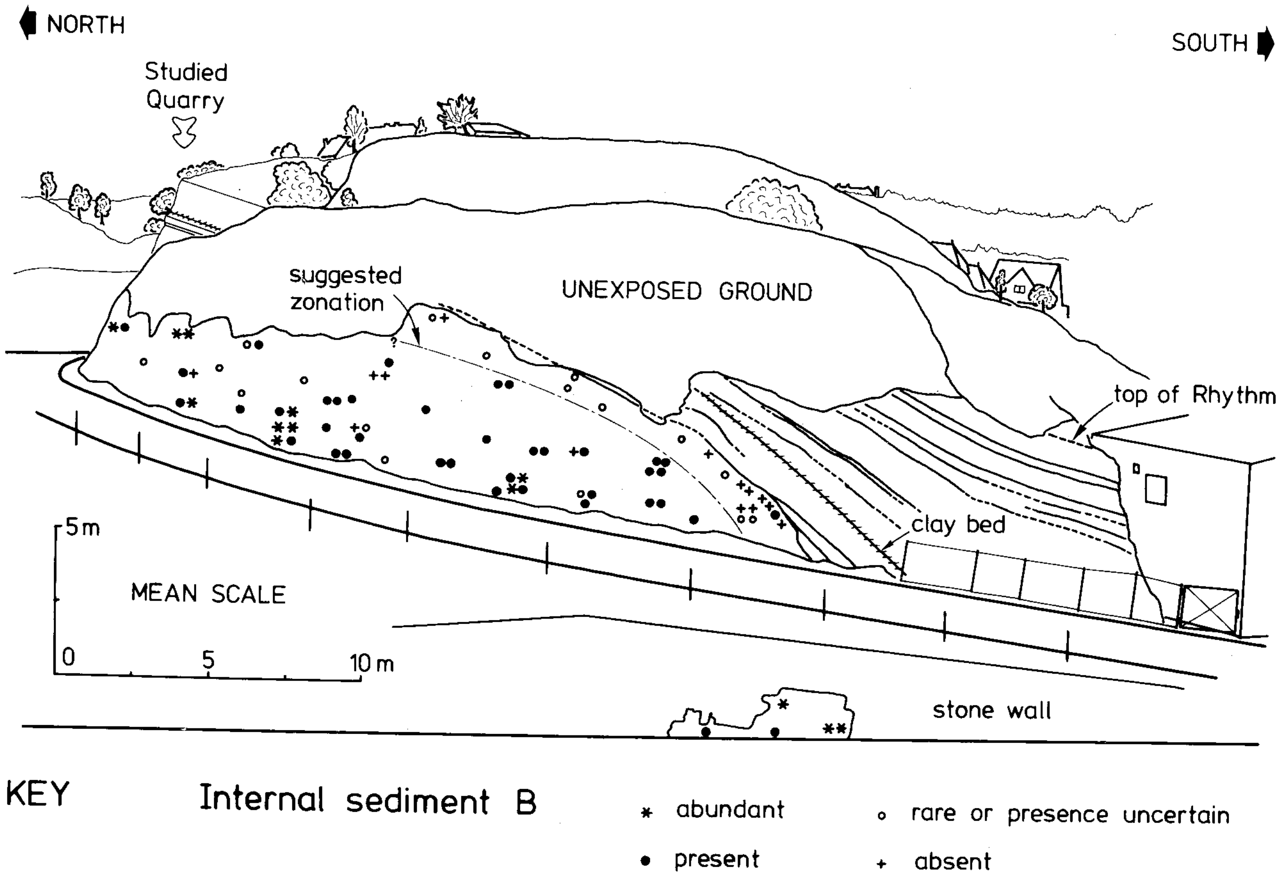


Fig. 16.- Western side of the Bomel large buildup (as viewed from the same point as Fig.8B) showing the distribution of Internal sediment B within the core facies. Clusters of symbols generally indicate several thin sections per sample. Note the scarcity or absence of Internal sediment B in the upper and outer parts of the buildup core.

buildups, Internal sediment B is scarcer than in the large one. This probably results from a less-developed cavity system due to relative scarcity of framebuilders, especially bryozoans.

According to several authors (Dunham, 1969; Aissaoui & Purser, 1983), the nature of Internal sediment B and its relations with early fibrous/bladed cements are diagnostic of vadose conditions. We agree with that interpretation which is consistent with the shallowing-upwards tendency inferred for the lower half of Rhythm 0 (see 8.1.).

(6) Coarse blocky calcite. Residual voids were filled with a mosaic of equant, anhedral, clear calcite (Figs 13 and 14). Individual crystals range up to several millimetres across (up to 15 mm) and it is common to observe a single crystal completely filling a cavity. The CL colour of this coarse calcite is brownish yellow to yellow-orange with an intensity ranging from dull to nearly non-luminescent. The CL is typically homogeneous although some crystals show generally vague zoning. Some large crystals have scattered, dark and limpid microinclusions which, under CL, appear to be calcite (of the latest stage; see below) and dolomite, respectively (Fig. 15). This stage is a major pore-filler including molds resulting from the leaching of Ca-sulphates (off-buildups), sponge spicules and possibly mollusc shells. It is not clear whether syntaxial overgrowths on echinoderm fragments were further enlarged at this stage or whether they were only related to the «clear terminations» stage. This phase also fills most veins including the large ones related to faults. In the buildups as well as in the lower part of Rhythm 0, this cement clearly postdates the early compaction responsible for grain breakage. It also seems to postdate chemical compaction as it has never been observed to be cut by stylolites. A limited number (N=13) of chemical analyses indicate very low iron and manganese content (150 ppm FeO; 210 ppm MnO). Magnesium shows values intermediate between those of the substrate and early fibrous/bladed cements (0.48 wt% MgO).

This cement stage also shows two other minor habits: fibrous and bladed. The fibrous habit is developed along stylolites, the calcite fibres being normal to the stylolite «plane» which parallels the bedding plane. The bladed habit is restricted to minor veins with the crystal long axes normal to the fracture wall.

The position of the coarse blocky calcite in the cement sequence (Table 1), its common coarse blocky character as well as its posteriority relative to grain-breakage and stylolitization, all point to a late burial origin for this calcite (see among others: Moore & Druckmann, 1981; Scholle & Halley, 1985). Although presumably precipitated under reducing conditions, this calcite has very low iron and manganese content, probably because those elements were not available (Scholle & Halley, 1985). Under CL, there is a notable similarity of colour and intensity between this cement and the primary sediment. The chemical composition of this late calcite is also close to that of the sediment.

These characters tend to indicate either a strong late neomorphism or a cement derived from a «rock-dominated system». General neomorphism is rejected because of the excellent preservation of original structures and early cement zoning. The late burial cements thus seem to have been derived mainly from dissolution of the original sediments and (to a minor degree) earlier cements by pressure-solution, especially along stylolites (Hudson, 1975). The calcium carbonate released by stylolitization could only have reached the residual rock voids thanks to a significant permeability increase. This seems to have been produced by fracturation related to a tectonic event (with faults) which postdated stylolitization. Fractures provided rapid pathways for the fluids to the already partly cemented voids. The cracks were themselves subsequently filled by the late calcite.

(7) Microgranular calcite. Very late micro-fractures, cutting through all structures and diagenetic phases, were filled with a clear microgranular calcite that may be syntaxial when cutting through the coarse blocky calcite. This calcite has a very distinctive CL signature in two stages: (1) a widespread first stage with a bright yellow CL (Fig. 15B); and (2) an occasional second stage with a moderately bright, yellow-brown CL. The latter was only observed in large veins where both stages may show some zoning. No chemical data are available for this calcite phase.

A striking occurrence of this late calcite in the buildups is as filling of Ca-sulphate (presumably anhydrite) molds. This calcite also replaces (rarely completely) (hyp)idiotopic dolomite rhombs and invades intercrystalline boundaries and cleavage planes of earlier calcite and dolomite phases. It is sometimes observed as tiny crystals, dark in transmitted light, in the coarse blocky calcite (Fig. 15).

This late calcite cementation is interpreted as a near-surface phenomenon. Microfracturing related either to unloading after burial and/or to a minor tectonic event allowed circulation of external fluids. The remaining Ca-sulphates were leached, with subsequent filling of all voids by the late, possibly manganoan (cf. bright CL), calcite. Some calcitization of dolomite also occurred, a phenomenon favoured by the dissolution of sulphates (Braddock & Bowles, 1963; Blount & Moore, 1969) and by near-surface conditions (De Groot, 1967).

7.2.- Neomorphism

Neomorphic textures are uncommon in the buildups. In some cavities, Internal sediment A has been replaced by a mosaic of equant clear *pseudospar* (Folk, 1965) with rounded crystals averaging 100μm in size. The CL zonation of the pseudospar suggests its growth started concomitantly with the clear termination of the fibrous/bladed cements. The late blocky calcite seems to have enlarged the pseudospar «nuclei» to their present size.

Although minor in volume, *microspar* (Folk, *op.cit.*) is quite widespread. Various CL signatures suggest that microspars formed at various times in the interval between deposition and the latest calcitic cementation.

7.3.- Dolomitization

The only dolomite recorded from the buildups is minor microdolomite, 1 to 10μm in size, with a moderate, red CL. It occurs as clear inclusions in echinoderm fragments and presumably results from the stabilization of original HMC to LMC (Lohmann & Meyers, 1977; Blake, Peacor & Wilkinson, 1982). Similar crystals were detected in the coarse blocky calcite but these are possibly of the Type 2 dolomite described hereafter.

Other types of dolomite have only been observed in the bioclastic beds at the base of Rhythm 0 (Phase 1; Fig.5). Except at St-Servais where a few beds are completely dolomitized, the dolomite content of the rock rarely exceeds 2-5 % by volume. Two types of dolomite have been recognized: (1) idiotopic to hypidiotopic non-ferroan dolomite (individual rhombs, about 100μm across); and (2) non-ferroan saddle dolomite (Radke & Mathis, 1980) with crystals, mostly anhedral, averaging 0.5 to 1 mm in size. The Type 1 dolomite has a brownish colour in transmitted light and a dark reddish CL although some rhombs do have a clear outer rim with a moderate red CL. This rim is perhaps an equivalent of the Type 2 dolomite which also has a moderate red CL.

The inferred time relationships with other diagenetic events are reported in Table 1. Though the saddle dolomite is probably a burial cement (see review by Scholle & Halley, 1985), immediately postdating the coarse blocky calcite, the origin of the Type 1 dolomite (which predates pressure-solution) is uncertain.

7.4.- Ca-sulphate pseudomorphs

Common, lath-shaped calcite pseudomorphs after anhydrite have been observed in the primary sediments of the large buildup. Several discrete levels of pseudomorphosed sulphates also occur in the upper half of Rhythm 0 (Phase 3 and top of Phase 2; Fig.5). Volumetrically, they are always minor, never exceeding 1 % of the phase (P2 or P3) where they occur. Judging from their lozenge to lensoid and wedge shapes, some of them were originally gypsum, but most show the lath, polygonal and nodular shapes typical of anhydrite. They have generally been observed in close association with stromatolites. The pseudomorphosing minerals are calcite (all phases of cementation recognized, including the early fibrous calcite), quartz (fibrous or not) and fluorite. As noted in Table 1, several phases of partial dissolution and replacement of the Ca-sulphates occurred from the time of deposition to the latest microgranular calcite cementation phase.

Hennebert & Hance (1980) have described common silicified anhydrite nodules (with chicken-wire structure) at Vedrin (Fig.1) from levels here classed as the top of Phase 2 and Phase 3. Two environments of formation were proposed by these authors: either supratidal sabkhas like those of the Persian Gulf or, preferably, Bahamas-like intertidal ponds.

7.5.- Silicification

Although volumetrically unimportant, this alteration is fairly widespread in the buildups where skeletal grains, Ca-sulphates, micrite, fibrous/bladed cements and even Internal sediment B may be selectively replaced by non-luminescent mega-, fibrous or micro- quartz. The fibrous quartz is generally chalcedonite, and rarely the lutecite or quartzine which are restricted to sulphate pseudomorphs.

Two additional silicification types seem to occur only in the non-buildup facies of Rhythm 0: (1) black chert nodules (and, rarely, thin bands) only present at St-Servais and Vedrin (Fig.3) in the lateral equivalents of the buildup foundation (A1 unit); and (2) spherulites of «microflamboyant quartz» (Milliken, 1979) with a mean diameter of 500μm which are very common at Lives and Bomel, immediately under the hummocky surface, in the lateral equivalents of the buildups (A2 and B2 units). As the spherulites are always intimately associated with cryptalgal structures, it is suggested that the precipitation of silica could be related to algal metabolism (cf. Park, 1976).

8.- DEPOSITIONAL AND DIAGENETIC HISTORY

8.1.- Depositional environments of Rhythm 0 (Fig.17)

This excludes discussion of buildup components. Although it is impossible to be sure, particularly in the case of bioclasts, the following discussion assumes that the grains are autochtonous or at least subautochtonous. Arguments in favour of this are: the very poor rounding of the grains; their poor sorting; and the presence of the same organisms unbroken and sometimes in growth position (e.g. coral colonies).

Phase 1. Normal marine conditions seem to have prevailed during Phase 1 as evidenced by the biotic assemblage with corals (often colonial), brachiopods, crinoids, echinoids, moravamminids, trilobites, plurilocular foraminifera and *Koninckopora,* among others. Such diversity also suggests unrestricted water circulation and «normal» salinity. Shallow water in the photic zone is suggested by the abundance of the assumed dasyclad *Koninckopora* (Flügel, 1982, Table 31, p.332), the presence of colonial corals (always broken), and common micritized grains (Swinchatt, 1969; Purser, 1980, pp.7 and 173). The packstones and poorly washed grainstones of this phase indicate moderate energy levels (decreasing with time) as already suggested by the very poor rounding and sorting of the grains.

Phase 2. This phase, which contains colonial corals in growth position and, later, stromatolites, was probably deposited in a shallower environment than Phase 1, although still mainly subtidal. A minimum value for water depth near the end of the growth of the buildups is given by the seafloor relief of the large buildup (about 7-8 m) and the fact that it was probably formed entirely in a subtidal environment. Evidence to be discussed in detail later suggests that growth of the buildups ceased because of a sudden and short-lived sea-level drop which resulted, locally, in subaerial exposure of the seafloor. The whole platform was then progressively drowned by a rising sea, and subtidal conditions were restored at the end of Phase 2.

Phase 2 is marked by the progressive increase in the fine fraction (packstone to wackestone trend; Fig.6) indicating a gradually decreasing energy. At the top of Phase 2, however, the micrite content suddenly decreases during a 1-2 m interval, indicating a higher energy at that level, perhaps related to the shallower conditions envisaged. The faunal diversity declines markedly upwards through Phase 2. Stenohaline organisms tend to disappear while euryhaline groups, such as molluscs, ostracods and the algal/bacterial associations responsible for the stromatolites, dominate.

Phase 3. The Phase 3 micrites, notably devoid of dessication features, were probably deposited under water. However, a very shallow environ-

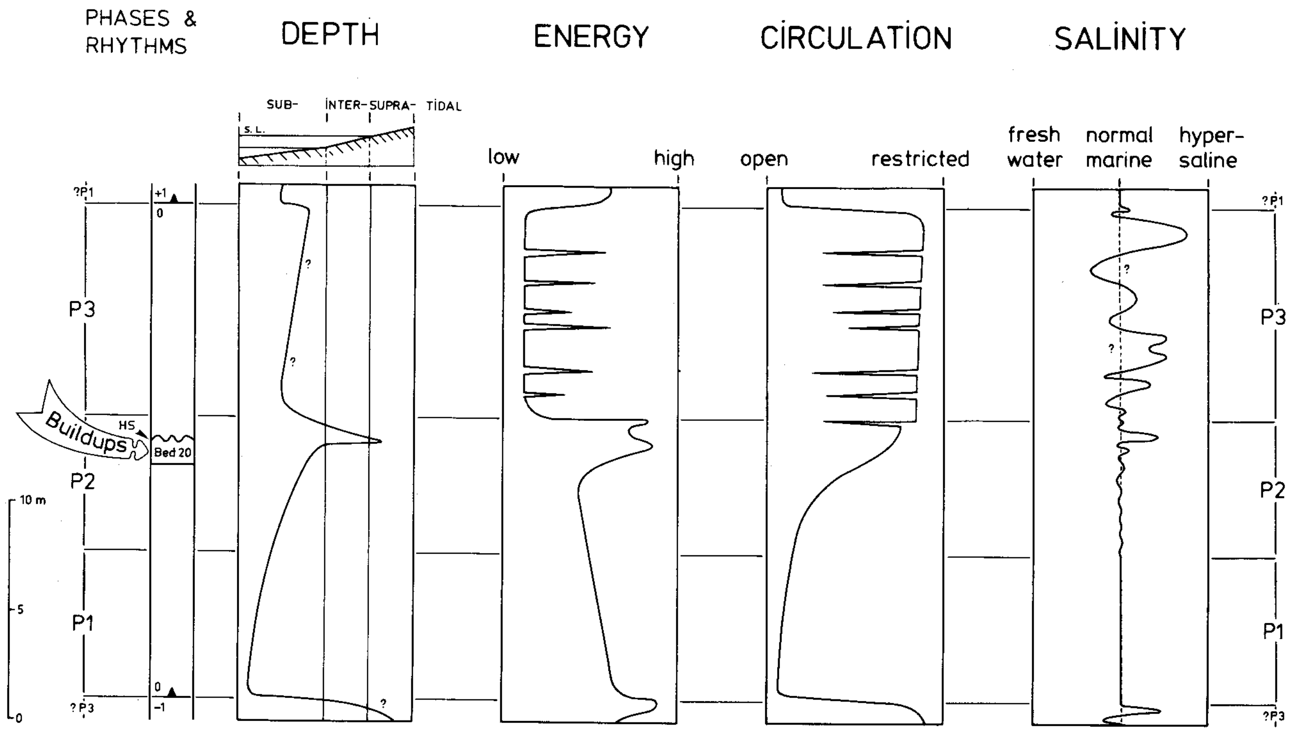


Fig. 17.- Evolution of selected environmental factors during the deposition of Rhythm 0. Note that this figure directly relates to Fig.6. HS = hummocky surface; S.L. = *sea-level.*

ment -possibly intertidal temporarily- is suggested by a few horizons of cryptalgal laminites with fenestrae, some flat pebble conglomerates and by the numerous large (0.2-2.0 mm) peloids the perfect elongate shape of which seems to indicate their early hardening (Bathurst, 1975, p.199; Purser, 1980, p.166).

Very calm conditions seem to have prevailed during Phase 3, allowing the deposition of several metres of carbonate muds. The presence of shale seams delimiting regular beds, some of which have been traced for several kilometres, again suggests a quiet environment. Thin bioclastic (normal marine fauna) and intraclastic levels in Phase 3 certainly indicate higher energy episodes, perhaps storms. The trend to conditions of restricted circulation, which had started in Phase 2, culminates in Phase 3 which is populated only by restricted euryhaline organisms, principally ostracods and rare stromatolites. Such an association may develop in any of three distinct environments: fresh water; hypersaline; or water of fluctuating salinity («schizohaline environment» of Folk & Siedlecka, 1974). Pseudomorphs after anhydrite, observed at several levels in Phase 3 (Fig.6) suggest that the trend was towards hypersaline conditions, at least from time to time. The specialized fauna and flora could equally be the response to important seasonal thermal variations (Purser & Seibold, 1973) together with significant rainfall -which would also account for the scarcity of birdseyes, the absence (or rapid healing) of dessication cracks (see Fig.31 of Gebelein, 1977) as well as the small volume of sulphates. The very early dissolution of the latter which has been noted in some cases (molds filled with the early fibrous cements) could indicate such episodes.

Another environment of deposition was postulated by Hennebert & Hance (1980): ponds filled with saline water like those of the Bahamas or even more brackish. In a similar situation Wanless *et al.* (1988, pp.727-728) described a hurricane deposit not extending more than 0.5-1.5 km across the tidal flats, generally leaving inner pond and inner algal marsh environments unaffected. So, the presence of the thin layers inferred to be storm deposits as well as the large scale lateral continuity of Phase 3 do not favour the «ponds» hypothesis.

8.2.- Inferred subaerial exposure. Discussion.

Several arguments favour the hypothesis that subaerial exposure occurred in the middle of Rhythm 0 and terminated buildup growth, but none is conclusive.

(1) The evolution of the depth and energy parameters in the lower half of Rhythm 0 (Fig.17) leads naturally to very shallow conditions, perhaps subaerial exposure, at the top of Bomel Bed 20, the lateral equivalent of the buildup cores.

(2) The common occurrence of fenestrae in the upper half of Phase 2 probably records a temporary intertidal (or even supratidal?) episode (Purser, 1980, pp.109-110; Shinn, 1983).

(3) The hummocky surface described at that level (Figs 4 and 9) has the features of a paleokarstic surface (Wright, 1982). The great lateral extent of this surface (Fig.3) indicates that a general rather than a localized event affected the early lithified limestone. A humid climate could lead to such a karstic feature under several environments:

(i) subaerial exposure with or without a soil cover;
(ii) intertidal conditions with periodic influx of freshwater; or possibly
(iii) very shallow, subtidal conditions with substantial freshening of the water, related to restricted circulation and influx of freshwater.

(4) As noted earlier, vadose conditions are suggested in the buildups by the features of Internal sediment B. Whether that be so or not, the distribution of that internal sediment in the large buildup argues for a significant event at the end of buildup core growth (Fig.16). That distribution and cross-lamination in the micritic Internal sediment B suggest some flushing through the buildup, hardly possible under water (Dunham, 1969).

(5) The arrival of Internal sediment B corresponds with the fracturing of the buildup. It is also penecontemporaneous with a corrosion surface within the clear cementation phase. As noted earlier this corrosion surface would result from the influx of freshwater in the large buildup. We therefore propose that the early fracturing of the buildup was a gravity effect following its exposure.

(6) From bottom to top of Bomel Beds 21 and 22, the stromatolitic structures evolve consistently from oncoids and columnar forms to undulose and flat ones. Because the flat laminites are regular and devoid of dessication features, indicating their subtidal origin (see review by Purser, 1980, pp.111-133), this development is interpreted as reflecting progressively quieter conditions. These are tentatively correlated with deepening due to progressive drowning of the carbonate platform after the proposed regression at the top of Bed 20.

(7) Beds 21 and 22 wedge out low on the flanks of the large buildup (Fig.9). This suggests unfavourable conditions on the mound even for stromatolites, such as subaerial exposure.

A search for more convincing emersion criteria at the top of Bed 20 was unsuccessful. Dessication structures and caliche textures are absent as are paleosols and rhizoliths, unless the shaly filling in the hollows of the hummocky surface represents soil relicts (Walkden, 1974; Wright, 1982). The absence of such features could be explained either by their non-development (e.g. for climatic reasons) or by their erosion, or even because Bed 20 was never emergent. As was pointed out by G. Walkden in the Upper Viséan limestones of Derbyshire, U.K. (Lecture at the Liège University, March 1990), a weaker development of paleokarst is often noted in algal limestones (with lower interconnected porosity) as opposed to grainstones. Such a poor development of karstic features may also result from the absence of a river system, which water is generally more aggressive than rain-water or dilute sea-water (Walkden & Davies, 1983).

Taking all available criteria into account, the favoured working hypothesis envisages a short-lived sea-level drop after the deposition of Bomel Bed 20, that is, after growth of the buildups. These were exposed to subaerial conditions for a short time while the topographic lows remained awash, at least intermittently. Restricted water circulation under a humid climate (influx of freshwater) led to brackish conditions in these lows and to leaching of the early cemented carbonates. As the dissolution is highly enhanced by under-water conditions (see review by Read & Grover, 1977), the leaching was more severe in the lows than on the tops. This explains a significant feature of the hummocky surface, namely, its absence from the top of the small buildups and from the exposed flank of the large one. In the buildups, especially the large one, vadose conditions first prevailed and then minor dissolution occurred in a short-lived meteoric freshwater/mixed-water lens.

9.- CONCLUSIONS. DEPOSITIONAL AND EARLY DIAGENETIC HISTORY OF RHYTHM 0 AND ITS BUILDUPS

(Fig.18; Stages 1 to 8)

Stage 1. The lower part of the rhythm (Phase 1 + lower half of Phase 2) was formed in an open marine environment in which a rich and diverse biota developed in clear, well oxygenated waters. Eventually, the seafloor was covered with coral thickets, most of which were mechanically broken, only a few being preserved, locally, in growth position.

Stage 2. Towards the end of Phase 2, continued shallowing led to restriction of circulation, to an increase of energy, and to salinity fluctuations. Locally, stromatolitic mounds formed by the activity of algal/bacterial communities on the favourable substrate represented by the preserved coral thickets. The large buildup which ultimately developed is an excellent example of competition between stromatolites and bryozoans, evidenced by mutual and alternating encrustations (Monty, 1974). Vermetid gastropods, sponges and brachiopods also played an important though secondary rôle in the formation of the buildups. Upwards through the buildup, the stromatolites became increasingly important relative to the other organisms, probably as a result of more restricted conditions. As the buildups and their lateral equivalents grew, the porosity of the sediment was substantially reduced by internal sedimentation (mainly peloids and small bioclasts) and rapid precipitation of inclusion-rich fibrous/bladed carbonate cements (mostly HMC). In the slightly buried sediments, growth of the cements proceeded more slowly with the syntaxial precipitation of a first stage of clear HMC.

Stage 3. The demise of buildups is tentatively attributed to a short-lived drop in sea-level. Apparently, only the buildups were subaerially exposed, the topographic lows of the seafloor being subject to very shallow subtidal, possibly intertidal, restricted conditions. Being no longer «water-supported», the partly cemented buildups fractured.

Stage 4. Freshwater influx led to fresh, or at least brackish, water conditions in and around the buildups. Poor circulation effectively isolated these waters from the open sea and extensive, though surficial, dissolution occurred in the shallow platform waters and perhaps in «ponds» between the buildups. This resulted in a hummocky seafloor for a distance of at least several kilometres around the buildups. Clays, presumably insoluble residues, accumulated in the hollows of the karstic surface. The residual permeability of the buildups, further increased by the post-emergence fracturing, allowed invasion by rain-water and resulted in the downward transport of an internal sediment of «vadose silt» and lithoclasts. Minor leaching occurred in cavities during this episode and later in a temporary freshwater lens. But seemingly little surface dissolution affected the buildups as subaerial dissolution by occasional water is far less effective than in submerged conditions.

Stage 5. As a result of a progressive sea-level rise, the small buildups were the first to be flooded under increasingly marine waters and were colonized by algal/bacterial communities building stromatolites. On seafloor around the buildups the deepening water resulted in the change from oncoids and columnar stromatolites, morphologies typical of an agitated environment, to undulose and flat cryptalgal laminites with thick laminae devoid of dessication structures, typical of

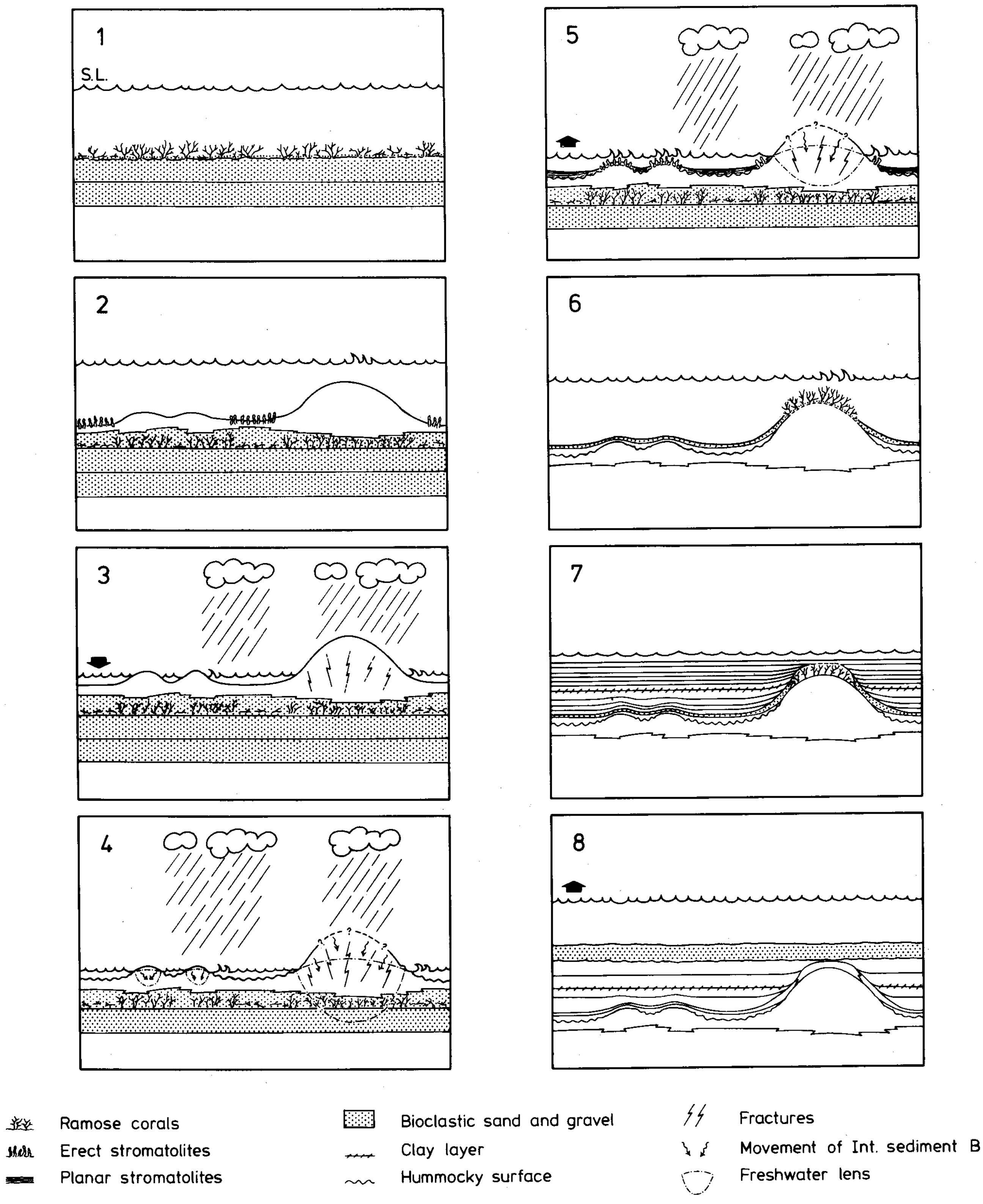


Fig. 18.- Depositional model for the carbonates of the upper part of Rhythm 0 (with the cryptalgal-bryozoan buildups; Stages 1 to 7) and base of Rhythm +1 (Stage 8): see text for discussion. Black arrows indicate sea-level (S.L.) change.

quiet subtidal conditions. However, immediately above the small buildups, the turbulence remained relatively important as shown by the persistence of columnar shapes. Meanwhile, the upper part of the large buildup, being 5 to 7 m higher than the small mounds, was progressively drowned and the suspected freshwater lens disappeared.

Stage 6. The large buildup was finally submerged and formed a hard shoal upon which coral colonies became established. Debris from the mechanical destruction of these colonies was spread over the surrounding seafloor.

Stage 7. Most localized organic buildup ceased and sedimentation of lime muds became the norm everywhere (during Phase 3) except on the flanks of the main buildup where minor algal growth persisted until swamped by the accumulating lime muds. The origin of these muds is uncertain but a review by Purser (1980, pp.328-329) indicates most present-day lime muds have a biogenic origin. As no dessication features have been recorded, the environment of deposition probably remained subtidal during their deposition. The relief initially created by the small buildups was completely levelled by mud accumulation just before the deposition of a clay bed corresponding to a volcanic ashfall. During the progressive burial of the buildups, the clear terminations (first stage) of the fibrous/bladed cements -locally etched during the meteoric episode- were slowly overgrown by a second stage of clear HMC.

It is possible that a «barrier», perhaps made of buildups similar to those described here, may have existed elsewhere and have been responsible for the restricted circulation (affecting salinity and resulting in specialized fauna and local precipitation of sulphates) on the platform during Phase 3. Alternatively, the restricted conditions of the upper part of Rhythm 0 may be explained by a platform of great extent and low gradients. The thin bioclastic levels interrupting the muddy sedimentation are interpreted as storm deposits transported from a more open sea some distance away -perhaps outside the postulated barrier.

Stage 8. The onset of the next sedimentary rhythm (+1) is characterized by the return of normal marine conditions and a diversified fauna (similar to Phase 1). As Rhythm +1 extends over an area as large as that of Rhythm 0, it is difficult to interpret the new trend as anything other than a sea-level rise (whichever hypothesis is adopted for the upper part of Rhythm 0). It is perhaps significant to note that the base of Rhythm +1 exactly corresponds with the top of the main buildup. Possibly the tops both of the postulated barrier and of discrete Bomel-like buildups had the same restrictive elevation. And, after filling of the inter-mound troughs, only a sea-level rise could restore open marine conditions on the whole platform.

10.- POSITION OF THE BUILDUPS IN THE SPECTRUM OF BELGIAN DINANTIAN «REEF» TYPES

Since the «type locality» of the mid-Dinantian Waulsortian «reefs» is in Belgium (see review by Lees, 1988), it is important to emphasize that the Bomel buildups are **not** Waulsortian. They differ from the Waulsortian buildups (Lees, Hallet & Hibo, 1985; Lees & Miller, 1985; and references therein) in several ways:

(1) Stratigraphic position. Waulsortian buildups formed in Late Tournaisian - Early Viséan times whereas the Bomel buildups occur in the Middle Viséan.

(2) Biotic constituents. The most conspicuous differences between the Waulsortian buildups and those described here are:
(i) crinoids and fenestellid bryozoans are the most common Waulsortian components whereas non-fenestellid bryozoans predominate at Bomel;
(ii) in the Waulsortian, cryptalgal coatings are minor in volume and are limited to the upper part of the buildups whereas in the Bomel buildups they are widespread and volumetrically dominant. They also show very well developed lamination which is rare in the Waulsortian; and
(iii) Waulsortian buildups lack a skeletal frame such as that developed in the Bomel buildups.

(3) Mud component. The Bomel buildups are not mud-mounds. They consist of a skeletal meshwork partially infilled with mud (generally peloidal and bioclastic), not like the Waulsortian which is often mainly wackestone.

(4) Cavity systems. As shown by Miller (1986), a Waulsortian reef-rock (his «bank facies») has typically a more complex cavity system, larger cement volumes and a more elaborate cement sequence than in Bomel. Actually studies in progress by A. Lees (pers. comm., 1989) have shown great variations of these parameters in the Waulsortian. For example, the Waulsortian Phases B and C in Belgium (Lees *et al.,* 1985) are commonly relatively poor in cements.

(5) Depositional environments. The Waulsortian buildups described by Lees *et al.* (1985) grew from subphotic depths, probably exceeding 300 m, to shallow conditions and possible emergence. On the contrary, the Bomel buildups completely developed under shallow conditions; a possible

subaerial exposure has also been proposed at the end of the buildup core development.

(6) Size. The Bomel buildups are very small when compared with the majority of Waulsortian buildups.

Few other, non-Waulsortian, buildups have been reported in the Dinantian of Belgium (all located in Fig.1 inset). Most are Upper Viséan. Several were briefly reviewed by H. Pirlet (in Paproth *et al.,* 1983, pp.209, 210 and 218) as stromatolitic limestone lenses with *Stromatactis:* Dinant area (Citadelle de Dinant; Chession-Leffe; La Valle-Bouvignes), Andenne area (Gaurre; Tramaka) and Bouffioulx. All are V3a (Fig.2) except the «Citadelle de Dinant» locality (V2b). Other cryptalgal buildups have been recently described in the V3b (Fig.2) of the Campine Basin, in the Visé area (Muchez & Peeters, 1987) and in the Heibaart and Poederlee boreholes (Muchez *et al.,* 1988 and 1991).

A more general review of cryptalgal-bryozoan buildups is beyond the scope of this paper. However, it is worth noting that the buildups reported from Newfoundland by Dix & James (1987) are strikingly similar to those described here and occur at about the same stratigraphic level.

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APPENDIX

For each studied section (Fig.1), the following information is presented in order: (1) outcrop reference number of the Geological Survey of Belgium; (2) brief description of the outcrop(s); (3) Lambert grid references in km; and (4) number of samples studied (=N).

1. Bomel, Pl. Namur 144 W n°23: (a) road cutting and low hill (185.36; 129.47); (b) eastern face of old quarry (185.48; 129.52); and (c) southern face of partially filled old quarry (185.55; 129.55); N=70 (non-buildup facies) and 101 (buildup facies).
2. St-Servais, Pl. Namur 144 W n°19: eastern face of old quarry (184.69; 129.63); N=50.
3. Lives-sur-Meuse, Pl. Champion 144 E n°36: river-side crags (189.74; 128.78); N=43.
4. Fond d'Arquet, Pl. Namur 144 W n°22: western face of old quarry (185.20; 129.68); N=0.
5. Vedrin, Pl. Namur 144 W n°409: natural exposure along stream (185.29; 132.13); N=39 (Hennebert & Hance, 1980).

All samples are lodged in Louvain-la-Neuve (given full address).