"We all allow, that the primary laws of nature are immutable — that all we now see is subordinate to those immutable laws — and that we can only judge effects which are past, by the effects we behold in progress."

Rev. ADAM SEDGWICK
(1785 - 1873)

G. L.

~~THE~~ SEDIMENTOLOGY AND PALAEOENVIRONMENTAL ANALYSIS OF THE MIDDLE JURASSIC ROCKS OF THE LOT VALLEY AREA, SOUTH–WEST FRANCE

BY

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ABSTRACT

A study of the Upper Toarcian to Upper Bathonian succession of the Cajarc area has revealed that at the end of the Toarcian open marine shelf conditions existed. This resulted in the deposition of the micaceous shales which now comprise the Larroque Formation.

Succeeding this is the Saint Martin Formation (60m) which commences with thin, fossiliferous bioclastic packstones that were also deposited in an open marine environment. In Middle to Upper Bajocian times a coastal barrier developed off the Massif Central and migrated westwards, resulting in the accumulation of thick oolitic limestones, some of which are now crystalline. These were deposited in both barrier and outer lagoonal environments.

As the barrier prograded further a tropical coastal lagoon complex became established in the Lower to Middle Bathonian, causing the accumulation of the Cajarc Formation (115m). This succession consists of oolitic grainstones, massive and laminated calcareous mudstones, lignitic marls and ostracod wackestones. The environment of deposition varied from subtidal lagoonal to intertidal, supratidal and lacustrine, with occasional sabkhas developing in the late Middle Bathonian.

Similar conditions probably existed in the Upper Bathonian when the Montbrun Formation (30m) was deposited. Despite subsequent brecciation, dolomitisation and dedolomitisation, it has been possible to discern the original succession which accumulated. Three mechanisms of brecciation have

been considered: tectonic, solution-collapse and hydraulic brecciation. These may all have played equal roles.

Rhythmic sedimentation occurred throughout the Middle Jurassic. It was probably controlled by subsidence.

Calcareous pseudomorphs after the following evaporites have been recognised:

- Nodular anhydrite
- Secondary anhydrite
- Discoidal gypsum
- Laminated gypsum
- Celestite

These were mostly formed in sabkha environments.

Large parts of the Saint Martin and Lower Cajarc Formations and most of the Montbrun Formation are composed of crystalline limestones. Originally these were dolomitised, either penecontemporaneously or during later diagenesis and subsequently became dedolomitised during uplift and erosion.

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The staff of the British Museum (Natural History) have been most helpful in identifying the fossils of the Cajarc area. Particularly, I would like to thank Dr. N. Morris (Mollusca), Dr. M. Howarth (Cephalopoda), Dr. H. Owen (Echinodermata), Mr. E. Owen (Brachiopoda), Dr. R. Bate (Ostracoda), Dr. C. Hill (Plantae) and Mrs C. Comben (Library).

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CONTENTS

CHAPTER 1

INTRODUCTION

Geologists have been interested in the Mesozoic rocks of Aquitaine since the mid - 1800's but it is only recently, with exploration for oil, gas and minerals, that economic interest has been aroused. Although a wealth of data has come from this work, very little detailed research has been published, and most of this has dealt with regional variations in lithology, thickness and environments of deposition, giving only general interpretations.

It has been the aim of the present study to complement these excellent regional studies by making a comparison of the rocks of a small part of the Mesozoic succession, with sediments being deposited in various parts of the World at the present day. As, from a perusal of the literature, it appears that no detailed work has been carried out on the Upper Toarcian to Upper Bathonian rocks of Eastern Aquitaine, this part of the succession has been chosen for such a study.

1.1 <u>The location of the Study Area</u>

The location of the area which has been studied is on the eastern margin of the Aquitaine Basin, centred on the town of Cajarc, in the department of the Lot (figure 1). This area has been chosen because the rivers Lot and Célé have cut deep valleys through the Bathonian and Bajocian rocks to give excellent exposures. Furthermore the rocks are structurally uncomplicated and thus

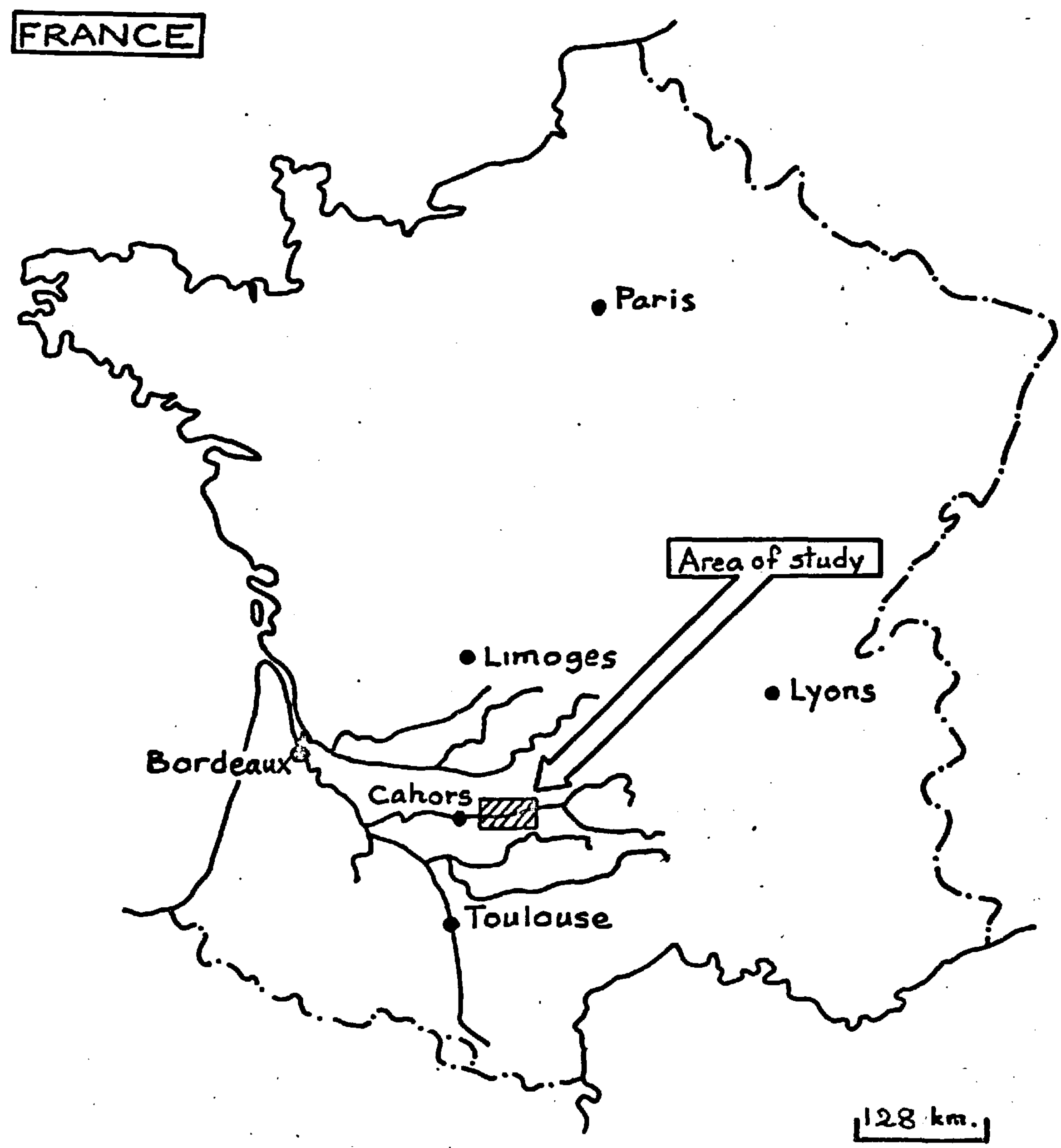


FIGURE 1 Location of the area of study.

Road Map.

Carte Michelin, scale 1/200,000.
Number 79, Bordeaux-Montauban.

Topographical Maps.

Cartes de France, scale 1/50,000., published by the Institut Geographique National.

Numbers	XXI	- 38, Saint Gery.
	XXI	- 39, Cahors.
	XXII	- 38, Figeac.
	XXII	- 39, Villefranche-de-Rouergue.

Geological Maps.

Carte Geologuque de la France, scale 1/80,000., published by the Bureau de Recherches Geologiques et Minieres.

Numbers	194,	Gourdon.
	195,	Figeac.
	206,	Cahors.

FIGURE 2 List of the maps covering the area of study.

they are ideal for sedimentological studies.

The relevant maps that cover the area are listed in figure 2. All grid references which are quoted in the text, have been taken from the topographical maps.

1.2 The Method of Study

The Upper Toarcian to Upper Bathonian succession of the Cajarc area is composed almost entirely of calcareous sediments. In the field stratigraphical sections have been measured, and the lithologies of the sediments have been recorded, in the form of logs, to a scale of 1 cm representing 1.5 m. An Abney Level and a Jacob's Staff have been used to measure the sections, and the lines of section have been marked at 1.5 m intervals, with spots of orange paint. Samples have also been collected at the same intervals to allow more detailed analysis in the laboratory.

Most of the field identifications have been made by using a hand lens on wetted, fractured surfaces. Difficult or more interesting types were flattened, using a glass plate and carborundum powder, and then either an acetate peel was made, or the surface was laquered, and then examined under a binocular microscope.

In the laboratory the petrology of the sediments has been investigated using acetate peels and thin sections. Polished slabs have also been made of selected samples for the study of sedimentary structures. The mineralogical composition of the sediments has been determined mainly from thin secticns, but in some cases confirmation has been sought by the use of X-ray diffraction or election probe analyses.

Each rock type has been considered in the following way:

Observed Properties	Comparison	Interpretation
grain size grain types mineral composition sedimentary structures fauna and flora diagenetic modifications	comparison with possible Recent analogs	Environment of deposition, diagenetic process, etc.

Although the range of types of calcareous sediments has been found to be almost infinite, it has been possible to divide them into broad lithological groups. Further, each of these groups appears to represent a particular environment of deposition, and following Bathurst (1971, P102 - 107) each group has been called a lithofacies type. On the section logs presented in this thesis (enclosures 1 to 10), detailed descriptions have been made of each sediment type. These are followed by lithofacies names so that the reader may refer to the text for more general discussions and interpretations of the sediments.

Also, the analysis of these rocks has made it possible to divide the succession into four lithologically distinct formations, listed in figure 3. Each of these will be discussed separately and the component lithofacies types will be described, together with their vertical and lateral distributions. Furthermore, an understanding

Chronological subdivision		Groups (series of French geologists).	Units recogn- ised on map for Gourdon.	Units recognised in Quercy by Delfaud and others since 1966		Units recognised by Daukoru (1970) in the Dordogne	Units recognised, in this thesis, in the Cajarc area.	
							Formations.	Members.
MIDDLE JURASSIC (DOGGER).	Callovian.	ROCAMADOUR GROUP.	Oxford- Callovien. J^{2-1}.	J_{B2}				
	(upper)		Bathonien Superieur. J_{i}.	J_{B1}	Marnocalcaire de Lacave (inf)	Blagour Breccia.	Montbrun Formation.	St. Suplice Mb. Chateau Mb.
	Bathonian.				Calcaire de Rocamadour (inf)			
	(lower)	AUTOIRE GROUP.	Bathonien Moyen et Inferieur. J_{ii-iii}.	J_A	Marnocalcaire de Cajarc.	Gluges Calcilutite.	Cajarc Formation.	Brenges Mb. Marcilhac Mb. La Plogne Mb.
								Larnagol Mb.
	Bajocian.		Bajocien. J_{iv}.		Calcaire de Autoire.	Mirandol Oolite.	St. Martin Formation.	Corn Mb. Ceneviers Mb. Latoulzanie Mb.
LOWER JURASSIC (LIAS)	Toarcian.	ST. ANTONIN GROUP.	Toarcien. I_4	L_4	Marnes de St. Antonin.	Floirac Shale.	Larroque Formation.	

FIGURE 3, Correlation chart showing the various subdivisions that have been made of the Middle Jurassic sediments of Quercy, compared with those recognised in this thesis.

of these rocks has made it possible to compare them with Recent sediments, and this has enabled the geological history of each formation to be considered in terms of present day processes.

1.3 Nomenclature

Dunham's (1962) classification has been chosen to name the rocks of the Cajarc area. This reflects the depositional textures of the limestones but it does not describe the component grains. However, Folk (1959) proposed a nomenclature describing grain types which has been adopted herein and used to prefix the textural descriptions implied by Dunhams classification, e.g. bioclastic-packstone, ooid-grainstone, intraclast - peloid - grainstone. Where diagenesis has been intense it has been necessary to adopt certain other names which will be discussed wherever appropriate.

The lithofacies types have been named after the most typical lithology developed therein. However, the members and formations that have been established, have been named after the locations where they are best exposed. The apparent symonyms of these units, erected by previous workers, can be found in figure 3. It should be noted that French geologists are currently employing the term 'Series' for groups of rock formations which should be classed as 'groups' according to current stratigraphic practice; for example the Cajarc and St. Martin Formations have been called the Series de Autoire, whereas they should be called the Autoire Group. In this thesis the term 'group' is used.

1.4 A Review of Previous Work

The first workers to become interested in the Jurassic rocks of Aquitaine were the geologists of the Service de la Carte Geologique de la France, who began mapping the region in the mid - 1800's. Since then interest has been sporadically maintained, until 1945, when exploration for hydrocarbons started and the phase of modern studies commenced. Several reviews have already been written concerning the work published before 1966. The first, by Delfaud (1967), mentions most of the work between 1842 and 1966, and another by Daukoru (1970), briefly discusses the publications between 1841 and 1965. Here, only the literature concerning the Middle Jurassic rocks will be reviewed and no attempt will be made to discuss papers written prior to 1966.

Since 1965 a multitude of papers have been published on the geology of the area, largely as a result of the exploration by petroleum companies operating in Aquitaine. Jean Delfaud of the University of Bordeaux, has played a leading role in the understanding of the Jurassic rocks in the sub-surface. Through his studies, Delfaud has become well aquainted with the sedimentology and stratigraphy of the Jurassic rocks of Aquitaine, and, with the assitance of the workers of the Centre de Recherches de Pau (S.N.P.A.), he has also accumulated much mineralogical and geochemical data.

The first two important papers published since 1965, were written by Delfaud (1966) and Delfaud and Henry (1976). These were both specific papers which described the stratigraphy, palaeontology and sedimentology of the Mont Sacon and Central Pyrenean areas respectively.

They also attempted to establish a notation for correlation that has been consistantly used ever since.

In 1969 Delfaud presented his doctoral thesis at the University of Bordeaux. In 1970 this was published as a special volume by the Société Linnéenne de Bordeaux, but some of the research had already been published, prior to 1969, in Delfaud (1967) and Delfaud and Gauthier (1968). These papers outline the stratigraphy and sedimentology of the Middle Jurassic rocks of Aquitaine. In the 1967 paper a reference sequence was established in N.W. Aquitaine, using ammonities. This was then traced eastwards into the poorly fossiliferous limestones of eastern Aquitaine, thereby establishing a scheme of lithostratigraphic correlation. Such a method was successfully employed as early as 1895, by Glangeaud, but Delfaud's work has confirmed the correlation and also added much more detail.

In 1968 Delfaud and Gauthier established the correlation scheme more definitely when they presented two general stratigraphic sections representing the shale and limestone sequence of Western Aquitaine (Charentes) and the limestone sequence of Eastern Aquitaine (Quercy), respectively. Mineralogical and geochemical data, for the carbonates and clays were also presented in conjunction with details of the fauna and the supposed environments of deposition of the rocks. Unfortunately, however, this was not presented in a very detailed manner.

The Jurassic palaeogeography was also considered and three main environments were recognised; haute-mer (open ocean); neritique; and sub-continental. The later two may be translated as meaning lagoonal environments behind a barrier complex that ran north-south through central Aquitaine.

Both the 1969 paper and the thesis contain isopach and palaeogeographical maps for the Jurassic rocks of the whole of Aquitaine.

At about the same time the geologists of the S.N.P.A. at Pau also began publishing results on the Jurassic rocks. But, whereas Delfaud's studies were concerned mainly with sediments at outcrop, the petroleum geologists had the opportunity to examine the same rocks in the sub-surface. Much of the information made available by the sub-surface studies was published by Bouroullec and Deloffre (1969), who described the sedimentology, stratigraphy and palaeogeography of the sub-surface Jurassic rocks of the whole of Southwest Aquitaine.

In 1970 Delfaud and Lenguin wrote a short note describing 'plate-forme' carbonate sedimentation using the Bathonian and Callovian rocks of the region of Quercy as an example. The plate-forme zone was described as being composed of a coastal lagoonal complex enclosed by a high energy barrier zone. In previous papers it had been called the neritique and sub-continental zone. Four environments of deposition were recognized: supratidal lagoonal, represented by unfossilferous micrites with gypsum pseudomorphs, lignitic clays and marls; intertidal lagoonal, represented by laminated limestones with birdseyes, intraclastic rocks, and micrites with ooids and gastropods; subtidal lagoonal, represented by decimetre - bedded micrites with Trocholina, micrites with algal balls and micrites with benthonic faunas; high energy or barrier zone, represented by massive or cross-bedded oolitic limestones, sometimes with coral debris. The authors considered the lagoons to be comparable with those of the present Persian Gulf.

Also in 1970 E.M. Daukoru presented a doctoral thesis at the University of London, on the palaeontology, sedimentology and stratigraphy of Upper Toarcian to Upper Kimmeridgian rocks in the Dordogne and Alzour valleys on the eastern margin of the Aquitaine Basin. Unfortunately he did not become aware that other studies were being conducted at the same time until he had nearly finished his research, and thus he worked almost completely independently. Even so, his sedimentological and straigraphical conclusions seem to have been reasonable, and they are broadly in agreement with those of the French geologists. He did not, however, relate any of his data to detailed stratigraphical sections, measured in the field. This is a shortcoming of many studies that have been made of the Jurassic rocks of Aquitaine.

A large part of Daukoru's thesis was concerned with the palaeontology of the rocks of the region. Considerable numbers of fossils were recovered and identified, but no photographs or diagrams were presented and regretfully none of his collection has survived. Thus, it has not been possible to check the identifications or to make comparisons with the fossils collected by the present writer. Unfortunately this makes much of Daukoru's palaentological data unusable, which is lamentable because he is one of the few people to have looked closely at the fauna of the

Middle Jurassic limestones since the early years of the 20th Century.

1970 also marked the beginning of more specialised studies, when Bouroullec and Deloffre published an inventory of the algae that have been found in the Jurassic rocks of Aquitaine, together with photographs and descriptions.

Delfaud (1971a) reiterated much of what had already been said in previous publications: he discussed the environments of deposition of the Jurassic rocks of Perigord and Quercy, and he outlined the usefulness of sequential analysis in establishing the stratigraphy of poorly fossiliferous rocks.

In a second paper (Delfaud, 1971b) he discussed the provenance of the clay minerals of the sediments of the Mesozoic Basins of France. He distinguished two types of association: subcontinental clays which were often associated with lignites - these were deposited in areas marginal to land masses; and open-marine clays associated with ammonities. Also in 1971, Delfaud and Lenguin considered some aspects of the petrology of the limestones of Quercy.

In 1972 Faber published an account of the Jurassic evaporitic deposits that have been found in the sub-surface in Southern Aquitaine. In the same year Delfaud (1972) discussed further the applications of sequential analysis of lithostratigraphic sections, using the Jurassic and Lower Cretaceous rocks of Aquitaine as an example. He emphasised the importance of making lateral comparisons between the various vertical successions in Aquitaine and he showed how correlation has been achieved. An updated regional lithostratgraphical correlation chart was also given.

Three other papers appeared in 1972 which concerned specific regions in Western Aquitaine: the first (Cassouldebat et al. 1972) described the sedimentology stratigraphy and environments of deposition of the Jurassic limestone of the Grands Causses, south of the Massif Central; the second (Capdeville et al, 1972) discussed the origin of the high energy oolitic sediments in the Perigord region; and the last paper (Bouroullec et al, 1972) described the petrography, and the origins of the laminated limestones of Quercy.

1972 also saw the completion of a book called 'Microfacies du Jurassique d' Aquitaine', written by Carozzi et al (1972) and published by the Centre de Recherches de Pau (S.N.P.A.). This was an improvement of the work already published by Bouroullec et al (1969). In it, were considered the rocks of the explored subsurface areas of Southern Aquitaine. All the lithological types that had been encountered were described together with photomicrographs, and these were accompanied by valuable discussions on lithostratigraphy, dating, geochemistry and the environments of deposition. The following more detailed subdivisions of the environments were also presented:

a) Lagoonal (plate-forme interne)
- subtidal (infracotidal)
- intertidal (intercotidal)
- supratidal (supracotidal)
- lacustrine.

b) Barrier (Haut fond)

c) Open Marine (plate-forme externe)

In 1973 Delfaud produced another three papers in which he discussed: the various types of reefs that possibly existed in the Jurassic; the various types of dolomitisation in Aquitaine; and a general summary of the Jurassic palaeogeography of Southern France. In the latter paper he put forward the concept of the 'Haut Fond Occitan' that was a positive area, running north - south through the Massif Central and the Pyrenees, which separated the Aquitaine and Subalpine depositional basins and controlled Jurassic sedimentation.

Finally in 1973 the Bureau de Recherches Geologique et Minieres, in conjunction with ELF - Re, ESSO-REP and the S.N.P.A., published a superb atlas called the 'Geologie du Bassin d'Aquitaine', which was a compilation of all the stratigraphical, sedimentological and palaeogeographical information that had been accumulated up to that date. The data was presented mainly in the form of maps, including isopach, palaeogeological and geophysical maps. Correlated sections of the rocks at outcrop and in the sub-surface were also presented, together with short descriptive and interpretive texts.

The section concerning the Jurassic rocks was written by Winnock et al (1973) and it compliments the textural descriptions given by Carozzi et al (1972). Together these two volumes form the most up to date and complete account of the geology of the Jurassic rocks of Aquitaine.

1.5 <u>The Depositional History of the Middle Jurassic Rocks of Aquitaine</u>

To understand the Middle Jurassic sediments of the Cajarc area of the Lot Valley, it is helpful to have some

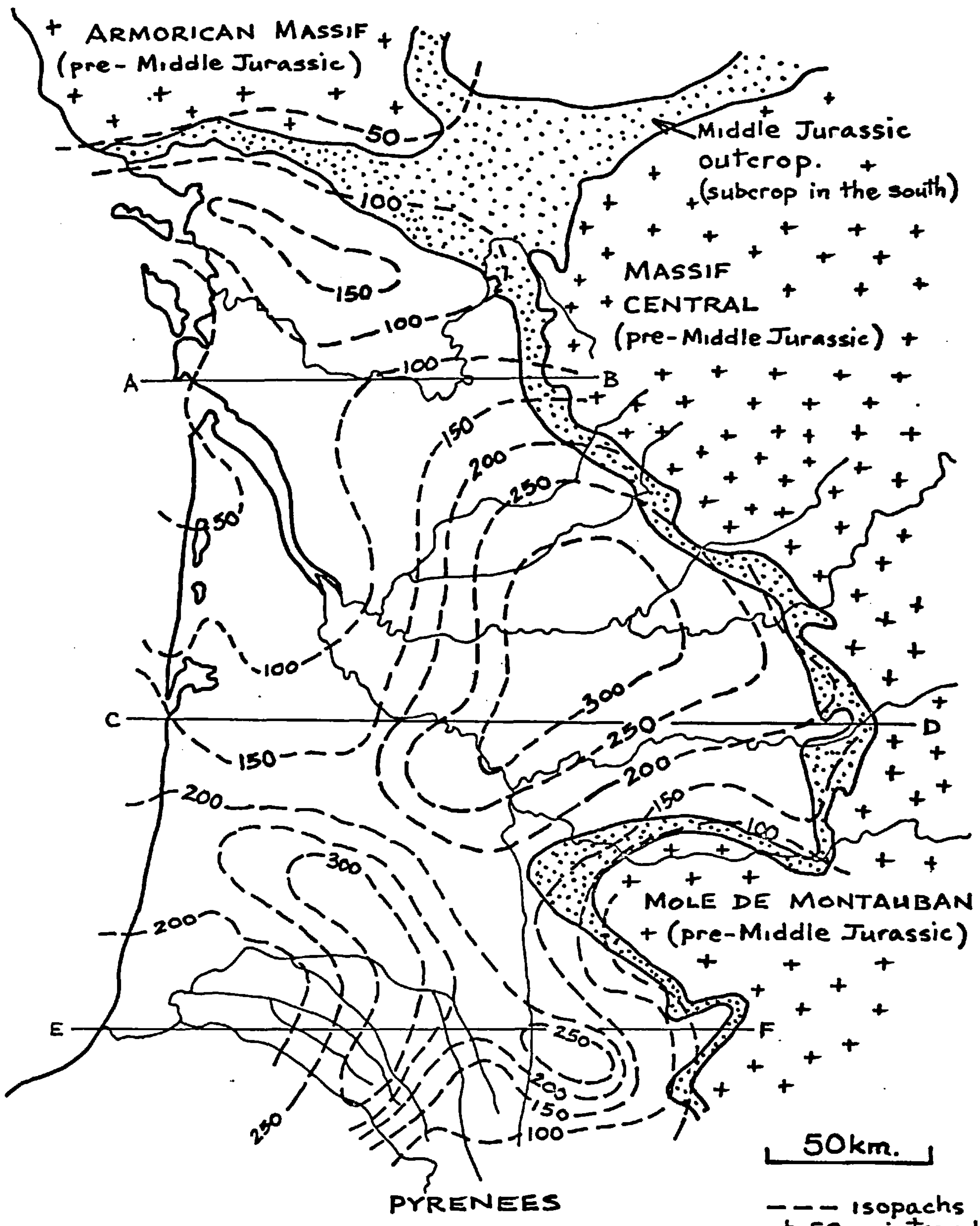


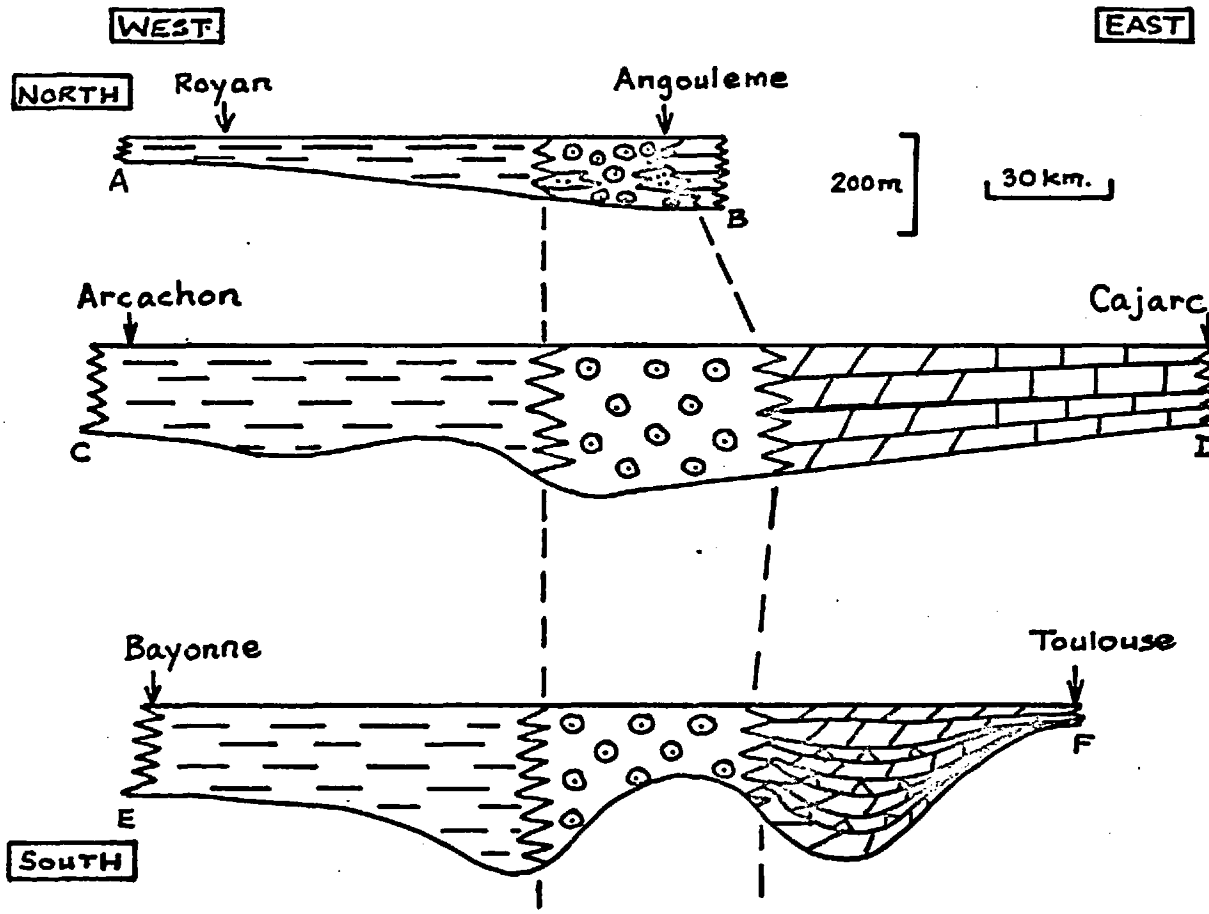
FIGURE 4 Map of Aquitaine showing the outcrop and sub-surface isopachs of the Middle Jurassic rocks, (taken from Winnock et al., 1973).

knowledge of the factors that controlled the deposition of sediments in the region. For this purpose a brief summary will now be made of the account given by Winnock et al (1973), in order to provide a background for the more detailed studies described in the following pages of this thesis.

Two elements seems to have dominated the depositional history of the Jurassic rocks of Aquitaine (see figure 4): in the west a subsiding basin and to the east the positive area of the Massif Central named by Delfaud (1973) as 'le Haut Fond de Occitan'. These two elements not only controlled the depositional history, but also the depth of burial, diagenesis, and subsequent uplift and erosion of the sediments.

For much of the Jurassic period the positive area seems to have been a landmass. Sometimes it may have been covered by shallow seas, but little or no sediment was deposited on it. In contrast, deposition appears to have been fairly continuous in the subsiding basinal area to the west, where open marine conditions, similar to those found on present day continental shelves, prevailed.

The Jurassic climate appears to have been tropical, perhaps varying from arid to humid. Also the sediment input from the Massif Central seems to have been very low. These conditions apparently provided an ideal setting for the deposition of calcareous sediments. In Bajocian times a coastal barrier complex composed of oolitic sands developed along the western margin of the Massif and this persisted throughout the whole of the Middle Jurassic. Once the barrier had become established, coastal lagoons also developed around the Massif.



ENVIRONMENT.	OPEN MARINE SHELF.	COASTAL OOLITIC BARRIER	COASTAL LAGOON
LITHOLOGY	Argillaceous limestones, marls and shales with cephalopods. Also limestones with "microfilaments".	Oolitic grainstones, mostly dolomitised except in the north; a few reefs also in the north.	Lagoonal calcareous mudstones and grainstones, dolomitised in many places. Interbedded evaporites in the south.

FIGURE 5 Diagramatic cross-sections of the Middle Jurassic rocks of the Aquitaine Basin showing the relationship between thickness, lithology and environment of deposition (after Winnock et al., 1973). The lines of the sections may be found in figure 4.

The general palaeogeography of Aquitaine may be seen in figures 5 and 6. Open marine continental shelf conditions are thought to have existed to the west (plateforme externe), and coastal lagoonal conditions in the east, these being separated by a coastal barrier complex.

Sediments thought to have been deposited in an open marine environment consist typically of shales or marls with ammonities and belemnites, interbedded with argillaceous limestones or limestones with microfilaments (Carozzi et al, 1972). Nearer shore areas are thought to be represented by bioclastic limestones which often show condensed sequences. The barrier zone was dominated by the accumulation of oolitic limestones which have subsequently largely been dolomitised. In the coastal lagoons, where conditions varied from subtidal to supratidal, mainly muddy and peloidal limestones were deposited, with the former being most abundant.

Generally these three groups of sediments are representative of the lateral facies variations that have been found in the Middle Jurassic sediments of Aquitaine (figure 5).

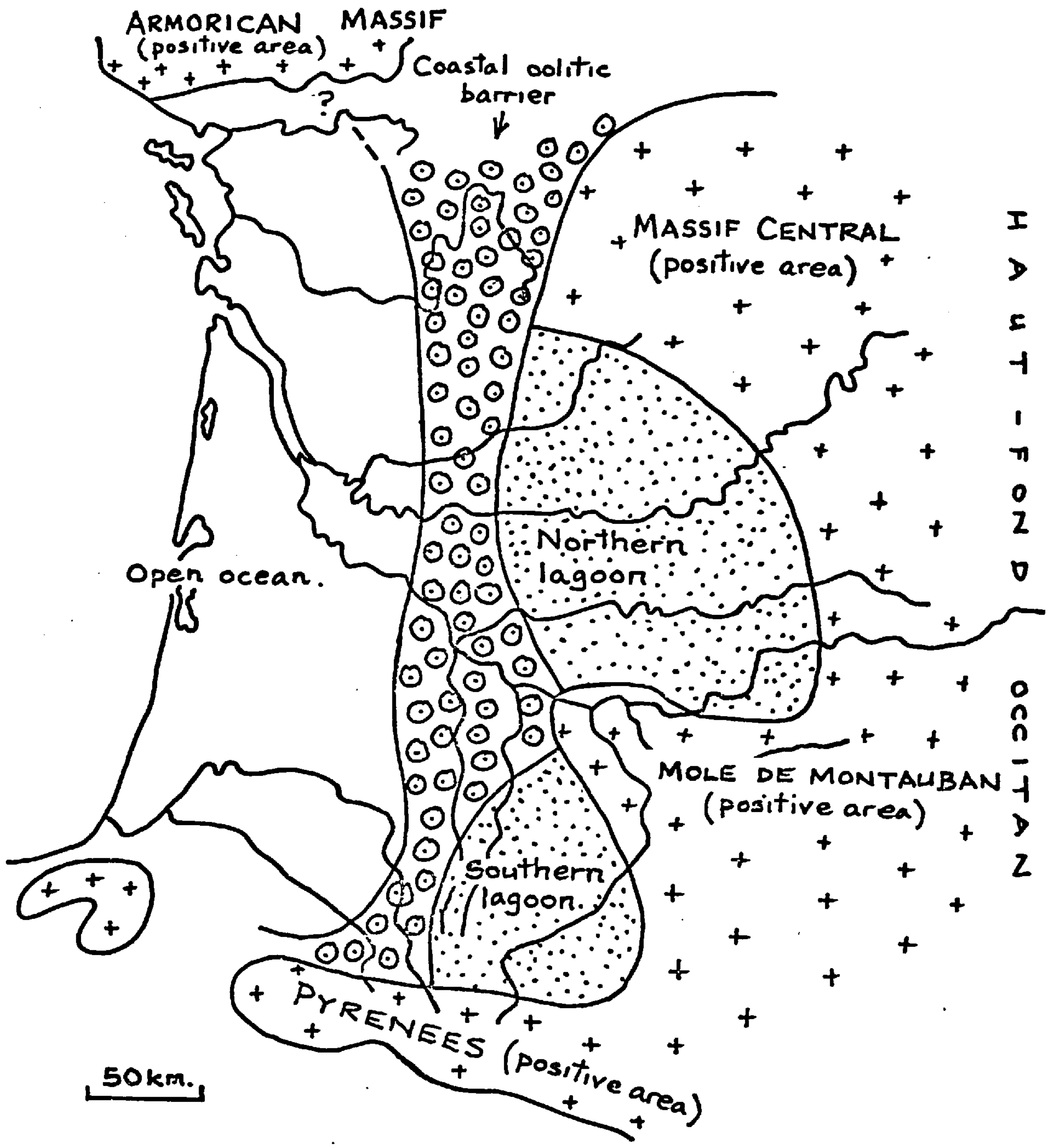


FIGURE 6 The palaeogeography of Aquitaine in Middle Jurassic times (after Winnock et al, 1973, and Delfaud, 1971, 1973).

However the picture is not quite as simple as this becuase, as in the Cajarc area, there is also a vertical passage through these groups of sediments in Lower to Middle Jurassic times, indicating a change from open marine, through barrier, to lagoonal conditions. This succession is thought to have resulted from the establishment of an oolitic barrier around the Massif Central, in early Bajocian times, which prograded westwards during the middle and upper Bajocian, to eventually become established as indicated in figures 5 and 6. Once this palaeogeographical pattern had stablised the accumulation of sediments resulted in the typical east - west facies variations shown in figure 5.

From the isopach and palaeogeographical maps, presented in figure 4 and 6, it has been possible to show that two coastal lagoonal complexes existed to the west of the Haut-Fond - Occitan in the Middle Jurassic; one to the north and the other to the south, separated by a positive area called the ' Mole de Montauban'. The northern lagoon covered the present site of the Causses of Perigord and Quercy, including the Cajarc area. The southern lagoon was situated in the region west of the river Garonne, and Faber (1972) has described evaporitic deposits from the Middle Jurassic of this latter area.

1.6 The Post-Depositional History of the Middle Jurassic Rocks of Quercy

Calcareous and evaporitic sediments are very susceptible to diagenetic alteration, and they are often altered beyond all recognition from their original depositional state.

Thus, to determine the original environments of deposition of such rocks, it is necessary to be aware of the diagenetic processes that might subsequently have operated. These processes seem to depend mainly on the course of the post depositional history of the rocks; such as for instance whether they have been deeply or shallowly buried, or what types of porewaters have flowed through them, and whether or not they have been exposed for long periods, both before and after burial.

In the case of the Middle Jurassic rocks of the Cajarc area it has been possible to trace their post-depositional history, and also to determine some diagenetic processes which appear to have operated. These are discussed, where relevant, in the following chapters, but a brief outline of the framework of events in which the diagenetic changes took place, will now be given.

According to isopach maps of Mesozoic and Tertiary rocks, published by Delfaud (1970) and B.R.G.M. etc (1973), the topmost Upper Bathonian sediments of the Cajarc area have been buried to a depth of at least 900 metres since their deposition, after the later Jurassic no significant thicknesses of sediment have accumulated above them. Furthermore, it has become apparent that the Massif Central has gradually been uplifted since later Jurassic - early Cretaceous times, continuing into the Tertiary, and consequently the Jurassic deposits have been uplifted into a dome-shaped structure with an outward regional dip of 1 or 2^{o}.

Gignoux (1950, p493 - 495) has shown that continental desert conditions prevailed over Quercy in the Eocene. He also noted that small pockets of 'Siderolithique' (probably residual lateritic or terra rossa soils)

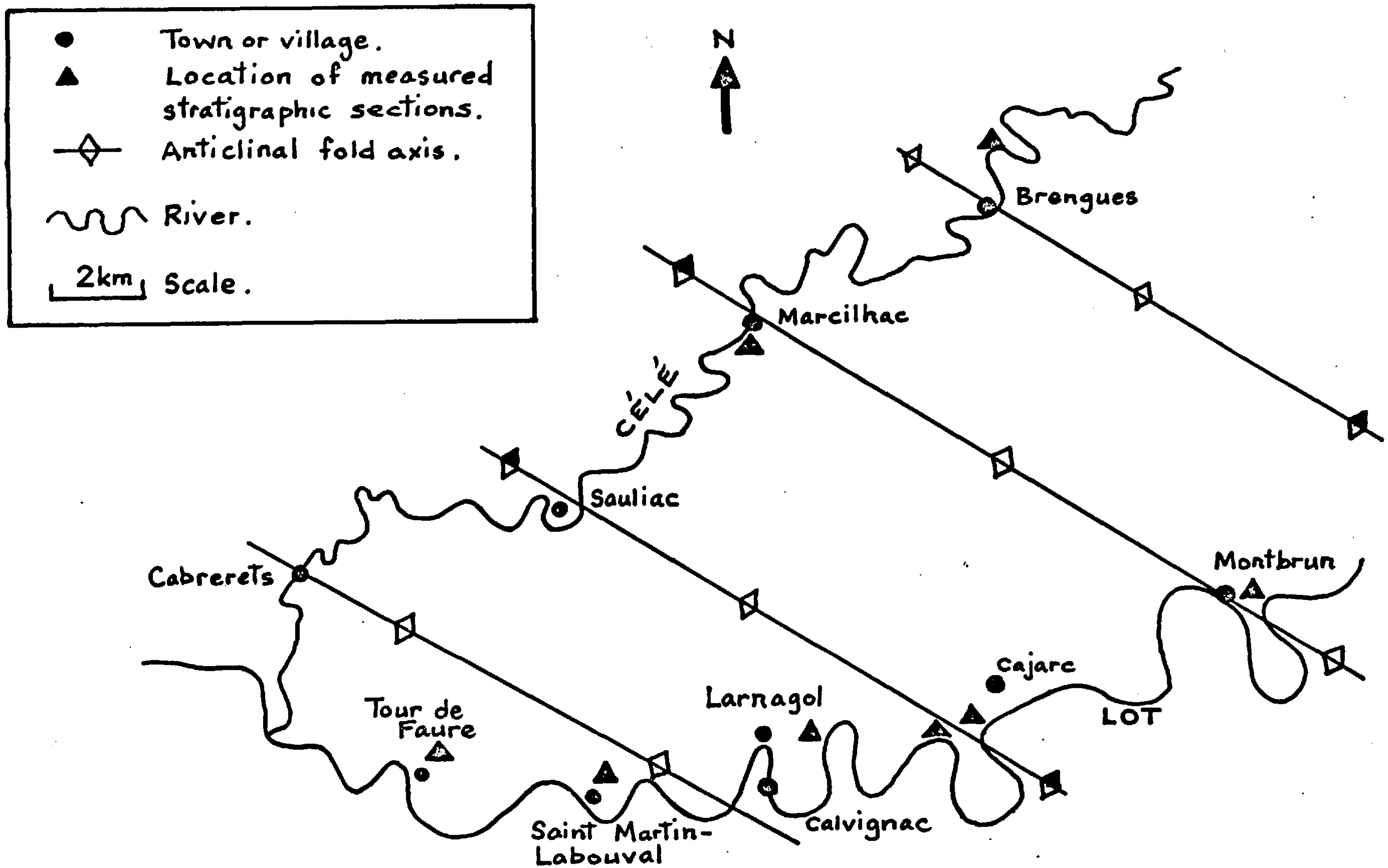


FIGURE 7 Sketch map of the area studied, showing the locations where stratigraphic sections have been measured. Also shown are the axial traces of the main folds in the area; note the absence of synclinal folds.

were deposited, and fissures in the karst surface which developed, were infilled by the famous phosphatic accumulations of Quercy (Thevenin, 1903). These sediments unconformably overlap the whole of the Middle and Upper Jurassic sequence in the Cajarc area. Thus it is possible to say that by late Eocene times, much of the dome, uplifted over the Massif Central, had been eroded away. Moreover, because the siderolithique rests directly ontop of the present-day plateau surface of the Causse, it is likely that this represents an early Tertiary land surface, and apart from the incision of the east - west rivers, such as the Lot, very little change seems to have taken place since Tertiary times.

After deposition, the Middle Jurassic limestones of the Cajarc area have also been folded into a series of gentle anticlines, trending ENE - WSW, with the dip on the limbs never exceeding 5°. The main fold axes are shown in figure 7, and it is interesting to note that, as yet, no complementary synclines have been found (see figure 8b).

On the geological maps of the Lot Valley, this folding may be shown to be pre-Siderolithique, and because it affects the whole Jurassic sequence it is of course post Jurassic. Because the folds are parallel to the southwest margin of the Massif Central, it seems probable that they are related to the uplift of this Massif. As already noted the uplift probably caused the formation of a dome of Jurassic rocks by drape folding, and subsequently the action of gravity on the mass of rock flanking the dome, might have set up a lateral buckling stress which

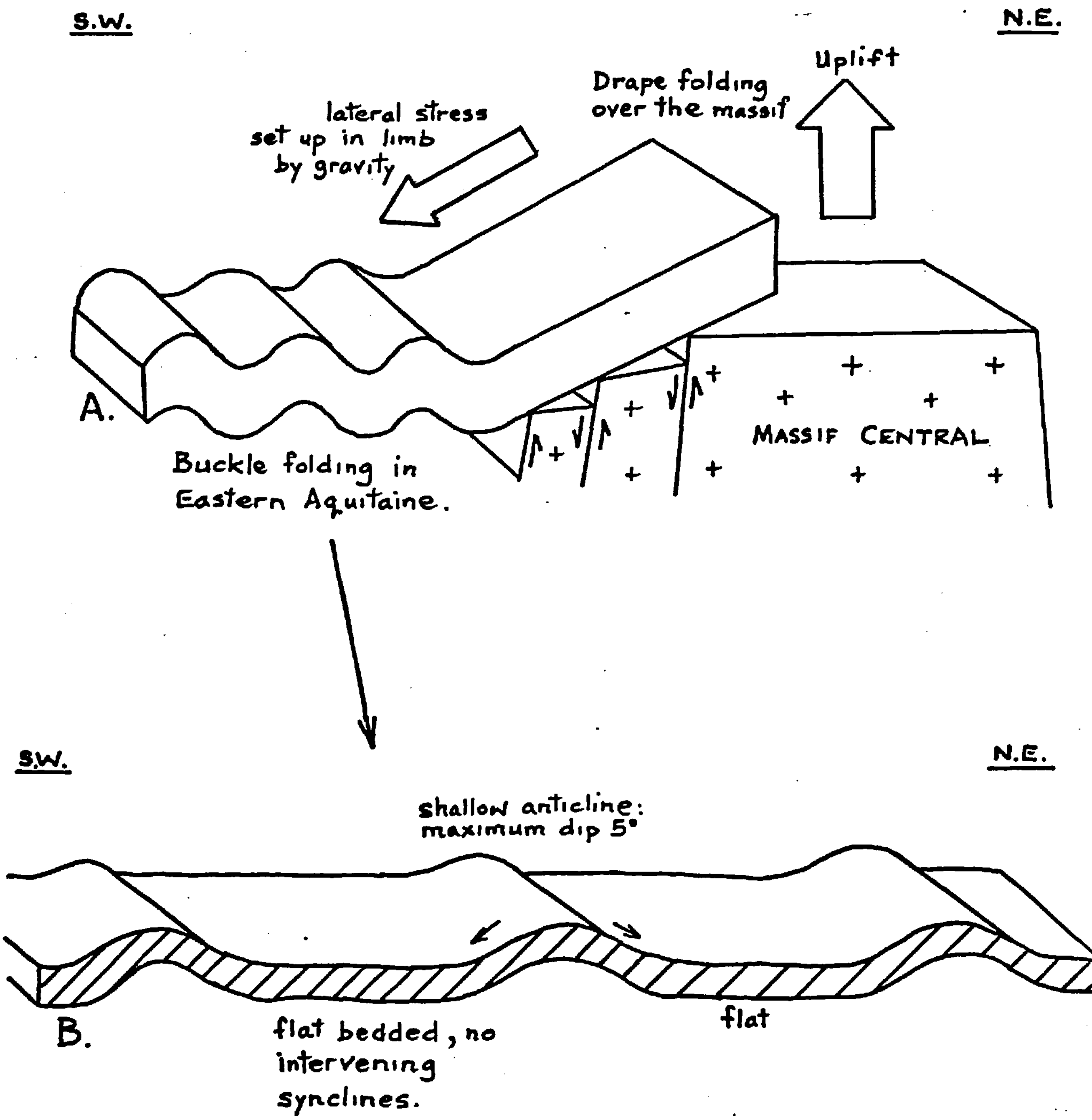


FIGURE 8 A) Diagram illustrating the proposed mechanism of folding of the Jurassic rocks of eastern Aquitaine.

B) Diagramatic cross section of the folded Middle Jurassic rocks of the Cajarc area.

caused folding to occur down dip (see figure 8a). This mechanism is not inconsistant with the pattern of folding that has been found in the Cajarc area (see figure 8b).

Apart from the incision of east-west flowing rivers, such as the Lot, very little erosion seems to have taken place since later Tertiary times. On the valley sides, enormous quantities of scree have been found which mask earlier cliffs. These screes are now mostly inactive and heavily vegetated by oak scrub. Where quarried the screes have been found to be composed of angular fragments of limestone which are now well cemented and steeply bedded.

Monkhouse (1967, fig.110) has shown that, in the Quaternary, Central and Southern France was a periglacial zone, situated between the ice caps of Northern Europe, the Alps and the Pyrenees. It was under this climatic regime that the screes were probably formed. It was also probably at this stage that the huge river valleys, now with markedly shrunken discharges, which are so typical of the causses, were formed while the ground was permanently frozen and the water discharge greatly increased, because of the summer thaw. In the caves of the area much evidence has been found to indicate that they were inhabited by prehistoric man, sheltering from the harsh climate.

Today the climate is of the cool temperate continental type, with a summer maximum of rainfall. Thin soils have developed on the limestone plateau of the Causses, and in the valleys considerable thicknesses of micaceous silt derived from the igneous and metamorphic rocks of the Massif Central, have been deposited. This has given rise to some rich agricultural land which contrasts strongly with the poor sheep grazing country of the Causses.

CHAPTER 2

THE LARROQUE FORMATION

The Larroque Formation is the basal unit of the rocks that have been studied in the Cajarc area. It has been named after the Village of Larroque Toirac, which is built on an outcrop of the formation. Only one stratigraphic section log has been made of the upper part of the Larroque Formation. This has been measured in the stream bed at Larroque - Toirac and is only 13.5 metres thick (see enclosure 10.), The lower parts of the formation have been examined at various isolated roadside exposures around Figeac, and also in the quarry at Puy Blanc, but it has not been possible to measure any sections of this part of the succession.

Lithologically, the Larroque Formation is composed almost entirely of micaceous shales. In the lower part of the succession some thin marly limestone bands are present, and in the middle a few layers of phosphatic nodules and ooids, are developed. In the topmost 2m. of the formation there are some beds of dolomitic - bioclastic - packstone and also a thin horizon of ferruginous - oolitic shale.

Outcrops of the Larroque Formation have been found at the base of the cliffs on the north side of the Lot Valley between St. Martin - Labouval and Larnagol. Unfortunately, because of their soft shaly nature, the sediments soon develop a soil cover and become colonised by vegetation, so usually they are only very poorly exposed. In most instances, the outcrop can only be detected by the presence of grassy or wooded slopes at the base of the cliffs formed by the red, cavernous limestones of the overlying St. Martin Formation. On the geological map of Gourdon (194), which includes the Cajarc area, rocks equivalent to the Larroque Formation have been mapped around Cajarc, but the present writer has found no evidence for this.

On the Gourdon sheet rocks equivalent to the Larroque Formation have been mapped as 'Toarcien (I^4)' and were described as "schists on marnes". The uppermost bed of this unit, called the "calcaires marneux à G.beaumonti", is considered in this thesis to be the basal part of the St. Martin Formation (see page 40). On the Cahors (206) sheet, covering the region to the south of the study area, the Larroque Formation has also been mapped as 'Toarcien (I^4)' and it was described as "marnes noires et calcaires marneux". Furthermore the formation may also be considered to be equivalent to the Marnes de St. Antonin (L^4), described by Delfaud (1971a), and the Floirac Shale of Daukoru (1970) (see figure 3).

In the present study, three lithofacies have been recognised in the upper part of the Larroque Formation; the micaceous - shale lithofacies; the ferruginous - oolitic shale lithofacies; and the dolomitised bioclastic - packstone lithofacies. The characters of these lithofacies will now, except for the dolomitic rocks (which are considered in the next chapter), be described and some environments of deposition will be suggested.

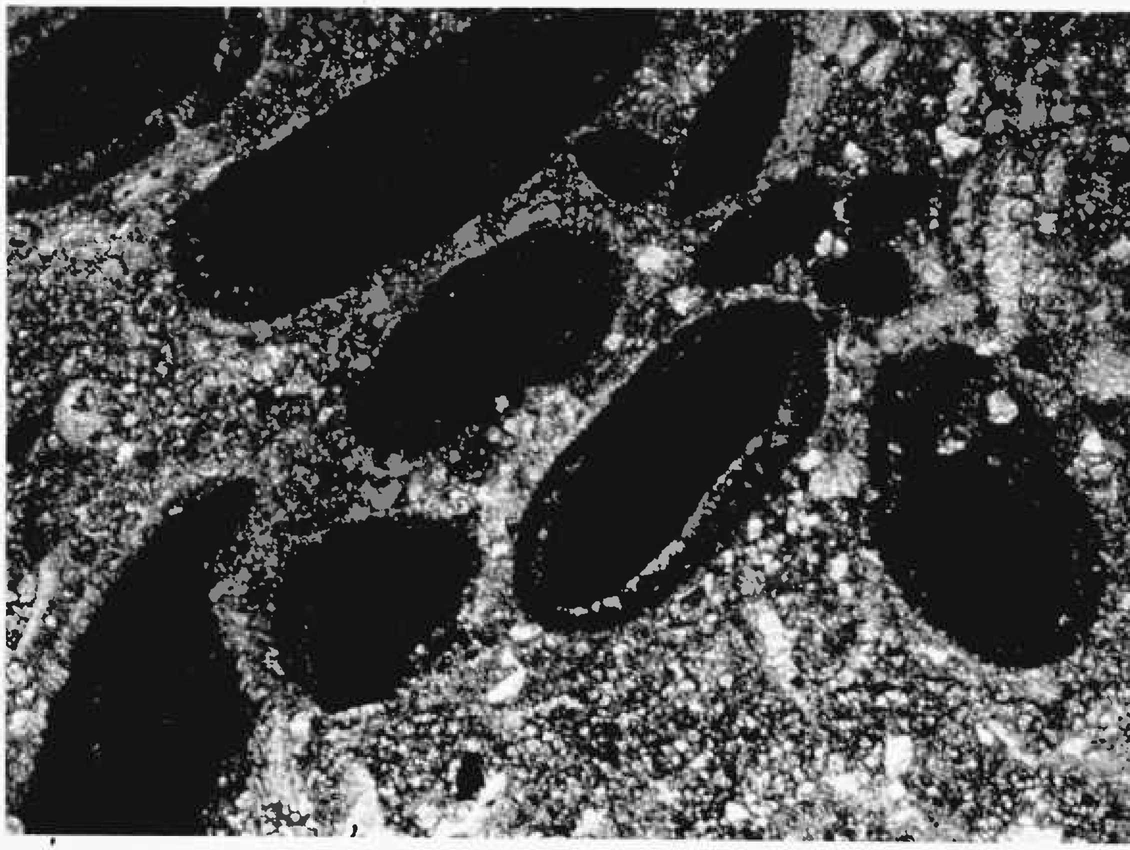
2.1 The Micaceous - Shale Lithofacies

Sediments of the micaceous - shale lithofacies form about 95% of the total thickness of the Larroque Formation. The best exposure of the lithofacies is in the stream section of Larroque-Toirac (159306) where the shales are typically dark grey, uncemented, millimetre - laminated clays and muds. Silt and fine - sand grade muscovite flakes are easily visible on bedding surfaces, and silt sized quartz grains have been found in minor amounts. X-ray diffraction analyses of whole rock samples have shown that both illite - and kaoline-group clay minerals are present in the shales together with possible chlorite. Small amounts of ankerite have also been detected.

The carbonate content of the shales increases markedly in the top 2m of the Larroque Formation. X-ray analyses have shown that most of this carbonate is in the form of ankerite, and in thin sections it appears as numerous silt-sized rhombic crystals set in a matrix of clay minerals (figure 9). Some calcite has also been found, but only in the form of bioclastic debris. The latter also become more abundant towards the top of the formation, and at Larroque - Toirac two hard, cemented bands of shaly quartzose - ankeritic - bioclastic wackstone/packstone each 50 centimetres in thickness, are developed at about 1.5 metres from the top. These bands are considered to belong to the bioclastic packstone lithofacies discussed on page 43 .

The Environment of Deposition of the Micaceous - Shale Lithofacies

Shales, or laminated silty claystones and mudstones, with a sparse fauna of cephalopods, are the most commonly developed of all Liassic sediments. They have been interpreted by many sedimentologists as being open marine continental shelf deposits. The accumulation of these Lower Jurassic sediments, over Northwest Europe, is thought to have taken place in a series of depositional basins situated between intervening highs or massifs.



A. (x65)

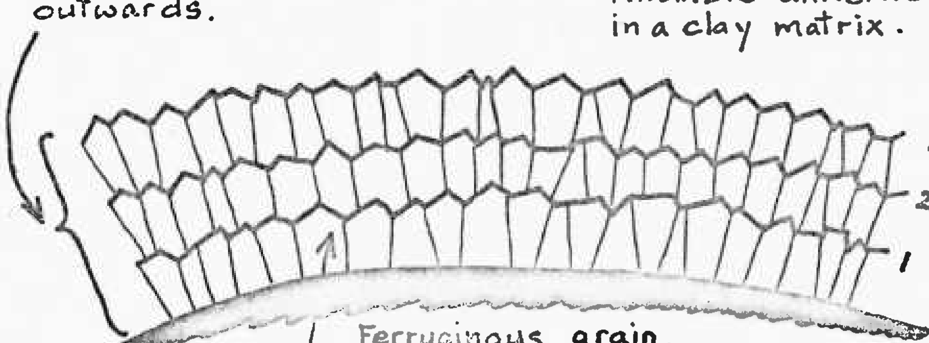


FIGURE 9., a) Photomicrograph of a ferruginous-oolitic shale with an ankeritic matrix, showing ferruginous grains with calcareous haloes (242/73; Larroque Formation at Larroque Toirac); and b) a detailed sketch of a calcareous halo.

One such basin probably existed across Aquitaine in the Toarcian, and it was at this time that the Liassic seas reached their maximum extent, transgressing over large areas of the adjacent metamorphic massifs (Bonnard et al, 1956). As a result, open marine conditions became established over most of Aquitaine, accompanied by the the deposition of micaceous and dolomitic shales, with a sparse pelagic fauna.

It seems reasonable therefore, to conclude that the micaceous - shales of the Larroque Formation, have probably been deposited in an open marine continental shelf environment, and on page 54 , an attempt will be made to verify this conclusion by making comparisons with some Recent depositional environments (figure 13).

2.2 The Ferruginous - Oolitic Shale Lithofacies

A thin band of ferruginous - oolitic shale is present at the top of the Larroque Formation, which is of the same age as the famous Minette ores of Lorraine. Above these there is a rapid passage into the bioclastic packstones at the base of the St. Martin Formation. The best exposures of this lithofacies are at Larroque - Toirac, and by the roadside near Latoulzanie (000245).

In thin section the ferruginous grains range in size from fine sand to very coarse sand grade. They are either structureless or oolitically coated and they vary in shape from elliptical to flattened and elongated (figure 9a). Furthermore, cavities formed by foraminifera and other skeletal debris, have been infilled with iron oxide. X-ray analyses have shown that this ferruginous material is made up of haematite and goethite, but no chamosite has been detected.

Minor amounts of anhedral, silt-sized grains of quartz, have been found in association with these ferruginous grains, together with a few fragments of bivalves and some benthonic formaninifera. All of these grains are set into a matrix of silt-sized, rhombic crystals of ankerite with interstitial clay minerals (figure 9). A small amount of siderite has also been detected on the X-ray trace of sample 168/73.

Some of the ferruginous grains are enclosed by haloes of radiating crystals of calcite (figure 9). By staining the thin-sections with a solution of potassium ferricyanide, it has been established that the calcite is iron-free. Using this technique the iron-rich ankerite crystals of the matrix were stained blue, thus highlighting the iron-free calcite crystals as clear, unstained zones surrounding the ferruginous grains.

Within the haloes, it has been observed that the calcite is stained brown by ferric oxide. The intensity of the staining increases towards, and sometimes concentric zones of staining have become developed. Normal ankerite crystals have been observed to surround the calcite haloes.

The origin of the haloes is thought to have been by the calcitisation of ankerite crystals (Fe-rich dolomite) around the ferruginous grains, so producing a zone of coarser calcite crystals. It is probable that during this process ferrous iron has been exsolved and that it has remained as a ferric oxide stain in the calcite crystals. This seems reasonable because, as the haloes have grown the staining appears to have become more intense as more iron became available. In some cases successive intense zones of ferric oxide have been preserved. These may record successive phases of calcitisation.

Although the successive zones have been found to be generally concentric, in detail they are irregular and mimic the composite boundary of the advancing front of the calcite crystals (figure 9b). This tends to confirm that successive phases of calcitisation have taken place, however, why this should have occurred preferentially around the ferruginous grains is not understood.

The Environment of Deposition of the Ferruginous - Oolitic Shales

As far as the writer is aware there is no known Recent environment where sedimentary grains, made up of iron oxides, are actually forming that are similar to those found in the upper part of the Larroque Formation. However, many ancient sedimentary iron deposits are composed of chamosite as well as iron oxide grains (e.g. Taylor 1949). As chamosite grains have frequently been found to be growing authigenically in present day open marine areas, (Porrenga 1967, Rohrlich et al 1969), and because these have occasionally been partially oxidised to iron oxides, it is possible that originally the ferruginous grains of the Larroque Formation grew as chamosite and were later oxidised to heamatite and goethite.

Rohrlich et al (1969) noted that, during diagenesis, chamosite may become oxidised and some of the iron can be expelled from its structure. Such an explanation might account for the iron rich haloes around the ferruginous grains of the Larroque Formation, and the change from chamosite to iron oxides could possibly have caused the dedolomitisation around the grains. Although the geochemistry of this process is far from clear, an understanding of it might confirm the original composition of the ferruginous grains.

Jones (1965) considered the ferruginous grains can form in either a marine or subaerial environment. In the latter, oolitic ferruginous grains grow by diffusion and oxidation of iron, in solid rock, during weathering, to produce iron-shot soils and oolitic laterites. However, a subaerial origin can immediately be discounted for the ferruginous - oolitic shales because no evidence has been found to suggest that subaerial exposure or soil formation has taken place. Indeed, the associated shaly sediments are considered to be indicative of open marine shelf conditions, and an unbroken sequence, together with a complete set of ammonite zones, has shown that breaks in deposition have probably not occurred, and a marine origin seems more likely for the ferruginous - oolitic shales of the Larroque Formation.

Both concentrically laminated or oolitic, and structureless, flattened ferruginous grains have been found in the ferruginous - oolitic shales. Jones (op. cit) considered that both these types could form in a marine environment. He envisaged that ooids could grow as hard brittle structures, by agitation on the sea floor, and that structureless grains form under tranquil conditions, in the surface layer of sediment, later being deformed while still plastic. Subsequently, however, Rohrlich et al (1969) found that chamositic minerals can become tangentially arranged around faecal pellets or detrital minerals, in areas with little or no bottom agitation, and they suggested that these eventually form chamositic ooids. Nevertheless, whatever the exact origin of the oolitic grains, the shapes of the ferruginous grains of the Larroque Formation are not inconsistent with a marine origin.

Further evidence supporting a marine origin, has also been obtained by comparing the ferruginous - oolitic shales with examples of sedimentary iron deposits described by Taylor (1949) and Hallam (1966).

Taylor (1949), in describing the Northampton Sand Ironstone Formation, noted that it contained an exclusively marine fauna of bivalves, brachiopods, echinoids and rarely ammonites. This led him to conclude that the ironstones were deposited in a shallow to moderately deep epicontinental sea, which was influenced by considerable wave and current activity. Similarly, the ferruginous - oolitic shales of the Larroque Formation also contain a marine fauna, albeit sparse, of burrowing bivalves and rare ammonites of the genus Dumorteria. This suggests that, like the Northampton Ironstones, the ferruginous oolitic shales were also probably deposited in an open marine environment.

Hallam (1966), in a general discussion of the Mesozoic oolitic ironore deposits of Britain, was able to show that the ores represent condensed sequences, equivalent elsewhere to much thicker deposits of sandy shales. Similarly, the upper part of the Larroque Formation and the lower St. Martin Formation can also be shown to represent a condensed sequence; the ammonite zones of D. radiosa, P. aalensis, L. opalinum, G. concavum, and P. obtectum, which range from Upper Toarcian to Middle Bajocian, are concentrated into only 0.5 to 4.0 metres of sediment (figures 12a and b).

Regarding the origin of the British ironstones, Hallam thought that they might have formed when iron was carried from rivers into an open marine environment, with a low rate of sedimentation. In such areas, which might for instance be offshore shoals, precipitation might have taken place, and current or wave activity probably could have formed oolitic grains. After considering the possible origins of iron in seawater in relation to Jurassic palaeogeography, Hallam concluded that the most likely site of ooid growth was probably in the distal portions of prodelta regimes.

In the foregoing examples, Taylor, Jones and Hallam have suggested that ferruginous sedimentary grains probably form in an open marine environment. As already indicated, the ferruginous - oolitic shales bare many resemblances to these examples, and it seems likely that they too have been deposited in an open marine environment where there was a much reduced rate of sedimentation. However, unlike Hallam's example, it has not been possible to relate the ferruginous grains to deltaic sedimentation, because the open marine sediments are succeeded by calcareous lagoonal sediments, and not by those of a delta.

Since these authors have published their findings, studies of Recent marine sediments have revealed examples of chamosite grains that are actually forming today. Porrenga (1967, figure 41) argued from the distribution of chamosite in Recent sediments, that it is forming in relatively shallow marine areas, adjacent to land masses in tropical regions. He noted that chamosite is only found in areas with very low rates of deposition. He extended these conclusions to ancient sedimentary iron deposits and noted that in both Recent and ancient examples chamosite may occur as ooids, structureless grains, or infilling skeletal ooids, such as those found in echinoid and foraminiferal debris. The iron oxides found in the upper part of the Larroque Formation occur in exactly the same fashion suggesting even more strongly, that they were originally chamositic. Oxidisation may have taken place soon after deposition (Porrenga 1967, Rohrlich et al 1969) or during later diagenesis, as indicated by the thin zones of dedolomitisation.

Thus a comparison with Recent sediments suggests that the ferruginous grains of the Larroque Formation were probably deposited in a tropical open marine environment. The climatic interpretation is supported by the succeeding calcareous lagoonal sediments which were almost certainly deposited under tropical conditions. Furthermore, palaeoenvironmental reconstructions (figure 6) also suggest a proximity to a contemporary landmass which was exposed to tropical weathering conditions.

However, Rohrlich et al (1969) have shown that chamosite grains can also grow in cold marine waters, and they argued, unlike Porrenga, that water temperature is not critical. But chamosite is still, by far, most commonly found in tropical areas, near the outflows of large rivers (Porrenga 1967). This abundance might be related to the increased rate of supply of iron in tropical areas, due to tropical weathering conditions on land, and not to water temperatures at the site of deposition.

2.3 The Fauna of the Larroque Formation

The micaceous shales of the Larroque Formation have been found to contain a sparse fauna of ammonites and belemnites. In the past a good pyritised ammonite fauna has been recovered from the quarries of Puy Blanc, but as these quarries are no longer worked, only poorly preserved specimens can now be found. Belemnites, however, are still abundant, and some quite large ones with well preserved phragmacones, have been found. Also freshly split samples of shale have revealed a profuse microfauna of small pectenids, 1 or 2 m.m. in size, in association with other larger, very thin shelled bivalves.

The ammonite fauna of the micaceous shales was collected by Gerard Lafaurie of Figeac. The specimens found include a poorly preserved specimen of *Pseudogrammoceras fallaciosum* in the stream sections at Larroque Toirac, and a well preserved specimen at Puy Blanc; *Grammoceras* cf. *thouarsense* and *Hammatoceras* sp. at Puy Blanc; and *Hildoceras bifrons*, *Pseudolioceras compactile* and *Ceolioceras crassum* in the marly shales with phosphate nodules exposed by the roadside on the D24, near Beduer, going toward Faycelles.

In the ferruginous oolitic shales at the top of the formation, ammonites of the genus *Dumorteria* have been found. These might be examples of *D. radiosa* which has often been used as an Upper Toarcian zone fossil in Aquitaine (Glangeaud, 1895, and Arkell, 1956).

2.4 The Age of the Larroque Formation

The presence of ammonites in the sediments of the Larroque Formation has made it possible to date it quite accurately. The relative stratigraphic positions of the ammonites are given in figure 12a. By comparing this succession with those published for Aquitaine by Glangeaud (1895) and Arkell (1956) it has been possible to correlate the ammonites of the Lot Valley with the Standard Zonal Scheme for Northwest Europe, set out by Arkell (1946, 1956, 1957) (figure 12b). From this comparison it can be seen that the Falcifer, Bifrons and Jurense zones are represented, thus giving the Larroque Formation a Toarcian age.

2.5 The Depositional History of the Larroque Formation

The sediments of the Larroque Formation have probably been deposited in an entirely open marine environment. They represent the deposits when the Jurassic sea had its maximum extent over Aquitaine. At the time when the uppermost parts of the formation were being deposited the rate of sedimentation was much reduced and during the period represented by the very top, conditions had become favourable for the deposition of ferruginous oolitic sediments.

The end of the deposition of the Larroque Formation is marked by the onset of nearer-shore open marine sedimentation which has resulted in the deposition of bioclastic packstones. The heralding of such a change is shown by the appearance of two thin bands of bioclastic packstone in the top 5 metres of the Larroque Formation at Larroque-Toirac.

CHAPTER 3

THE SAINT MARTIN FORMATION

The Saint Martin Formation succeeds the Larroque Formation and marks the beginning of Middle Jurassic carbonate sedimentation in the Cajarc area. It has been named after the village of Saint Martin-Labouval, where it crops out as impressive red and yellow weathering cliffs overlooking the village from the north. All the cliffs on the northern side of the Lot valley between Saint Martin-Labouval and Larnagol, are formed by the rocks of this formation and the flat, rolling Causse or limestone plateau above the valley is underlain by the eroded remnants of the overlying Cajarc Formation.

Detailed stratigraphical sections of the Saint Martin Formation have been measured at Saint Martin-Labouval, Latoulzanie, Larroque-Toirac and Corn. These have been compiled into three section logs, presented in figure 10 and in enclosures 2, 8 and 10. From these it may be seen that this formation varies in thickness from 56 m. at Larroque-Toirac to just over 66 m. at Corn. On lithological grounds it has been possible to subdivide the formation into three members; the Latoulzanie, Ceneviers and Corn Members (figure 10). These have all been named after the locations where they are best exposed. In some sections, recrystallisation has masked the original characters of the members.

The lowest or Latoulzanie Member varies from 3.5 m. to 8.5 m. in thickness at Corn. It is composed entirely of fossiliferous bioclastic and rhodolithic packstones. The lower limit of this member has been taken as the boundary of the ferruginous oolitic shales of the Larroque Formation, and the bioclastic packstones of the Saint Martin Formation, and the upper limit as the top of the rhodolith packstone bed.

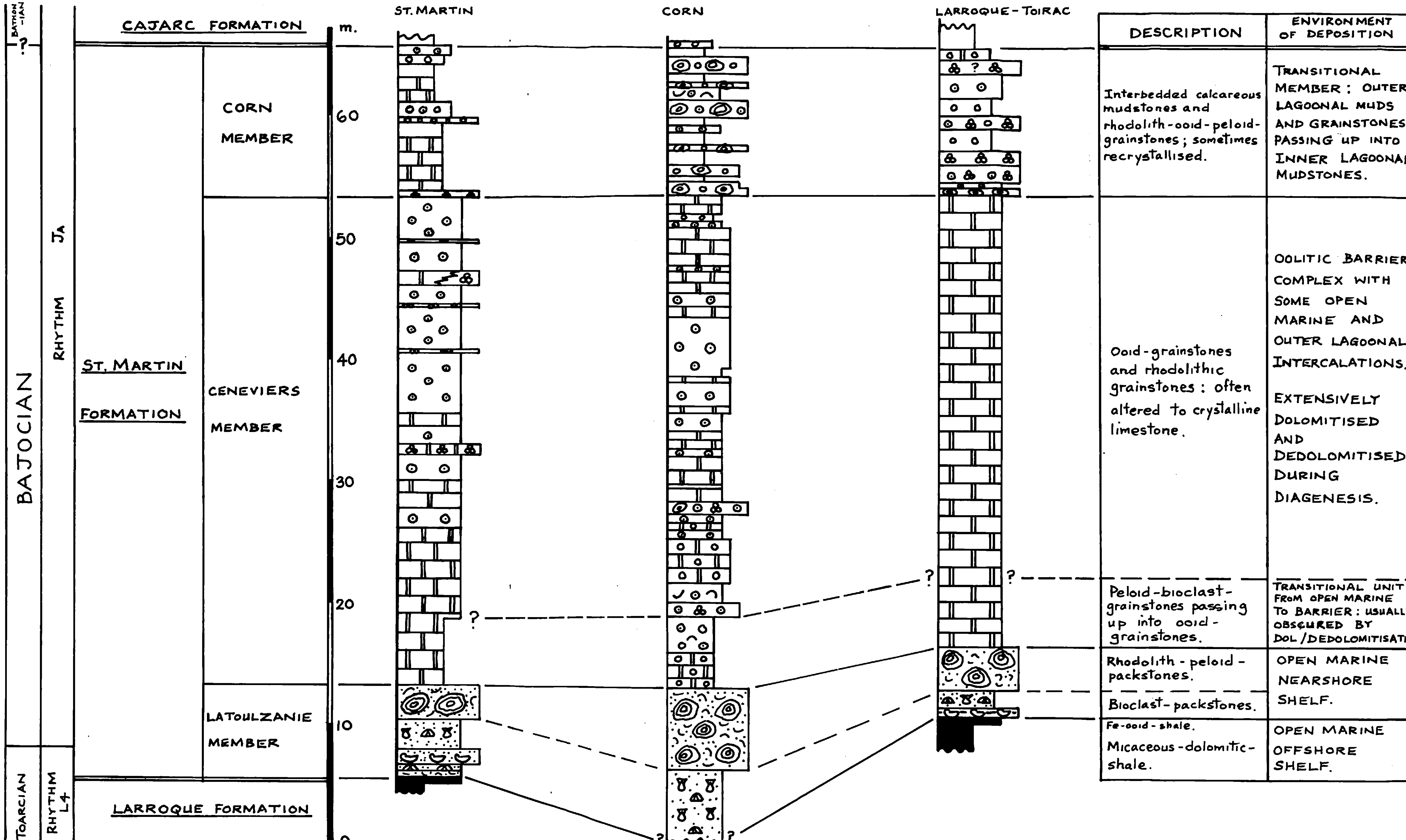


FIGURE 10. Lithostratigraphic subdivision and general interpretation of the St. Martin Formation.

The middle or Ceneviers Member varies from 38.25 m. at Larroque-Toirac to 42 m. thick at Corn. It is made up of oolitic and crystalline limestones. The lower limit of this member has been taken as the top of the rhodolith packstone bed, and the upper limit as the base of the first rhodolith grainstone bed exposed in the road section near Saint Martin-Labouval; the latter is a very distinctive bed and it has been recognised also at both Larroque-Toirac and Corn.

The uppermost or Corn Member is consistently 12 m. in thickness throughout the Lot and Célé valleys. It is composed of peloidal, oolitic and rhodolithic grainstones, interbedded with calcareous mudstones. It's lower limit has been taken to be the base of the previously mentioned distinctive bed of rhodolithic grainstone, and the upper limit as the rooted horizon in the road section at Corn (enclosure 8).

On the geological map for Gourdon (194), the rock unit equivalent to the Saint Martin Formation has been mapped by the French geologists as 'Bajocien (J IV)' and described as 'Calcaires roux, caverneux ou cargneuliform'. In the 'notice explicative' accompanying the map, the 'Bajocien' is subdivided into a lower unit of 'dolomies ferrugineuses et caverneuses', which is equivalent to the Latoulzanie Member of the Saint Martin Formation, and an upper unit of 'Calcaires blancs', equivalent in part to the Ceneviers Member of the Saint Martin Formation. From the map it is apparent that the upper part of the 'Bajocien' also includes the Larnagol Member, of the Cajarc Formation, which has often been recrystallised and is, therefore, difficult to distinguish from the underlying rock units. The lowest part of the Saint Martin Formation, the *Gryphea beaumonti* bed has been mapped as 'Toarcien (I 4)'.

To the south, on the Cahors (206) sheet, the equivalent of the Latoulzanie Member has been mapped as 'Aalenien (I^5). Rocks equivalent to the Ceneviers and Corn Members and possibly the Larnagol Member of the Cajarc Formation, have again been mapped as 'Bajocien (J IV)'. On both maps beds equivalent to the Latoulzanie Member have been described as being very fossiliferous.

The Mirandol Oolite (Daukoru, 1970) found in the Dordogne Valley to the north, is a lateral equivalent of the Saint Martin Formation. The formation is also the lowest portion of rhythm JA, defined by Delfaud (1971a) and it is approximately equivalent to the Calcaire d'Autoire of the same author.

In the present study six lithofacies types have been recognised in the Saint Martin Formation; bioclastic packstone, rhodolithic packstone, oolitic grainstone, oolitic peloidal grainstone, rhodolithic grainstone, crystalline carbonate and calcareous mudstone. These will now be described, but a discussion of the calcareous mudstones will be delayed until chapter four.

3.1 The Bioclastic Packstone Lithofacies

This lithofacies is exposed by the roadside at Latoulzanie and Corn and also in the cliff section at Larroque-Toirac. It comprises blue, red or yellow coloured, massive or decimetre-bedded bioclastic packstone sediments. It contains varying contents of siliciclastic material and where this is important it has given the packstones a shaly, centimetre-bedded appearance at outcrop (e.g. the *Gryphea beaumonti* bed at Latoulzanie). Lignite lenses up to 2 cm. thick and 10 cm. long, occasionally occur within this lithofacies.

The sediments consist of fine sand to very coarse sand sized bioclasts, together with a few peloids and silt to fine sand sized anhedral grains of quartz (figure 11). The bioclastic material is fragmented, angular and is largely unmicritised. It varies in composition from being composed predominantly of echinoid debris to rocks composed predominantly of bivalve debris; large foraminifera are also sometimes present (figure 11a).

In most of the thin-sections of bioclastic packstone that have been examined, the matrix of the sediment has been recrystallised to either ankerite (figures 11b & c) or a coarser mosaic of calcite crystals (figure 11c). In one or two examples, however, it consists of lithified calcareous mud, with clay minerals in the more shaly types (figure 11a). Recrystallisation of the matrix is thought to have occurred during diagenesis when processes of dolomitisation (see p.373) probably caused the growth of crystals of iron-rich dolomite or ankerite. These crystals are rhombic in shape and have interstitial clay minerals, probably concentrated at the boundaries during the growth of the crystals, which appears to have been displacive (figure 11c). Subsequently, in some cases the ankeritic matrix is thought to have been calcitised, and this has resulted in the generation of a coarse mosaic of anhedral calcite crystals (p.358) enclosing some unreplaced, but corroded relicts of ankerite (figure 11d). The bioclasts have only been slightly affected by these processes, with ankerite crystals sometimes just encroaching at their edges (figure 11b).

The colour of the bioclastic packstones varies according to the state of the matrix. Those with ankerite are blue in colour, whereas those with calcitised matrices are usually red or yellow. The change in colour is thought to have been due to the release of iron during calcitisation of the ankerite crystals.

One bored horizon or hardground occurs within the sediments

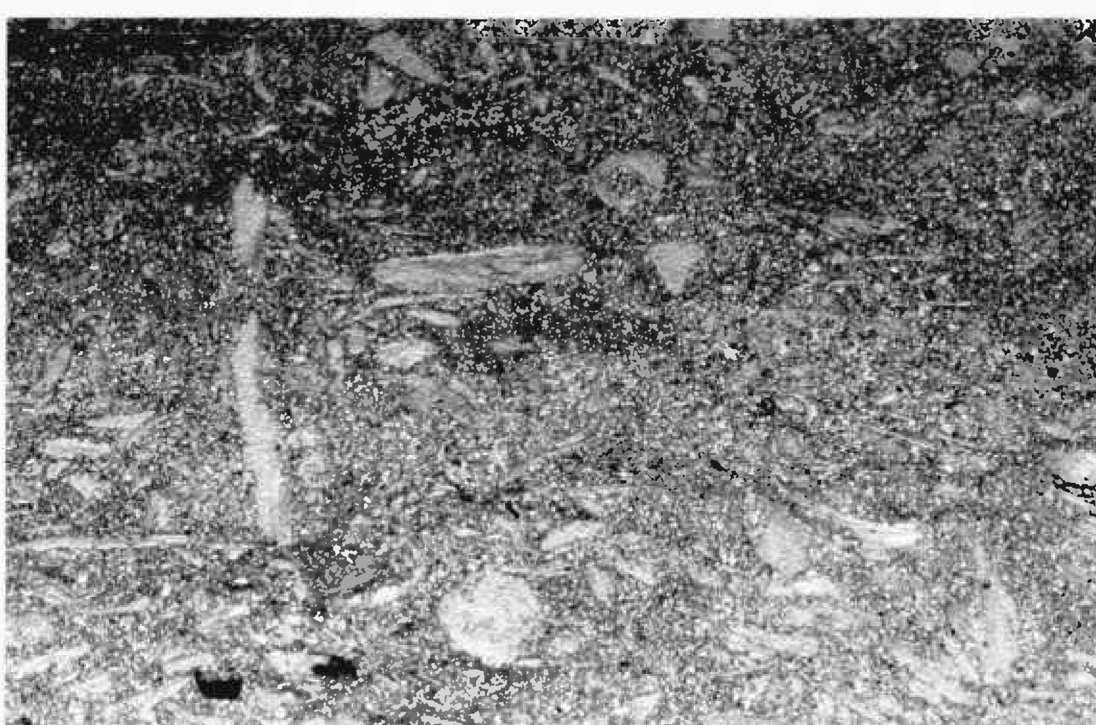
FIGURE 11 A) Photomicrograph of a bioclastic packstone, composed of bivalve, gastropod and echinoid debris, with some benthonic foraminifera and a muddy calcareous matrix (244/73; Latoulzanie Member at Larroque-Toirac).

B) Photomicrograph of dolomitised bioclastic packstone: the matrix and some of the bioclasts have been recrystallised to iron-rich dolomite, or ankerite, but the remaining bioclasts are relatively uneffected (247/73; Latoulzanie Member at Larroque Toirac).

A.

(x10)

B.

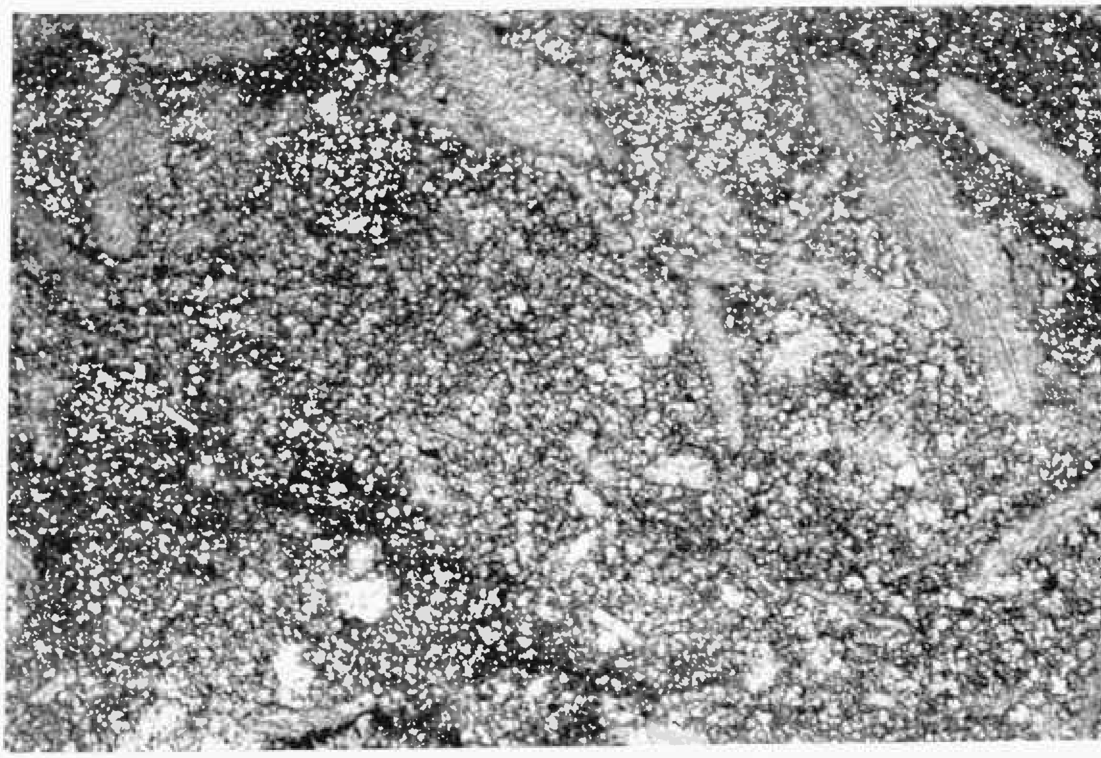


(x25)

FIGURE 11 C) Photomicrograph showing the matrix texture of a dolomitised bioclastic packstone: note the euhedral ankerite crystals and the interstitial clay minerals (the dark areas between the crystals) (247/73; Latoulzanie Member at Larroque Toirac).

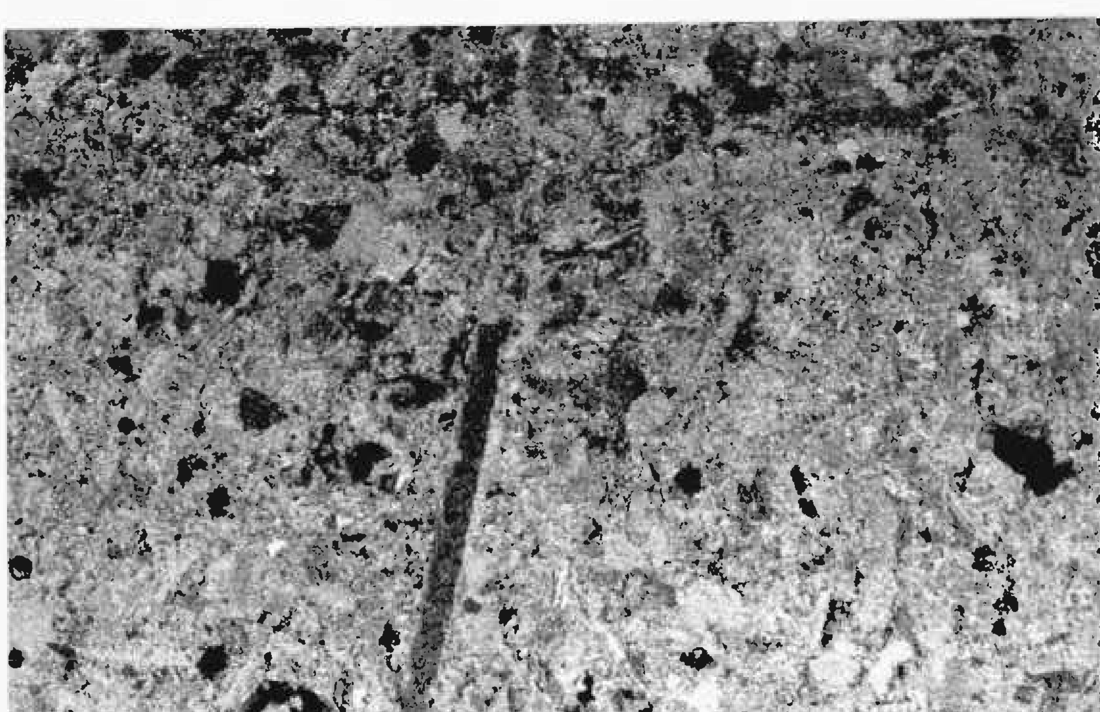
D) Photomicrograph of a crystalline bioclastic packstone, showing coarse anhedral crystals of calcite and ghost bioclasts. This texture has resulted from the dolomitisation and dedolomitisation of a bioclastic packstone, like that shown in figure 11a. In some cases the bioclasts have remained uneffected (crossed-polarisers (164/73; Latoulzanie Member at Latoulzanie).

C.



(x50)

D.



(x35)

of this lithofacies at Latoulzanie.

The Fauna of the Bioclastic Packstone Lithofacies

Bioclastic packstones have only been found at the base of the Saint Martin Formation where they have yielded a succession of faunal assemblages consisting of: ammonites, belemnites, brachiopods, bivalves and echinoderms. The diversity and abundance of the fossils varies from bed to bed. The various assemblages will be discussed in order of their stratigraphic appearance, which is shown in figure 12a.

The first assemblage to appear consists of a profusion of Gryphea beaumonti (Riviere), in association with Eopecten sp. (Douville) and belemnites in a matrix of dolomitic shale. The shale content varies along its strike. The maximum development is 70 cm. at Latoulzanie, from where it thins both east and westwards; at Monsales it is only poorly developed and at Balaguier, Lissac and Faycelles it is absent. Homoeorhynchia cynocephala (Richard) var. meridionalis (Ager) appears near the top of the bed.

At Latoulzanie, the next assemblage to appear consists of an abundance of Pleydellia aalensis (Zieten), belemnites, H. cynocephala, Loboidothyris perovalis (Sowerby), Lobothyris sp. (Buckman) and occasional bivalves such as Myophorella stratus (Sowerby). This bed has been named the 'brachiopod bed' because of the abundance of brachiopods within it.

Above the brachiopod bed, H. cynocephala becomes stunted and eventually it disappears. The brachiopod assemblage is replaced by one containing an abundance of bivalves in association with echinoids, ammonites and belemnites. The fauna of this 'bivalve bed' includes:

FIGURE 12a. The fauna, sedimentology and stratigraphy, of the Upper Larroque Formation, and the Latoulzanie Member of the St. Martin Formation.

STAGE (after Arkell 1946).		STANDARD ZONES FOR N.W. EUROPE (after Arkell 1957).	ZONES IN THE EASTERN PARIS BASIN (after Arkell 1956).	ZONES IN AQUITAINE (after Glangeaud 1895, taken from Arkell 1956).	ZONE FOSSILS FOUND IN THE LOT VALLEY AREA.
BAJOCIAN	U	Parkinsonia parkinsoni.	P. parkinsoni.	P. parkinsoni and G. garantiana	G. garantiana
		Garantiana garantiana.	G. garantiana.		
	M	Strenoceras subfuractum.	S. subfurcatum.	Stephanoceras bladgeni.	? ? ?
		Stephanoceras humphriesianum.	S. humphriesianum.		
		Otoites sauzei.	O. sauzei.	O. sauzei.	
		Sonnina sowerbyi.	S. sowerbyi		Planammatoceras obtectum?
	L	Ludwigia murchisonae.	Graphoceras concavum. L. murchisonae.	G. concavum. L. murchisonae.	G. concavum.
		Lioceras opalinum.	L. opalinum.	L. opalinum.	L. opalinum?
TOARCIAN		Lytoceras jurense	Pleydellia aalensis Pleydellia mactra.	P. aalensis	P.aalensis,Cotteswoldia sp., Cattuloceras sp.
			Dumortieria moorei. Dumortieria radiosa.	D. radiosa.	Dumortieria sp.
			Phlyseiogrammoceras dispasum,Hammatoceras insigne.	H. insigne.	Hammatoceras sp.
			Pseudogrammoceras fallaciosum. Grammoceras thouarsense.	G. thouarsense.	Pseudogramoceras fallaciosum. G. cf. thouarsense.
			Haugia variabilis. Phymatoceras lilli.	H.variabilis, Pseudolioceras compactile	H.variabilis, H. bifrons, P. compactile, Lytoceras sp.,C.crassum.
		Hildoceras bifrons	Catacoeloceras crassum. Peronoceras subarmatum. Dactylioceras commune.	H. bifrons.	H. bifrons, Harpoceras mulgiarium.
		Harpoceras falcifer	H. falcifer, Dactylioceras sp., etc.	H. falcifer.	H.falcifer,H.serpentium, Dactylioceras annulatum.
		Dactylioceras tenuicostatum	Dactylioceras tenuicostatum.		

FIGURE 12b A suggested correlation of the ammonites found in the Lot Valley area, with the standard zones for Europe. (mostly collected by G. Lafaurie of Figeac).

Echinodermata: Plesiechinus cf., ornatus (Buckman)
Stomechinidae, gen. and sp. indet.(Pomel)
Ossicles of Pentracrinites sp. (Blumenbach)

Bivalva: Ceratomya bajociana (d'Orbigny)
Myophorella (Promyophorella) striatus (Sowerby)
Inoperna sowerbyana (d'Orbigny)
Gresslya sp. (Agassiz)
Pleuromya sp. (Agassiz)

Gastropoda: various indeterminate gastropods

Cephalopoda: Pleydellia aalensis (Zieten)
Cotteswoldia sp. (Buckman)
Belemnites

The brachiopod and bivalve faunas are intermixed at some localities.

During diagenesis, the skeletal material of most of the molluscan fossils has been removed and the moulds which were left have given the bivalve bed a nodular appearance. Some examples of C. bajociana look rather like pseudo-nodules up to 12 x 20 cm. in size.

At Latoulzanie the 'bivalve bed' is overlaid by bioclastic packstones with a sparse fauna of bivalves, echinoids and ammonites. The following forms have been collected from this bed:

Echinodermata:	Stomechinidae (Pomel)
Brachiopoda:	L. perovalis (Sowerby)
Bivalvia:	sparse indeterminate forms.
Cephalopoda:	Planammatoceras ?obtectum (Buckman) Lioceras ?opalinum (Reinecke) Graphoceras concavum (Sowerby) ?Lytoceras (Suess)

Large benthonic foraminifera, comparable with Rotalid and Miliolid forms, occur in a number of thin sections of the bioclastic packstone sediments. These are thought to be indicative of shallow water conditions of deposition.

Concerning the environment in which the macro-fauna probably lived; G. beaumonti seems to have prefered a more muddy substrate, whereas the brachiopod and bivalve faunas prefered a more sandy carbonate substrate, where the rate of deposition may have been slower.

The assemblages have been found to consist of both pelagic and benthonic forms. Ammonites and belemnites formed the pelagic component with the rest of the fauna being benthonic. Some bivalves, such as the oysters and G. beaumonti, and all the brachiopods, are thought to have been epifaunal. Other bivalves, such as C. bajociana and M. striatus were probably shallow burrowers. Gresslya and Pleuromya were probably deep burrowers.

The Environment of Deposition of the Bioclastic Packstones.

It has already been noted that towards the top of the Larroque Formation, micaceous shales become interbedded with two thin bioclastic packstone bands, and in the upper parts these shales pass rapidly into bioclastic packstones (p. 39). These shales have been interpreted as open marine shelf sediments. Also, Milliman (1974, p.211-214) has observed that, in Recent environments, shaly or muddy sediments become more sandy towards the inner shelf areas, and they are composed of molluscan and echinoderm debris, with benthonic foraminifera. The possibility arises, therefore, that the bioclastic packstones of the Saint Martin Formation might have been deposited in an open marine shelf environment, and compared to the shales, they may represent nearer-shore conditions. An attempt will now be made to prove this assumption by making comparisons with some present day examples of open marine sedimentation, two in the Persian Gulf and one in the Bahamas.

Bathurst (1971, p.181-188, 191) reviewed two examples of open marine sedimentation from the Persian Gulf; one off the coast of Qatar and the other off Abu Dhabi. Around Qatar the nearshore shelf sediments consist of bioclastic sands and gravels or marly bioclastic sands and gravels. These pass offshore, through bioclastic marls, into marls composed of clay minerals, siliciclastic silt and windblown low-magnesium calcite and dolomite. Inshore where the turbulence has been found to be highest, the bioclastic components are abraded and rounded and no mud-grade sediment is accumulating. In contrast, more offshore and in scattered depressions, where current activity is lower, bioclasts are angular and unrounded and have been broken down mainly by feeding animals rather than by abrasion; muddy sediments are being deposited in these areas and they are intermixed with angular molluscan debris.

Off the coast of the Abu Dhabi barrier - lagoonal complex sand sized and marly bioclastic sediments have again been found to be accumulating. The bioclastic component is made up of both complete articulated and broken angular shells and the breakdown of this material is thought, again, to be due more to feeding animals than to current activity.

Except in that the calcareous mud fraction has sometimes been recrystallised to ankerite, the micaceous shales of the Larroque Formation appear to be lithologically very similar to the offshore marls of the Persian Gulf. Also they both contain a sparse pelagic fauna with little or no preserved benthos. Thus the micaceous shales have been interpreted as open marine, offshore, shelf sediments.

The bioclastic packstones of the Saint Martin Formation are also comparable with the nearshore shelf sediments of the Persian Gulf, because the sediments of both areas are composed of angular bioclastic debris in a marly or shaly matrix. Moreover, the passage from micaceous shales into bioclastic packstones is exactly the sequence that might be expected if the environments of deposition, in the Persian Gulf, prograded seawards (figure 13). Thus the bioclastic packstones have probably been deposited in a nearer shore environment than the micaceous shales, and the succession from the Upper Larroque to Lower Saint Martin Formations represents a change from offshore to nearer-shore conditions.

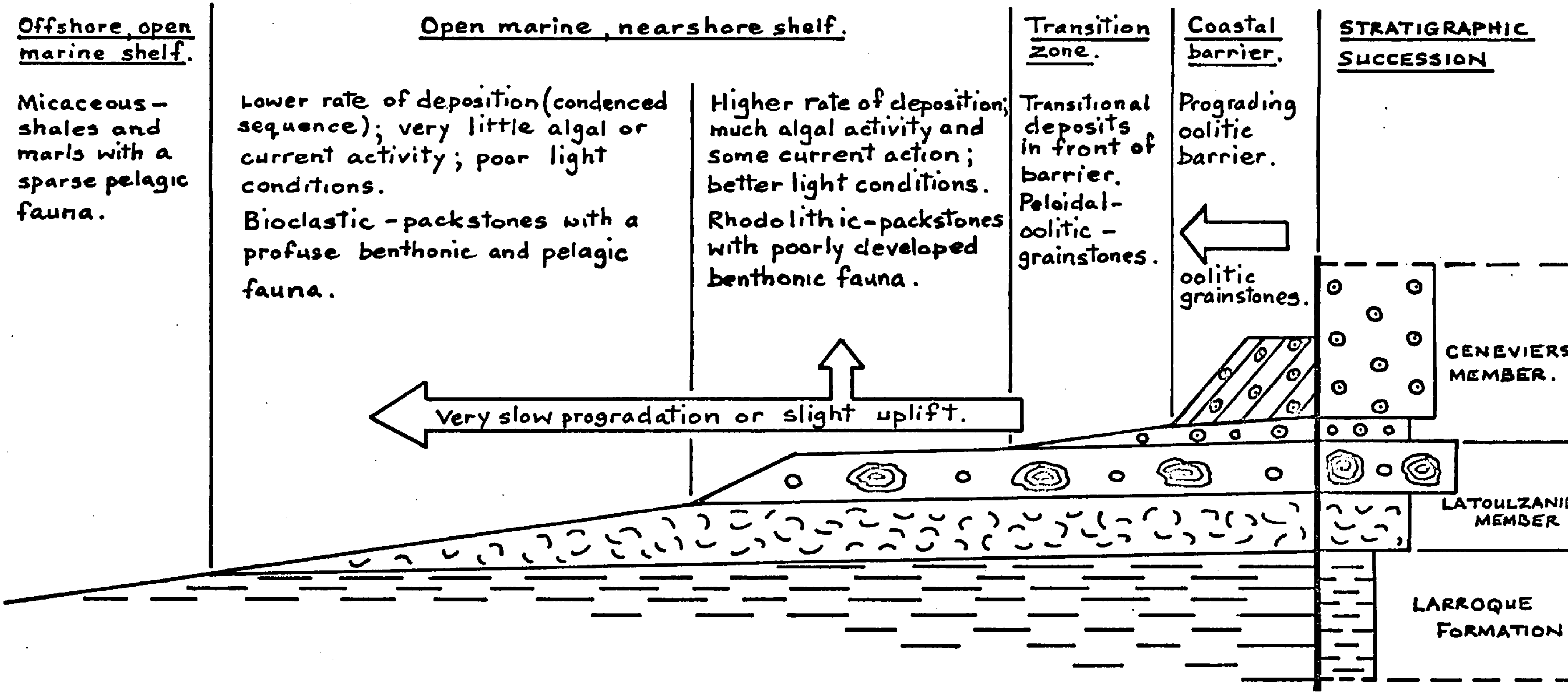


FIGURE 13 An environmental explaination of the lithological succession of the Upper Larroque Formation and Lower St. Martin Formation.

Unlike the micaceous shales, the bioclastic packstones have been found to contain a highly diverse, abundant fauna with both pelagic and benthonic components. This is thought to be typical of normal salinity, open marine conditions. However, for the establishment of benthonic organisms, the environment of deposition of the bioclastic packstones must have become shallower than that of the micaceous shales, which have an almost entirely pelagic fauna. Thus, it is apparent from this that the bioclastic packstones also represent a shallower water environment, which is in keeping with their nearer-shore situation.

Illing (1954, p.61-62) and Bathurst (1971, p.108-117) have described another Recent occurrence that is possibly analogous with the bioclastic packstones of the Saint Martin Formation. Seawards of the reefs, cays and oolitic shoals of the Bahamian Platform, on the narrow marginal shelf, rippled and dune bedded sand grade sediments are accumulating. These are composed almost entirely of bioclastic debris from corals, coralline algae, molluscs and echinoids, together with benthonic foraminifera and grains encrusted by algae. The fauna includes corals, calcareous algae, rotalid foraminifera, echinoderms and nineteen species of bivalve. From the description of the sediments it is apparent that there are many similarities with the bioclastic packstones described above, but in contrast the dominant grain types of the Bahamian sediments are coral and algal fragments derived from the abundant reefs, whereas the dominant grain types in the packstones are molluscan fragments; this is not surprising because no evidence has been found of the existence of contemporaneous reefs in the Bajocian of the Cajarc area. The lack of ripples or dunes in the bioclastic packstones is also notable, but these may have been destroyed by bioturbation.

Also, it is of interest to note that Ager (1965) noticed that the Mesozoic brachiopods of the genera <u>Homoeorhynchia</u>

and _Loboidothyris_ have nearly always been found in sandy bioclastic packstones, oolitic grainstones and ironstone sediments. He considered them to be typical of shallow water, sublittoral, nearshore conditions. As _Homoeorhynchia cynocephala_ and _Loboidothyris perovalis_ have both been recovered from the bioclastic packstones of the Saint Martin Formation, a similar environment of deposition may also be inferred which is exactly the same as that which has previously been indicated from the sedimentological evidence.

Some Thoughts on the Faunal Assemblages

The recent sedimentary lithofacies and foraminifera assemblages that are developed in the nearshore shelf region around Qatar are probably controlled by water depth, which is, in turn, related to a series of sea floor terraces (Bathurst 1971, figure 190). Similar depth controls in the Bajocian may also have influenced the succession of faunal assemblages that has been found in the bioclastic packstones at the base of the Saint Martin Formation. In particular the Gryphea - brachiopod - bivalve succession might be an example of this, but is has been difficult to ascertain whether these assemblages lived contemporaneously and have been superimposed by the progradation of the environments of deposition, or whether they have arisen as successive assemblages living in the same environment at different times. Two things are clear however, firstly all three assemblages occur in the same "aalensis" sub-zone and, secondly, at some localities the three assemblages have been found to be intermixed. These points tend to suggest that the assemblages were in fact contemporaneous, and the separation of the fauna into three assemblages at many localities might have been due to depth controls similar to those found around Qatar. In contrast, the assemblages of higher ammonite zones are obviously younger faunas that lived in the same geographical position at later dates.

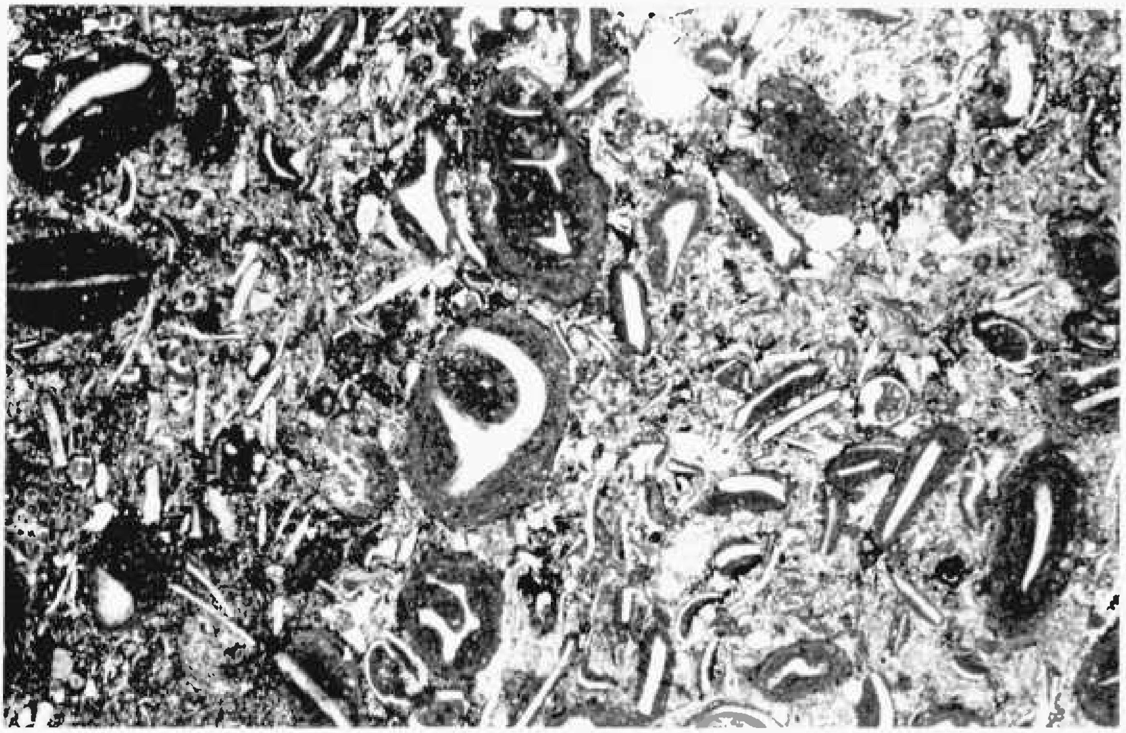
It has also been noticed that, within the bioclastic packstones, some beds are sparsely fossiliferous, whereas others have an abundant fauna. The differences in abundance might have been the result of variations in the rate of sedimentation. The fossils are concentrated into thin beds with more condensed ammonite zones, and thicker beds with less condensed zones are almost completely devoid of them. This suggests that when the rate of deposition was low, as indicated by the zones, the fauna became concentrated and conversely, when it was higher, the fauna became 'diluted' by sediment. Thus in the absence of ammonite zones, a concentration of fossils could possibly be taken to indicate a condensed sequence.

3.2 The Rhodolithic Packstone Lithofacies

Sediments of this lithofacies are exposed in roadside sections at Latoulzanie and Corn, where they crop out as a single unit varying from 3 - 3.5 m. in thickness. This unit is consistently developed throughout the Cajarc and Figeac areas and it forms an easily recognisable stratigraphic marker.

The rhodolithic packstones are massive or decimetre-bedded, and the bedding planes are picked out as more shaly horizons. At outcrop, the sediments bear a strong visual resemblance to the bioclastic packstones described on pages 43-49. The textures appear to be similar and weathering has produced the same blue, red or yellow colouring. There are, however, differences between the two lithofacies types, the main ones being the presence of rhodoliths, which stand out well on weathered surfaces, and the abundance of peloids in the rhodolithic packstones. In contrast the bioclastic packstones described earlier are composed almost entirely of shell debris.

Thin sections of the rhodolithic sediments show them to be rhodolithic peloidal-bioclastic-packstones and grainstones (figure 14). The peloids, which vary from silt to fine



(x7)

FIGURE 14 Photomicrograph of a rhodolithic packstone, with rhodoliths that have formed around bioclasts; the matrix has been dolomitised (115/74; Latoulzanie Member at Ceneviers).

sand sized material with occasional medium sand sized fragments of bivalves and gastropods. Most of the bioclastic material has been rounded and partially micritised. A few coarse sand grade grapestone grains also occur in this lithofacies. In addition, some bioclasts and grapestone grains have sometimes been concentrically encrusted by calcareous algae to form gravel-sized rhodoliths. (These will be discussed in pages 62-66).

Like some of the bioclastic packstones, all the samples of rhodolithic packstones that have been examined, have recrystallised matrices. In some cases the matrix has been either partially or completely dolomitised and in others calcitisation of the dolomite has taken place, leaving a few corroded relicts of dolomite crystals in an anhedral matrix of coarse calcite crystals. This has made the interpretation of these rocks difficult but fortunately individual grains have been largely unaffected.

The Fauna of the Rhodolithic Packstones

Except for rare, indeterminate terebratulids, and some foraminifera that have been observed in thin section, the rhodolithic packstones are unfossiliferous. Only Rotalid and Miliolid type foraminifera occur, together with one planispiral form comparable to Glomospirella (Plummer).

The Origin and Significance of Rhodoliths

Daukoru (1970) identified similar concentrically laminated grains in the lateral equivalent of the rhodolithic packstones, in the Dordogne Valley. He considered them to be oncoids, produced by the blue-green alga Spongiostroma (Guerich). Although in hand specimens from the Cajarc area these grains certainly looked like oncoids, they have been found to be associated with open marine, nearshore, continental shelf sediments. As true oncoids have never been described from any similar present day environments, Daukori's identification is doubtful. Calcareous algal balls have, however, commonly been described from open marine environments (Milliman 1974, p.214). This has suggested that the concentrically laminated grains might, in fact, be calcareous algal balls, but before attempting to prove this, it is useful to define the terms 'oncoid' and 'calcareous algal balls'.

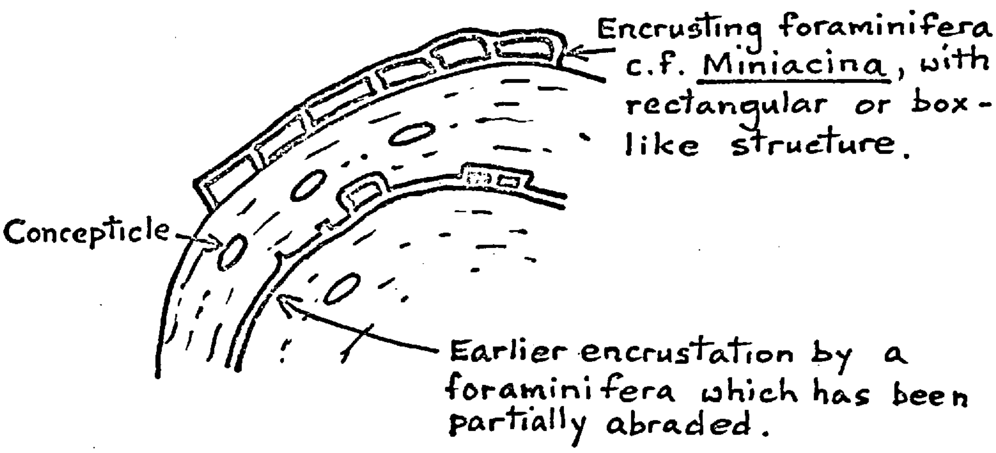
Logan et al (1964) have defined oncoids as being spheroidal stromatolitic algal structures that form when green and blue-green algae trap and bind sediment around an intermittently mobile nucleus. They have only been observed in lower intertidal and submerged shoal areas within coastal lagoons and embayments.

In contrast, calcareous algal balls, or rhodoliths (Bosellini and Ginsberg 1971, 1973) have been described as being constructed by crustose coralline red algae of the Phyllum Rhodophyta. These organisms grow by the precipitation of calcium carbonate, around their filaments and between cells. Johnson (1954) has observed that crustose coralline forms have commonly encrusted other organisms and inorganic nuclii, sometimes developing into irregular nodular masses and even rounded balls. Bosellini and Ginsberg (1971) and Adey and Macintyre (1973) have also noted that, when rolled or agitated, these algae are capable of producing nodules or balls with irregular concentric structures.

Thin-sections of the rhodolithic packstones of the Saint Martin Formation, show that the concentrically laminated grains therein, are not constructed of successive layers of sediment, with irregular cavities, characteristic of soft binding algal structures. Instead, they possess a faintly laminated framework with a vague tubular or cellular appearance that has largely been destroyed by micritisation (see figure 15) and in some cases concentric lines of very

FIGURE 15 A) Photomicrograph of a rhodolith grain encrusted on one side by foraminifera; this probably grew while the grain was stationary. Subsequently, agitation has partially destroyed the structure of the organism, and resulted in the renewed activity of calcareous algae.

B) Photomicrograph of a rhodolith grain which has grown around some serpulid (?) worm tubes. Note the encrustation by foraminifera.



C) Photomicrograph of a rhodolith grain which has nucleated around a bioclast, showing encrustation by serpulid (?) worms. Note the faintly laminated internal structure of the grain, and the vague tubular or cellular structure, now largely destroyed by micritisation; also note the presence of poorly developed concepticles (A, B and C: 115/74; Latoulzanie Member, Ceneviers).

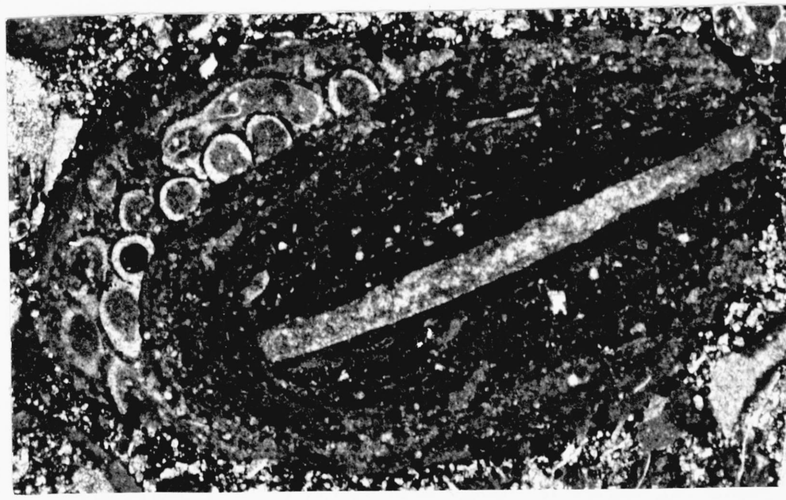
A.

(x48)

B.

(x25)

C.



(x45)

small circular or oval, cement-filled cavities may be seen. These structures are considered to be similar to those which would be produced by calcareous algae, especially the lines of cavities, which are comparable with the conceptacles of the latter. This evidence has suggested very strongly that the concentrically laminated grains should be interpreted as calcareous algal balls or rhodoliths.

Furthermore, at various stages in their growth the grains have become encrusted with bryozoans, serpulid worms and foraminifera comparable with Miniacina (Galloway) (figure 15). All these organisms usually live on hard surfaces, and to allow the successive growths of encrusting organisms that have been found, the surfaces of the grains must have been hard at all stages in their enlargement. Moreover, as oncoids are soft structures by definition, it is unlikely that they would have been encrusted by the organisms mentioned above. Thus it seems almost certain that the concentrically laminated grains have grown as rhodoliths and not oncoids.

The palaeoenvironmental significance of rhodoliths has been considered by Adey and Macintyre (1973), who thought that because their study was only at an early stage, care should be exercised if rhodoliths are to be used in any interpretation. Even so, although rhodoliths have been described as ranging from intertidal to the lower limit of the photic zone, they considered that, in general, rhodoliths have typically been found on continental margin areas in waters ranging from 50 to 150 m. in depth. Recent rhodoliths have also been found in all latitudes, so they are not necessarily indicative of tropical conditions. However, in clear tropical waters they have been found offshore at depths ranging from 50 to 200 m., and also they may be relatively abundant in protected lagoonal areas. According to Adey and Macintyre massive concentrically bounded rhodoliths have generally been found in deeper tropical waters, whereas Bosellini and Ginsberg (1971) have noted that smooth surfaced laminated types form in areas of higher current activity. The latter authors also considered that rhodoliths prefer substrates with low rates of deposition and intermittent current or wave activity.

Thus, the present study has revealed the possibility that other so-called examples of oncoids might, in fact, also be rhodoliths. After all, it has only been the unusual association of 'oncoids' with open marine sediments that prompted a closer look at the grains. A re-investigation of 'oncoids' may reveal a much more frequent development of rhodoliths in the stratigraphic record. One example that immediately comes to mind is the Bajocian Pea Grit of England, which is almost certainly composed of rhodoliths and not oncoids! This distinction is important because the environments of deposition and interpretation of the two are completely different; rhodoliths seem to be typical of open marine or subtidal outer-lagoonal conditions, whereas oncoids are dominantly intertidal and usually associated with soft algal mats.

Finally some possible diagnostic features that might assist in the recognition of rhodoliths are:

1. the presence of concepticles.
2. a preserved cellular structure (usually micritised in the writer's experience).
3. encrustation by foraminifera, etc.
4. association with open marine or outer lagoonal sediments.

The Environment of Deposition of the Rhodolithic Packstones

Rhodolithic packstones occur only at one level in the Cajarc and Figeac areas. This is at the base of the Saint Martin Formation where they are sandwiched between nearshore, open marine, bioclastic packstones, and peloidal bioclastic oolitic sediments, thought to have been deposited as a coastal barrier complex (p. 87). The barrier may be shown to have prograded seawards over the rhodolithic packstones, suggesting that the rhodolithic sediments are open marine in character, and since they are also similar in some ways to the bioclastic packstones, this seems even more probable. Moreover, the fact that recent examples of rhodoliths have most commonly been found in open marine shelf areas, has tended to confirm the assumption.

Thus it seems reasonable to infer that the rhodolithic packstones have been deposited in a nearshore, open marine, shelf environment, similar to the conditions under which the bioclastic packstones have probably been deposited (figure 13). There are, however, several compositional differences between the bioclastic and rhodolithic packstones, so there must have been some difference in their environments of deposition; these will now be outlined and discussed.

At outcrop the bioclastic packstones have been found to pass rapidly upwards into rhodolithic packstones. The appearance of the latter deposits is marked by an increase in peloids and benthonic foraminifera, the growth of rhodoliths, and a reduction in the content of molluscan and echinoderm debris. The bioclastic material is also much more rounded and more micritised than in the bioclastic packstones.

The peloids have probably originated from two sources. First, some may have been due to organisms burrowing in the sediment and producing faecal pellets. Second, many peloids might have formed as a result of the micritisation (Bathurst 1971) of bioclasts, particularly foraminifera. This has become apparent because most of the peloids are of the same size as the co-existing foraminifera and as the latter have been observed in all stages of micritisation it seems logical that the peloid content of the rhodolithic packstones has probably been derived largely from bioclastic material (a recent example of the micritisation of foraminifera can be found in Kendall and Skipwith, 1969).

The growth of rhodoliths and the micritisation of bioclasts have probably both been due to algal activity. As no evidence of the latter has been found in the bioclastic packstones, it would seem that the change in composition, from bioclastic to rhodolithic packstones, has partly been the result of algal activity. Because algal growth is usually controlled by the intensity of light penetrating to the sea floor, it is possible that the rhodolithic packstones have been deposited in the photic zone, whereas the bioclastic packstones have accumulated in deeper waters where light penetration was lower.

If light penetration has been the main cause of the upward change in composition of the sediments, there must have been a difference in the depth of their environments of deposition. The rhodolithic packstones might have formed in shallower nearer-shore waters, superceding the bioclastic packstones by lateral progradation (figure 13). Equally, however, they might represent a general change in water depth in the open marine shelf areas, due to a slight uplift of the sea floor, bringing the bioclastic sediments into stronger light and modifying their composition by algal activity.

Houbolt (1957) unknowingly described a Recent example of the control of light penetration on the composition of near-shore open marine sediments of the Persian Gulf, that bears some similarities to the sediments described above. He considered that the difference between the near-shore, shallower-water, rounded bioclastic sands, and the more offshore deeper-water, angular bioclastic sands, is probably due to increased current abrasion nearer shore. However, Shearman (personal communication, 1975) has re-examined Houbolt's samples and concluded that the increase in rounding nearer-shore has been due mainly to micritisation in shallower water with good light penetration, aided by some current activity. Offshore, where light penetration and current activity are lower, the bioclasts have only been affected by feeding animals, and thus they are angular and unmicritised.

One could imagine that, in the shallower areas, if algal activity became more intense, peloids might become abundant and rhodoliths might even start to grow and these would pass offshore into angular bioclastic deposits.

Bosellini and Ginsberg (1971) have noted that smooth, laminated types of rhodolith usually grow in areas of higher but intermittent current activity. If the rhodoliths that occur near the base of the Saint Martin Formation have formed in response to a shallowing of the sea, the sediments would also have increasingly been subjected to intermittent agitation by waves, thereby forming conditions favourable for the growth of rhodoliths, and at the same time aiding the breakdown of skeletal material. Thus, Houbolt's observation of increasing current activity with a shallower, more inshore bottom, can also be perceived in the rhodolithic and bioclastic packstones and emphasises the comparability of the sediments of the Latoulzanie Member with present day open marine, nearshore, shelf deposits.

A last point concerns the rate of deposition of the rhodolithic packstones. Ammonite zones and concentrations of fossils have indicated that the rate of accumulation of the bioclastic packstones was probably very low. Bosellini and Ginsberg (1971) have noted that rhodoliths probably form more readily in areas with a low rate of sediment deposition. Therefore, the possibility arises that the rhodolith packstones have also been deposited very slowly, especially since they have probably been deposited in a similar open marine environment to the bioclastic packstones. Furthermore, the presence of rhodoliths in other parts of the geological column might also indicated low rates of deposition.

3.3 The Oolitic Sediments of the Saint Martin Formation

An examination of thin sections of oolitic sediments of the Saint Martin Formation has revealed the presence of several lithofacies types comparable with those established by Bathurst (1971, p.121-136) in his review of the recent oolitic sediments of the Bahamas (see figure 18). It has been difficult to apply these lithofacies in detail, however, because at many localities the sediments have been recrystallised. Nevertheless, the following lithofacies have been recognised: ooid-grainstone; ooid-peloid-grainstone; rhodolithic-grainstone; and crystalline carbonate. These will now be described respectively.

The Ooid-Grainstone Lithofacies

This lithofacies is exposed near Saint Martin Labouval on the slopes just below the D.24 at 996249 , and also in the quarry at 002247 . At outcrop the grainstones are white coloured, metre-bedded and internally either structureless or low angle planar cross-bedded. Individual laminae have occasionally been found to be graded. No hardgrounds or burrowed horizons have been detected in this lithofacies.

Petrologically the grainstones have been found to consist of medium to coarse sand sized ooids, with varying proportions of bivalve, echinoderm and rarely coral debris. Most of the ooids that have been examined are narrow centred types that have become nucleated around peloids, bioclasts and sometimes grapestone grains. Some ooids have been found to show evidence of repeated phases of micritisation followed by further deposits of oolitic envelopes. Others show only one final phase of micritisation.

The Ooid-Peloid-Bioclast-Grainstone Lithofacies

This lithofacies is exposed at 158307 in the section near Larroque-Toirac. It consists of grainstones composed of various admixtures of peloids, ooids and bioclasts, but most examples have been found to be dominantly oolitic, with subordinate fine sand sized peloids and foraminifera (figure 16)

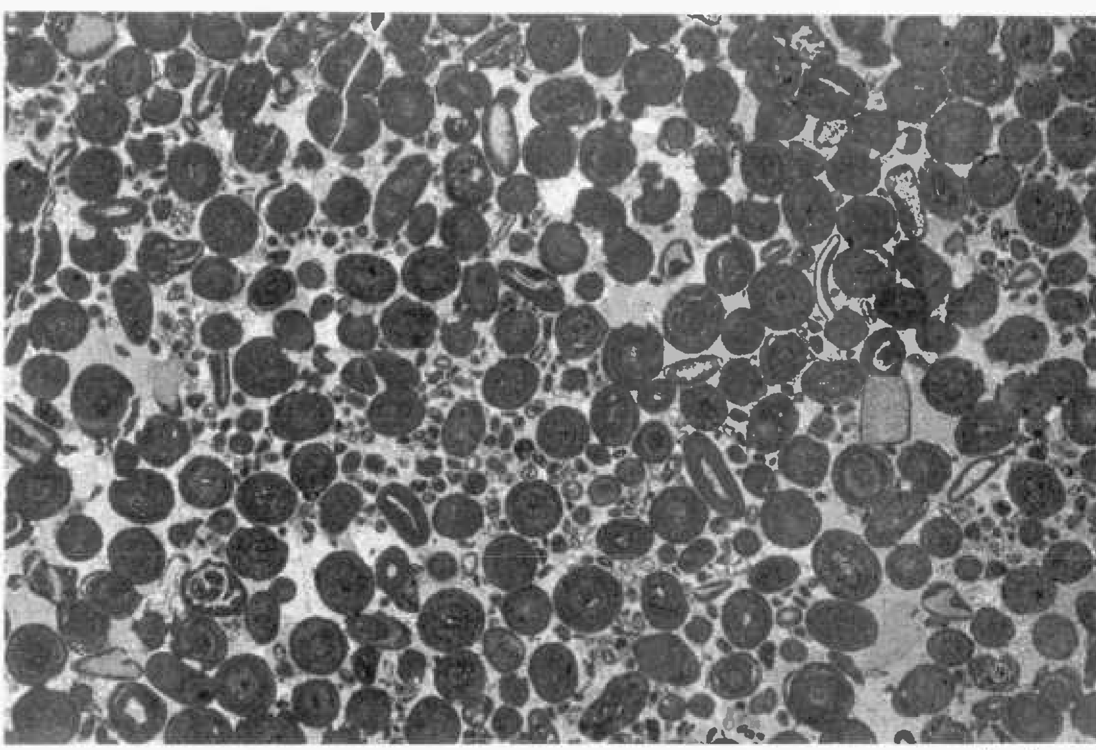


FIGURE 16 Photomicrograph of ooid-peloid-bioclast grainstone, showing the comparable size of peloids and foraminifera and also micritised foraminifera (138/73; Ceneviers Member at Saint Martin-Labouval).

Many of the fine sand sized grains possess crystalline centres and micritised circumferences. These have probably been derived from molluscan fragments by micritisation and recrystallisation. The majority of the foraminifera have also been observed to be of fine sand size, as it is possible that some peloids may have been derived from them by micritisation (see pages 67-69).

Other types of sediment that are also considered to belong to this lithofacies are peloidal grainstones, in which peloids are the dominant grain. These are nowhere near as commonly developed as oolitic grainstones. At outcrop the peloidal grainstones have been found to be massive or trough cross-bedded, and in the latter individual laminae are often picked out by laminae of ooids, only one grain in thickness.

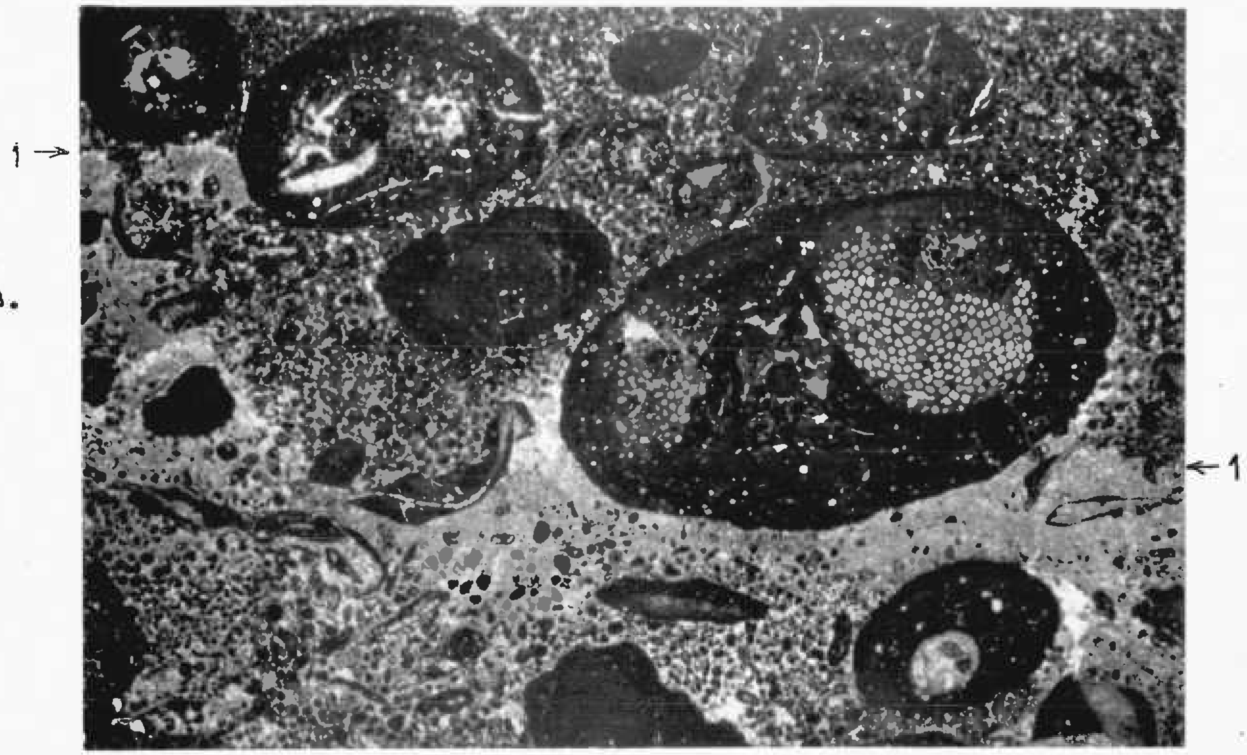
The Rhodolithic-Grainstone Lithofacies

This lithofacies is exposed near Saint Martin Labouval, on the D.24 at 996249. The sediments consist of peloid-ooid-grainstones with a few micritised bioclasts and some composite grains or grapestone grains. The latter grains are composed of peloids, ooids and bioclasts and they have often been concentrically encrusted by calcareous algae to form gravel sized rhodoliths (figure 17a & b).

The rhodoliths have been identified as such because they have been found to possess concentric layers of calcite-filled, circular or oval cavities that have been recognised as the concepticles of calcareous algae (p.65). Micritisation has largely destroyed the cellular structure of the algae, leaving only vague concentric lamination. One or two rhodoliths have been found to be bored (figure 17c).

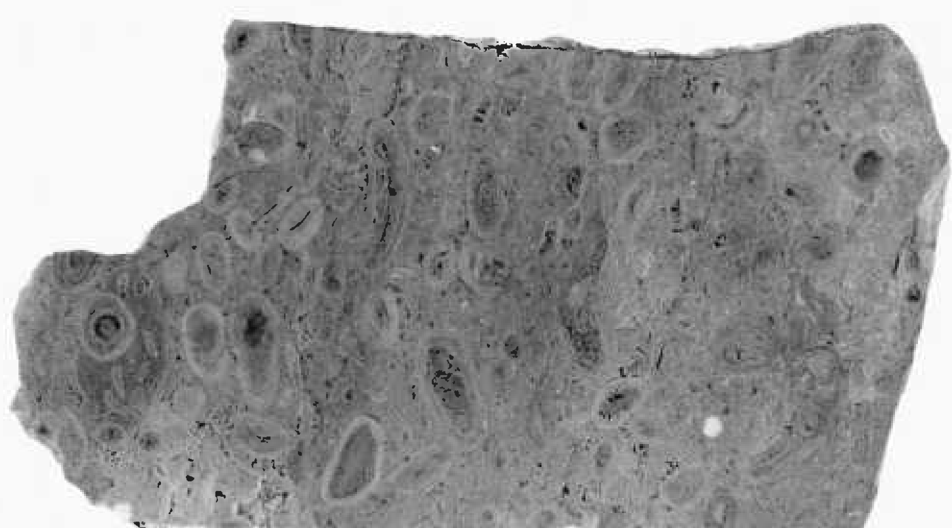
Concerning the grapestone grains, it is possible, as noted by Winland and Matthews (1974), that the initial binding of the grains was achieved by calcareous algae. Subsequently

A.



(x 5)

B.



(x1)

FIGURE 17 A) Photomicrograph of a rhodolithic grainstone; note the crystalline area in the lower half of the photograph and also the front of dolomitisation and dedolomitisation (1).

B) A polished slab of the rhodolithic grainstone shown in figure 17a (124/73; Corn Member, Saint Martin-Labouval).

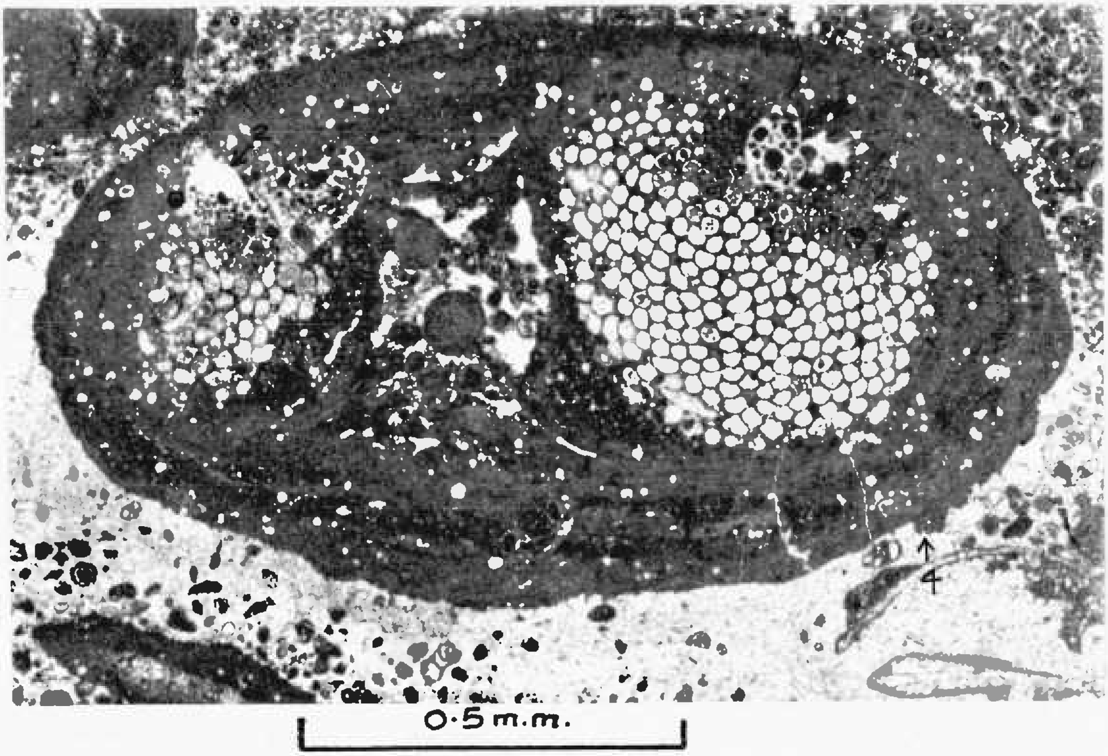


FIGURE 17c Photomicrograph of an individual rhodolith grain. The core is made up of peloids, micritised ooids, and two calcareous algal bioclasts, with a calcite cement. This probably started life as a grapestone grain and later became coated by calcareous algae. Note the vague concentric laminations and concepticles (1) in the outer layer. The cellular structure of the algae has been destroyed by micritisation. The grain appears to have been bored in two places (2). Also note that the cement in the lower part of the photograph has been dolomitised and dedolomitised, and that the original dolomite crystals probably encroached on to the edges of the rhodolith grains (these have angular boundaries composed of rhombic shapes: 4). (124/73; Corn Member, Saint Martin-Labouval).

these may have also encrusted the surface of the grains to produce rhodoliths. Some bioclasts have also been encrusted to form calcareous algal balls.

In the rhodolithic grainstones both fine and medium sand grade peloids occur with the latter being in the majority. Fine sand types may have been derived both as faecal pellets and by micritisation of foraminifera, which are abundant in this lithofacies (p. 72). Medium sand types have been found to be the same size and shape as the co-existing ooids in the sediment, so they have probably been derived, by micritisation from ooid grains.

The Crystalline Carbonate Lithofacies

An examination of the stratigraphic section of the Saint Martin Formation has revealed that a large part of the succession consists of crystalline limestones that has sometimes weathered to produced a cargneuliform lithology. In chapter 7 it will be shown that these rocks have been produced by the calcitisation of dolomitic rocks. In this section reasons will be given for believing that the crystalline calcareous rocks were once oolitic sediments that have been modified during diagenesis.

To the north of the Cajarc area, in the Dordogne Valley, the Bajocian Mirandol Oolite crops out (Daukoru 1970, p.34-40). This formation is a lateral equivalent of the Saint Martin Formation, and in contrast to the latter it is composed entirely of unaltered oolitic sediments. Thevenin (1903) has also described some oolitic sediments in the Saint Antonin area, that are laterally equivalent to the Saint Martin Formation, and which pass laterally into dolomitic rocks.

These examples suggest that the crystalline limestones of the Saint Martin Formation may once have been oolitic sediments. Examination of thin sections has confirmed this, because some have been found to have ghost depositional textures probably inherited from oolitic rocks. Further more, in figure 10, it may be seen that oolitic beds pass laterally into crystalline beds, implying that oolitic sediments have been recrystallised in places to crystalline limestone.

The recrystallisation is thought to have been due to dolomitisation, followed much later by re-calcitisation (see pages 358-365). Further evidence of this has also been found in the interbedded oolitic sediments which have often been partially dolomitised and then calcitised, leaving recrystallised patches with rhombic outlines in otherwise normal oolitic grainstones (see pages 365-368).

Thus, the crystalline limestones have probably originally been deposited as oolitic grainstones. Some examples have small circular or oval patches of coarser calcite, of comparable size to rhodolith grains. Since these rocks pass laterally into rhodolithic grainstones, the coarser patches probably represent recrystallised rhodoliths, a view also held by Delfaud (1973,personal communication).

The Fauna of the Oolitic Sediments

Apart from one or two fossilferous horizons near the top of the Ceneviers Member, the oolitic sediments are only sparsely fossiliferous. The fossiliferous levels may be examined near Saint Martin-Labouval, on the D.24 at 996249 and together with the quarry at Faycelles, they have yielded the following assemblage:

Echinodermata: Hemicidaridae, possibly Gymnocidaris (Agassiz) or Hessotaria (Pomel) - Faycelles.
Pentacrinites sp. (Blumenbach) - St. Martin.

Brachiopoda: Rhynconellacea (Gray) - Saint Martin.

Bivalvia: Ostrecea (Rafinesque) } St.Martin.
Amusium (Pecten) pumilus (d'Orbigny) }

Gastropoda: cf. Nerinella (Sharpe) - St. Martin.

Cephalopoda: Garantiana garantiana (d'Orbigny) - Faycelles.

Coelenterata: Thamnasteria sp. (Lesauvage) - St. Martin.

Daukoru (1970) mentioned that numerous corals have been found in the Mirandol Oolite of the Dordogne Valley. He also noted that they have all been recrystallised, and have often been mistaken as chert nodules in the past. He assigned them to the genus Thamnasteria. Similar corals have been found in the Lot Valley but they are much less abundant here and usually branched or fragmented. Following Daukoru, they have also been identified as Thamnasteria.

It has not been possible to identify the rhynchonellids that have been found; they are medium sized globose forms. The gastropods that have been recovered are high spired types comparable with Nerinella. Ammonites have been found to be extremely rare in the oolitic sediments of the Saint Martin Formation and only one specimen, identified as Garantiana garantiana, is known to have been recovered. This was found by Gerard Lafaurie of Figeac, in the quarry at Faycelles.

The sparse fauna of the oolitic sediments of the Saint Martin Formation is exactly what might be expected from looking at Recent oolitic deposits. Purdy (1964) has noted that, contrary to expectations, rich faunal assemblages have often been described from 'oolites'. In fact, these assemblages usually represent whole rock formations or members, rather than just the true oolitic sediments, and the rich faunas have been recovered from other types of sediment, above, below or interbedded with the ooid-grainstones that have been deposited in an open marine or lagoonal environment.

This type of description has been given by Glangeaud (1895) for the Bajocian oolitic sediments of Aquitaine. He has given a faunal list for the whole of the Bajocian that really only applies to relatively thin bioclastic packstones below the oolitic sediments. The latter are, in actual fact, only poorly fossiliferous. In this thesis an attempt has been made to rectify this by giving separate lists for the open marine bioclastic packstones (p 49) and the oolitic sediments respectively.

The Environments of Deposition of the Oolitic Sediments

The deposition of the oolitic sediments of the Saint Martin Formation has been understood by comparing them with Recent oolitic deposits. The majority of geologists have now accepted that, in most cases, Recent ooids are forming in well agitated, shallow marine waters, supersaturated with respect to $CaCO_3$. Bathurst (1971, p.121-136) reviewed such a Recent environment from around the edges of the Great Bahama Bank. Here, ooids are only actively growing in a narrow shoal zone, 1-3 km. wide, bordering the platform. The shoals are composed entirely of unstable or mobile oolitic sands, and sometimes these have been redistributed into the lagoon by storms and the dominant flood tide and also, to a very limited extent, on to the open marine sea floor. Lagoonwards, ooids become less and less abundant, but sometimes they have been spread out into a belt up to 60 km. wide. In the quieter, deeper waters of the lagoon, the derived oolitic sands have often been partially cemented to form grapestone grains. Seawards of the shoals, bioclastic sands are accumulating. These environments and the sediments being deposited, are summarised in figure 18. A map showing the lateral relationships of the sediments may be found in

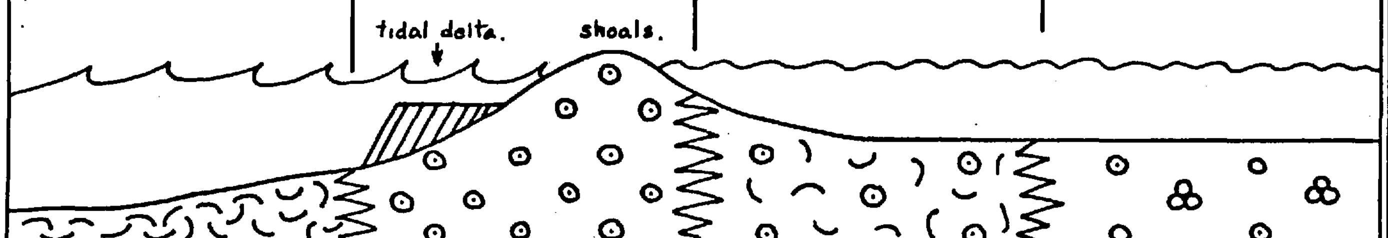
Bioclastic - rhodolithic - packstones.	Cross-bedded ooid - grainstones.	Ooid - peloid - bioclast grainstones.	Rhodolith - grapestone - peloid - ooid - grainstones.	POSSIBLE EQUIVALENT IN THE ST. MARTIN FORMATION
CORALGAL	OOLITE	OOLITIC	GRAPESTONE	BAHAMIAN LITHOFACIES
Abundant fauna.	Sparse fauna.	Common fauna.		FAUNA
coral-algal-peloid sand.	100% ooid sand.	mainly ooid sand (67%); some peloids and bioclasts.	mainly peloid-grapestone sand; some ooids and bioclasts.	SEDIMENT COMPOSITION
Open marine shelf: seawards of coastal barrier.	Oolitic coastal barrier and tidal deltas, normal to tidal flow; average water depth 2m; site of active ooid growth; mobile substrate.	Outer lagoonal area. Just behind ooid shoals; shallower area; ooids transported from shoals by tides and storms and mixed with other grains; megaripples and subtidal algal mats.	Deeper, quieter lagoonal areas with stable bottoms; only rarely disturbed by storms; relict ooid sediments reworked; partial cementation of grains — grapestones; bioturbation; little current activity.	ENVIRONMENT OF DEPOSITION.
				CROSS SECTION.

FIGURE 18 A suggested comparison of the depositional environments of recent oolitic sediment in the Bahamas (after Bathurst 1971), with the oolitic sediments of the St. Martin Formation.

Bathurst (1971, figure 129).

Bathurst (1971) also noted that within the oolite and oolitic habitats of the Bahamas, various sub-environments may also be recognised: oolite shoals or banks, with ripples and megaripples; tidal deltas, spreading ooids lagoonwards; and tidal channels, cutting through the shoals. Although some of the shoals may be exposed at low water, most of the sub-environments are sub-tidal. In the Persian Gulf, however, oolitic barrier sands have accumulated to such an extent that they form a series of islands with complexes of subaerial dunes and intertidal zones (Evans et al, 1973). Also, tidal deltas have been found indicating the redistribution of ooids, seawards.

In the Saint Martin Formation, although no evidence of intertidal or subaerial oolitic deposits has been found, the three different lithofacies, described on pages seem to be comparable with those recognised by Bathurst. Each of these will now be discussed.

From sedimentalogical evidence, the ooid-grainstone lithofacies appears to be an ancient analogue of Bathurst's 'oolite' lithofacies. Like the Recent deposits, the ooid grainstones are composed entirely of ooids, together with a few bioclasts. Also they are almost completely devoid of any fauna. Purdy (1964, p.261-262, fig.14), noted that, because of the unstable bottom, the fauna of the Bahamian ooid shoals is only very sparse. Both massive and unidirectional planar cross-bedded ooid grainstones have been found. The latter types may have been deposited either as tidal deltas or megarippled shoal sands. The massively bedded types may also have originally been deposited in this fashion with the sedimentary structures later being destroyed by bioturbation.

It is likely, because of the presence of fine sand sized grains and benthonic foraminifera, sediments of the ooid-peloid-bioclast grainstone lithofacies have probably been deposited in a less turbulent environment than the ooid grainstones; finer grains would not have been deposited had the currents been stronger. In most examples the bulk of the grains have been found to be ooids, although sometimes peloids are dominant. These points have suggested that the ooid-peloid-bioclast grainstone lithofacies is most akin to Bathurst's oolitic lithofacies which is forming in an outer lagoonal environment, just behind the oolite shoals and where currents are less strong.

The ooid-peloid-bioclast grainstones have also been found to be massive or trough cross-bedded. The latter was probably due to the formation of megaripples which have often been observed in recent analogues. Concerning the massive ooid-peloid-grainstones, Purdy (1964) noted that in the Bahamas, behind the oolite shoals, the substrate is more stable and the fauna becomes much more abundant, resulting in bioturbation. This may account for the absence of sedimentary structures in some ooid-peloid-bioclast-grainstones.

Turning now to the depositional environment of the rhodolthic-grainstones, it is interesting to note that rhodoliths have nearly always been found in association with grapestone grains, suggesting affinities with Bathurst's grapestone lithofacies. Moreover, the grapestone grains of the Saint Martin Formation are petrologically very similar to those figured from Bahamian grapestone sediments by Winland and Matthews (1974, plate 4). In both cases the grains have been formed mainly from aggregates of ordinary or recrystallised ooids, cemented only at the margins.

Bathurst (1971) considered that grapestone grains are formed in deeper lagoonal waters where sandy sediments are subjected to intermittent agitation during storms. In periods of calm the surface layer of sediment becomes partially cemented to form a crust which is broken up to form grapestone lumps during storms. (If this goes to completion a hardground is probably formed).

Winland and Matthews (1974) have considered two possible origins for the Bahamian grapestone sediments. Firstly, ooids might have been transported from their site of origin by storms, and deposited on an intermittently agitated bottom within the lagoon: according to Bathurst this is an ideal site for grapestone formation. Secondly, ooid sands may have formed in situ, after which a transgression deepened the sea over the site, causing the bottom to become more and more stable and initiating the growth of grapestone grains in relict ooid sediments. Looking at sediment distribution maps for the Bahama Platform the former explanation certainly seems possible, but the authors have convincingly given dating evidence to show that the second explanation is more probable.

In the rhodolith grainstones of the Saint Martin Formation, increased amounts of peloids and micritised bioclasts have been found when compared with the ooid grainstones. Furthermore, the peloids seem to have been formed mostly by the micritisation of ooids. Winland and Matthews (1974) have described the same features from the grapestone sediments of the Bahamas. They argued that once the sea has been deepened and ooid formation ceases, and because the rate of deposition becomes very slow and the bottom more stable, existing ooids become micritised, grapestone grains start to grow and bioclasts start to accumulate; the only difference between normal ooid sands and relict sands are the modification of some ooids and the addition of bioclastic material.

Thus it seems that Recent grapestone sediments form from relict ooid sands in response to a deepening of the sea. Presumably this can take place either in an open marine or outer lagoonal environment, depending on whether the site of ooid growth (the barrier) re-establishes itself more lagoonwards or seawards respectively. Applying this to the Saint Martin Formation it would appear that sediments with a fair proportion of grapestone grains represent relict ooid sediments, that have been reworked in an open marine or outerlagoonal environment.

Although the rhodolithic grainstones are certainly similar in many ways to the Recent grapestone sediments of the Bahamas, the problem of the origin of the rhodoliths still remains. On page 65 , however, it has been noted that Recent rhodoliths have been observed to be forming in both open marine and outer lagoonal environments, where the rate of sedimentation is low and where bottom agitation is only intermittent. This is exactly where one might expect to find relict sediments with grapestone grains, especially if there has been a recent change in sea level. Therefore it is no surprise that rhodoliths have grown in relict ooid sediments in the Saint Martin Formation, and even though no recent analogues are known, the rhodolithic-grainstones are thought to be comparable with Bathurst's grapestone lithofacies.

Finally, like on page 69 , one is again brought to the conclusion that the presence of rhodoliths may be taken to indicate periods of very slow, or even non-deposition. It is during these periods, when ooid sediments become relict, that sedimentary structures might be destroyed by bioturbation. It is also at these times that fossiliferous sands may be deposited. Indeed, it seems most likely that the fossiliferous horizons near the top of the Ceneviers Member, might have been the result of a marine transgression, causing the reworking of relict ooid shoal sediments in a more open marine environment, which favoured a more profuse fauna.

3.4 The Age of the Saint Martin Formation

The fossiliferous nature of the bioclastic packstones of the Latoulzanie Member has made it possible to date the lower part of the Saint Martin Formation with ease. The faunal assemblages that have been recovered (figure 11) have given an uppermost Toarcian to lower Bajocian age to the bioclastic packstones (figure 18).

According to Glangeaud (1895), G. beaumonti and H. cynocephala may be taken to indicate an uppermost Toarcian date. What is more, Ager (1956-67) has also noted that H. cynocephala has been most frequently recovered from the jurense zone of Arkell (1957) in the Toarcian rocks of Britain. Following these authors the 'Gryphea bed' has dated as uppermost Toarcian.

In the succeeding 'brachiopod bed', H. cynocephala has been found in association with the ammonites P. aalensis and Cotteswoldia sp. Glangeaud considered the assemblage to also be uppermost Toarcian, but at some localities in the Cajarc area these fossils found are associated with C. bajociana, P. ornatus, M. striatus, I. Sowerbyana and L. perovalis. All these have been considered as being typical Bajocian fossils by Neaverson (1928), so there seems to be some discrepancy in the dates given by the assemblages.

However, in the discussion on page , the faunas of the Gryphea, brachiopod and bivalve beds have been considered to have lived contemporaneously in slightly different habitats. At first this did not seem compatible with the dating evidence, but it must be remembered that the rate of deposition in the particular environment concerned was probably very slow and as such the successive environments would have prograded very slowly. Hence, it seems probable that the successive faunas are in fact diachronous and visibly cut across established time planes.

Another complication hitherto unmentioned, concerns the range of some of the fossils. Arkell (1956, p.103) has pointed out that in the Jura region, P. aalensis ranges from the jurense zone into the opalinum zone. Also, Ager (op.cit.) has observed that H. cynocephala ranges into the opalinum zone. Thus it appears that these two fossils can equally be found in lowermost Bajocian rocks, tending to support the conclusions of Neaverson and refute those of Glaugeaud and it seems that the faunal assemblages of the bioclastic packstones represent contemparaneous faunas which lived in a period overlapping Toarcian and Bajocian times.

In the less fossiliferous bioclastic packstones that overlie the 'bivalve bed', rare examples have been recovered of the ammonites G. concavum, P. obtectum and possibly L. opalinum. These are considered to represent the opalinum, murchisonae and sowerbyi zones of Arkell (1957), dating the rocks as lower to early middle Bajocian (figures 12a and b).

P. obtectum has been recovered from the top of the bioclastic packstones at several locations. In Britain this fossil is usually found in the sowerbyi zone, so in the Cajarc area it is also considered to indicate an early mid-Bajocian age. It follows from this that the superceding rhodolithic packstones range from early mid-Bajocian times, but it has been difficult to date these rocks because they contain such a poor fauna. Similarly, it has been almost impossible to precisely date the oolitic and crystalline rocks of the Ceneviers Member which form the bulk of the Saint Martin Formation. Nevertheless, in Aquitaine, early writers such as Glaugeaud (1895) and Thevenin (1903) have regarded the oolitic rocks which succeed Liassic rocks, as being Bajocian in age. Glaugeaud (1895, fig.22), and much later Delfaud (1972, fig.5), have been able to trace the 'Bajocian Oolites' northwards from the Lot Valley, through the Dordogne, into the Charente area, where they pass laterally into a more easily dated succession of calcareous mudstones and shales with ammonites. This has indicated a Bajocian age for the 'oolites'.

Confirmation of this has since been obtained in the Figeac area, because recently Gerard Lafaurie has recovered a specimen of the ammonite Garantiana garantiana from the recrystallised oolitic sediments of the Ceneviers Member at Faycelles. Furthermore, in 1903 Thevenin reported finding a specimen of Parkinsonia (Sowerby) sp. indet., in the oolitic sediments exposed in a quarry near Mauriac, in Aveyron. The latter example is from rocks laterally equivalent to the Saint Martin Formation. Thus considering them together, the ammonites indicate an upper Bajocian age.

No middle Bajocian fossils have been found in the oolitic sediments, but the passage from early middle to upper Bajocian appears to be unbroken in the Lot Valley. It has been assumed, therefore, that the Ceneviers Member ranges from middle to upper Bajocian. No date has been obtained for the Corn Member.

Thus the Saint Martin Formation can be dated as uppermost Toarcian to upper Bajocian. Daukoru (1970) reached similar conclusions for the Mirandol Oolite of the Dordogne Valley.

3.5 The History of Deposition of the Saint Martin Formation

The lithological distinctiveness of each of the component members of the Saint Martin Formation has already been outlined. In this section each of these units will be shown to represent a distinct period in the depositional history of the formation, and consideration will be given to the factors that controlled deposition.

The history of the formation started with the establishment of nearshore, open marine, shelf conditions (figure 13). This was accompanied by the deposition of bioclastic and rhodolithic packstones, which now make up the Latoulzanie Member. The thickness of these beds varies from location to location and at Lissac and Balaguier the bioclastic packstones are absent. An examination of the fauna has shown that this member is a condensed sequence, with 0 to 4 metres of sediments representing Upper Toarcian to early middle Bajocian times (Jurense zone to Sowerbyi zones) (see figures 12a and b). One hardground horizon has been found in bioclastic sediments at Latoulzanie.

Only one bed of rhodolithic packstone occurs in the succession and it succeeds the bioclastic packstone. Unlike the latter, the rhodolithic sediments are persistently present throughout the Lot and Célé Valleys, in the study area. This bed was probably deposited in a slightly shallower water environment than the underlying bioclastic packstones, and may represent nearer shore conditions (figure 13). It is also thought to have been deposited in early middle Bajocian times and again the rate of deposition was probably slow.

At most locations the history of the rocks succeeding the rhodolithic packstones has been obscured by recrystallisation. However, at Corn, despite partial recrystallisation, the picture has been found to be clearer. Here, rhodolithic packstones have been found to be succeeded by peloidal grainstones, which soon pass upwards into peloidal oolitic grainstones and then oolitic grainstones proper. This unit is considered to be the base of the Ceneviers Member and marks the next stage in the history of the Saint Martin Formation.

The Ceneviers Member is the thickest unit of the formation. It is composed of oolitic or recrystallised oolitic sediments. These were probably deposited as a coastal barrier complex with open marine and/or outer lagoonal interludes. Oolitic sedimentation is thought to have started in middle Bajocian times and continued into the upper Bajocian (G. garantiana zone).

The closing stages of the history of the Saint Martin Formation are preserved in the Corn Member, which is probably very late Bajocian in age. This unit is composed of interbedded rhodolithic grainstones, peloidal oolitic grainstones and calcareous mudstones. In comparison with the Ceneviers Member there is a marked overall reduction in the ooid content of the sediments. They are thought to have been deposited in an outerlagoonal environment with occasional influxes from an oolitic barrier. This member is transitional from the oolitic sediments of the Ceneviers Member into the lagoonal sediments of the Larnagol Member of the Cajarc Formation.

The succession of the upper Larroque and lower Saint Martin Formations, probably represents a seaward lateral migration of shallower water environments accompanied by the deposition of related sediments (figure 13). This regressive phase encouraged the deposition of micaceous shales followed by bioclastic and rhodolithic packstones. The nearshore open marine sediments are thought to have prograded into the Cajarc area in upper Toarcian to early middle Bajocian times (figure 19A).

According to the sedimentological evidence, an oolitic barrier complex became established in the area in middle Bajocian times, and despite minor fluctuations, persisted in the region until upper Bajocian times (figure 19B). However, in the later upper Bajocian predominantly outer lagoonal sedimentation had started (figure 19C), which gave rise to the deposition of the Corn Member. This was probably instigated by the further seaward migration of the barrier out of the area, thus establishing lagoonal conditions behind it.

Generally, therefore, the succession of sediments in the Saint Martin Formation may be shown to represent an upward passage from open marine deposits, through oolitic barrier sediments, into those of an outer lagoonal environment. This has probably resulted from the migration of an oolitic coastal barrier complex through the area in Bajocian times.

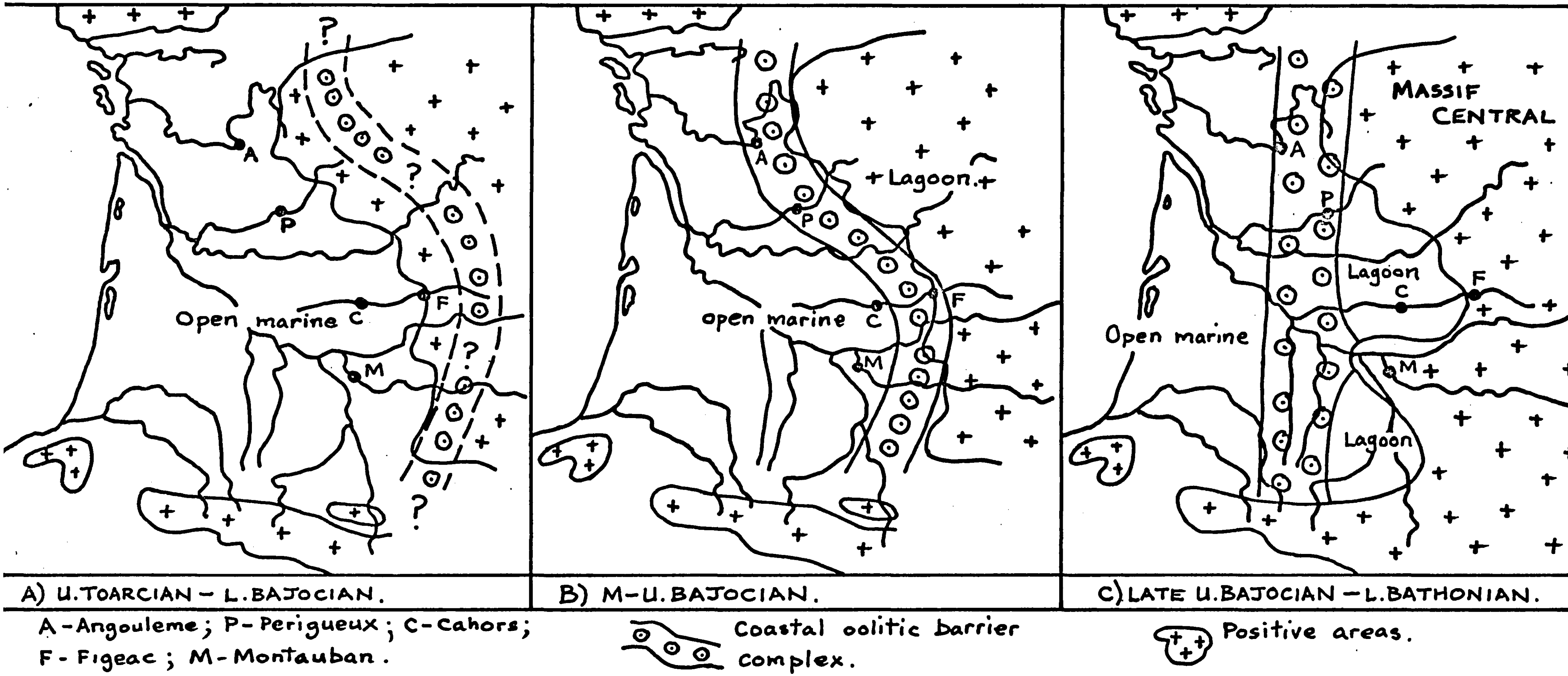


FIGURE 19 Palaeogeographical maps of Aquitaine showing the progressive development of an oolitic coastal barrier complex in the Bajocian. (Compare with figure 4.)

FIGURE 20. Diagram showing how the migration of the environments of deposition in the Bajocian, influenced the development of the St. Martin Formation in the Cajarc area. Note the progressive upward change from open marine to outer lagoonal conditions (the environments of deposition are represented and not the actual thickness of sediment which accumulated).

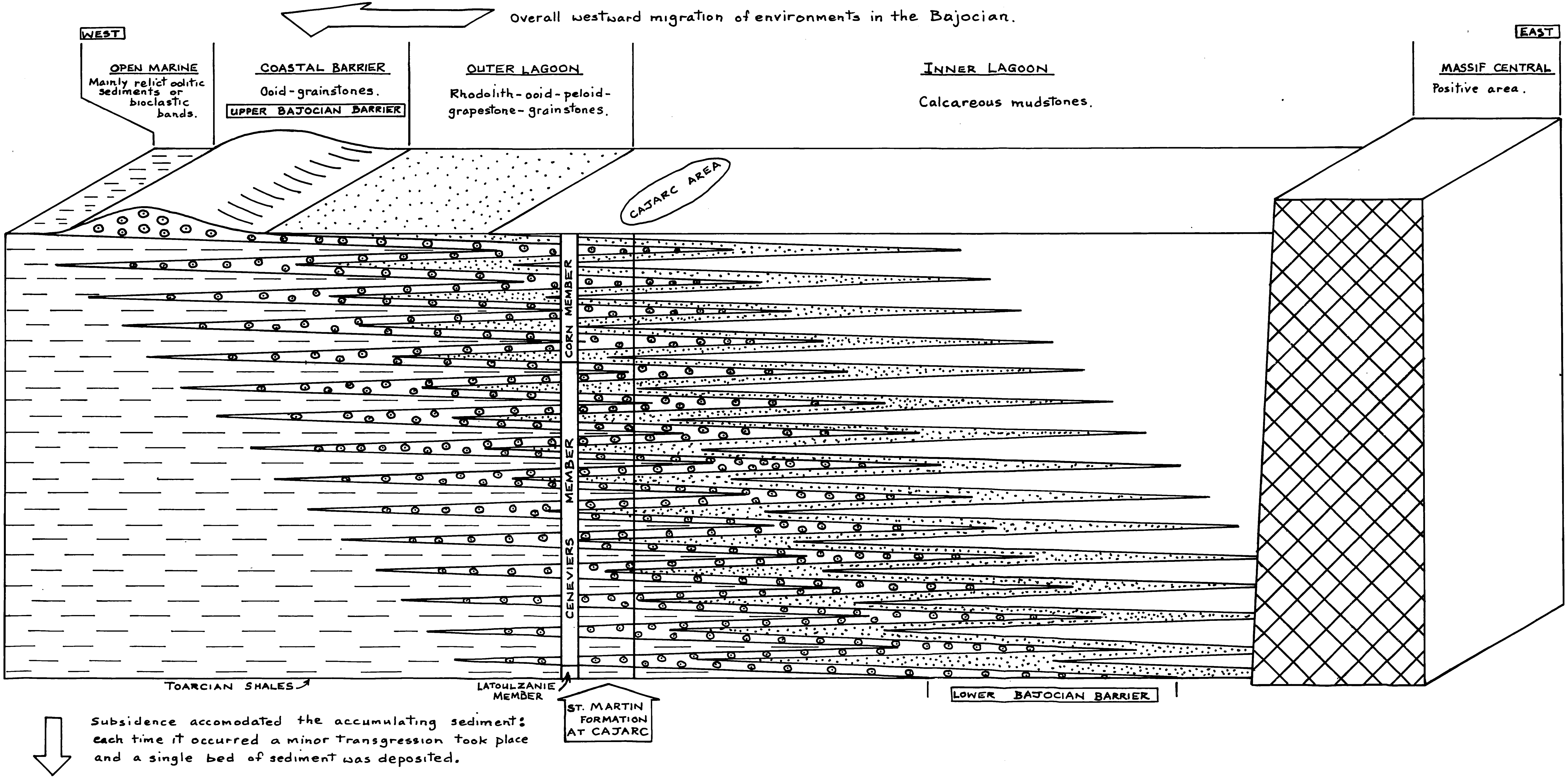


Figure 20 is a diagrammatic representation of the migration in relation to subsidence. Only depositional environments are indicated and not the thicknesses of sediment deposited. It is suggested that the migration was not a simple one, but consisted of a series of prograding beds laid down on top of one another, with the environments of deposition being shifted slightly westwards in each successive phase. The open marine phases represent transgressions during which previously deposited oolitic sediments have been reworked in an open marine environment, and perhaps bioclastic bands have been laid down. An attempt is made to show how the shifting environments influenced the deposition of the Saint Martin Formation and also how this is now represented in the stratigraphic column.

The barrier itself is thought to have become established around the positive area of the Massif Central in lower Bajocian times, and then to have migrated westwards through the Cajarc area, in middle Bajocian times (figures 19 and 20). This had led to the speculation that the oolitic and rhodolithic sediments of the Ceneviers and Corn Members should pass laterally eastwards into inner lagoonal calcareous mudstone sediments, around the borders of the Massif Central. However, it has not been possible to prove this, because the rocks have been removed by erosion.

To the west of the Cajarc area the Saint Martin Formation dips under younger rocks and little has been written about its extent towards the centre of the basin. Nevertheless, boreholes that have been made in western Aquitaine have shown that the Saint Martin Formation is laterally equivalent to limestones with microfilaments and shales and marls with ammonites, that were probably deposited in an offshore, open marine, shelf environment (Delfaud 1972, Winnock et al 1973). Furthermore, schematic sections given by Glaugeaud (1895, fig.22) and Delfaud (1972, fig.5), have shown that in northern Aquitaine, in the department of Charente, Bajocian oolitic sediments of Brântome and Montbrun pass laterally westwards into 'Calcaires a silex' with ammonites in the valley of the Charente, towards La Rochelle.

Palaeogeographical reconstructions that have been made by Delfaud (1971, 1973) and Winnock et al (1973), have suggested that in the middle Jurassic an oolitic barrier complex existed to the west of the Massif Central, enclosing a lagoon therein and passing westwards into open marine sediments (figure 4). Borehole data has confirmed the existance of this barrier, but a study of the Saint Martin Formation has shown that, initially, the barrier developed much closer to the Massif Central (figure 19A) and that it prograded westwards in middle and upper Bajocian times (figure 19B,C). Moreover, it seems probable that it did not become established in the position indicated in figure 6 until very late Bajocian or early Bathonian times, but as yet the writer has no stratigraphical proof of this.

Wherever Bajocian sediments outcrop on the western and southern margins of the Massif Central, they have been described as being oolitic. North of the Cajarc area, in the Dordogne, Daukoru (1970) described a succession that is almost exactly the same as the Saint Martin Formation. Further north at Brântome and Angouleme, Bajocian sediments are also oolitic, and again the same is true on the southern margins of the Massif, at Saint Antonin and Millau. It appears, therefore, that the present day outcrop coincides with the geographical position of the oolitic barrier that bordered the Massif Central in middle Bajocian times (figures 6 and 19B).

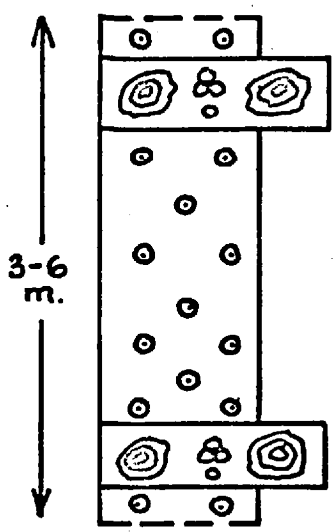
Over most of Perigord and Quercy the Bajocian oolitic sediments exceed 50 metres in thickness. But in Recent environments, presently forming oolitic deposits are only a few metres in thickness. Clearly, therefore, the Bajocian succession must have been due to repeated phases of oolitic sedimentation, accommodated by a gradual subsidence of the sea floor, or possibly in some cases a eustatic rise in the sea level. Evidence of this may be found in the sediments of the Ceneviers and Corn Members of the Saint Martin Formation, where the three lithofacies that have been recognised, have been found to be rhythmically repeated (figure 21). As each of these lithofacies has been deposited in a slightly different environment (figure 21B), their repetition implies a rhythmic variation of the environment of deposition as suggested in figure 20.

One such rhythmic lithofacies repetition is represented in figure 21A. Here ooid-peloid-bioclast grainstones or cross-bedded ooid grainstones are succeeded by a thin bed of rhodolithic grainstones. This succession might have been produced by the seaward migration of an oolite shoal, followed by a relative rise in sea level, whereby the shoal sands and outer lagoonal sediments became relict deposits in an open marine environment (figure 21B). This would then be superceded by a new rhythm when a younger shoal migrated out over the older relict sediments.

In present day examples, such as the Bahamas and the Persian Gulf, the site of active formation of ooids is only 1 to 3 km. wide, and actually forms the barrier itself. However, oolitic sediments may be spread out over a zone 20 to 80 km. in width. Within this zone slight fluctuations in sea level might cause the site of active ooid growth to migrate back and forth and this, combined with a background of subsidence, might result in an interbedded sequence of ooid shoal sediments with outer lagoonal oolitic and relict oolitic sediments, and even open marine bands (figures 20 and 21).

Such a zone of sedimentation cannot be considered as a single barrier because the resulting deposits are made up of a complexed succession of barriers and outer lagoonal and open marine sediments. This sort of complex might accumulate in a zone 100 km. or more in width, which explains the apparently considerable width of the middle Bajocian 'Barrier' that

A.



LITHOLOGY	ENVIRONMENT OF DEPOSITION
Rhodolith-grapestone-peloid-ooid-grainstone.	Outer lagoonal or open marine; probably relict ooid sands.
Cross-bedded or massive ooid-grainstone, or ooid-peloid-bioclast-grainstone.	Oolitic shoal, tidal delta or just lagoonwards of shoals.

B.

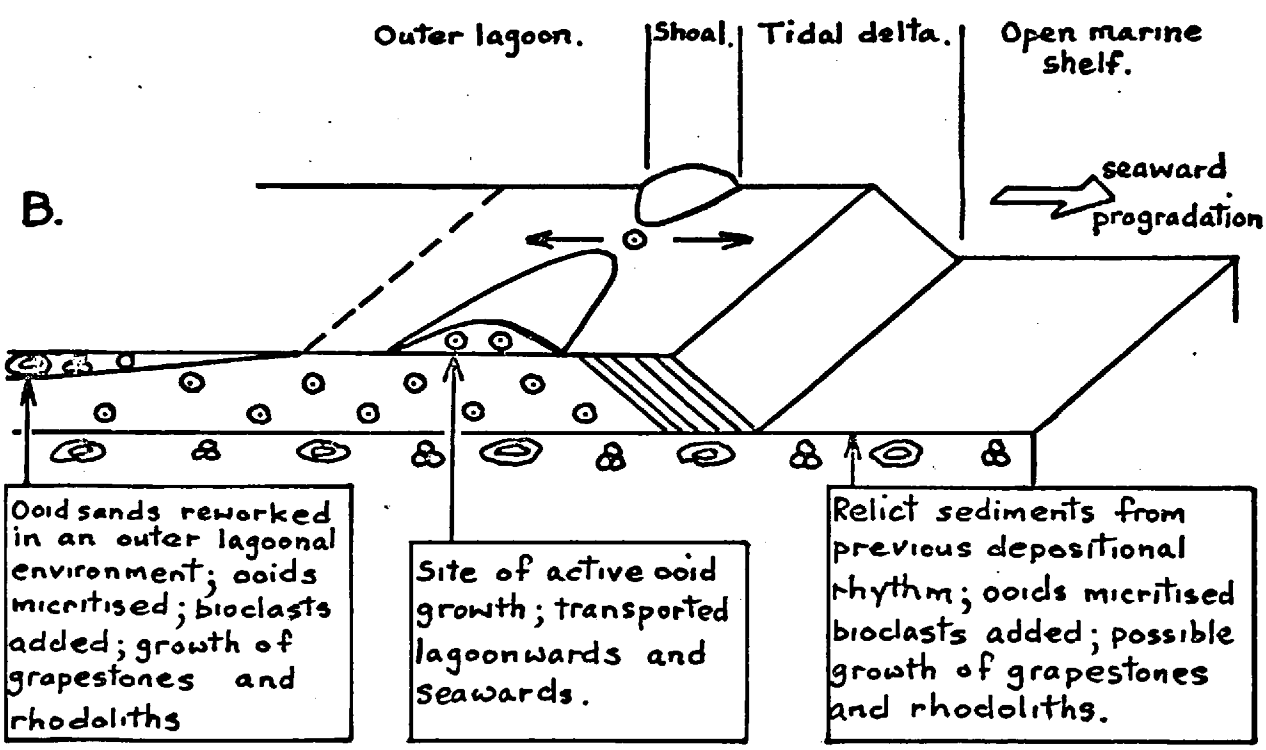


FIGURE 21 A) A typical sedimentary rhythm from the Ceneviers Member of the St. Martin Formation.

B) The suggested environments of deposition.

is in fact a barrier complex over 100 km. in width, in places. Further, it was a complex rather than a single barrier that prograded westwards in the Bajocian, eventually becoming established in a zone running north-south from Angouleme, through Marmande to Tarbes (figure 4 and 19C).

Also in the Bahamas coral-algal reefs have been described in association with the oolitic barrier sands. Such a reef complex has also been described from the Bajocian sediments around the Montbrun region, in Charente, where oolitic sediments are associated with in situ coral reefs (Glaugeaud 1895, fig.22; Delfaud 1972, fig.4).

Thus, in the Bajocian the Massif Central probably acted as a platform rather like the Great Bahama Bank today, with a fringing oolitic and coral reef barrier and lagoonal sediments within. The scale of development was almost exactly the same as the Bahamian example. Delfaud (1973) also arrived at similar conclusions although he called the Massif 'le Haut-fond Occitan'.

CHAPTER 4

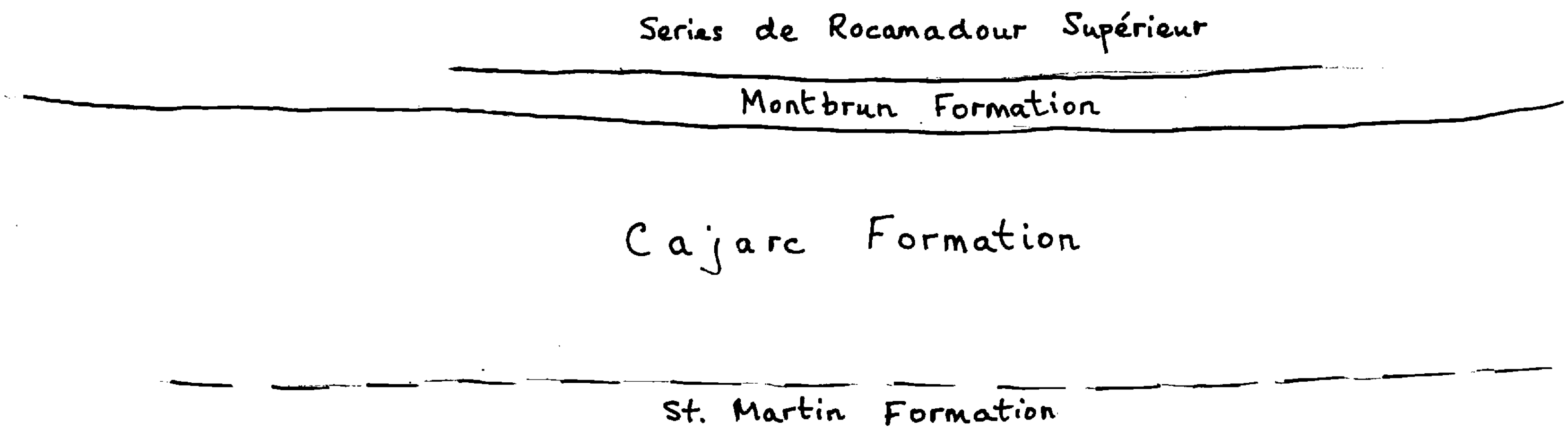
THE CAJARC FORMATION

This formation, which succeeds the Saint Martin Formation, is named after the town of Cajarc where it forms the lower parts of the cliffs surrounding the town. The whole of the unit has been studied in detail and stratigraphic sections have been measured and logged at La Tour de Faure, Saint Martin-Labouval, Larnagol, Cajarc, Montbrun and Larroque-Toirac in the Lot Valley and at Marcilhac, Espagnac, Brengues and Corn in the Célé Valley.

As a unit, it is well exposed on the north side of the Lot Valley between La Tour de Faure and Saint Affré and in the Célé Valley between Sauliac and Corn. Unlike the Saint Martin and Montbrun Formations, this unit is well bedded and it rarely produces steep cliffs. More usually it forms stepped hillsides with partial vegetation (figure 22).

The total thickness of the formation varies from 111 metres at Larnagol to about 121 metres at Espagnac and Corn. It is composed mainly of massive and laminated calcareous mudstones, crystalline limestones and subordinate beds of calcareous grainstone and lignitic marl. Calcitised evaporitic deposits have also been recognised.

On lithological grounds it has been possible to subdivide this formation into four members: (figure 23):
Larnagol Member
La Plogne Member
Marcilhac Member
Brengues Member
(each of which is named after the location where it is best exposed).


Series de Rocamadour Supérieur
Montbrun Formation
Cajarc Formation
St. Martin Formation

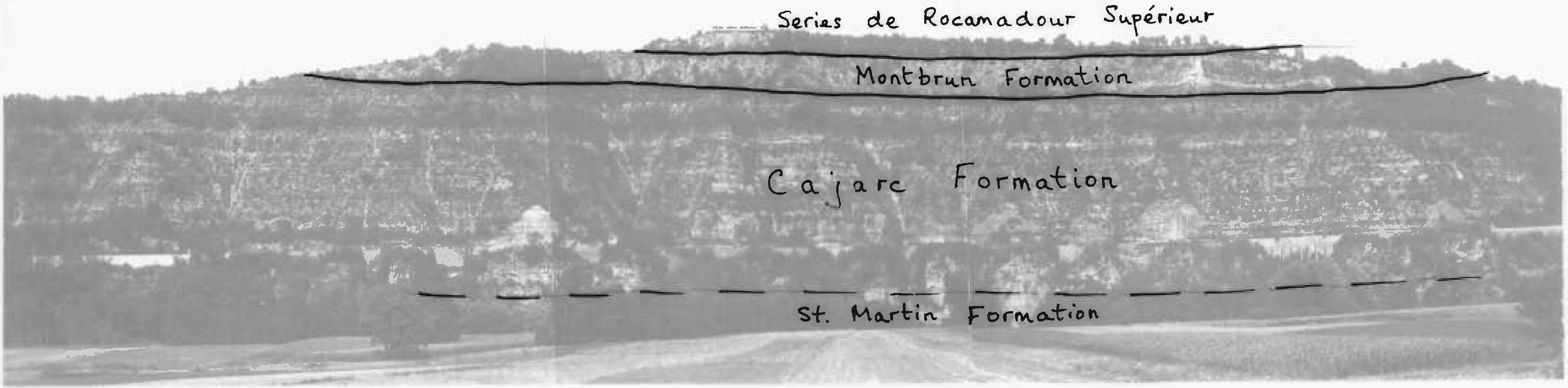


FIGURE 22. A general view of the Larnagol section showing the upper St. Martin Formation at the base, followed by the Cajarc Formation, the Montbrun Formation, and Series de Rocamdour Superieur at the top. Note the red and yellow weathered rocks in the lower part of the section, which are dedolomitised and cargneuliform in appearance. Also observe the stepped nature of the outcrop of the Cajarc Formation which is quite well vegetated. (A section log of this exposure is given in enclosure 4).

FIGURE 22. A general view of the Larnagol section showing the upper St. Martin Formation at the base, followed by the Cajarc Formation, the Montbrun Formation, and Series de Rocamdour Superieur at the top. Note the red and yellow weathered rocks in the lower part of the section, which are dedolomitised and cargneuliform in appearance. Also observe the stepped nature of the outcrop of the Cajarc Formation which is quite well vegetated. (A section log of this exposure is given in enclosure 4).

The lowest unit is the Larnagol Member, which succeeds the Corn Member of the Saint Martin Formation. It may be examined in the roadside (N662) section at Larnagol or in the roadside (D24) section above Saint Martin-Labouval, where it is approximately 22 metres in thickness. The lower limit of this member is the horizon with abundant fossil roots at Corn (page 42), however, where this cannot be found the Larnagol Member may be defined as being composed of calcareous sediments which lack ooids or rhodoliths (i.e. no lithologies comparable with those of the Corn Member). The upper limit is the top of a bed of oolitic peloidal grainstone, exposed in the roadside (N662) section near Larnagol (044263), which forms a well developed marker horizon throughout the Lot and Célé valleys. At most locations the Larnagol Member is composed mainly of crystalline limestones with subordinate beds of calcareous mudstone and peloidal grainstone, but at Montbrun the rocks are not recrystallised and have retained their original depositional characters.

The next unit is the La Plogne Member, of which the best exposure is in the quarry just below La Plogne (064260) on the N662. It is about 51 metres in thickness. The lower limit is the thick lignitic marl which overlies the bed of grainstone at the top of the Larnagol Member and the upper limit is the bed of ostracod wackstone just below the fourth important grainstone bed in the succession of the Cajarc Formation (figure 23). It is composed mainly of massive and laminated calcareous mudstones, sometimes recrystallised in the lower part of the member, with subordinate horizons of lignitic marl and beds of peloidal oolitic grainstone.

The La Plogne Member is succeeded by the Marcilhac Member which is best exposed in the roadside (D17) section near Marcilhac (023350 to 020359). It varies in thickness from 20-25 metres and it starts with a bed of peloidal oolitic grainstone which succeeds the bed composed of ostracod wackstones defined in the previous paragraph. The upper limit is marked by the sudden appearance of some marly and shaly

Second order rhythms of deposition	Description	Environment of deposition
6	Marls, algal boundstones, laminated and massive calcareous mudstones, and oolitic grainstones passing upwards into ostracod wackestones. Calcitised evaporitic deposits.	Outer lagoonal to supratidal sabkha. (Dominantly supratidal) Lacustrine at the top.
5, 4	Laminated and massive calcareous mudstones, algal boundstones, oolitic grainstones, and a few thin marls; ostracod wackestone near the top. Calcitised evaporitic deposits.	Outer lagoonal to supratidal sabkha. (Dominantly intertidal) Sometimes lacustrine.
3, 2, 1	Laminated and massive calcareous mudstones, oolitic grainstones, and a few algal boundstones and thin lignitic marls; some ostracod wackestones. Horizons of roots and plant debris. (no evidence of evaporites)	Outer lagoonal to supratidal. (Dominantly subtidal to intertidal). Sometimes lacustrine.
	Mainly dolomitised and dedolomitised to produce crystalline limestone; otherwise calcareous mudstones, oolitic grainstones, ostracod wackestones and lignitic marls with layers of roots. Evidence of evaporites at two horizons.	Outer lagoonal to supratidal (Dominantly supratidal?) Sometimes lacustrine.

FIGURE 23. Lithostratigraphic subdivision and general interpretation of the Cajarc Formation.

beds which are defined in the next paragraph. Lithologically this unit is similar to the La Plogne Member, but it is differentiated because of the presence of calcitised evaporitic deposits, and also the increased abundance of algal boundstones.

Finally, the uppermost or Brengues Member is best exposed in the roadside section (between Brengues and La Cayre) near Brengues (075364). It varies in thickness from 10-12 metres. In the Brengues section it commences with a bed of peloidal oolitic grainstone, above which laminated marls suddenly become more abundant (figure 23). The upper limit of the unit is the bed of oolitic grainstone at the base of the Montbrun Formation. Lithologically this member is composed of calcareous mudstones, algal boundstones and oolitic grainstones, interbedded with marls. Calcitised evaporitic minerals are abundant and in the upper part there are thick deposits of ostracod wackstone.

On the geological map for Gourdon (194), rocks that are equivalent to the Cajarc Formation were mapped by the French geologists as 'Bathonien moyen et inferieur (Jii-Jiii)' and described as 'calcaires sublithographiques en dalles'. On the Cahors (206) sheet they were mapped as 'Bathonien infeurier (Jii-iii)' and described as 'Calcaires en plaquettes avec passées d'argile ligniteuse'. The Cajarc Formation is also equivalent to the upper part of rhythm J_A and to the upper Series d'Autoire, as defined by Delfaud (1974, fig.4). The Gluges Calcilutite of the Dordogne area, defined by Daukoru (1970) represents exactly the same stratigraphic interval as the Cajarc Formation.

In the present study the following lithofacies have been recognised in the Cajarc Formation:
oolitic grainstone
calcareous mudstone
laminated calcareous mudstone

organic laminated limestone
laminated algal boundstone
algal boundstone
oncolitic wackestone/packstone
disrupted algal boundstone
birdseye mudstone
ostracod wackestone
marl
crystalline limestone

These lithofacies will be described and discussed in the following sections.

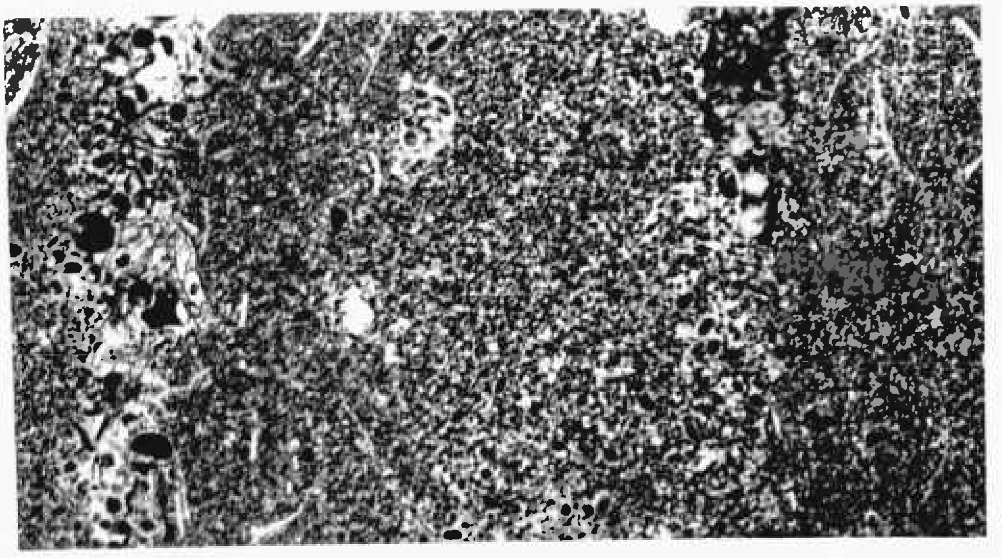
4.1 The Oolitic Grainstone Lithofacies

This lithofacies consists of massively bedded oolitic grainstones with minor amounts of other lithofacies. Sedimentary structures and bedding planes are nearly always absent but in a few case where marly partings or thin layers of calcareous mudstone are present, flat centimetre scale bedding is developed. Some good examples of this lithofacies may be found in the section exposed at 064260 near Cajarc.

Nearly all the samples of this lithofacies that have been examined are grainstones, but some packstones and wackestones have been observed where the oolitic grainstones pass upwards or downwards into calcareous mudstones. Some algal boundstones are also present within this lithofacies.

Petrological and X-ray analyses have indicated that the oolitic grainstones are composed almost entirely of calcium carbonate with occasional traces of quartz. The rocks consist of five types of grains: ooids, bioclasts, peloids, grapestone grains and intraclasts. Varying proportions of these grains appear to account entirely for the range of lithologies within this lithofacies. The most commonly developed lithology is a medium sand grade oolitic-peloidal-bioclastic grainstone (figure 24), with or without a few

A.



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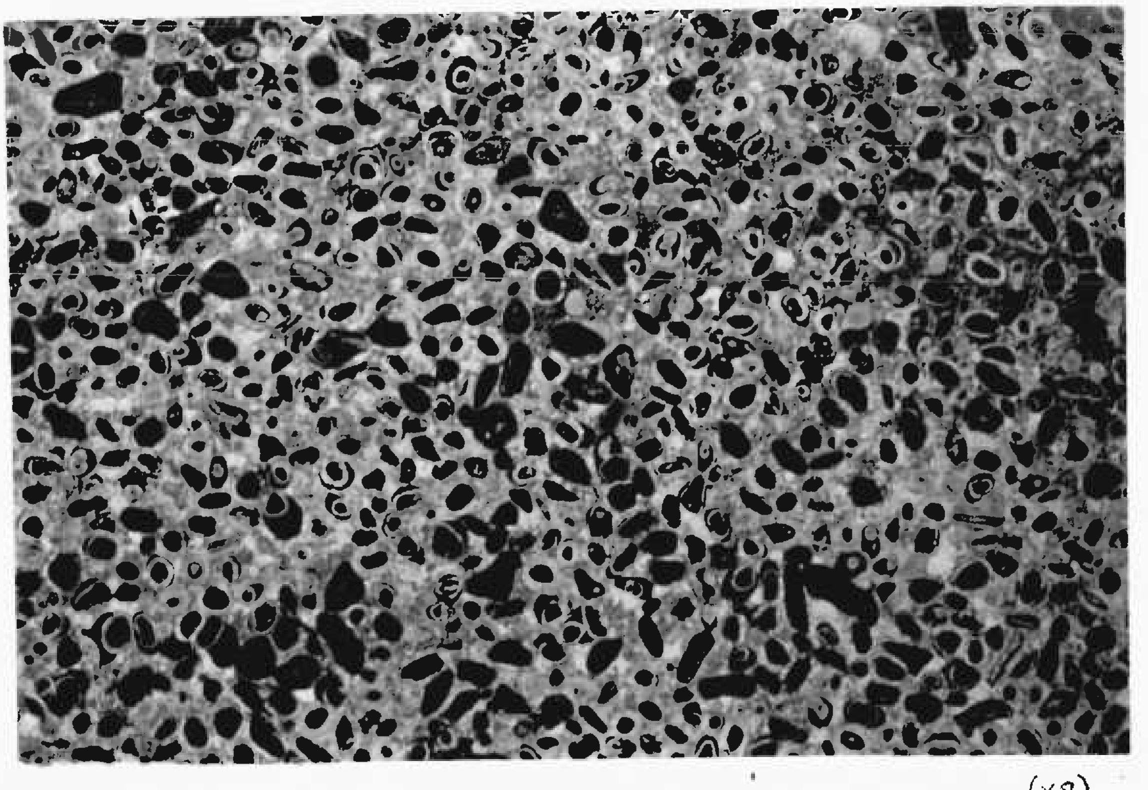
B.



(x8)

FIGURE 24 A A photomicrograph of an ooid-peloid-bioclast-grainstone (Marcilhac Mb. Larnagol).

FIGURE 24 B A photomicrograph of an almost pure oolitic grainstone (Marcilhac Mb., La Plogne).

intraclasts, calcareous algal fragments and grapestone grains; but some purely oolitic or peloidal grainstones have also been found (figure 24).

As so much is now known about the petrology of calcareous grains in Recent sediments, it is interesting to compare them with the grains of this lithofacies, to assist with the interpretation of the latter.

Ooids: these are mostly of medium sand size and vary from spherical to elongate in shape, depending on the shape of their nuclei. The latter are characteristically large and the oolitic coatings relatively thin (figure 24b); however, in some cases the reverse is true. These two types have been described as superficial and true ooids respectively, by Illing (1954), Beales (1958) and Purdy (1963). Most of the ooids have been nucleated around peloids or bioclastic debris (figure 25) derived from molluscs, echinoids, calcareous algae, foraminifera, and rarely, even whole charophyte oogonia.

Some of the ooids have well preserved radial and concentric structures and good pseudo-uniaxial extinction figures may be obtained using crossed-polarisers. Shearman et al (1970) described analogous features from the Recent oolitic grains of Abu Dhabi, in the Persian Gulf, and furthermore, the light brown body colour that they found in the Recent ooids has also been observed in the oolitic grains from the Cajarc Formation. Shearman et al thought this was probably due to the presence of inherent organic matter in the grains.

The ooids of this lithofacies have suffered varying degrees of micritisation: some have only suffered one final phase of micritisation, but others have been subjected to repeated phases of oolitic coating followed each time by micritisation, which has resulted in the formation of alternating micritic and oolitic jackets (figure 25). In the cases where only one final phase has occurred the outer surfaces of the grains are sometimes pitted; this has been described from recent oolitic sediments by Shearman et al (op. cit.)

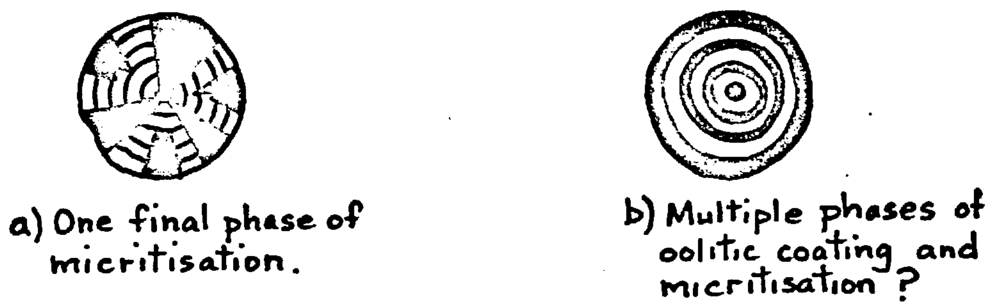


FIGURE 25 Micritisation of ooids in the oolitic grainstone lithofacies.

Bioclasts: a few of these grains are present in nearly every example of the oolitic grainstone lithofacies. More often, however, they do not form individual grains, because they have been incorporated into grapestone grains or ooids, or micritised and rounded until they are almost indistinguishable from peloids and intraclasts (depending on size). The following types of bioclasts have been observed: echinoderm fragments or spines, molluscan debris, calcareous algal fragments, whole and broken foraminifera and rarely charophyte oogonia. All these have been micritised to varying degrees and in some case micrite envelopes (Bathurst 1966; 1971, p.381-392) have become well developed (figure 26).

According to Bathurst (1964 and 1966) it is possible to distinguish between molluscan grains that were originally composed of calcite and those which were aragonitic, even after all traces of aragonite have been removed during diagenesis. In the oolitic grainstone lithofacies the calcitic

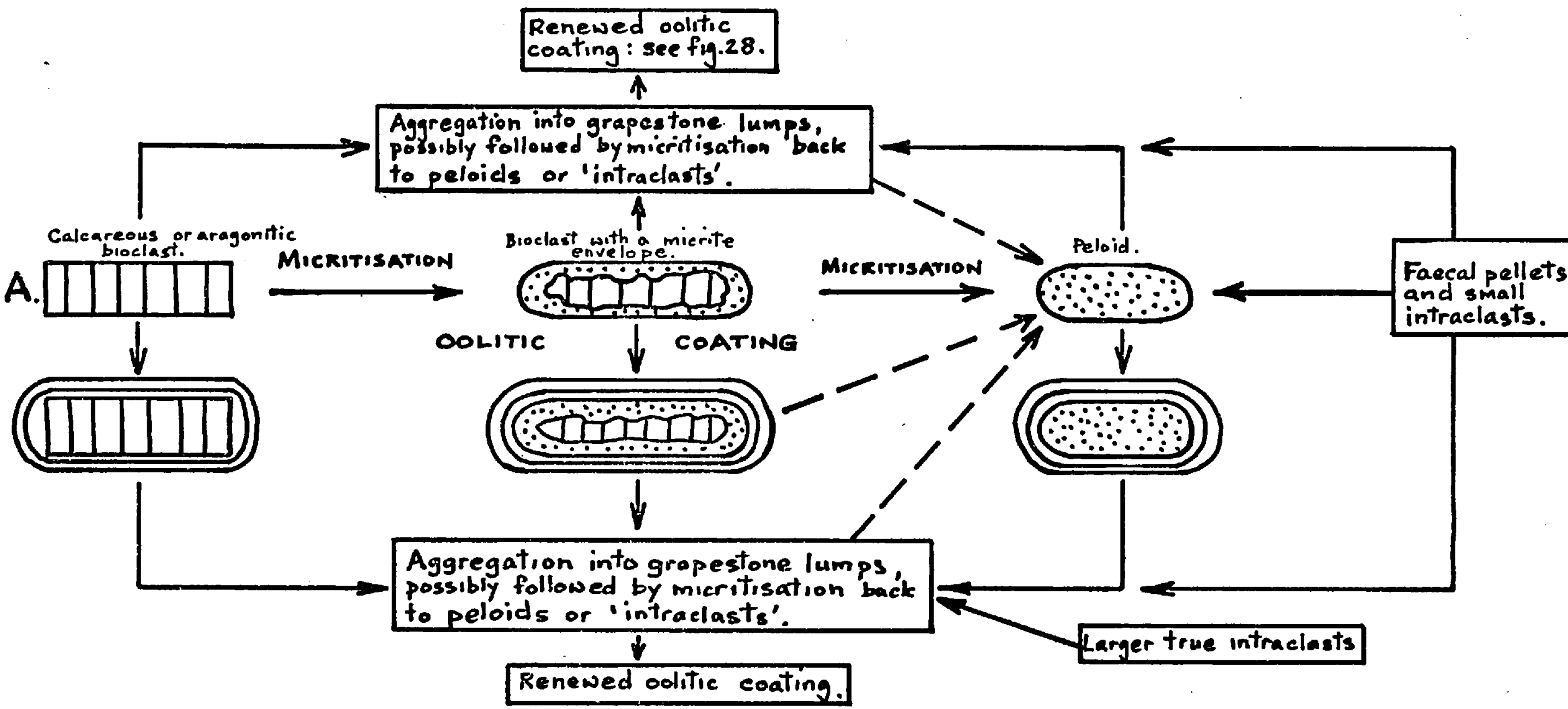


FIGURE 26 Evolution of grains in the oolitic grainstone lithofacies (aragonitic bioclasts have been further modified during diagenesis: see figure 27).

types are recognisable because they have retained their original internal structures, but the grains which were aragonitic are now represented by void-infilling mosaics of calcite within faint dust-trail outlines or micritic envelopes (figure 27).

Many of the calcareous algal fragments found in this lithofacies are comparable to the genus Halimeda, figured by Bathurst (1971, p.62) and Horowitz and Potter (1971, p.215). These fragments have been micritised to varying degrees, and often internal cavities have been infilled with micrite to make them almost indistinguishable from intraclasts. A similar phenomenon has also been observed in the Recent skeletal sands of the Bahamas and the Persian Gulf, where calcareous algal grains may become micritised and encrusted and reviewed the subject and suggested that they might arise as faecal pellets, inorganic accretions, or by the micritisation of skeletal debris and other grain types such as ooids. Purdy (1963) noted that in the Recent Bahamian calcareous sands, skeletal material is often micritised but he also suggested that peloids or crypocrystalline grains might have multiple sources. Bathurst (op.cit.) concluded that peloids are probably largely derived from bioclastic debris.

In most thin sections of the oolitic sediments of the Cajarc Formation, the bioclasts show varying degrees of micritisation (from incipient to almost complete). It has already been noted that some peloids have probably been derived from foraminifera by micritisation. Furthermore, heavily micritised bioclasts are often similar in shape and size to adjacent peloids. Therefore it is possible that many peloids may have been formed by the micritisation of other kinds of bioclastic debris (figure 26). Some peloids are similar in shape and size to adjacent ooid grains and as many of the latter grains have been micritised to varying degrees, they may have been derived from ooids by micritisation (figure 26).

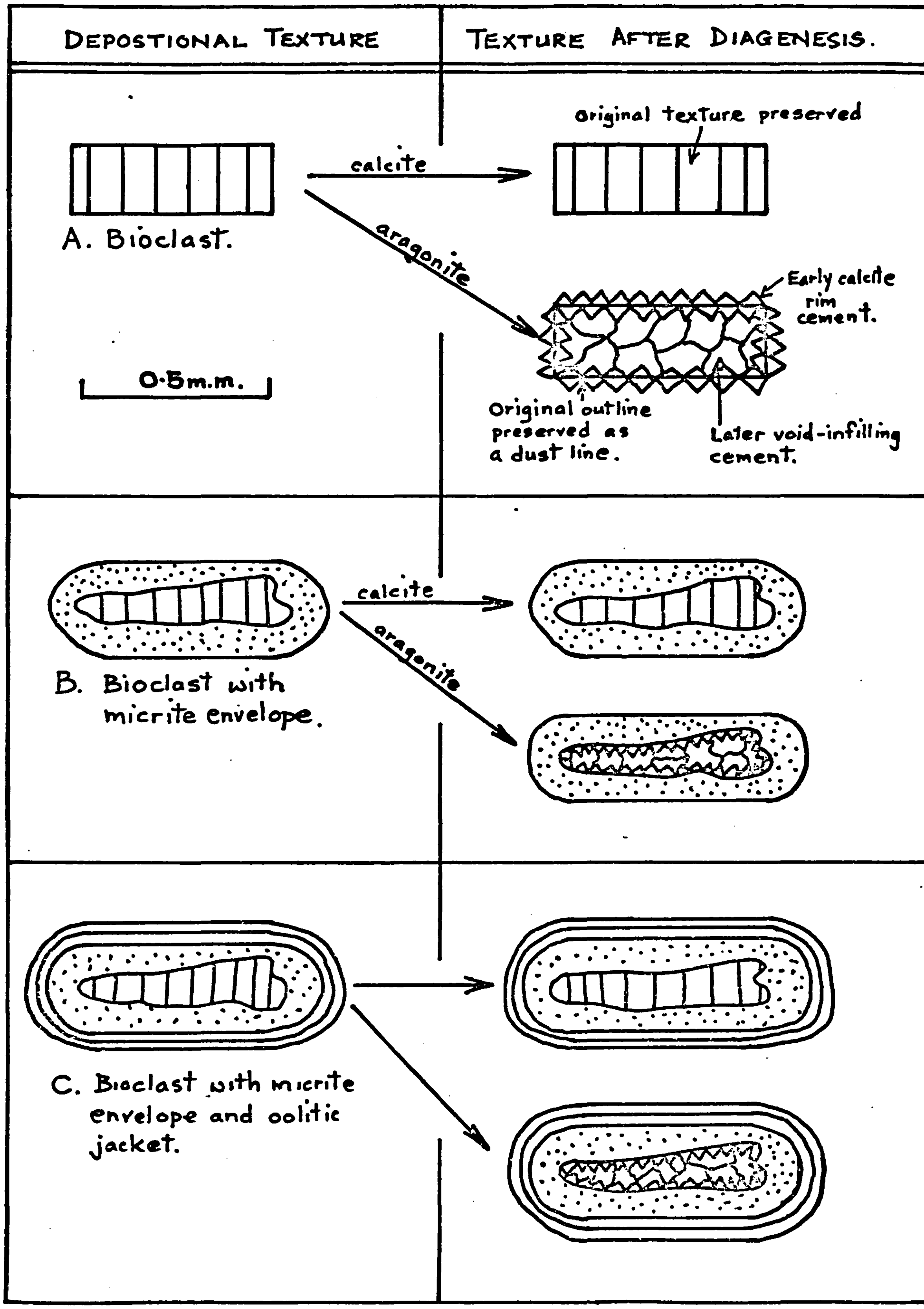


FIGURE 27 Textural evolution of grains in the oolitic grainstone lithofacies during diagenesis.

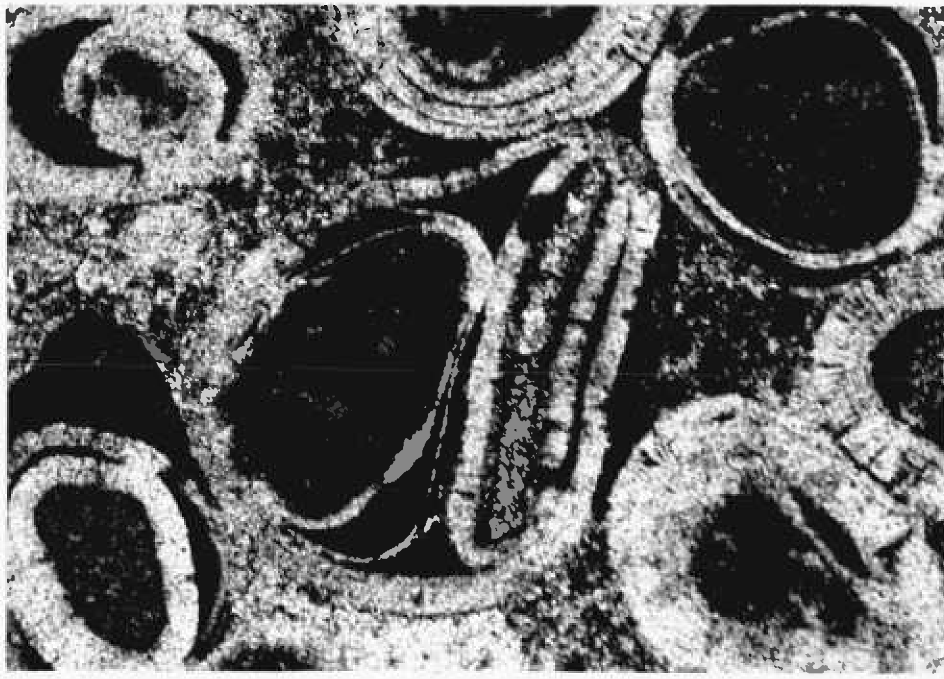
In one or two examples, peloids have been found to be squashed, suggesting that they were soft at the time of deposition. These could have originated as faecal pellets. Another possibility is that some peloids were initially small mud lumps or intraclasts that were eroded by current action from contemporaneous mud sheets (Fahraeus et al 1974). Thus it appears that the peloids of the oolitic grainstone lithofacies are multiple in origin (figure 25).

Grapestone and accretional grains: the former term was first used by Illing (1954) and folloiwng him, any grains in the Cajarc Formation that are composed of two or more simple grains, cemented or bound together, are also called grapestone grains (figure 28). In the oolitic grainstone lithofacies these generally form less than 5% of the sediment. They range from medium sand to granule size, and are composed mainly of ooids, peloids and bioclasts held together by micritic material.

Taylor and Illing (1969) noted that in certain environments in the Persian Gulf, limited numbers of grains may become firmly cemented together. Also in his review, Bathurst (1971) summarised that grapestone grains have been found in a number of Recent carbonate provinces where the component sand grains are commonly rounded, intensely micritised and cemented together by micritic aragonite. Illing (1954) and Purdy (1964a) both observed that prolonged rolling and abrasion may destroy the external morphology of the lumps, but that the composite nature of the grains is usually still recognisable. All these features have been found in the oolitic grainstones of the Cajarc Formation (figures 26 and 28), but some of the grapestone grains have suffered from varying degrees of micritisation making them almost unrecognisable as such.

Accretional grains are usually associated with the grape-

A.



(x100)

FIGURE 28 Grapestone and accretional grains in the oolitic grainstone lithofacies of the Cajarc Formation:

A) Photomicrograph showing oolitically coated bioclasts and peloid grains which have been aggregated together and then subjected to further oolitic coating and micritic accretion (23/73, Marcilhac Mb., La Plogne).

B) Simple aggregated or grapestone grains.

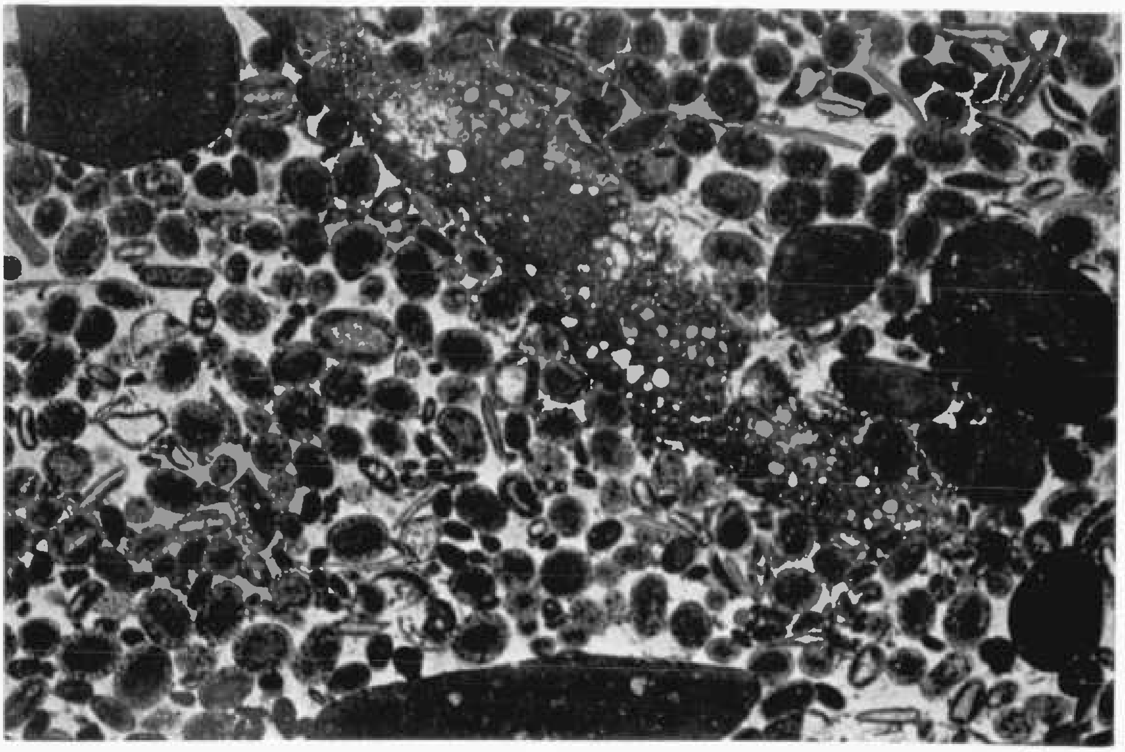
C) Aggregated and oolitically coated grain.

D) Grain formed by alternating oolitic coating and micritic accretion.

stone grains (figure 28). Although these are not true grapestones, they have probably formed as a result of the same processes, because in an environment where some grains are being cemented together, it is possible that others could be coated assymetrically with micrite (perhaps by calcareous algae). Occasionally these are oolitically coated, and sometimes up to four separate phases of accretion and oolitic coating have occurred (figure 28). The ooids mentioned on p.103 may also have formed in this way (Newell, 1960).

Intraclasts (Folk 1959): usually these only make up a very small proportion of the sediment but sometimes they form 'conglomerates' at the bases of beds of oolitic grainstone. They vary from coarse sand to gravel grade and they are always composed of calcareous mudstones.

Some of the intraclasts appear to have been derived, by erosion, from underlying deposits of calcareous mudstone, or from the erosion of interbedded sheets of contemporaneous calcareous mud. Typically, the intraclasts are flattened and elongated and they look like 'mud flakes' or 'chips'. Alternatively other intraclasts show evidence of having been derived by micritisation (figure 26), from other grains such as grapestone grains, rhodoliths and calcareous algal fragments; but this is only discernable where micritisation has been incomplete (figure 29). In these cases the term intraclast, as defined by Folk (1959) is not applicable and as the origin of the 'intraclasts' is often obscure, perhaps it is better to call them structureless cryptocrystalline grains.



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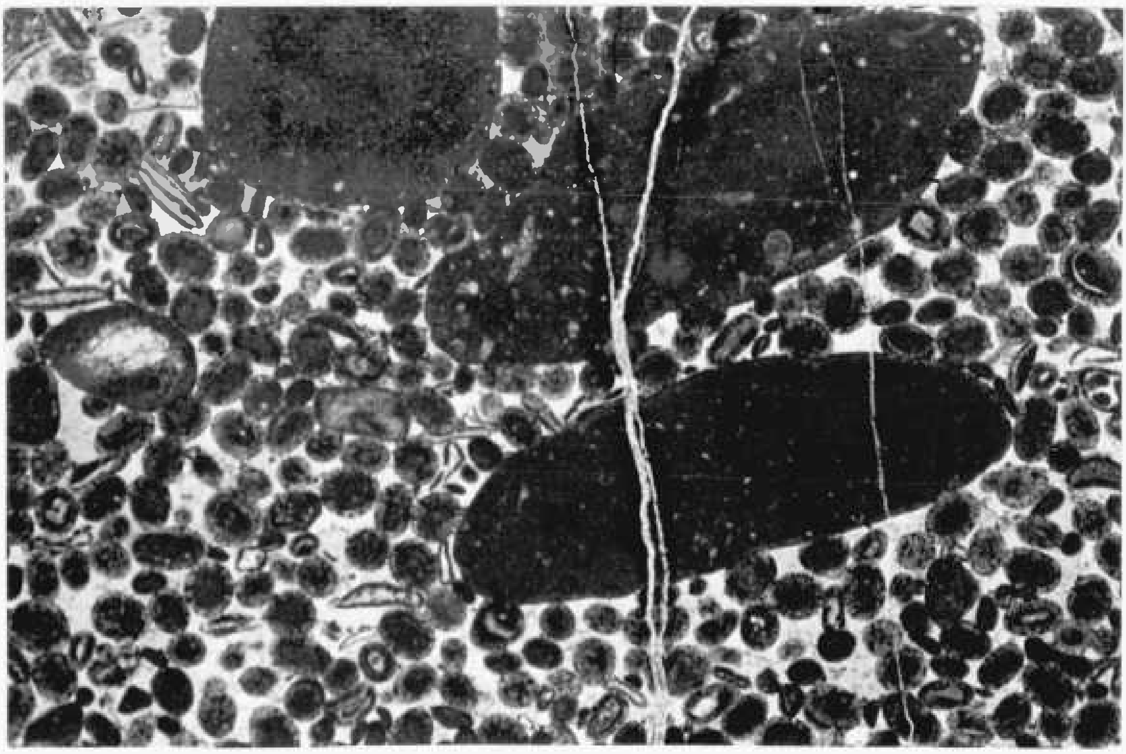


(x15)

FIGURE 29 Photomicrographs of intraclasts which have probably been derived from fragments of calcareous algae. Note the micritised fragment of Halimeda (?) (1) and possible concepticles (2) in the intraclasts (Marcilhac Member, near Cajarc).

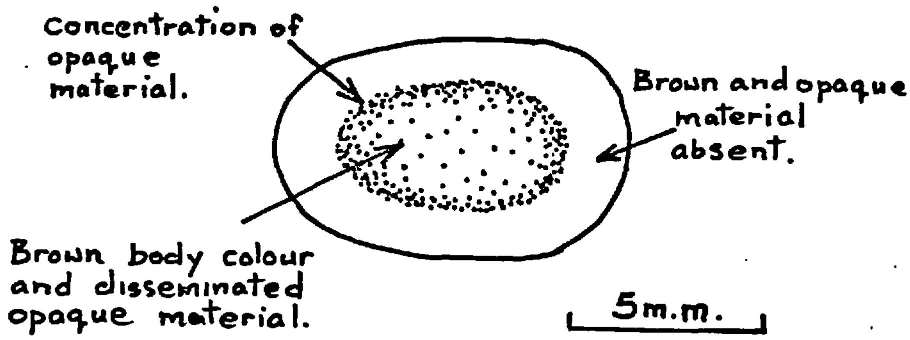


FIGURE 30 Sketch of an intraclast showing a weathered exterior (acetate peel 288/83; Marcilhac Member, near Cajarc).

Sometimes these 'intraclastic' grains possess weathered or lighter coloured edges. An acetate peel of sample 288/73 has suggested that this is due to the removal of insoluble material from the outer edges of the grains (figure 30) and the concentration of similar material as a concentric ring within. The insoluble material is made up of brown translucent and opaque matter: the former is also present in ooid grains in the same sample and according to Shearman et al (1970) this might be organic matter; the opaque matter is possibly iron oxide formed by the oxidisation of pyrite during weathering. These grains probably were weathered during their deposition.

In conclusion, it is apparent that in most cases each of the grain types of the oolitic grainstone lithofacies may have been derived from other grains as summarised in figure 26, by way of micritisation, oolitisation, accretion and aggregation. It is also possible that bioclastic debris may have formed the basic material from which all the grains were ultimately derived. However, some grains such as some peloids (faecal pellets) and true intraclasts (excluding the types formed by micritisation) were probably also derived independently of this evolving system.

The Fauna of the Oolitic Grainstones

The fauna of this lithofacies is very sparse. Only rare examples of Nerinella sp (Sharpe) have been recovered from the sediment. However, the bioclastic component of the grainstones suggests that other animals may have lived in or on the sediment but these have not been preserved and in any case they might have been transported from elsewhere.

The Environment of Deposition of the Oolitic Grainstones

The most distinctive feature of the oolitic grainstone lithofacies is the assortment of grains making up the sediments. As it has already been noted, Recent analogs may be found for all of these types and if the Great Bahama Bank is considered, sediments similar to the oolitic grainstones are being deposited in the more seaward or outer areas of the lagoon (Illing 1954, Purdy 1963 and Bathurst 1971). Bathurst (op.cit.) in his review, emphasised that in this environment sediments composed of varying proportions of ooids, bioclasts, peloids and grapestone grains are being deposited; the lateral relationship of the variations and the sub-environments of deposition have already been outlined on pages 78-83 and figure 18.

The grain types present in many of the oolitic grainstones are forming in three different sub-environments on the Great Bahama Bank today; ooids are actively forming in a narrow shoal zone at the Bank edge and form a barrier on the seaward edge of the lagoon - some are also growing on shoals within the lagoon; peloids and bioclasts are being deposited with derived ooids, behind the shoals in slightly deeper, less agitated waters; and grapestone grains are forming further within the lagoon in still deeper and even quieter waters.

Very few of the grainstones in the Cajarc Formation are pure oolitic limestones and those that are have usually suffered heavily from micritisation. It is possible that these were initially deposited as oolite shoals and that subsequent environmental changes caused the development of oolitic coatings to cease and micritisation or micritic accretion to commence.

The two types of ooid, superficial and true, which are present, are not considered to be environmentally significant. Their nature is probably only a reflection of the size of the nuclei that were available at the time of growth. In any one sample all the ooids whether true of superficial tend to be similar in size. This suggests that once coating has commenced the grains only reached a certain maximum size which probably depended on the conditions of deposition. Thus, if only small nuclei were abundant with merely occasional larger ones, most of the subsequent ooids would have been true types; however, if large nuclei were abundant, then most of the resulting ooids would have been superficial types. In the Bahamas true ooids are only found in the Pleistocene bay rock and all the actively growing Recent ooids are superficial types (Illing 1954).

Most of the oolitic grainstones are composed of mixtures of ooids and other grains such as peloids and bioclasts. In the Bahamas sediments of this type are being deposited today in an outer lagoonal environment, just behind the oolite shoals (Bathurst 1971). Often a few grapestone grains are also present in the grainstones. These too are considered to indicate an outer lagoonal environment (p 81-83).

Some grapestone grains appear to have grown by the aggregation of a number of simple grains, but other associated grains seem to have formed mainly by micritic accretion, between periods of oolitisation (figure 26), although sometimes these have also been aggregated together. A possible Recent analog of this phenomenon was recognised by Illing (1954), who noted that in the Bahamas some grains are being coated with micritic aragonite when calcareous algae infill the hollows and encrust the surfaces of the grains. He also noticed that aggregated grains sometimes become oolitically coated and he called these 'botryoidal lumps'. Beales (1958) also found similar grains in some ancient pisolitic deposits.

In one or two examples, heavily micritised rhodoliths have been observed in the oolitic grainstones. These are thought to indicate fairly slow, quiet conditions of deposition (p.83) and they might even represent relict sediments. However, together with the grapestone grains they almost certainly imply outer lagoonal conditions and the abundance of associated ooids suggests a proximity to oolitic shoals in most cases.

Thus the majority of the oolitic grainstones can be fitted easily into Bathurst's (op.cit.) scheme of sub-environments. This probably indicates that they were deposited in one or other of the various situation within an outer lagoonal environment. Some, however, show complicated histories of deposition with suggestions that the grains may have been reworked in several different sub-environments. For example, some sediments appear to have started life in a grapestone environment, later to be subjected to much more turbulent conditions which resulted in the grains being oolitically coated and then finally there was a reversion back to tranquil conditions which restarted the growth of grapestone grains and caused the micritisation of ooids.

Such complicated histories were probably related to oscillations in sea level. For example, after an oolitic deposit had started to accumulate, a change in water depth could have caused the sediment to become relict in an outer lagoonal or open marine environment where the rate of deposition would probably have been much slower. In these situations bioclasts might be expected to have accumulated and together with the relict ooids, these would probably have been extensively micritised. Grapestone grains could also have formed under these circumstances.

Therefore some of the more heavily micritised examples of oolitic grainstone might be comparable with the relict oolitic sands of the Bahamas described by Purdy (1963) and Bathurst (1971). These are thought to have formed when grain agitation ceased in response to a drop in water turbulence. This has probably resulted from a change in water depth and in cases where multiple phases of oolitisation and micritisation have occurred, there may have been multiple oscillations in sea level.

Another possibility, however, is that large quantities of oolitic grains, which probably originally grew in turbulent shoal areas, may have been transported lagoonwards by storms or seawards into more tranquil waters, where micritisation commenced. But when all the grains have suffered to the same degree, and the same number of times, depth changes have most probably been the cause because this would have most provided a mechanism for the whole sediment to be reworked each time.

Depth changes might also have caused grapestone sediments to be reworked in a more turbulent environment, thereby acquiring an oolitic coating. Conversely, ooid sands could possibly have been exposed to more tranquil conditions and the aggregation of ooids into grapestone grains could have occurred.

Therefore it seems possible to explain all the features of the oolitic grainstone lithofacies in terms of the processes operating in present-day outer lagoonal environments.

Often, beds of oolitic grainstone overlie upper intertidal and fresh or brackish lacustrine deposits, and they are usually succeeded by subtidal calcareous mudstones. Clearly these sequences must have resulted from some considerable changes in the environment of deposition, due perhaps to marine transgressions and not as a result of the action of ephemeral storms. It is surprising, therefore, that erosional contacts are only rarely visible, and that when they are developed they form only minor features. Typically, an oolitic grainstone might cut across a few laminations in an underlying bed of calcareous mudstone, or a basal intraclast layer may be present which has been derived from an underlying bed.

Illing (1954) and Purdy (1963) both noted that rare fragments of Pleistocene Cay-rock occur in the oolitic sands of the Bahamas. These are thought to have been derived partly during the occasional severe storms which affect the area and partly as a result of the general transgression which took place over the region in the early Holocene. The timing of this event, and also its relationship to the present day sediments, might give an insight to the periods of time which elapsed between the different phases of deposition in the Cajarc Formation.

The Lack of Bedding and Sedimentary Structures

A puzzling feature of the oolitic grainstone is the general absence of internal bedding planes and sedimentary structures. Most of the beds are massive and structureless and only a few examples of weakly developed, flat, centimetre bedding and one case of low-angle planar cross-bedding (figure 86.) have been observed.

Newell et al (1959) noted that ripple marks are not common in the oolitic habitat (in contrast to the oolite habitat of the barrier) and absent in the grapestone habitat of the Bahamas. This is because they form stable sand areas where little regular movement of grains occurs. Imbrie et al (1965) also noticed that no sedimentary structures are present in the sands of the 'mound' areas, where active bioturbation is taking place. Bathurst (1971) described large scale megaripples in the same habitats, but he thought these had been produced only during hurricanes. He also noted that megaripples are absent in areas covered by subtidal algal mats. Neumann et al (1970) considered that subtidal mats protect the underlying sandy sediments from current activity and they noticed that as these mats grow, all traces of lamination in the sediment are destroyed by bioturbation.

If it is accepted that the oolitic grainstones of the Cajarc Formation have been deposited in a similar environment to the outer lagoonal Bahamian sands, then it is not surprising that sedimentary structures are generally absent in the former; they were either prevented from forming by algal mats, or they were destroyed by bioturbation, or both. Furthermore, there is evidence to suggest that many grainstones became relict at least once, and under such conditions it is not unreasonable to expect that the sediment would have been reworked, thus destroying any original sedimentary structures. In support of this, possible evidence has been found of subtidal algal mats in the grainstones, but these could equally be intertidal mats that developed in response to a shallowing of the sea.

The only example of cross-bedding (figure 86) that has been found in the oolitic grainstone lithofacies, might have originated as megaripples which were the result of storm activity. An interesting point with respect to this, is that unlike any other of the beds of oolitic grainstone in the Cajarc Formation, this particular deposit shows no evidence of having been reworked in a slightly different environment subsequent to its initial deposition. In fact it was probably uplifted and cemented very soon after it had accumulated (p. 218), so it seems that it is only by chance that sedimentary structures have been preserved. Normally they would be probably been destroyed by reworking and bioturbation.

The History of Cementation of the Oolitic Grainstones

The pore spaces of all the oolitic grainstones are now completely filled by sparry calcite cements; these have been identified as such using the criteria laid down by Bathurst (1971, p.417). An examination of some thin sections of these rocks has shown that two types of cementation can be distinguished which probably occurred during late and early diagenesis respectively. The criteria that have been used for distinguishing these types are listed in figure 31.

Grainstones which are thought to have been cemented at an early diagenetic stage are characteristically loosely packed and a rim cement is usually developed. The term 'loosely packed' is taken here to mean that some grains are in contact with other grains in every direction, some only in contact with one other grain, and that some 'float' freely in the cement.

Those which were probably cemented at a much later diagenetic stage are more tightly packed and the porosities are much lower than in the previous types. All the component grains touch one another and interpenetrating or stylolitic contacts are ubiquitous. Moreover, the outer coatings of some oolitic grains have occasionally been spalled-off, and in many cases collapsed micritic envelopes (Bathurst, 1966) are also evident. Rim cements are not usually developed.

The evidence of compaction in the tightly packed grainstones

Section number.	9b	10	10a	21	23	24	61	70	73	77b	81	100	285 A	287	288	292	67/74	65/74	73/74
Grains not in contact.	✓			✓	✓	✓	✓	✓		✓	✓	✓			✓		✓	Recrystallised.	Recrystallised.
Grains in contact.	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓		
Loose packing.	✓	S	S*	✓	✓	✓	✓	✓		✓	✓	✓			✓		✓		
Tight packing.		✓	✓						*✓				✓	✓		✓			
Collapsed micritic envelopes.	S	✓	✓	S		S	*✓	✓	S	S	✓		✓	✓	S	✓	S		
Spalled ooids or broken grains.																	S		
Stylolitic or interpen-itrating grains.	*S	✓	✓		S				S		S		✓	✓	S	S	S		
Rim cement.	S			✓	✓	✓	✓	✓	✓	✓	S						S		
Time of cementation.	E	L	L	E	E	E	E	E	E	E	E	E	L	L	E	L	E		

S – some.
L – late.
E – early.

* (96, 61) Weak compaction has occurred, perhaps because rim cement was not strong enough to resist the weight of the overburden.

* (73) Tightly packed appearence because of fine grain size (?)

* (10a) Loose packing under shelter of large grains.

FIGURE 31. Criteria used to elucidate the cementation and compaction history of the oolitic grainstone lithofacies.

is quite noticeable, but in the loosely packed types it is almost absent. To allow the preservation of a loosely packed texture a degree of cementation must have taken place at an early diagenetic stage, before burial occurred, thus preventing any later compaction.

In most of the loosely packed grainstones a rim cement is present, whereas in the tightly packed types these are absent. Shearman (pers.com., 1975) considered that calcareous rim cements are probably precipitated as a result of the volume increase when an aragonitic sediment recrystallises to calcite. This is a relatively early diagenetic process which probably takes place under the influence of connate waters.

Therefore, it seems reasonable to conclude that where rim cements are present they have probably been precipitated at an early diagenetic stage before burial took place and they have possibly prevented compaction from occurring. Furthermore, where rim cements are not developed the rocks were probably not cemented before burial and strong compaction resulted. Complete cementation of the grainstones before burial would also have prevented compaction features from developing, but in the Cajarc Formation this probably occurred much later, under the influence of metioric waters during and after the uplift and exposure of the rocks.

An exception to the above pattern is the peloidal oolitic grainstone exposed in the roadside (N662) section at 044 236, near Larnagol. This rock shows no evidence of compaction but neither is a rim cement developed. Furthermore, none of the component grains is in contact with another! The sedimentary structures of this deposit are unusually well preserved and a karst surface is developed above it. This suggests that soon after the bed was deposited it was uplifted into a subaerial environment where it was subjected to the influx of fresh water. Here, full cementation of the sediment probably took place and because there was little or no overburden the growth of the calcite crystals of the cement forced the individual grains of sediment apart.

Other exceptions to the pattern are grainstones, with rim cements, which have undergone slight compaction. This is probably because the early cements were not strong enough to completely resist the weight of the overburden, but they did stop intense compaction from occurring.

Finally it has been possible to formulate the following model of compaction and cementation for the oolitic grainstone lithofacies:

1. Complete cementation in a subaerial environment before burial (no compaction).

2. Partial cementation before deep burial (slight compaction in some cases).	Followed by complete cementation during uplift and exposure.
3. No cementation before deep bural (strong compaction).	

Presumably this model is also true for the remainder of the Cajarc Formation, but because the sediments are so fine grained it has not been possible to see if it applies.

4.2 The Calcareous Mudstone Lithofacies

On the local geological maps this lithofacies has been described as 'calcaire sublithographique'. It consists of decimetre or metre bedded, light to medium grey, fine grained, porcellenous or lithographic limestones. A large proportion of the Cajarc Formation is composed of these rocks, but they can be examined most easily in the quarry (075262) on the N662, just west of Cajarc (at the base of the La Plogne section).

Unlike siliciclastic rocks, the classification of fine grained calcareous sediments has always been problematical. Usually the former are subdivided according to grain size: Wentworth (1922) divided sediments finer than 62μ into clays (finer than 4μ) and silts (4-62μ); Twenhofel (1937) later introduced the term 'mudstone' as a general field term which included rocks made up of clay or silt, or mixtures of both. More recently, mud and mudstone have generally become accepted to mean sediments composed of mixtures of clay and silt grade material, with claystone being a pure clay rock and siltstone a pure silt rock. It has also been realised that a more natural clay/silt division is 2μ, which probably represents the boundary between clay minerals and other detritus.

Most shallow water fine grained calcareous rocks have probably originated as aragonitic muds composed of precipitated aragonite crystals and broken down shell debris. After lithification and diagenesis these sediments appear as cryptocrystallin or microcrystalline aggregates of calcite crystals, ranging in size from 1-35μ (see discussion by Bathurst, 1971, p.89). Therefore in limestones a subdivision at either 2 or 4μ is of no practical significance and, as such, none is usually made.

The fine grained calcareous sediments of the Cajarc Formation consist mainly of microcrystalline crystals of calcite ranging in size from 4-7μ; some have an average size greater than 10μ, but these will be discussed later. Most of the rocks made up of crystals less than 20μ in size have an even texture. Above the size of 20μ, discreet sedimentary grains, such as small peloids and bioclasts, become recognisable. Medium to coarse silt grade material of this type is an important component of many of the fine grained rocks of the Cajarc Formation, with some examples being composed entirely of silt grade peloids.

In the past, various names have been proposed for fine grained calcareous rocks; these include the lithographic limestones of early writers, calcilutite, micrite (Folk 1959) and mudstone (Dunham 1962). None of the rocks in the Cajarc are micrite in the sense that Fold (op.cit.) defined them (i.e. with upper grain size limit of 4μ). Nevertheless, they clearly fall into the mudstone range (1-20μ) as defined by Dunham (op.cit.).

The term mudstone is, however, a more useful general field term (as used by Twenhofel, 1937) because unless thin sections are available, all grains smaller than very fine sand size are virtually invisible to the naked eye or hand lens, especially when they are set into a finer matrix; in the field it has been very difficult to distinguish between mudstones (1-20μ) and pure calcareous siltstones, so they have all been grouped together as mudstones. Dunham (op. cit.) would probably have recognised the calcareous siltstones as grainstones, and the silty mudstones as wackestones. Thus all rocks finer than 62μ (very fine sand grade) are considered as mudstones and those coarser than 62μ as wackestones, packstones, etc. (figure 32). This size also corresponds to the mud/sand boundary in siliciclastic rocks.

This procedure presents a problem, because if rocks with a grain size less than 62μ are all to be generally called mudstones, then a new term must be erected for sediments finer than 20μ, where no discreet sedimentary grains are recognisable. As the term micrite (1-4μ) cannot be usefully applied to the Cajarc Formation, it is proposed herein to adopt this for rocks with a grain size ranging from 1-20μ, thereby releasing the term mudstone for general identifications in the field.

All components finer than 62 μ		62 μ Some components coarser than 62 μ.			Organically-bound rock.	Replaced or recrystallised rock.
		Grains suspended in a matrix.	Grains in contact.			
		Micritic or silty matrix. (depositional)		Calcareous cement matrix. (diagenetic)		
All MUDSTONE in the field.		WACKESTONE.	PACKSTONE.	GRAINSTONE.	BOUNDSTONE.	CRYSTALLINE CARBONATE.
SILTY MICRITE. (micrite + silty material)						
MICRITE. (1 – 20 μ)	SILTSTONE. (20 – 62 μ)					

FIGURE 32 Classification used for the description of the limestones of the Cajarc Formation (modified after Dunham, 1962); the grain-types have usually been used to prefix these terms: e.g. oolitic grainstone.

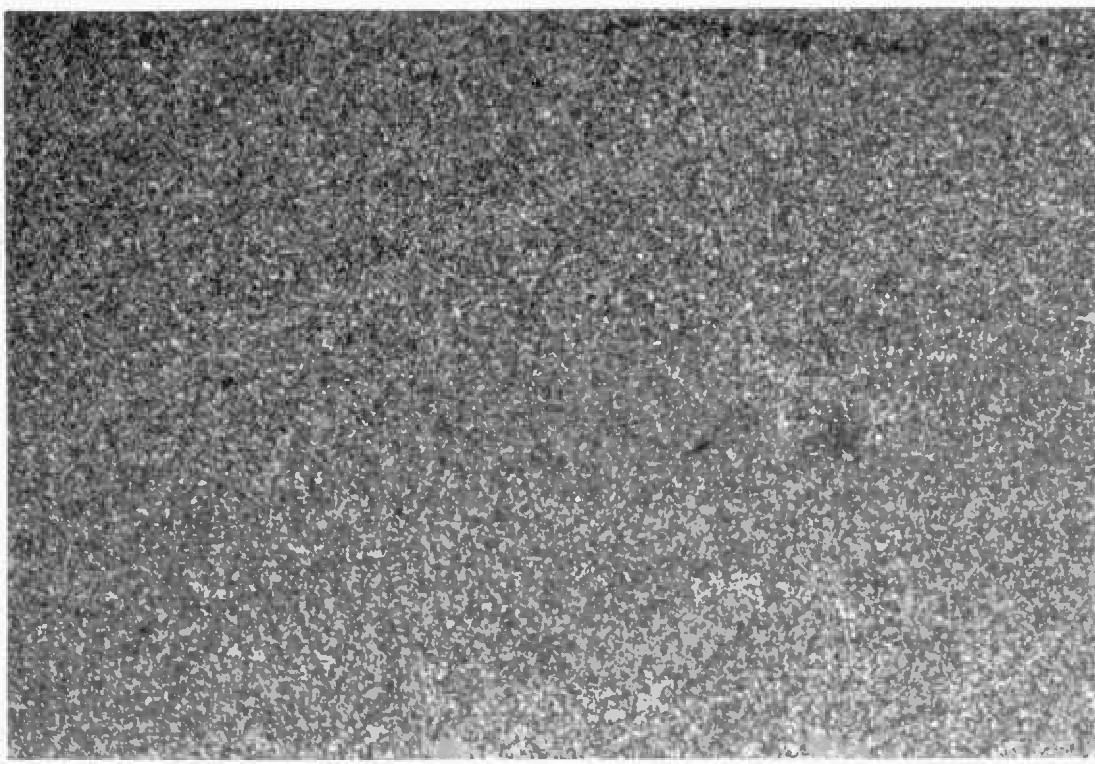
Therefore the following subdivisions are the ones that have been found most useful for studying the Cajarc Formation (also see figure 32):

(i) Micrite (1-20μ).
(ii) Silty micrite (1-65μ) - consisting of micrite and discreet silt grains.
(iii) Calcareous siltstone (20-62μ) - consisting of discreet silt grains only.

Micrites: discreet sedimentary grains are indistinguishable in these rocks. Mostly they are composed of even-textured microcrystalline aggregates of calcite crystals (1-20μ), but some possess clotted textures.

Silty micrites: these are composed of micrite (1-20μ) together with silt-sized peloids and bioclasts. Sometimes the silt is evenly intermixed with micrite and other times it forms distinct silty layers interbedded with micrite. Homogeneous and mottled silty micrites are thought to have been produced by bioturbation from the latter, especially since burrows are often apparent, and both types of sediment usually occur in close proximity to each other.

Calcareous siltstones: these are composed almost entirely of silt sized peloids (figure 33), cemented together by clear, crystalline calcite. The textures resemble the "structure grumeleuse" described by Cayeux (1935). Evamy (1967) considered that sometimes this texture may be a result of dedolomitisation, but no evidence has been found of this in the peloidal siltstones of the Cajarc Formation, because the sedimentary structures found within the rocks suggest they were deposited as discreet silt grains and not as mud that was later diagenetically altered. In some cases slight recrystallisation has blurred the edges of the peloids, but where intense dolomitisation and dedolomitisation has occurred, the original microscopic depositional texture has usually



(x20)

FIGURE 33 Photomicrograph of a calcareous siltstone composed almost entirely of peloids (La Plogne Mb., quarry below La Plogne).

been obliterated; although ghosts of sedimentary structures may be visible in hand specimens.

Siliciclastic and calcareous sediments have very similar specific gravites, so they probably behave in a similar way under the same hydrodynamic conditions. Hence the classification proposed above parallels the one in modern usage for siliciclastic rocks, and by applying it to the Cajarc Formation it has been possible to recognise patterns of sedimentation that, up to now, have only been described from intertidal siliciclastic deposits.

Recrystallised mudstones: on fractured surfaces some calcareous mudstones have an extremely fine-grain micritic texture, whereas others have a coarser grained silty appearance. Petrological examination has shown that some of these rocks are micritic and that others are silty micrites or calcareous siltstones; but it has also indicated that many of the coarser textured rocks have been replaced/recrystallised either to dolomite or to slightly coarser crystals of calcite. Many of the latter rock types are structureless, but occasionally ghosts of cross-laminations are preserved, suggesting that the rocks were once calcareous siltstones.

Both partially and completely dolomitised mudstones have been found. Individual dolomite crystals are silt sized and rhombic in shape. They have been identified as such by staining with alizarine-red S and also by using X-ray diffraction techniques. Sometimes very slight etching using a weak hydrochloric acid has been found to reveal the rhombic appearance of the crystals.

It was mentioned earlier that some of the finer grained limestones have textures with an average grain size coarser than 10μ.. These rocks have a recrystallised appearance. Moreover, in some cases they possess a faint ghost-like rhombic texture and in one or two examples corroded, silt sized dolomite rhombs have been observed. These features suggest that the textures of the coarser grained micrites have been produced by the calcitisation of a fine grained dolomite rock; but many workers would probably identify these as neomorphically recrystallised rocks, especially when looked at in isolation without the evidence of corroded dolomite rhombs or interbedded dolomitic sediments. The resultant texture is probably a slightly coarser grained regeneration of the original texture of the sediment. Sedimentary structures are sometimes preserved, but the original microscopic depositional texture is usually masked.

Other variations: although the bulk of the sediments of this lithofacies are calcareous mudstones, occasionally sand sized bioclasts, intraclasts and peloids are present. Sometimes the grains form distinct grainstone or packstone layers within the calcareous mudstones, but more often they have been disseminated through the sediments by bioturbation. Where calcareous mudstones pass into oolitic grainstones, oolitic wackestones and packstones have been observed.

With regard to origins of these sand grade grains, the bioclasts are, of course, derived from contemporary indigenous animal populations. Peloids have probably originated as faecal pellets and also from the erosion of contemporary mud sheets. Intraclasts may also have been fored by erosion, either from cohesive mud deposits or hardground surfaces, during storms or sea level changes. Often the grains are concentrated into layers which may represent periods of slower deposition, or merely storm lag deposits.

Sedimentary Structures in the Calcareous Mudstones

Superficially most of the calcareous mudstones appear to be massive structureless rocks, but a more thorough examination both in the field and laboratory, has revealed that many of the mudstones possess sedimentary structures. It is possible to distinguish four kinds of mudstone:

massive, structureless mudstone; mottled and burrowed mudstone; cross-laminated mudstone; and wavey or lenticular-bedded mudstone.

Massive types are, as their description implies, structureless, evenly coloured sediments lacking sedimentary structures and interal bedding planes.

Mottled and burrowed mudstones have well developed mottled patterns due to colour and grain size variations. These have probably been produced by bioturbation of mudstones which may have originally possessed sedimentary structures.

Cross-laminated or trough cross-sets are common in the Cajarc Formation (figure 73a). These structures are only usually found in peloidal siltstones, but sometimes ghosts of cross-laminations may be preserved in recrystallised mudstones that were presumably calcareous siltstones.

Trough cross-lamination (figure 34) is thought to have resulted from the migration of small scale ripples at the time of deposition of the sediment but some may have arisen by the infilling of small current scoured depressions. Often it is difficult to distinguish between the two types.

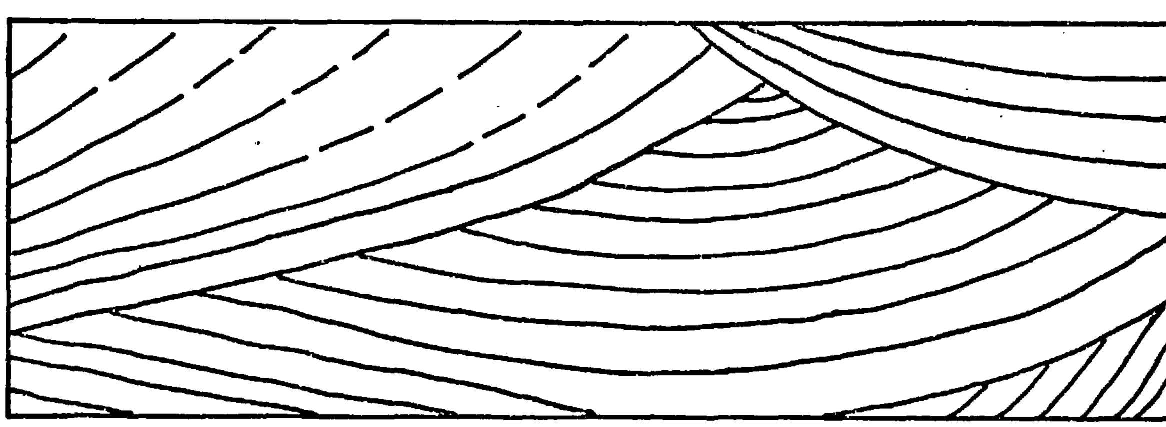


FIGURE 34 Trough cross-lamination in the calcareous mudstone lithofacies (x2).

The origin of the planar cross-laminations may also have been two-fold. Some of the lower angled types could possibly have formed megaripples with shell lags in the troughs. Another possibility, however, is that they were formed as point bar deposits resulting from the migration of rills in an intertidal environment, especially the higher angled types.

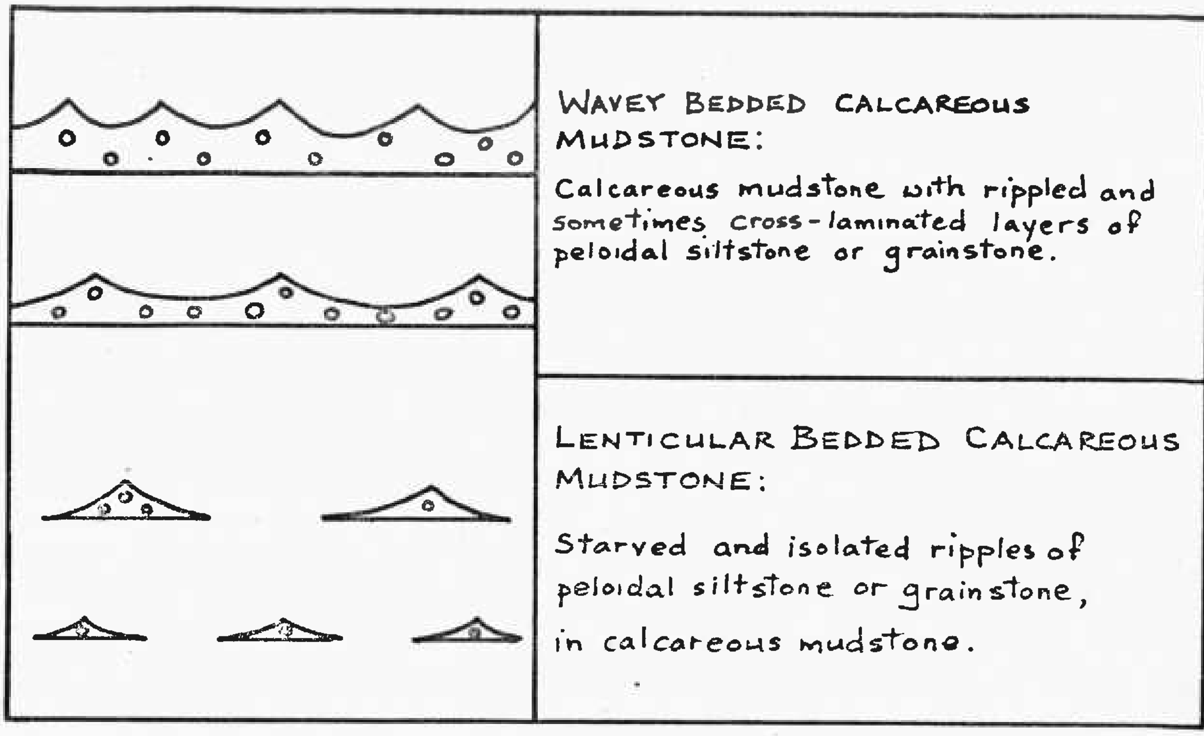
Wavey and lenticular-bedded (Reineck & Wunderlich, 1968) calcareous mudstones are made up of calcareous mudstone interbedded with rippled layers of peloidal siltstone or grainstone in wavy types and isolated siltstone or grainstone ripples in the lenticular types (figure 35a). Individual layers may be anything from 1 to 10 cm. in thickness. Most of the grainstone layers are cross-laminated. The ripples vary from symmetrical to asymmetrical types, either sharp or round crested, and in one case the amplitude was measured as 2 cm. and the wavelength as 10-18 cm. (figure 35b).

Many of the peloidal siltstones in which cross-laminations are preserved are extremely even in grain size. This is surprising since it would be expected that there was some variation to account for the preservation of discreet laminae. However, these may have been rendered visible by the differential packing of individual laminations during deposition, so that porosity/permeability differences resulted. Later, during diagenesis, this might have affected the pattern of cementation, thus causing individual laminations to become apparent. It may also have allowed some layers to become preferentially stained by, say, iron oxide, so preserving the cross-laminations by differential colouring.

<u>The Fauna of the Calcareous Mudstone</u>

Generally, fossils are rare in the calcareous mudstone lithofacies. Occasionally, richly fossiliferous beds

A



B.

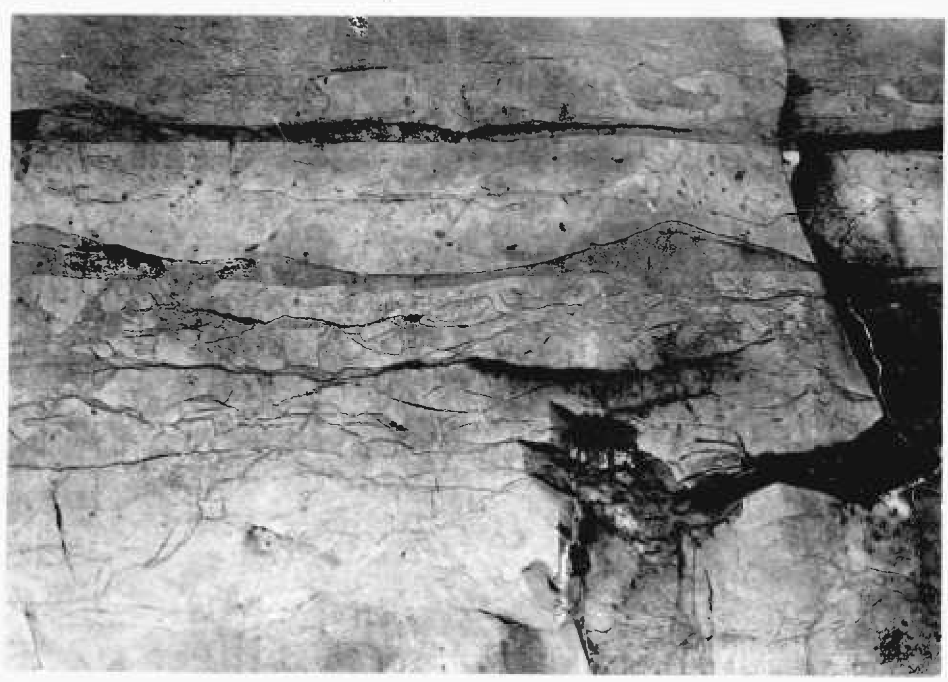


FIGURE 35 A) Wavey and lenticular bedding in the calcareous mudstone lithofacies (after Reineck and Wunderlich, 1968).

B) Wavey bedded calcareous mudstone, showing peloidal grainstone layers (La Plogne Member; D17 road section near St. Martin Labouval).

may be found, but most of the fauna that has been recovered is too poorly preserved for identification. Nevertheless, it has been possible to compile the following faunal list:

Plantae:	?Equisetum (Lamark)
Echinodermata:	Acrosalenia sp. (Agassiz)
Brachiopoda:	Ornithella sp. aff. bathonica (Rollier)
Bivalva:	Bakevillia ?waltoni (Lycett)
	Entolium sp. (Meek)
	Ostrea sp. (Linnaeus)
	Gervillella sp. indet. (Waagen)
	Inoceramidae
	Lucinidae
Gastropoda:	Nerinella sp. indet. (Sharpe)

These fossils probably all inhabited a truly marine environment in a warm water, coastal lagoonal situation. Except for some oysters and Nerinella sp., which may have also colonised lower intertidal flat areas, most of the species also probably lived in a subtidal environment.

No attempt has been made to make a detailed study of the fauna, but in the field the following assemblages are apparent:

1. Nerinella assemblage: thin concentrated layers of Nerinella sp. occur commonly in the calcareous mudstones usually just above hardgrounds or other depositional breaks; isolated specimens have also been found in many beds. Nerinella sp. probably lived as a grazing, epifaunal gastropod, in a subtidal to lower intertidal environment, similar perhaps to the frequently described cerithid assemblages found in Recent tropical lagoons.

2. Lucinidae-Inoceramidae-Gervillella-Entolium assemblage: these forms have all been found associated together in

beds of calcareous mudstone and sometimes Nerinella sp. and Bakevillia ?waltoni also occur in this assemblage. These forms probably lived in a subtidal lagoonal environment. The mode of life of each form was probably not the same; some were epifaunal, some infaunal and others free swimming. However, the presence of Lucindids and Gervillellids, which were probably both burrowing forms, suggests that the assemblage lived in an environment with a soft muddy bottom.

3. Ornithella assemblage: concentrations of Ornithella sp. aff. bathonica have been found in some beds of calcareous mudstone. The position of this assemblage in the rhythms of sedimentation suggests that Ornithella lived in a subtidal or lower intertidal (?) environment.

4. Cemented oyster assemblage: at some horizons within beds of calcareous mudstone, Ostrea sp. has been found to be cemented onto bedding surfaces. Originally these surfaces were probably hardgrounds and therefore the oysters may have lived in anything from subtidal to intertidal conditions.

Also, within the Cajarc Formation, some thin, crudely laminated bands of oyster grainstone/packstone have been found; usually in beds of laminated or massive calcareous mudstone. The origin of these layers is uncertain: one possibility is that they represent in situ accumulations where colonies of oysters once lived; another is that they formed as shell banks or storm deposits, especially where the oysters are associated with intraclasts and other bioclastic debris.

5. Bakevillia-Entolium assemblage: besides occurring in other assemblages, these two forms have also been found in exclusive association. Often they have been observed in beds of calcareous mudstone lying just below layers

of laminated calcareous mustones and ostracod wackestone. It is possible, therefore, that although these were probably both marine forms, they may also have been able to withstand lower than normal salinities, and they might represent the colonisation of lagoonal areas where influxes of fresh water were frequent. Alternatively, some parts of the lagoon may have become cut off from the regular influence of marine waters, so that fresh water influxes from coastal lakes and swamps could possibly have caused the water of the lagoon to become more brackish. Sometimes this assemblage is associated with Equisetum sp. roots, suggesting that as the lagoon was infilled it became fresh or brackish, and eventually Equisetum sp. became established; this plant does not inhabit saline environments today.

6. Acrosalenia assemblage: thin layers of echinoid debris, consisting of spines and plates of Acrosalenia sp., sometimes occur in the rocks of the calcareous mudstone lithofacies, although they are most commonly found in laminated calcareous mudstones. Often these layers have erosive bases, with scour marks frequently being developed and in many cases all the spines are aligned parallel to one another. Clearly this has been caused by strong current activity. Furthermore, because the layers are positioned towards the tops of sedimentary rhythms in upper intertidal sediments where regular intense reworking would not have been expected, it is thought that they represent storm deposits. The bioclastic debris was probably derived from subtidal areas of the lagoons because Acrosalenia sp. almost certainly inhabited a subtidal environment.

Only one specimen of this echinoid has been recovered from the Cajarc Formation. It was found in the La Plogne Member at Tour de Faure (959254) and it was associated with intraclasts, oysters and echinoid spines.

The rarity of this fossil may have been because storm activity destroyed most of the whole echinoid tests, which would have been very fragile.

The Environment of Deposition of the Calcareous Mudstones

Calcareous muds and pelleted calcareous muds have been described from most areas of Recent calcareous sedimentation (Bathurst, 1971). In the Bahamas, Florida Bay and the Persian Gulf, these sediments are being deposited in coastal lagoonal areas. Both muds and pelleted muds may be found in sheltered subtidal areas, but in the intertidal zones where currents are stronger, the mud fraction is often winnowed-out to leave only the pellets; in the Persian Gulf the pellets are both hard and soft, and after winnowing a pellet sand remains; however, in the Bahamas the pellets are soft, so although they behave as discreet grains during deposition, afterwards they probably merge with one another and the sediment may, therefore, appear to be an ordinary calcareous mud (this might account for some of the mottled textures which have been observed in thin sections of calcareous mudstone).

The various environments where ordinary and pelleted calcareous muds are being deposited are summarised below, together with their main characteristics (taken from Bathurst 1971; Shinn et al 1969 and Kendal et al, 1969):

a) Subtidal zone: sheltered lagoonal areas with accumulations of mud and pelleted mud; pellets soft (20-50μ) in the Bahamas and either hard or soft in the Persian Gulf; no rippling; bioturbated; cerithid gastropod, and peneropolid-miliolid foraminifera assemblage; passing laterally into grapestone and oolitic sediments in less sheltered areas.

b) Lower intertidal zone: bordering ponds and channels in the Bahamas, or forming extensive flats in the Persian Gulf; soft pellets (40-80μ) in the Bahamas, hard pellet sands in the Persian Gulf; rippled; runnels and bars developed in Persian Gulf; bioturbated; gastropods.

c) Channels: soft pellets or mud in the Bahamas, hard pellets in the Persian Gulf; coarse shell lags developed in channels ; laminated calcareous or dolomitic mudstone fragments in lag deposits; cross-bedded at point bars, also rippled; wispy laminated deposits in straighter sections of channels; commonly bioturbated; migrating channels reworking intertidal flat and pond sediments.

d) Ponds: in the Bahamas channel levees often pond-up marine water at low tide; sediments muddy with very few pellets; bioturbated.

Shinn et al (1969) noted that it is very difficult to distinguish between the sediments deposited in the environments described above, and the fact that they have often been bioturbated makes this even more of a problem. Moreover, the fauna associated with the various habitats does not vary greatly. Therefore, when applying these conclusions to ancient calcareous mudstones, the geologist is left with a rather helpless feeling that, in many examples, the most accurate interpretation that can be used is 'subtidal to lower intertidal lagoonal'. As an example, Roehl (1967) and Lucia (1972) both concluded that the most diagnostic feature of intertidal calcareous sediments is their position immediately below upper intertidal marsh deposits apart from which there are no distinctive features.

With regard to the calcareous mudstones of the Cajarc Formation, it has already been noted (p.133) that the fauna therein is typical of a marine, coastal lagoonal environment; but in the majority of cases the sediments have no features which are exclusively characteristic of any one particular sub-environment. In many places, however, calcareous mudstones pass upwards into laminated calcareous mudstones which were probably deposited in an upper intertidal environment (p.164); also sometimes they lie above outer lagoonal oolitic grainstone sediments (p.113). This 'sandwiching' between subtidal outer lagoonal and upper intertidal sediments suggests that the calcareous mudstones have been deposited in an environment varying from subtidal to lower intertidal; those immediately above oolitic grainstones, or at the base of sedimentary rhythms have probably been laid down in a subtidal environment, whereas those occurring just below laminated calcareous mudstones are probably lower intertidal sediments. This is, of course, only a generalisation as each sedimentary rhythm has its own peculiarities, and often beds of calcareous mudstone are not related to other more easily understood deposits. In such cases no definite interpretations can be made.

Nevertheless, some of the calcareous mudstones have been found to possess features that are perhaps indicative of intertidal deposition. For instance, channels which have only rarely been found in the Cajarc Formation often cut down from upper intertidal sediments into calcareous mudstones. These are thought to have developed in an intertidal environment. Therefore where channels cut into calcareous mudstones, the latter are interpreted as lower intertidal deposits.

Cross-laminated and wavey and lenticular-bedded calcareous mudstones were probably influenced by intermittent current activity throughout their depositional history. In Recent examples, ordinary and pelleted calcareous muds which have been found to be accumulating in subtidal areas are, except during storms, largely protected from strong current activity; but within the intertidal zone currents play a very important role and indeed sedimentary structures have probably nearly always been generated, but they are soon destroyed by bioturbation (e.g. Trucial Coast). However, Reineck (1972) noted that on Recent intertidal flats, rapidly deposited sediments are often relatively disturbed by the burrowing activities of animals. Furthermore, Reineck and Wunderlich (1968) concluded that wavey and lenticular bedded sands and muds and rippled (cross-laminated) silts and sands are characteristic of environments dominated by tidal currents.

In the Cajarc Formation, similar sediments probably represent an intertidal environment, and the preservation of these features may have been the result of rapid progradation. The mottled and heavily bioturbated calcareous mudstones which are also common were probably deposited more slowly in a system where progradation was much less rapid as such the sediment would remain under the influence of a particular environment for much longer and thus bioturbation could be more complete.

Some cross-laminated peloidal siltstones may have been the result of the lateral reworking of tidal flat deposits by channel migration in an intertidal environment. This would have resulted in all the fine grained material being removed, to leave only silt or very fine sand sized peloids. This is particularly possible for siltstones with high angle planar cross-laminations (figure 36).

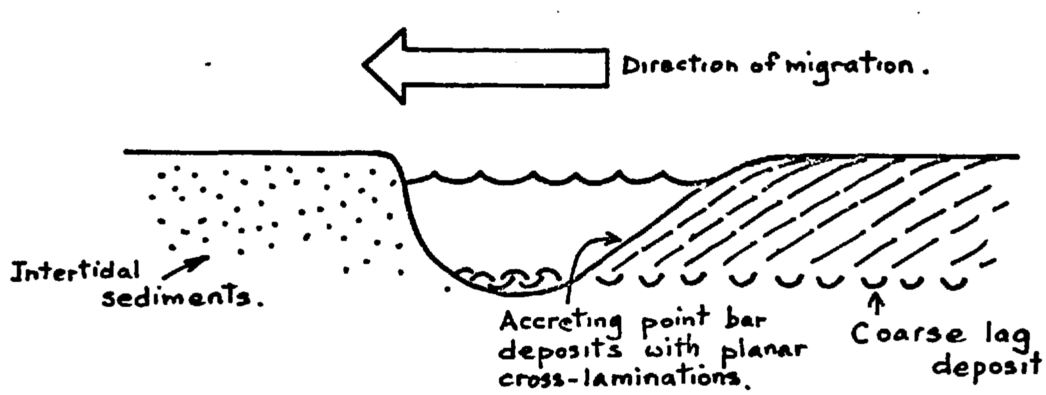


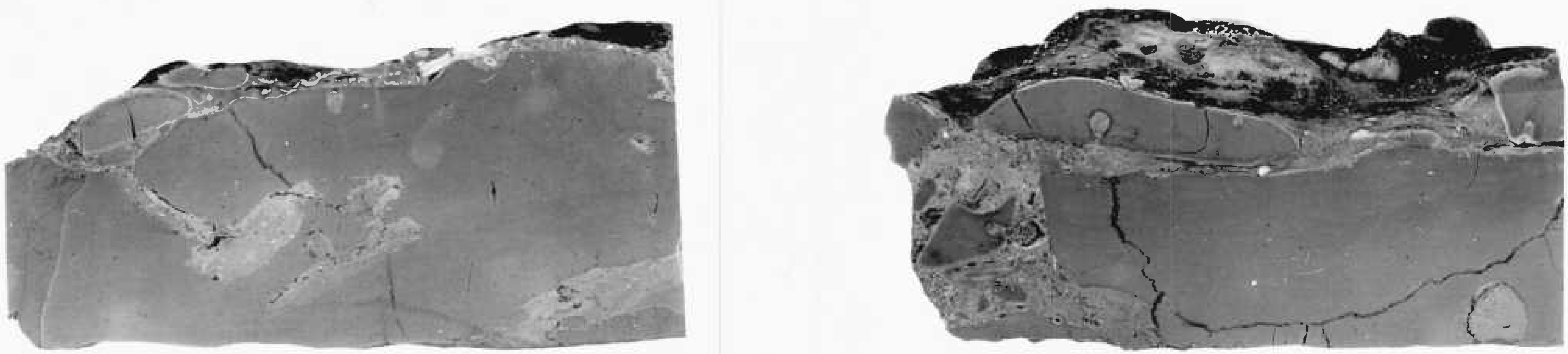
FIGURE 36 Reworking of intertidal sediments by channel migration.

However, on the whole, the tidal channels that have been found in the intertidal sediments of the Cajarc Formation show very little evidence of lateral migration. In most cases they are simply large scale cut and fill structures (p.156) that have been infilled by upper intertidal (laminated calcareous mudstones) and supratidal (marls and lignites) sediments (figure 47). Reineck (1972) noted that if the rate of supply of sediment is high then progradation should be rapid and channels might not have time to migrate significantly; if this is true it might also help to explain the lack of bioturbation in some beds in the Cajarc Formation, as well as explaining the lack of channel migration.

The rarity of channels in the Cajarc Formation is a puzzling feature. To some extent this might have been due to a lack of lateral migration, leaving large volumes of sediment unaffected by channel development; but Shinn et al (1969), after studying the intertidal flats of Andros Island, suggested that in transgressive deposits channels become well developed, but in regressive or prograding types they do not become well developed. As it seems, from evidence presented in previous paragraphs, that many of the beds of calcareous mudstone were deposited rapidly, then the suggestions of Shinn et al, go someway in explaining the relative lack of channels in the Cajarc Formation.

4.3 Hardgrounds in the Cajarc Formation

Three possible types of hardgrounds have been observed within the calcareous mudstones of the Cajarc Formation, these are: bored types (figure 37), unbored but encrusted types, and blackened types. They are visible in the field as sharp lithological and/or colour changes, and in many cases they have been weathered-out as bedding planes. They often have concentrations of coarse shell debris and intraclasts above them.



(x 1·3) (x 1·4)

FIGURE 37 A bored hardground surface in the calcareous mudstone lithofacies. Note the concentration of coarse material and the change in lithology above the surface. Also note the presence of bored and weathered intraclasts which were probably eroded from the hardground (La Plogne Member; quarry below La Plogne).

These 'hardgrounds' are thought to have originated by the lithification of the calcareous mud at the sediment/water interface. They have been described from both ancient and Recent sediments (some examples of which may be found in Shinn, 1969; Purser, 1969 and Evans et al, 1973) and in most cases the lithified horizons have been bored and/or encrusted by marine organisms.

Regarding the Cajarc Formation, a good example of a bored (?) horizon is developed in the mottled and cross-laminated peloidal siltstones which occur at the base of the quarry at 075262, on the N662 just west of Cajarc. This surface is parallel to the bedding planes of the sediments and it extends along the whole of the quarry face (figure 74). It is bored (or burrowed) to a depth of about 10 centimetres and it is overlain by a lighter coloured peloidal siltstone (figure 74). The actual surface itself has been weathered and lightened in colour to a depth of about 0.5mm and the walls of the biogenic structures are similarly affected. Above the surface there is a concentration of shell material and of weathered intraclasts which have probably been derived by erosion from underlying sediments; evidence of erosion has been found because cross-laminations in the sediments below the horizon are truncated by the overlying deposits.

The shape of the biogenic structures varies from simple vertical or oblique tubes, to upturned tubes and even enlarged chambers which occur just below the weathered surface (figure 74). (Another example of this can also be seen in figure 37). It has not been possible to establish whether these structures have resulted either from the burrowing or boring activities of marine organisms. Purser (1969) has shown that the only definite evidence of boring is that of truncated shells and grains, but no such evidence has been found in the Cajarc Formation because the sediments concerned are too fine grained.

In thin section, the edges of the biogenic structures are very sharp and any laminations present in the sediment are truncated abruptly and without disturbance. If these had been produced by organisms burrowing into a soft sediment, then there should be some evidence of disturbance of the laminations. Thus, the limited amount of information that is available suggests that this horizon became lithified during the deposition of the sediment, and it later became bored.

Studies of Recent calcareous sediments have shown that whenever breaks in deposition occur the surface layer of sediment rapidly becomes lithified (Shinn op.cit., Evans et al., op.cit.) The horizon at the base of the quarry shows evidence of erosion having occurred, and the concentration of coarse material above, together with the change in lithology, suggests that a break in deposition almost certainly occurred. Therefore it could easily have been a hardground and moreover it is possible that many of the other breaks in deposition that are visible in the Cajarc Formation, were also hardgrounds.

Some examples of horizons marking breaks in deposition, with concentrations of coarse material above, have not been bored. Instead, they have occasionally been encrusted by oysters. These levels are probably also fossil hardgrounds but in cases where no encrustation has occurred it is possible that the horizon may have been eroded by the lateral migration of intertidal channels, which left a coarse grained lag deposit (figure 36).

Blackened erosional surfaces have also been found in the Cajarc Formation, but none of these have been bored. Hallam (1969) described a blackened and bored hardground, of Liassic age, in which the colouration was thought to be due to the concentration of pyrite into the hardground surface. Likewise, it is possible that the blackened surfaces in the

Cajarc Formation might also represent hardgrounds.

Bathurst (1971, p.395) noted that it is very difficult to determine in which environment a hardground was originally formed. Thus, often the time significance of the latter cannot be fully realised, but most authors have agreed that a break or slowing down of deposition is a necessary pre-requisite. A perusal of the relevant literature has indicated that there are several possible ways in which hardgrounds might originate:

1. a break in deposition might be caused by a slight regression of the sea with subsequent subaerial exposure and accompanied by lithification. If this was to be followed by a transgression, the resulting sea floor would be hard and could become bored and encrusted - regressive subaerial hardground.

2. a break might also be caused by a transgression without any previous emergence. This could cause the environments of deposition to become laterally displaced so that a particular area might suddenly become starved of sediment and a hardground may form. This type has been described by Purser (1969) - transgressive submarine hardground.

3. lastly, in an area of constant sea level, sediment might accumulate until it reaches a level, perhaps controlled by wave-base, where the rate of supply of sediment equals the rate of removal and a hardground is formed. This type has been described by Evans et al (1973) - equilibrium hardground.

The break in deposition represented by subaerial exposure would be very important stratigraphically and a large portion of the local geological record may be missing. Equally above transgressive submarine hardgrounds, the sediment

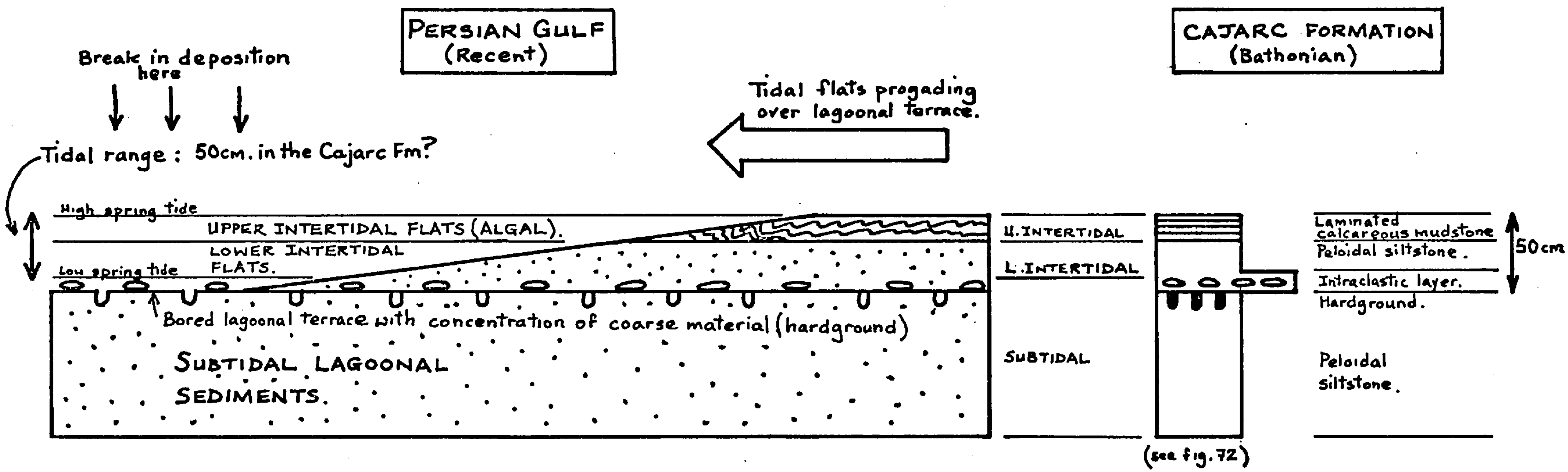


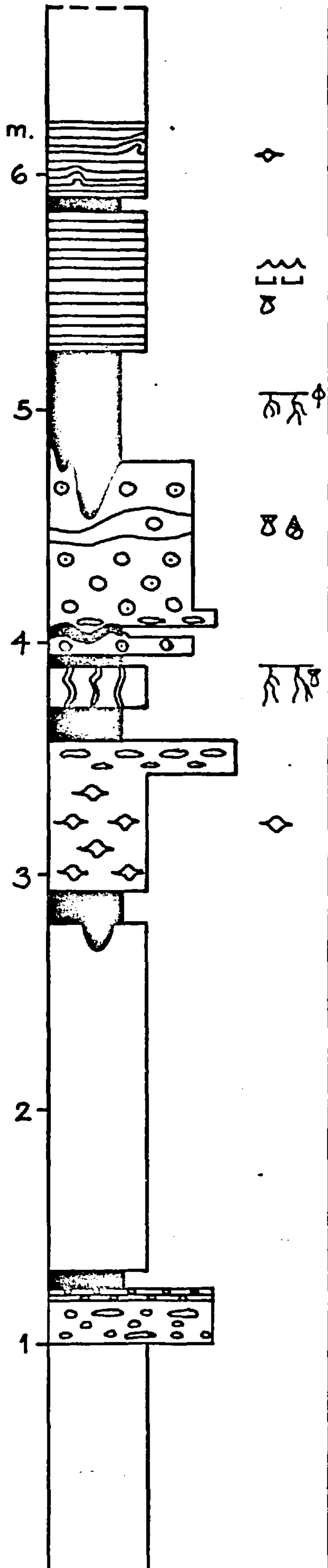
FIGURE 38 Hardground development in the Cajarc Formation.

might be drastically condensed, with a large part of the record being absent. Equilibrium hardgrounds, however, like those described from the Persian Gulf (Evans et al, 1973), only represent a break of a few thousand years, so they are unimportant stratigraphically. Moreover, the first two types could possibly become developed regionally, whereas the last type is probably much more local.

Unlike the example described by Purser (op. cit..) the hardground that has been found in the quarry near Cajarc is a simple type where only one phase of boring has occurred. Its stratigraphic position within a typical sedimentary rhythm (figure 38), is comparable with the hardgrounds that have been described from the prograding lagoonal sediments of the Persian Gulf (Evans et al, op.cit.). The latter are thought to form around or just below the level of normal low tide (Evans, 1973, pers.comm.), and therefore with respect to the Cajarc Formation, it may be possible to use such hardgrounds to subdivide subtidal from intertidal sediments; this would otherwise be extremely difficult. Furthermore, from the thickness of sediment above the hardground at the base of the quarry near Cajarc, the tidal range of the lagoon at the time of deposition of the bed in question was probably at least 50 cm. (figure 38).

4.4 Upper Intertidal, Supratidal and Brackish and Fresh Water Sediments.

In the upper portions of many of the beds of calcareous mudstone which make up the Cajarc Formation, laminated and unlaminated calcareous mudstones are present in association with lignitic marls and rooted horizons (figure 39). Within these deposits evidence has been found to indicate that periods of subaerial exposure have possibly occurred during their deposition, and in some cases fresh and brackish water fossils have been recovered. Furthermore, in general, the



Description	Lithofacies	Environment of Deposition
Massive calcareous mudstone	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL LAGOONAL.
Flat mm. laminated algal boundstone with rare heads and birdseyes.	LAMINATED ALGAL BOUNDSTONE	UPPER INTERTIDAL
Wavey and lenticular laminated calcareous mudstones with ripples, mud-cracks and ?Pronella raristriata.	LAMINATED CALCAREOUS MUDSTONE	UPPER INTERTIDAL OR LACUSTRINE ?
Lignitic marl with roots, 40–190 cm. in thickness; irregular karst surface below (fig. 64); solution hollows infilled with thick deposits of lignite.	MARL.	TERRESTRIAL SOIL.
Mottled, peloidal-ooidal-bioclastic-grainstone/packstone, with Viviparus. Lignitic debris and two marl bands near the top; intraclastic at the base.	OOLITIC GRAINSTONE	SUBTIDAL OUTER LAGOONAL WITH SUPERIMPOSED SUPRATIDAL AND LACUSTRINE CONDITIONS ?
	MARL	SUPRATIDAL
Calcareous mudstone with Equisetum roots (fig. 65 and 66), and Bakevillia waltoni	CALCAREOUS MUDSTONE	LAGOONAL OR LACUSTRINE ?
Marl	MARL	SUPRATIDAL
Calcareous mudstone with gas-bubble birdseyes; intraclastic at the top.	BIRDSEYE MUDSTONE	LACUSTRINE
Marl; cut and fill structures; lignite.	MARL	SUPRATIDAL
Mottled, chalky calcareous mudstone; Sometimes lignitic or laminated; Occasional large oncoids.	OSTRACOD WACKESTONE	LACUSTRINE
Marl	MARL	SUPRATIDAL
Intraclast-peloid-grainstone, laminated at the top.	STORM DEPOSIT OR BEACH? RIDGE?	SUPRATIDAL ?
Massive calcareous or intraclast-peloid-wackestone.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL LAGOONAL.

FIGURE 39 Succession showing the relationship of upper intertidal, supratidal and lacustrine sediments (Cajarc Formation; D127 road section at 114264 on North bank of Lot, opposite Cadrieu).

sedimentological features of these rocks are similar to those that have been described from Recent upper intertidal and supratidal sediments in the Bahamas (Black, 1933; Roehl, 1967; Shinn et al, 1969) and from Florida Bay (Multer, 1971).

However, it is important to point out that in much of the literature the term 'supratidal' has been used rather loosely. To quote Nuttall's Standard Dictionary (1907), 'supra' is a latin prefix signifying above, over or beyond; therefore strictly the word 'supratidal' means above or beyond the limit of the tides. Unfortunately many workers use theterm very loosely; for example, Shinn et al (op.cit.) described an environment as being supratidal even when it is affected by tidal waters at least once a month - their actual definition was the zone between normal high tide and the level to which the highest storm surges reach; though what is meant by 'normal' high tide is not clearly defined. In reality this environment should be known as the upper intertidal zone and only areas out of the reach of the normal tidal cycle, e.g. those areas only affected by storm surges or other unusual events, should be called supratidal zones (see figure 40 for a comparison of various usages).

Evans (1970) has used the term 'supratidal' in this stricter sense. He called the zone affected by the rise and fall of the tides, the intertidal zone and the zone above this, which is influenced by sea water only during storm surges, the supratidal zone.

The intertidal zone can be defined as the zone between the lowest level of the spring tide ebb and the highest level of the spring tide flood. In most of the know examples, the intertidal shoreface may be subdivided into two distinct areas, the lower intertidal flats and the upper intertidal flats (e.g. Evans, 1970). The lower flats are

This thesis.	Evans (1965, 1970). NORTH SEA COAST AND WADDEN SEA.	Evans & Purser (1973) PERSIAN GULF	Shinn et al (1969) BAHAMAS	Kendall and Skipwith (1968), Evans (1970) PERSIAN GULF.
SUPRATIDAL ZONE.	Supratidal or peat zone.	Supratidal or sabkha zone.	↑	Sabkha.
UPPER INTERTIDAL ZONE.	Upper intertidal salt marsh and mud flats.	High intertidal or algal flats.	Supratidal marsh. ↓	Algal flats.
LOWER INTERTIDAL ZONE.	Lower intertidal or sand flats.	Lower intertidal or sand flats.	Channelled belt.	Intertidal sand flats.

FIGURE 40 The varying nomenclature for intertidal and supratidal environments, compared with the terms used in this thesis.

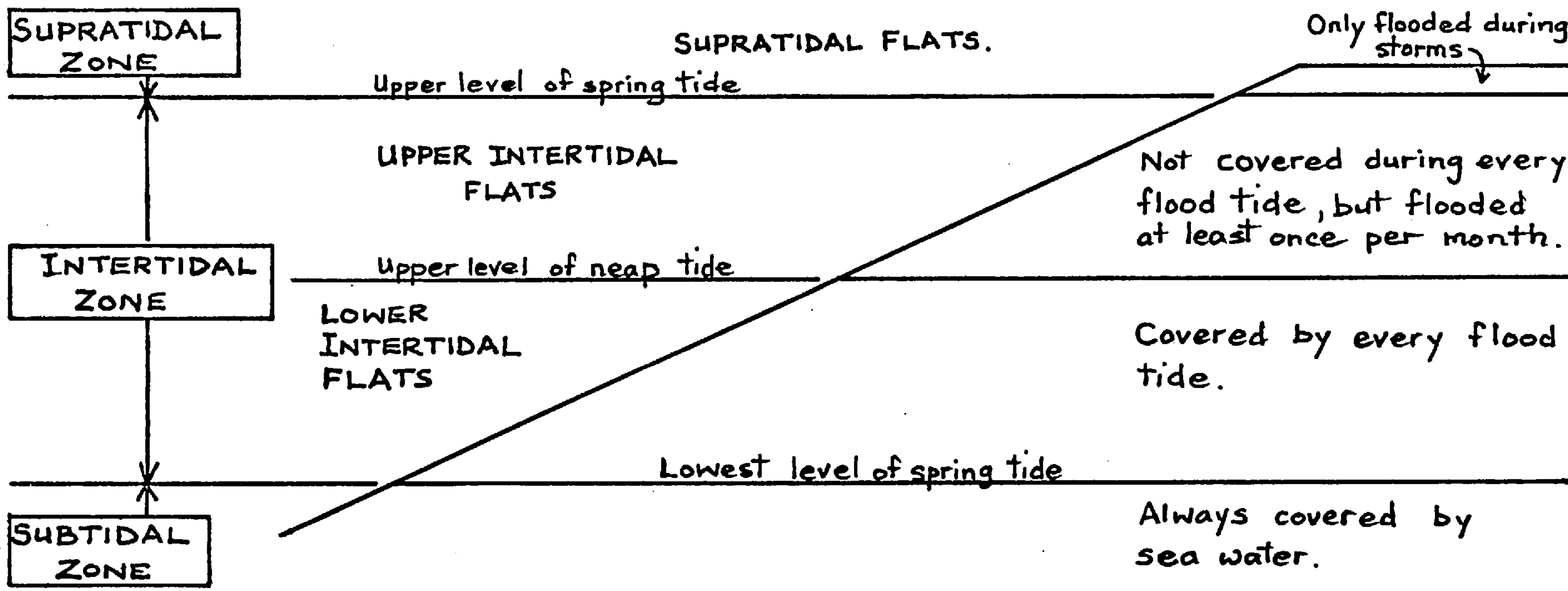


FIGURE 41 Definition of the subtidal, intertidal and supratidal zones.

affected each and every day be seawater, but the upper flats are not; they are inundated progressively less often as one passes away from the sea towards the supratidal zone. The limit between these areas is the highest level of the neap tide flood (figure 41). These are the definitions which will be used in this thesis (see also figure 40).

The characteristics of the sediments that are deposited on the upper and lower intertidal flats are not the same. The differences may be explained in terms of the processes that operate over these areas, because the upper flats are subjected to longer subaerial exposure, less wave activity and weaker current action than the lower flats.

If an intertidal zone is considered which is under the influence of a temperate climate and where siliciclastic sediments are being deposited (e.g. the Wash; Evans, 1965; Amos, 1974), the upper intertidal flats (which are called mud flats and salt marshes) are characterised by laminated muds, silts and sands. The supratidal zone consists of a rooted subaerial soil and the lower intertidal flats of rippled and cross-laminated sands and some muds. Thus there are three distinct sedimentological environments (figures 40 & 41).

In the Persian Gulf the lower intertidal zone is typified by rippled and bioturbated peloidal sands, the upper intertidal zone by algal mats, and the supratidal zone by a sabkha environment in which the main process operating is one of diagenesis, and where sedimentation, due to wind and storm flooding, takes place (Evans, 1970 and Kendall and Skipwith, 1968). The algal flats are probably the tropical equivalent of the salt marshes that are found in temperate regions (Evans, 1970).

The lower intertidal zones of the Bahamas are dominated by bioturbated and pelleted, calcareous muds (Shinn et al, op.cit). The upper intertidal zone, which was anomalously named as the supratidal marshes by Shinn et al, is an area of deposition of laminated calcareous sediments which sometimes have become dolomitised.

In all three examples the differences between the upper and lower flats may be explained in terms of the index of exposure (Ginsberg, 1971) and the strength of the tidal current activity. Hence it is possible to make correlations between the three regions as in figure 40, provided that the strict definitions of the various intertidal and supratidal environments are respected.

Furthermore, from these three examples it is apparent that laminated sediments are persistently developed in upper intertidal areas. Thus, for this reason, and others which will be discussed later, the laminated sediments of the Cajarc Formation are considered to be mainly of upper intertidal origin.

Another feature of the Recent examples that is of interest with regard to the Cajarc Formation is that the higher parts of the upper intertidal flats of the Wash support brackish water gastropods. Also, in the Bahamas, some hollows in the higher parts of the upper intertidal zone are periodically filled with fresh or brackish water. In the Cajarc Formation similar relationships have also been found. However, some of the sediments, although alike in many ways to the upper intertidal rocks, have probably been deposited when lagoonal areas became cut off from the sea and were influenced by fresh or brackish water; also some may have been laid down in inland lakes in a subaerial environment. Because of their often close relationship with upper intertidal deposits these rocks have been included in this section.

Finally, according to their faunal content and sedimentological features, it has been possible to subdivide the upper intertidal, supratidal and fresh and brackish water deposits of the Cajarc Formation into the following lithofacies:

laminated calcareous mudstone
organic laminated limestone
laminated algal boundstone
algal boundstone
oncolitic wackestone/packstone
disrupted algal boundstone
birdseye mudstone
ostracod wackestone
marl.

4.5 The Laminated Calcareous Mudstone Lithofacies

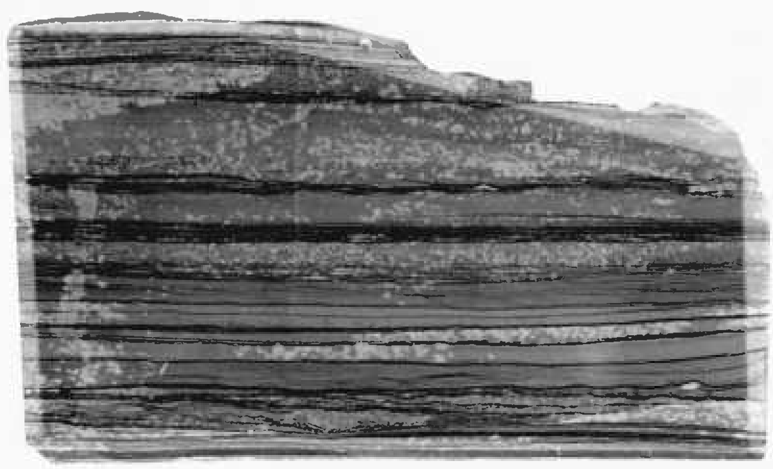
This lithofacies is well developed in the approach cutting for the railway tunnel (135287) near Montbrun. Lithologically, it consist mainly of flat, millimetre-laminated calcareous or dolomitic mudstones and siltstones (figure 72c and 74), with occasional centimetre-scale layers of peloidal grainstone. Various combinations of laminations have been observed; these include superimposed laminations of calcareous mudstone; alternating laminations of calcareous mudstone and siltstone; alternating laminations of siltstone and peloidal grainstone; and combinations of calcareous mudstone, siltstone and peloidal grainstone laminations.

The laminated nature of the sediments is apparent mainly because of grain size variations (figure 42a) and also sometimes, because of the presence of very thin layers composed of clay minerals and organic material (figure 42b). The latter are particularly noticeable in sediments where there is no grain size variation, but where lamination is still well developed.

A.

(x1)

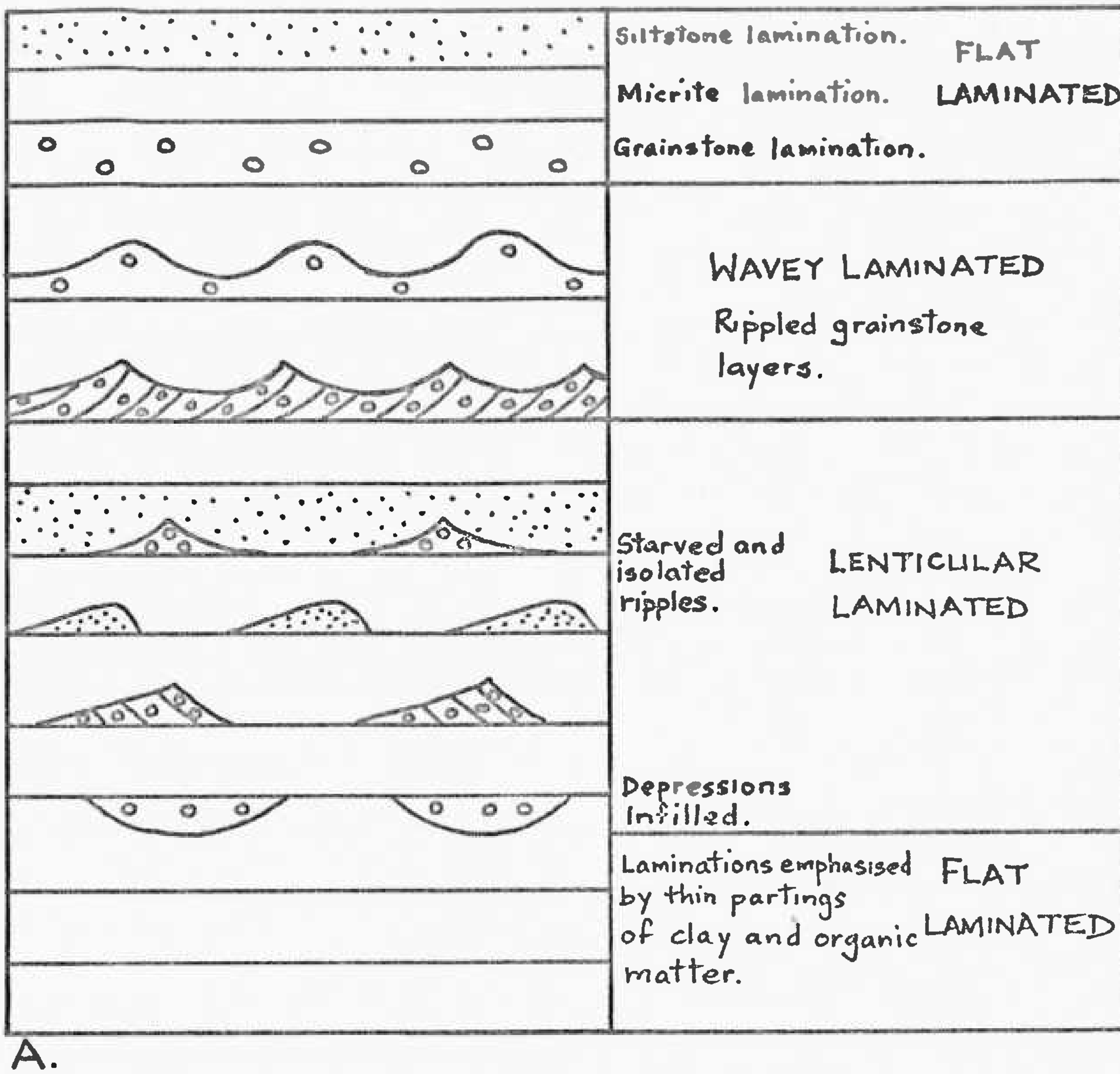
B.



(x1·3)

FIGURE 42 A) A laminated calcareous mudstone; the laminations are visible mainly because of variations in grain size. Note the presence of microfaults.

B) A laminated calcareous mudstone with little or no variation in grain size; the laminations are emphasised by thin layers composed of clay minerals and organic matter.
(La Plogne Mb., near St. Martin).



B.

(x1)

FIGURE 43 A) Summary of the bedding features of the laminated calcareous mudstone lithofacies.

B) Starved and isolated ripples of grainstone in a laminated calcareous mudstone of the La Plogne Mb.

Generally the sediments of this lithofacies are flat laminated. The laminations of calcareous mudstone are usually continuous and even in thickness, but the siltstone and grainstone laminae are sometimes rippled on their upper surfaces and as such they form wavey or undulating layers (figure 43) of uneven thickness and may even be discontinuous. Often these rippled layers show internal cross-laminations. Laminations of mudstone occasionally drape the rippled surfaces; grainstone layers never do this, they only infill depressions.

Isolated lenses of siltstone or grainstone are also common in the laminated calcareous mudstone lithofacies. These have probably originated either as trains of starved ripples or by the infilling of depressions (figure 43).

The various bedding features of this lithofacies are comparable with the wavey and lenticular types of bedding that have been described by Reineck and Wunderlich (1968), the only difference being that in the laminated calcareous mudstones the features are only developed on a millimetre scale, whereas in the example used by Reineck and Wunderlich they are of centimetre size (figure 43).

Good polygonal mud-cracks have frequently been found in this lithofacies. An excellent example of these can be seen in the quarry (251992) on the D24, near Saint Martin-Labouval, where a mud-cracked surface forms the floor of the quarry (figures 44 & 45). Sometimes the edges of the polygons may be upturned to form dish-like structures (figure 50a).

Birdseye structures (figure 45) and burrows are uncommon in the laminated calcareous mudstones, but microfaulting is often developed (figure 42a).

'Cut-and-fill' structures also occur in this lithofacies.

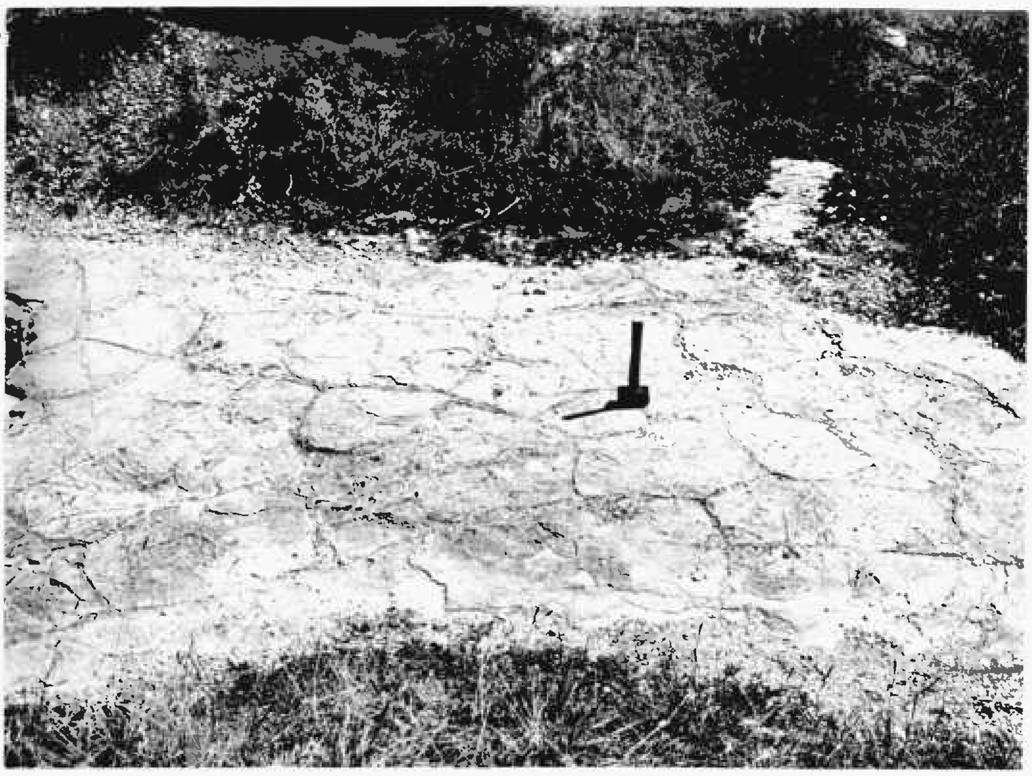
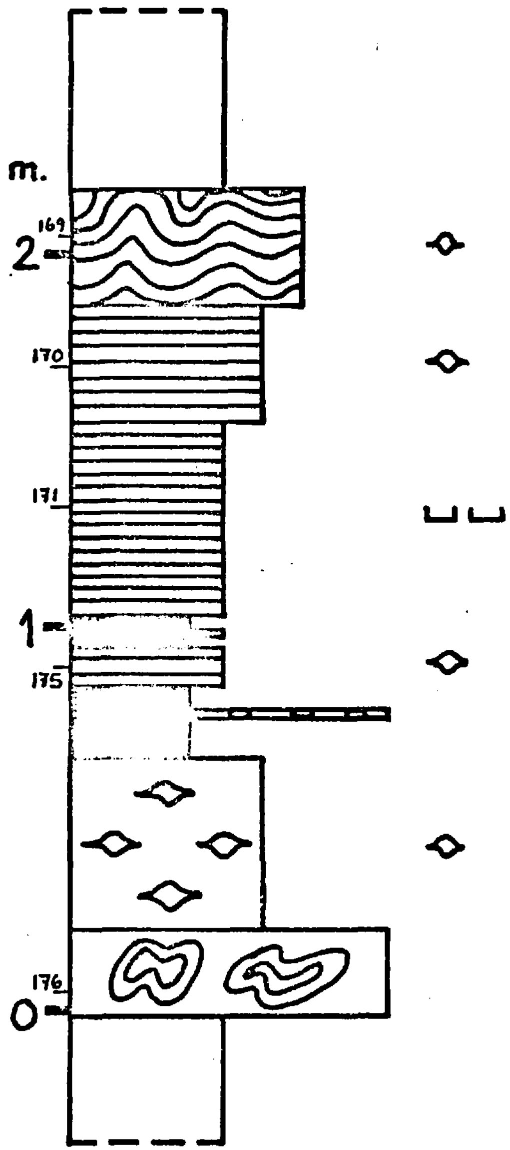


FIGURE 44 (above) A mud cracked and laminated calcareous mudstone which forms the floor of the quarry at 251992 near Saint Martin-Labouval (La Plogne Member).

FIGURE 45 (opposite) The lithologies present in the lower half of the quarry at 251992 on the D24 near Saint Martin-Labouval (La Plogne Member).



DESCRIPTION	LITHOFACIES	ENVIRONMENT OF DEPOSITION
Massive calcareous mudstone	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL LAGOONAL
Centimetre bedded algal boundstone with large 'heads', birdseyes and mud-chip (intraclast) layers (fig. 46A and 51B).	ALGAL BOUNDSTONE	UPPER INTERTIDAL
Wavey organic laminated calcareous mudstone and peloid-grainstone with birdseyes (fig. 46B).	ORGANIC LAMINATED LIMESTONE	
Flat laminated calcareous mudstones exposed on quarry floor (fig. 44); good polygonal mud-cracks and birdseyes; some organic laminations.	LAMINATED CALCAREOUS MUDSTONE	
Lignitic marl and laminated algal boundstone	MARL	SUPRATIDAL
Laminated calcareous mudstone with gas bubbles (fig 46C).	LAM. CALC. MUD.	LACUSTRINE ?
Lignitic marl with an intraclastic layer.	MARL	TERRESTRIAL?
Calcareous mudstone / peloid-wackestone with gas-bubble birdseyes.	BIRDSEYE MUDSTONE	LACUSTRINE
Either oncolitic (?) or intraclastic (?) wackestone ; fining upwards.	ONCOLITIC ? WACKESTONE	LOWER INTERTIDAL ?
Massive calcareous mudstone	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL

FIGURE 45.

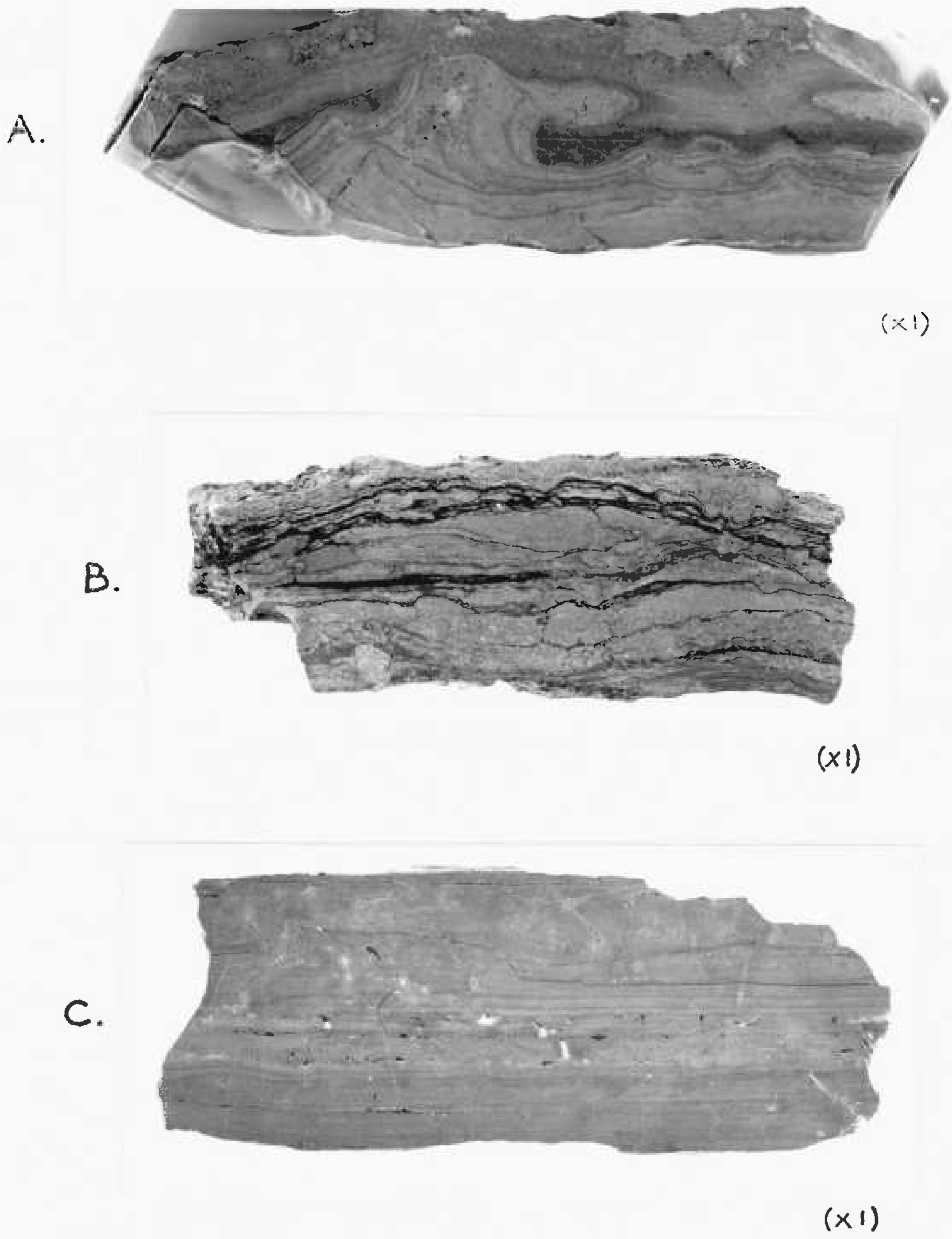


FIGURE 46 Some lithologies from the quarry at 251992 near Saint Martin:

A) An algal boundstone with 'heads' and desiccation birdseye structures (169/73).

B) A wavy laminated organic limestone with birdseye structures (170/73).

C) A laminated calcareous mudstone with gas-bubble birdseye structures (175/73).

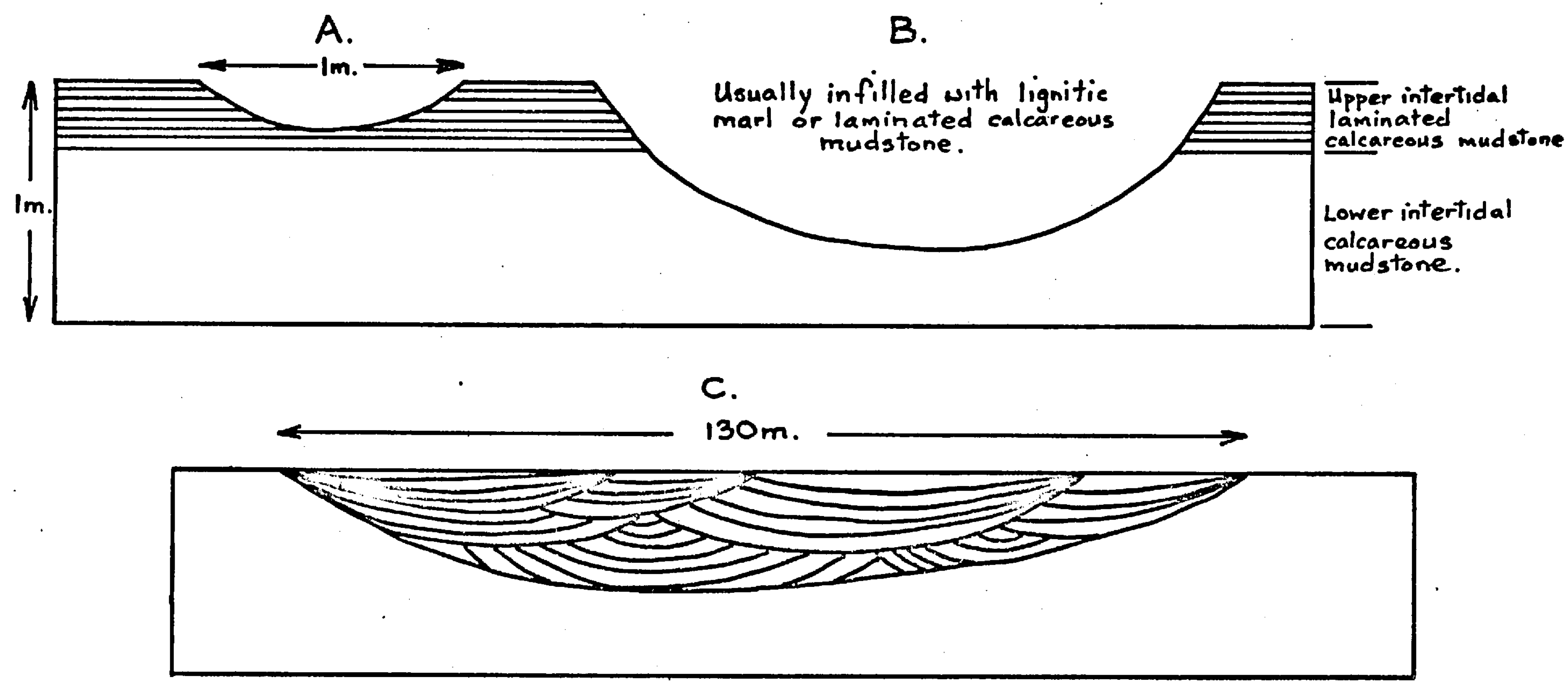


FIGURE 47 Cut and fill strctures or channels in the Cajarc Formation:

A) A small scale channel.

B) A large scale channel.

C) A channel complex in the N662 road section at 133282, near Montbrun (schematic representation).

A.

B.

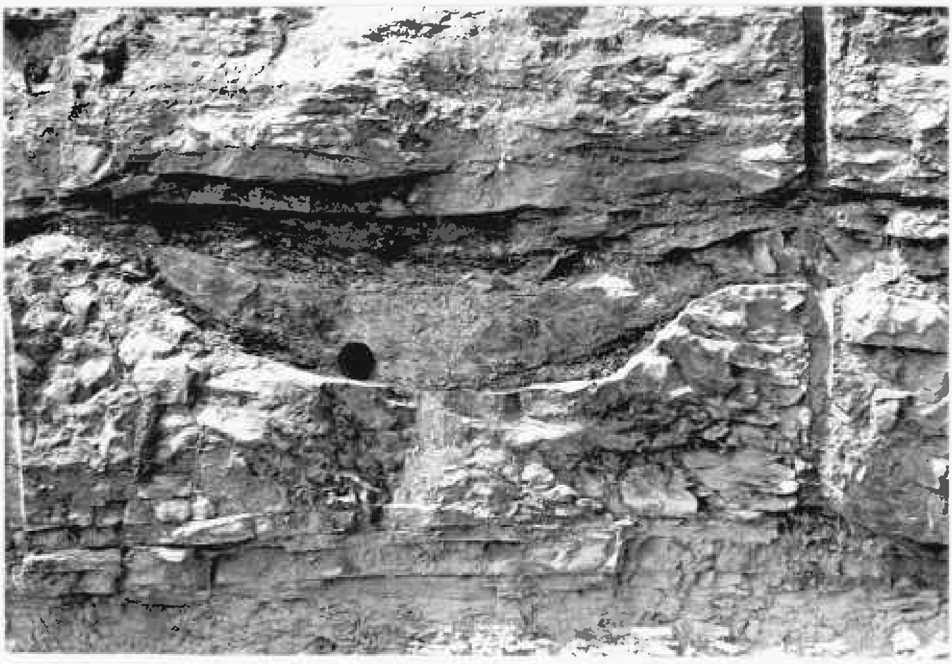


FIGURE 48 A) An infilled channel complex in the La Plogne Member of the Cajarc Formation at 135283 on the N662 near Montbrun.

B) A minor infilled channel in the Marcilhac Member of the Cajarc Formation at 022355 on the D17 near Marcilhac.

They are developed on various scales and are usually filled with lignitic marl or laminated calcareous mudstone (figures 47 & 48). Smaller ones may be 1 m. across and 10-50 cm. in depth, but larger ones reach tens of metres in width and they sometimes cut down through the laminated calcareous mudstone lithofacies into underlying deposits of calcareous mudstone. In one example (p166), smaller scale structures are developed within a large scale cut-and-fill structure (figure 47 & 48).

Some of the laminated calcareous sediments have been partially or completely dolomitised and in thin section silt sized dolomite crystals form between 10 and 100% of these rocks. The rhombic shape of the crystals is only rarely visible, but a light etching in weak hydrochloric acid (1%) has been found to emphasise the shape more clearly.

In other examples, laminated calcareous sediments have been recrystallised to both saccharoidal and coarsely crystalline limestones in which the laminations are only crudely preserved. In thin-section these rocks possess dedolomitisation textures (p.360) (Shearman et al, 1961) and previously therefore they must have been composed almost entirely of dolomite.

It is possible that in cases where dolomitisation was only slight and where the resulting dolomite crystals were small, any subsequent calcitisation might fail to leave visible evidence to indicate that dolomitisation and dedolomitisation had occurred. Moreover, as evidence of dedolomitisation is common in the lower parts of the Cajarc Formation but not in the upper parts, it is likely that many of the laminated calcareous rocks may once have been at least partially dolomitic.

The Fauna of the Laminated Calcareous Mudstones

Generally, fossils are sparse in the laminated calcareous

(x3)

FIGURE 49 An example of ?Pronoella raristriata (Sandberger) from the laminated calcareous mudstone lithofacies of the Cajarc Formation (La Plogne Mb., Tour de Faure).

mudstones, but sometimes, when split open, the more fissile varieties have revealed rich coquinas of the heterodont bivalve, ?Pronoella raristriata (Sandberger) (figure 49). These are preserved on the bedding planes as moulds. Usually the valves are still articulated but gaping.

Sometimes the bivalves are associated with fresh water ostracods such as Fabanella bathonica and Bisulcocypris sp. (p.198). One or two specimens of Protocardia sp. (Beyrich) have also been found in the coquinas.

The Environment of Deposition of the Laminated Calcareous Mudstones.

It has already been noted that when Recent environments of deposition are considered, laminated calcareous sediments are frequently being deposited in upper intertidal areas (p.152). There is much evidence to suggest that the laminated limestones of the Cajarc Formation were deposited in a similar environment: firstly, the general sedimentary characteristics of the rocks are similar to the Recent examples; secondly, the laminated limestones are often sandwiched between lower intertidal and subtidal deposits, and rooted lignitic horizons (figure 72c); and thirdly, they possess a fresh or brackish water fauna.

Considering each of these points in turn, the main sedimentary features of the laminated calcareous mudstones are; flat millimetre sized laminations, cross-laminated and rippled grainstone layers, isolated ripples, microfaulting, mud-cracks (i.e. high index of exposure), minor channel features and dolomitisation.

Both Evans (1965) and Amos (1974) have described similarly laminated siliciclastic deposits from the upper intertidal zone of the Wash, on the east coast of England. The various laminations have resulted from the variation of the grain size of the sediments being deposited. Muddy laminations are probably deposited by normal tidal activity, whereas the coarser sand grade layers are the result of storm activity and the action of winds at low water. Each mud layer is probably the result of a whole tidal cycle (neap to spring), with most of the sediment being deposited during the spring tide flood.

The processes which operate are forming a millimetre-laminated mud deposit, with occasional wavey or lenticular laminae. Rippling is rare and only produced in silts and sands which become reworked during periods of high current activity. Often these ripples are starved and isolated. Sometimes cross-laminations are present within the silty or sandy layers.

Passing landwards across the intertidal zone the sediments become finer grained and the muds become coated with a thin film of green algae. The latter probably helped to preserve the laminations where grain size variations are not apparent. Mud cracks also become more frequently developed.

If these deposits were to become preserved, they would form a laminated mudstone which fined upwards and contained occasional sand layers. Moreover, the sedimentological features would have resulted largely from the mechanism of deposition imposed by the actions of the tides and modified to some extent by desiccation during periods of subaerial exposure.

A similar relationship also probably exists in areas where Recent calcareous sediments are being deposited in an upper intertidal environment. Some examples of these have been described by Black (1933), Roehl (1967), Shinn et al (1969) and Multer (1971), where the laminated sediments are being deposited on channel levees and salt marshes. They are probably also being deposited in other environments, such as the lower intertidal zone, but bioturbation usually destroys the primary sedimentary structures.

In the Bahamas laminated calcareous muds are being deposited together with occasional wavey or lenticular layers, but in comparison with the Wash, because of the tropical climate, dessication plays a much more important role in determining the final characteristics of the upper intertidal flat sediments. Mud-cracks and birdseye structures are common, and with increasing degrees of exposure they may completely destroy any evidence of lamination (Shinn et al, op.cit.).

Roehl (op.cit.) noted that on Andros Island vast stretches of laminated calcareous muds and silts are being deposited. As on the upper intertidal deposits of the Wash, these are being produced almost entirely by the mechanical processes of the tides and algae play little or no role in determining the final characters of the sediments. Roehl also observed that it is very difficult to distinguish between the laminated sediments of the levees and the salt marshes.

Again there are many similarities with the laminated calcareous mudstones of the Cajarc Formation, so it is probable that the latter sediments have also been deposited by mechanical processes, i.e. the tidal currents in an upper intertidal zone. This fact was recognised by Bouroullec et al (1972) who accordingly named the rocks 'laminates mecaniques'.

Furthermore, it is possible that the laminated sediments may have been deposited both on upper intertidal flats and on channel levees. As in the Bahamas it is very difficult to distinguish between these, but the cut-and-fill structures described on page 162 are thought to have resulted from tidal channel erosion and laminated sediments that are associated with these structures might be levee deposits. In particular, a large scale cut-and-fill structure, exposed by the roadside (N662) at 132292, near Montbrun, is filled by a complex of laminated cut-and-fill structures (figures 47 & 48). These are interpreted as a complex of levee deposits which have been built up in situ.

In the middle and upper parts of the Cajarc Formation many of the layers of laminated calcareous mudstone are, or were once dolomitic. It is well known that in the upper intertidal zones of Andros Island, laminated calcareous sediments undergo penecontemporaneous dolomitisation. This is thought to take place when Mg/Ca ratio in seawater is increased by evaporation, leading to the replacement of aragonite by dolomite. It occurs both in channel levee and upper intertidal marsh deposits (Shinn et al, 1965). The percentage of dolomite in these sediments varies from 0-80% (Shinn et al, 1965) and it reaches its maximum development nearest the sea (Multer, 1971). Inland it decreases as the influence of freshwater increases.

The dolomitic or formerly dolomitic laminated sediments of the Cajarc Formation are thought to have originated in a similar way, and it is possible that the undolomitised examples may have been influenced by freshwater influxes which did not allow the concentration of Mg to become sufficiently high for dolomitisation to occur.

The concentration of large numbers of one species of bivalve in the laminated calcareous mudstones suggests that abnormal salinity conditions may have existed during the deposition of the sediments. Sandberger (1870-75) considered that ?P. raristriata is a fresh or brackish water form and Palmer (1973) suggested that Protocardia, which is a typical genus of the middle and upper Bathonian, may have been able to tolerate reduced salinities. Furthermore, the ostracods which have been found in association with these bivalves are also probably fresh and brackish water forms (p.198). Thus it appears that the fauna represents unusual salinity conditions.

The higher portions of the upper intertidal salt marshes of the Wash, although flooded by sea water during spring tides, are also influenced by fresh and brackish water, due to rainfall and they are able to support brackish water faunas. It is possible, therefore, that the fauna of the laminated calcareous mudstones may have a similar significance, especially when it occurs at the tops of rhythms of deposition.

However, present day examples of Pronoella are shallow burrowing, infaunal suspension feeders. Thus, although ?P. raristriata occurs in upper intertidal deposits, it is doubtful that it actually lived in an upper intertidal flat environment, where it would have had to cope with prolonged periods of dessication. It is more likely that it lived in association with ostracods in temporary fresh or brackish water lakes, which might have bordered the tidal flats, and that it was displaced onto the intertidal flats during storms. Most of the valves, which are still articulated, show little or no evidence of transportation.

4.6 The Organic Laminated Limestone Lithofacies

The organic laminated limestones of the Cajarc Formation form a very distinct lithofacies, composed of millimetre laminated calcareous sediments with extremely fine layers of dark grey or black material. Two types of lamination have been distinguished; flat, millimetre lamination (figure 73b) and wavey or ramifying laminations (figure 46b & 73a).

Individual dark laminations are only 10-100 microns in thickness, but sometimes they may be combined to form layers up to ·1 or 2 cm. thick. There is very little calcareous material within the dark laminations, but alternating with these are grey, white or cream layers of almost pure calcareous sediment which may be up to 2 cm. in thickness.

The composition of the calcareous layers varies from mudstone or wackestone to peloidal or intraclastic-bioclastic grainstone. The intraclasts are either rounded or have a 'mud-chip' appearance (p.176). The bioclasts consist largely of fragments of large, possibly marine bivalves, with a shell structure similar to Inoceramus sp. Infrequently the grainstone bands may be graded.

In some examples the calcareous layers have been partially or completely dolomitised. The resulting dolomite crystals are of silt size, and form between 10 and 100% of the layers, which are interbedded with dark material.

The composition of the dark layers has been much more difficult to ascertain, but the following features have been observed: firstly, the dark material is insoluble in hydrochloric acid, but it reacts strongly with hydrogen peroxide; and secondly, after all the calcareous material has been removed a green or brown translucent substance is left. These characteristics suggest that the dark material is, in part at least, composed of organic matter.

To confirm the latter, some of the dark material has been analysed using apparatus that was originally designed for detecting carbon, hydrogen and nitrogen in crude oils (by gas analysis). Two samples were used, one treated with 10% hydrochloric acid to remove any calcareous material, and the other untreated. The results that have been obtained are; without acid N=0.00%, C=14.3%, H=1.499%; after acid N=0.9%, C=14.5%, C/H=9.54%. As the two values of C that have been obtained are within the range of experimental error of the apparatus, they are considered to be reliable. Therefore, using a conversion factor of 1.6 (Trask, 1939) the amount of organic matter that is present in the dark layers is:

$$14.5 \times 1.6 = 23.2\%$$

To determine the composition of the remaining 77% of the dark material, a thin section was prepared for electron microprobe analysis. The probe was used to detect Ca, Al and Si. It was found that the dark layers are rich in Al and Si and poor in Ca, whereas the reverse is true for the calcareous layers. The concentration of Al and Si in the dark layers suggested that clay minerals might be present and this has since been confirmed by X-ray diffraction analysis of the laminated limestone.

Thus, it is very probable that the dark layers are made up of clay minerals and organic matter, roughly in the proportions of 3 to 1.

No fauna has been found in this lithofacies.

The Environment of Deposition of the Organic Laminated Limestones.

The organic laminated limestones have been found in a similar situation to, or in association with, laminated calcareous mudstones which were probably deposited in an upper intertidal environment, and frequently one type passes into the other (figures 52 & 54). Moreover, the organic laminated types bare a strong resemblance to the laminated algal sediments which have been described from the upper intertidal and supratidal zones of Andros Island and Florida Bay (Black 1933; Roehl, 1967; Shinn et al, 1969; and Multer, 1971); compare figures 42b, 46b and 73b with Black (op.cit.) plate 25, figures 21,22 and 25. The unusually high organic content of the dark laminations does not contradict this, although no evidence of algal filaments has been detected.

In hand specimen and in thin section, individual dark laminations are draped over all the depositional irregularities of the underlying sediments; they form laminae of constant thickness in both depressions and over intraclasts. This is to be expected if the laminations are the remains of algal mats.

Black's description of gelatinous algal mats covering flat or wavey laminated, white or cream coloured calcareous sediments, could easily relate to the organic laminated limestones of the Cajarc Formation. Most of the calcareous sediment is deposited during storms and spring tides, and the sandy layers are sometimes graded. During periods of non-deposition blue-green algae grow on the surface of the sediment and form dark gelatinous coatings or 'mats'. Black thought these mats did little to modify the sediment, apart from accentuating the mechanically produced laminations, but subsequent workers have shown that after the deposition of a sheet of sediment, due to a storm for instance, blue-green algae rapidly permeate the sediment from below and tend to preserve it from re-erosion. A new sediment-free mat then becomes established on top of the layer that has just been laid down.

Black showed that successive influxes of sediment, alternating with periods of algal growth, have given rise to millimetre or centimetre laminated deposits, with alternating dark and light layers. If this became compacted and preserved it would be very similar to the organic laminated limestones of the Cajarc Formation.

Another Recent example of flat millimetre laminated algal sediments has been found in the coastal sabkhas bordering the Gulf of Sirte, near Miserata in Libya, where algal mats are growing on open supratidal mud flats, (N. Sherif, pers.

comm., 1974). Box cores have revealed many similarities with the organic laminated limestones of the Cajarc Formation and the sediments are made up of algal rich layers alternating with sediment rich ones.

Wavey or ramifying organic laminations have only been found in grainstones in the Cajarc Formation and they are usually pervaded with birdseye structures. Roehl (1967) noted that on the upper intertidal to supratidal areas of Andros Island wavey continuous mats are common. Black (1933) thought that these wavey mats develop only on sandy substrates in response to surface irregularities. He considered that strong irregularities might even lead to the development of algal heads; a possible example of this has been found in the Cajarc Formation (p.179).

In conclusion, the organic laminated limestones have probably been deposited in an upper intertidal or supratidal environment. It follows therefore, that any dolomitisation of these sediments that has occurred was probably due to a process similar to that described on page 167.

Finally, in some instances, coarse sand or gravel grade peloidal intraclastic grainstones or oyster bands, with crude organic laminations, are closely associated with other upper intertidal and supratidal deposits in the Cajarc Formation. It is possible that these represent storm wash-over deposits upon which algal mats subsequently became established.

4.7 The Laminated Algal Boundstone Lithofacies

Superficially this lithofacies resembles the laminated calcareous mudstone lithofacies, but in detail there are a number of differences that suggest that algae, rather than just fluctuations in current activity, have played an important role in the deposition of the sediment. The term 'boundstone' is used here exactly as it was intended by

Dunham (1962) and the sediments of this lithofacies are thought originally to have been bound together by algae. A good example of this lithofacies can be seen at the road-side exposure (O44263), on the N662 near Larnagol, where it is exposed just above a thick bed of lignitic marl (figures 85 & 86).

The laminated algal boundstones are composed mainly of flat millimetre laminated calcareous mudstones and peloidal silt stones, with subordinate layers of fine sand grade peloidal grainstone (figure 86b). The laminations are alternately light tan or grey in colour. Sometimes thin centimetre scale layers of flat gravel grade intraclasts are developed which appear to have been derived from laminated mud deposits by penecontemporaneous erosion.

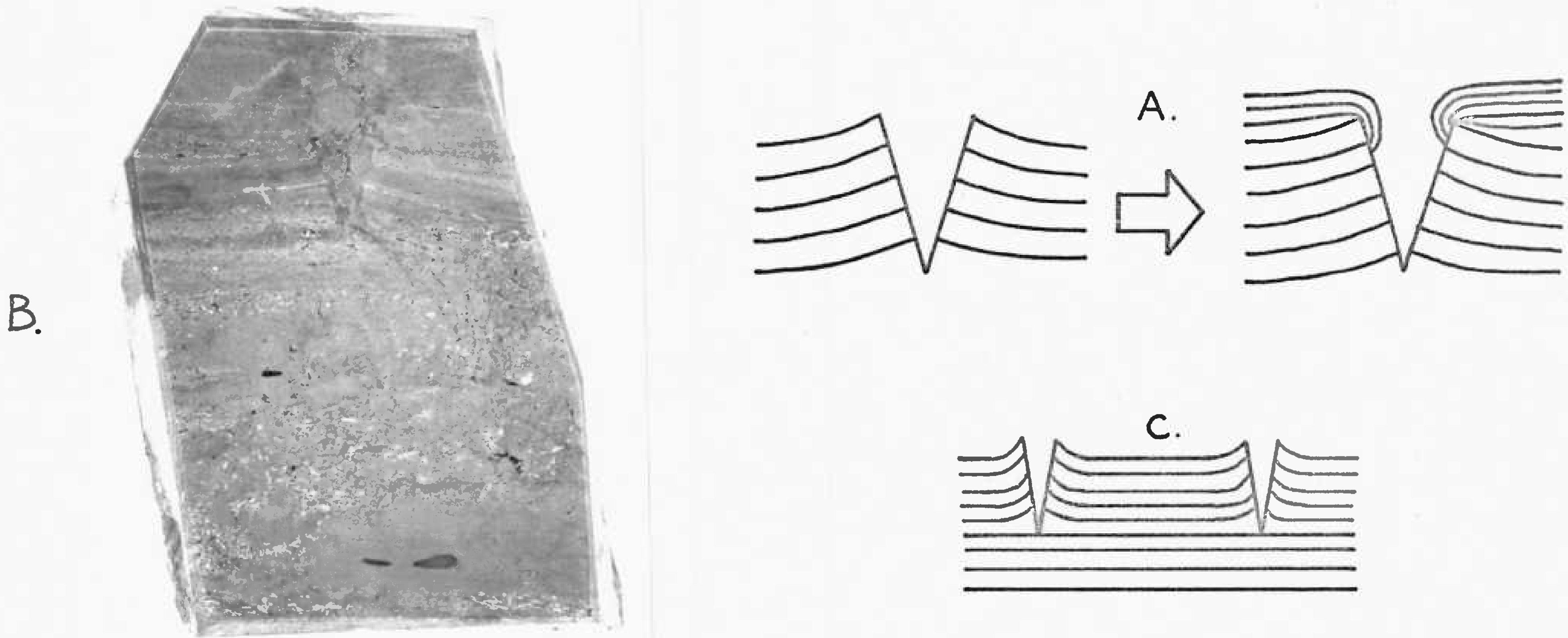
Rarely, some of the laminations are preferentially crinkled (figure 86b) to form small 'heads' 1 to 2 cm. in height. Also, in one case, several layers have observed to be overturned and folded back upon themselves (figure 86b). Wedge shaped mud cracks and birdseye structures have commonly been found, but no organic laminations are present in this lithofacies.

No fauna has been found in this lithofacies.

<u>The Environment of Deposition of the Laminated Algal Boundstones</u>

This lithofacies also resembles some of the algal sediments that have been described from the upper intertidal and supra-tidal zones of Andros Island, by Black (1933) and Shinn et al (1969); this can be seen by comparing figure 86b with Shinn et al (op.cit., figures 21 and 22).

Both the ancient and Recent examples show evidence of sub-aerial exposure, e.g. mud cracks and birdseye structures and in both cases small scale 'heads' are only rarely developed.



(x1·3)

FIGURE 50 Mud-cracks in the Cajarc Formation.

A) Algal thickening of the lips of wedge-shaped cracks.

B) Actual example of algal modification from the laminated algal boundstone lithofacies of the La Plogne Mb.

C) Dish structures caused by the development of mud-cracks.

Flat millimetre laminated algal sediments with crinkles, overfolds and storm layers, have also been described from the upper intertidal zones of Shark Bay (Davies, 1970) and the Khor al Bazam in the Persian Gulf (Kendall and Skipwith 1968).

No algal filaments are preserved in the laminated algal boundstones of the Cajarc Formation, but the fact that thin groups of laminations have been preferentially crinkled or overfolded (possibly by storm activity) suggests that the muds and silts were probably bound together by algal filaments; this would have enabled thin layers of sediment to behave as cohesive sheets.

Further evidence of the influence of algae has been gained by examining mud cracks and tracing their progressive development. If a non-algal sediment becomes cracked and dried out, the edges of the cracks turn upwards to form dish-like structures (figure 50). The same should also be true for an algal mat, but after the initial drying out, algal laminations may grow downwards into the cracks, thereby thickening the lips of the cracks and 'inverting' the dish structures (Black, 1933). Eventually this might produce algal heads (type C of Black). Mud cracks with lips thickened by algal growth have been found in the laminated algal boundstone sediments of the Cajarc Formation (figure 50).

Black (1933) also observed that all traces of organic matter may be completely removed by bacterial action soon after burial, while algal mats are still actively growing above. In such instances only a laminated calcareous sediment would be preserved. Therefore, although there is no direct evidence of algae in the laminated algal boundstones, a comparison with Recent deposits has suggested that these sediments have been laid down under the control of algal mats in an upper intertidal environment.

4.8 The Algal Boundstone Lithofacies

One of the best examples of this lithofacies is exposed at the base of the quarry on the D24 near Saint Martin-Labouval at 992251, where a bed 30 cm. in thickness crops out (figures 45 and 46a).

It is composed of wavily bedded or undulating layers of caleareous mudstone and peloidal grainstone which are developed on a centimetre scale and not, as in the previous lithofacies, on a millimetre scale. Algal 'heads' (figure 51) are nearly always well developed, sometimes reaching 6 cm. in diameter and possessing crude, concentric, internal lamination. Birdseye structures are ubiquitous and sometimes quite distinct. Layers of flat, 'mud-chip' intraclasts, up to 10 cm. in thickness are often interbedded with the algal boundstones (figure 51). No organic laminations are present in this lithofacies, although the sediments occasionally pass upwards or downwards into organically laminated rocks.

No fauna has been found in this lithofacies.

The Environment of Deposition of the Algal Boundstones

This lithofacies is very similar to certain algal sediments that have been described by Black (1933) (his type-B lithology), and it can be assigned the code L.L.H., after Logan et al (1964). The similarity of the algal boundstones with Recent algal mats that are growing mainly in upper intertidal environments (Black op.cit., Logan et al, op.cit., and Kendall and Skipwith, 1968) and also in supratidal areas (Black, op.cit.), has suggested that they too have been deposited in an upper intertidal to supratidal environment. This interpretation is supported by the stratigraphic position of the lithofacies within the sedimentary rhythms (figure 79), also by its association with upper intertidal deposits

A.

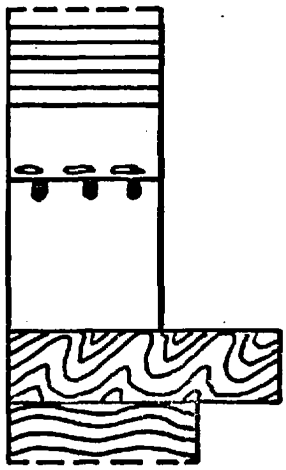
(x 0.5)

B.

(x 1)

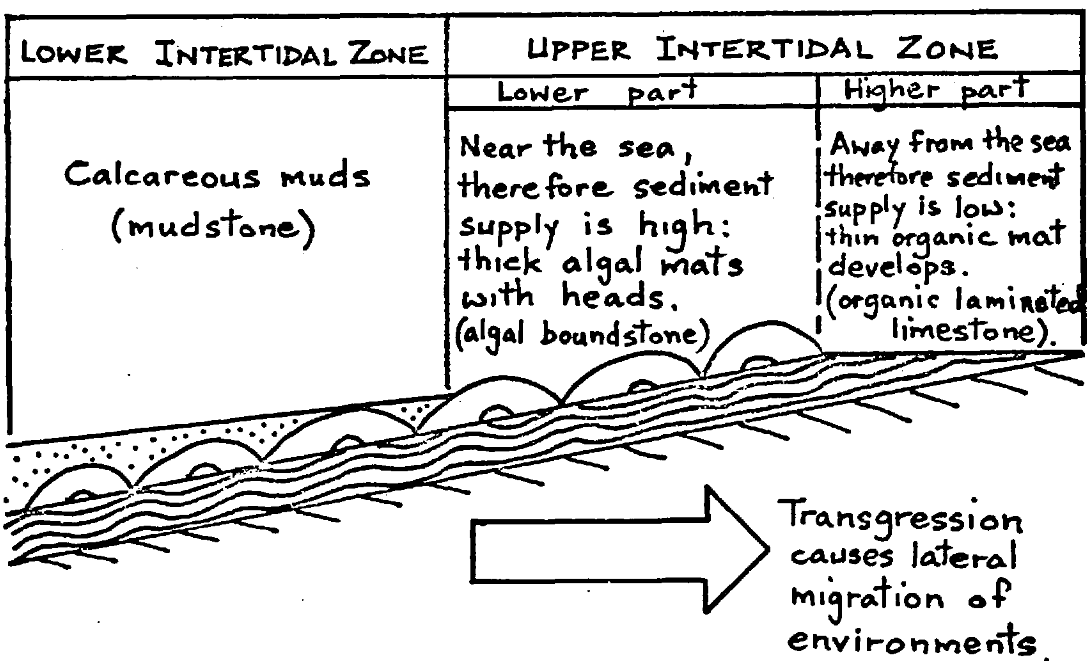
FIGURE 51 A) An algal boundstone showing well-developed algal heads (La Plogne Mb. near Tour de Faure).

B) A polished slab of an algal head showing birdseye structures and an overlying intraclast barrier (also see figure 46a) (La Plogne Mb. near St. Martin).



LITHOFACIES	ENVIRONMENT	INTERPRETATION
Laminated calcareous mudstone.	UPPER INTER-TIDAL	PROGADING INTERTIDAL FLAT. (REGRESSIVE)
Calcareous mudstone.	LOWER INTER-TIDAL	
	SUBTIDAL LAGOONAL	LAGOON BECOMING INFILLED
	L. INTERTIDAL	TRANSGRESSIVE BASAL DEPOSITS.
Algal boundstone.	UPPER INTERTIDAL	
Organic laminated limestone.		

A.



B.

FIGURE 52 A) Sedimentary rhythm at the base of the quarry at 251992, near St. Martin showing a transgressive algal boundstone.

B) Interpretation of the basal deposits.

(figure 45) and finally by the constant presence of birds-eye structures: the latter may be interpreted as an indication that periods of desiccation occurred, during the deposition of the sediment, possibly in an upper intertidal environment.

With regard to the algal heads, Black (op.cit.) thought that the development of certain types (his type-B) is dependent on surface irregularities. In the quarry near Saint Martin, the algal boundstone passes upwards from a wavey organic-laminated limestone (discussed on page 172), and the 'heads' of the algal boundstone have apparently grown from already established irregularities.

This particular algal boundstone occurs at the base of a transgressive sedimentary rhythm (figure 52a) and it is overlain by a calcareous mudstone. It is possible that as the transgression took place the algal boundstone developed from the organic laminated deposit in response to an increase in the supply of sediment, until eventually it was overwhelmed by an advancing lower intertidal environment (figure 52b).

The thick layers of intraclasts which are a typical feature of this lithofacies often appear to have smothered any underlying algal heads. Black (1933) has described similar layers from the Recent algal mats of Andros Island. These are thought to be storm deposits and they nearly always have swamped or smoothered any pre-existing algal sediments.

4.9 The Oncolitic Wackestone/Packstone Lithofacies

Only one example of this lithofacies has been found in the section at 064260, near Cajarc, where a bed of gravel grade oncolitic wackestone/packstone, with a calcareous mudstone matrix, crops out just below an ostracod wackestone (enclosure 5). This bed passes laterally into an algal boundstone, with well developed algal heads, and it is thought to have been produced by erosion from algal mat sediments. It is interpreted as an upper to lower intertidal deposit (figure 54).

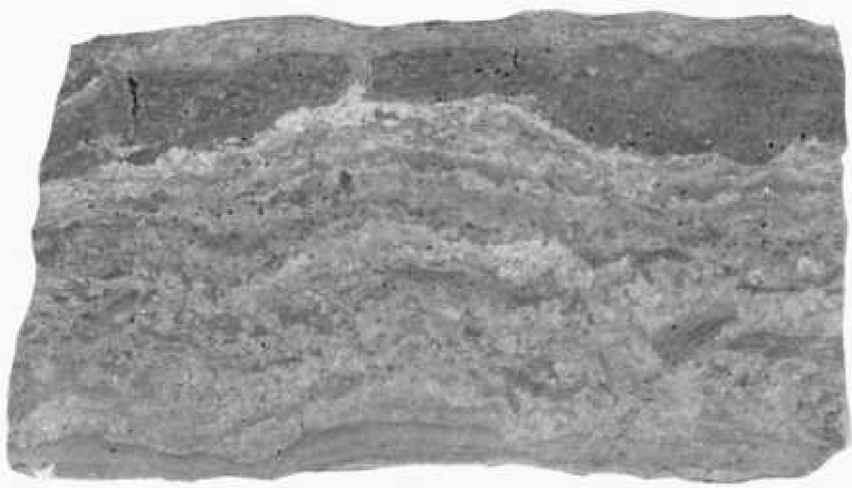
4.10 The Disrupted Algal Boundstone Lithofacies

This lithofacies has been found only in the upper parts of the Cajarc Formation in association with calcitised evaporitic deposits (p.305). Numerous examples can, however, be seen in the road section at 365074, near Brengues, where a series of undulating beds up to 20 cm. in thickness crop out.

At first glance these boundstones appear to be structureless, but a closer look has revealed that they are composed of disrupted and sometimes chaotic mixtures of organic laminated limestones, laminated algal boundstones, algal boundstones and peloidal grainstone, with birdseye structures, mud cracks, ostracods, gypsum pseudomorphs, calcitised nodules of anhydrite and layers of large 'mud-chip' intraclasts (figure 53). All the previously identified algal sediments have been found in this lithofacies, but they have all been disrupted by a combination of desiccation and the growth of evaporitic minerals. Abundant organic material has also been described by Bouroullec et al (1972), from similar disrupted algal sediments (see discussion on page 184), found in the Bathonian limestones of Quercy.

The Environment of Deposition of the Disrupted Algal Boundstones

Thomson (1968) described some Recent chaotic laminated sediments from the Gulf of California, which are actively being disrupted by a combination of desiccation and the growth of



(x1·6)

FIGURE 53 Disrupted algal boundstone lithofacies, with birdseye structures, mud-cracks disrupted laminations, and gypsum pseudomorphs. (Brengues Member, at 365074 near Brengues).

evaporitic minerals. This is taking place in an upper intertidal environment. Kendall and Skipwith (1968) have also described an example of this from the Persian Gulf, where upper intertidal algal mats become more and more disrupted as they approach the supratidal sabkha zone. Once progradation has occurred and the algal mat is left stranded in a sabkha environment the growth of evaporitic minerals may completely destroy the structure of the mat (see also Evans et al, 1969).

In the Cajarc Formation the association of the disrupted algal boundstones with lower intertidal calcareous mudstones and sabkha deposits, suggests that this lithofacies may have been laid down in an environment similar to that described by Kendall and Skipwith (op.cit.) i.e. an upper intertidal area bordering a coastal sabkha zone (figure 54).

4.11 A Discussion of the Laminated Limestones of the Cajarc Formation

Bouroullec et al (1972) studied the laminated limestones of the Middle Jurassic of the Causse de Quercy and they concluded that these sediments had probably been deposited in an intertidal to supratidal environment. A comparison with Recent deposits made by the present writer has confirmed these conclusions and also added much more detail. For instance in the Recent examples laminated sediments are found mainly in upper intertidal areas, where both burrowing and desiccation are not strong enough to destroy the laminated nature of the deposits (figure 54); thus it can be said, with a reasonable degree of certainty, that most of the laminated limestones of the Cajarc Formation have been deposited in an upper intertidal environment.

Black (1933), however, recognised that besides forming in upper intertidal marshes and creek levees, laminated calcareous sediments are also being deposited in and around

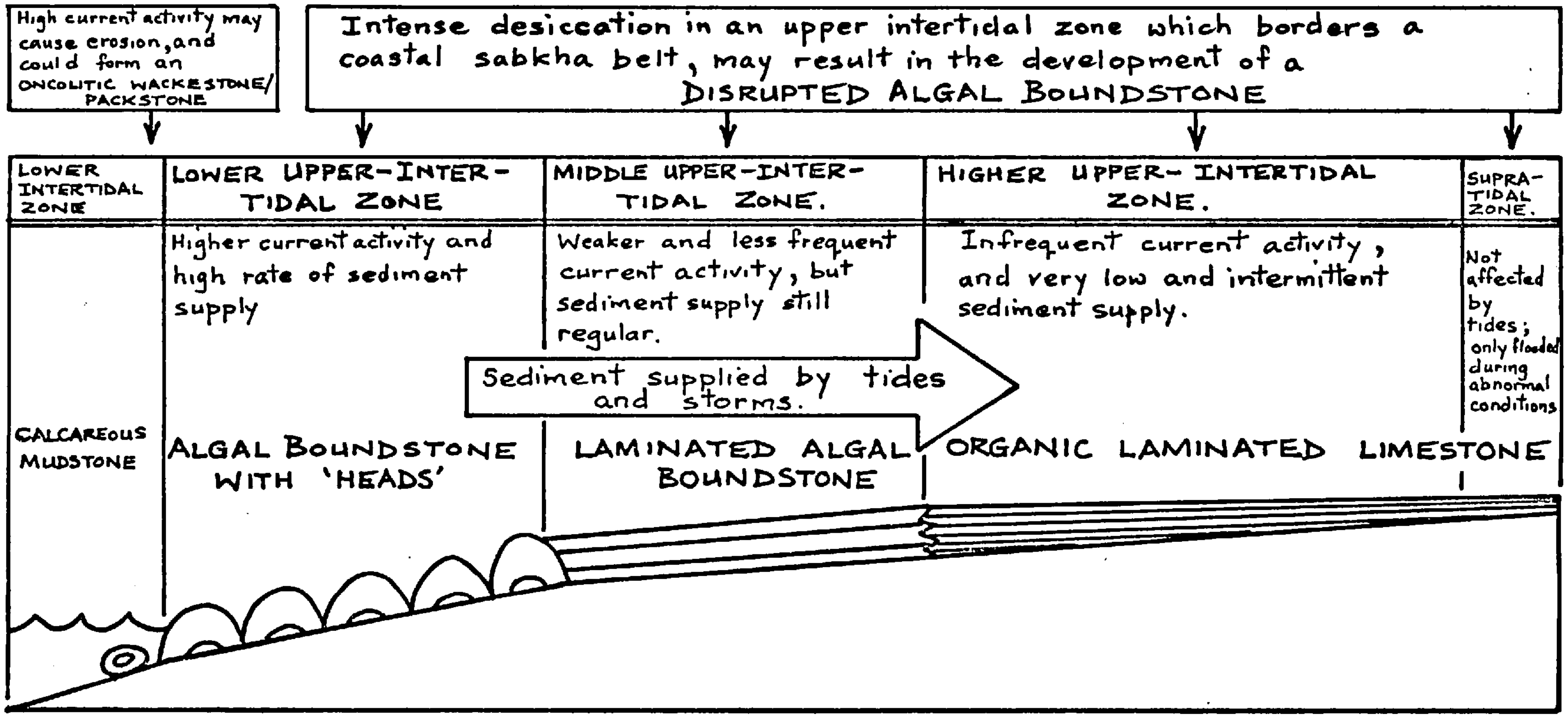


FIGURE 54 Possible relationship of algal sediments in the Cajarc Formation.

fresh water lakes, both in the supratidal zone and inland on Andros Island. This may also be true with regard to the laminated sediments of the Cajarc Formation.

Bouroullec et al (op.cit.) recognised that the laminated deposits had probably been constructed by both mechanical and organic processes of deposition, and they subdivided the rocks into 'laminites mecaniques' and 'laminites organiques', respectively. However, they did not appear to realise that many of the flat laminated limestones are, in fact, algal boundstones; the only algal sediment they recognised was 'micrite a laminites contournees', which is equivalent to the algal boundstone lithofacies, and all the flat laminated rocks were considered to have been mechanically deposited. They also concluded that each lamination represented an annual layer of sediment, but Amos (1974) has shown that in an upper intertidal zone, each layer probably represents a single spring tide, or a tidal cycle, or a storm wash-over deposit. Nevertheless, their interpretation of the intraclast bands as the result of storm activity seems to be the most probable.

With regard to the supposed algal sediments, Bouroullec et al found no trace of algal filaments in these deposits, but they did detect the presence of organic carbon. This evidence, together with the typical morphological features of algal mats was considered to justify their identification as such; a similar method has been employed in the Cajarc Formation by the present writer to identify sediments, the deposition of which was controlled by algae.

Four types of calcareous sediment influenced by algae have been identified in the Cajarc Formation; organic laminated limestone, laminated algal boundstone, algal boundstone and disrupted algal boundstone. All of these are thought to have formed in an upper intertidal environment, so the differences cannot be explained in terms of general environmental variations. The morphology of the deposits may, however, have been dependent on grain size and also on the rate of supply of sediment. This, in turn, is probably a function of proximity to the sea and to creeks; the more often an area is flooded then the greater the rate of supply of sediment.

The organically laminated deposits are thought to have formed in areas where sediment influxes were very infrequent, and thin algal mats developed during periods of non-deposition. The laminated algal boundstones have no concentrations of organic matter. They probably formed in a similar environment to the organic laminated limestones, but in a situation where sediment influxes were much more frequent, and where algae were continuously growing through new layers of sediment. The more crudely developed algal boundstones, which frequently possess 'algal heads', probably represent conditions where the supply of sediment was almost continuous, and where current activity was higher. Hence it is possible that the different types of deposit represent different rates of supply of sediment and therefore different positions within the upper intertidal zone, in relation to the sea and to tidal channels (figure 54).

In some cases in the Cajarc Formation the rate of supply of sediment does seem to have influenced the morphology of the algal deposits. The change from organic laminated limestone to algal boundstone in response to a transgression, that has already been described from the quarry near Saint Martin-Labouval, is probably a response to an increased rate of supply of sediment.

Moreover, organic laminated limestones have most commonly been observed at the transgressive bases of sedimentary rhythms, whereas the other types of algal sediment usually occur in the regressive upper parts of the rhythms. Often the former types rest on erosional and perhaps hardened surfaces and they rapidly pass upwards into massive calcareous mudstones. These conditions may have resulted in there being a low rate of sediment supply at the start of the rhythm, but towards the upper part much more sediment would have probably been available. This might explain why the various types of algal sediment occur in different positions within the sedimentary rhythms, and at the same time it tends to verify that the rate of supply of sediment does dictate the kind of algal deposit that forms.

4.12 The Fissility of the Laminated Limestones

On the geological map of Gourdon (194), the Cajarc Formation has been described as 'calcaires sublithographique en dalles avec couches ligniteuse', and on the Cahors (206) map it has been called 'calcaires en plaquettes a lit marneux blanc'. The conspicuousness of laminated limestones in the Cajarc Formation is emphasised by these descriptions and it may be said that they are the most typical feature of the formation. In the not too distant past, platy limestones were commonly used in the Causse region as roofing material for houses, barns and pigeoniers.

Not all of the laminated limestones are fissile, however, and although many have weathered to produce platy lithologies some have not developed any prefered planes of parting; these remain massive and weather just like beds of unlaminated calcareous mudstone, despite their internal laminations.

The property which seems to control the fissility of the rocks is the presence or absence of thin laminations of organic material and/or clay minerals. All the fissile rocks possess this feature, whereas the non-fissile ones are usually composed entirely of calcareous sediment. The thin layers of non-calcareous material probably act as barriers which prevent the sediment from becoming completely cemented.

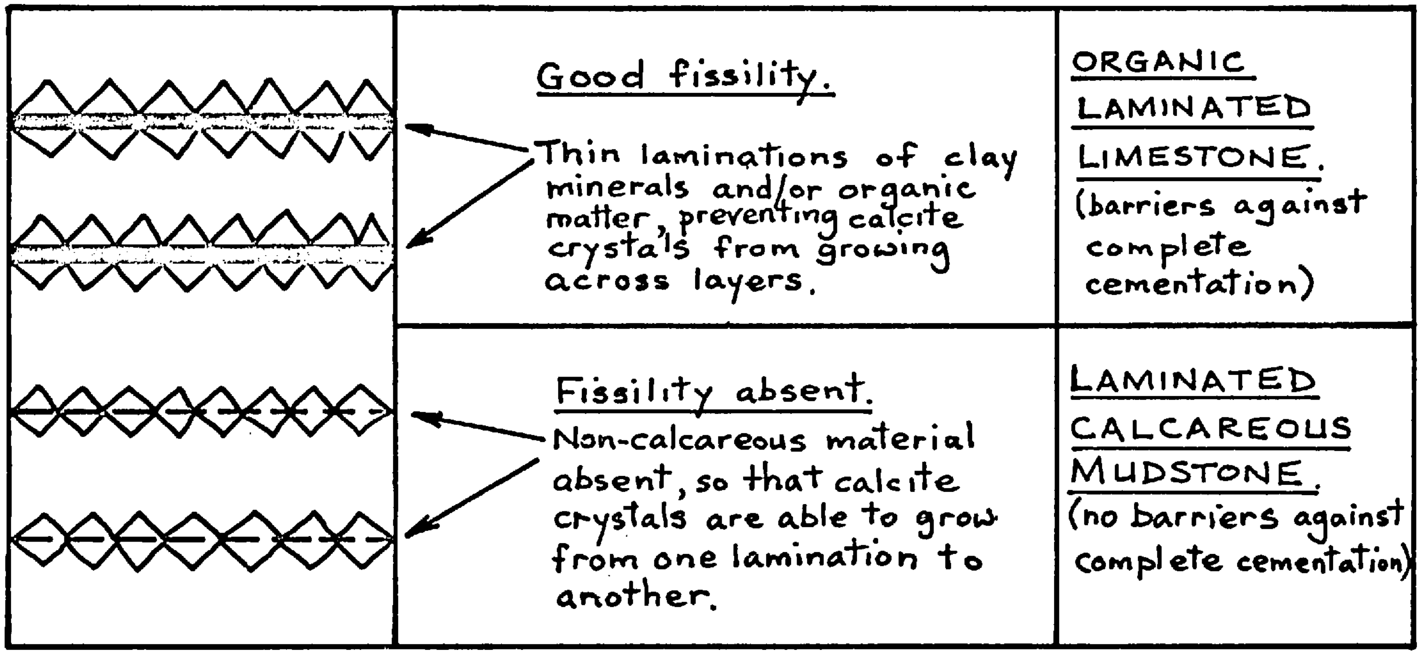


FIGURE 55 Fissility in the laminated limestones of the Cajarc Formation.

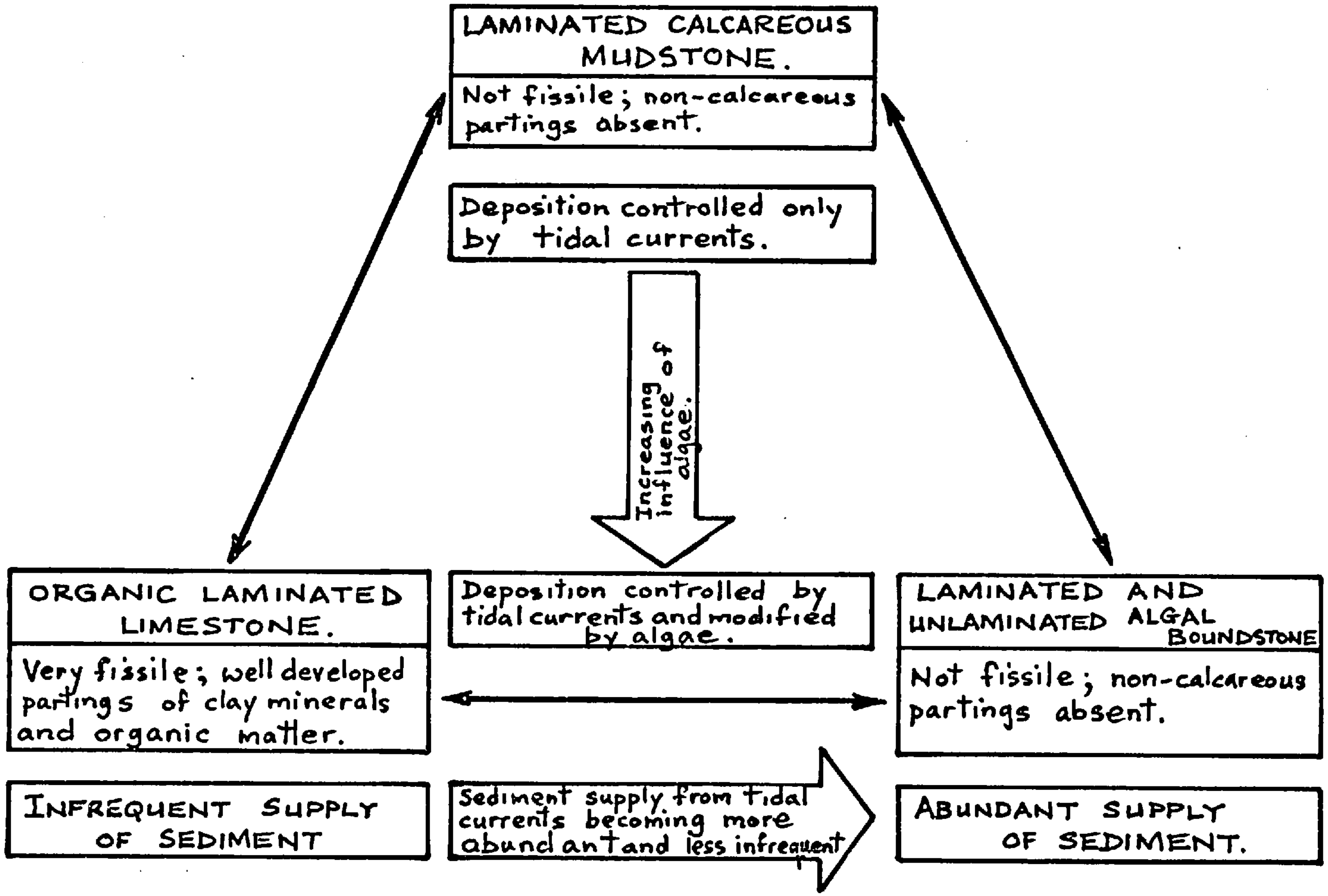


FIGURE 56 Summary of the processes which have probably been responsible for the deposition of the upper intertidal limestones of the Cajarc Formation.

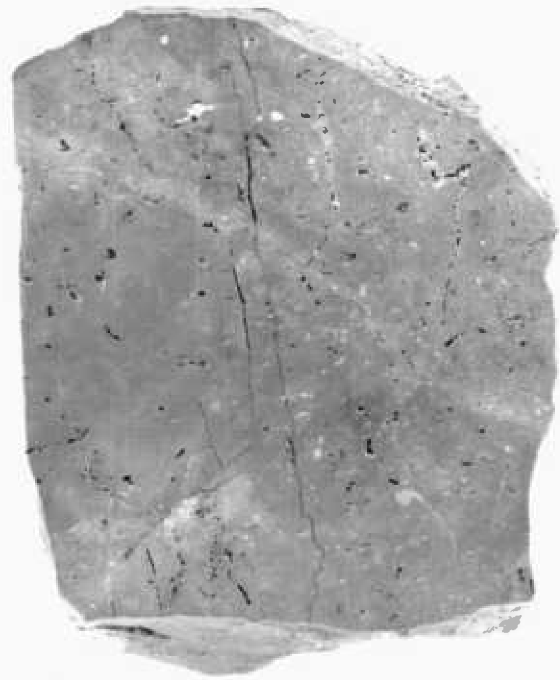
Layers of calcareous sediment are sandwiched between thin laminations of organic matter and/or clay minerals and although each calcareous layer becomes cemented, the bond cannot penetrate the non-calcareous material. Hence the rocks retain built-in planes of weakness, therefore they remain fissile and when weathering takes place these planes are preferentially picked-out until only platy limestones are left at outcrop. In laminated rocks with no cementation barriers, complete cementation takes place and they do not weather as platy limestones (figure 55).

In many instances laminated calcareous mudstones, which have been produced by mechanical processes of deposition, do not possess non-calcareous laminations and therefore they are often not fissile. The same may be said for most of the algal sediments, but the organic laminated limestones always have a well-developed fissility and some even look like 'paper' shales. By taking into account the processes of deposition, which probably operated in the upper intertidal areas, and also the lithologies which have resulted, it is possible to erect three end members (figure 56) which represent these features. Needless to say, many intermediate lithologies have also been observed for example mechanically laminated limestones have been found with occasional organic partings (figure 42b); and there is a considerable amount of overlap between the various laminated lithofacies which are present in the Cajarc Formation.

4.13 The Birdseye Mudstone Lithofacies

This lithofacies is composed of light grey coloured calcareous mudstones and peloidal-bioclastic-wackestones (figure 57), with no diagnostic features other than birdseye structures (Shinn, 1968). On fractured surfaces these sediments have a chalky appearance. Sometimes faint laminations may be preserved. The birdseye cavities have been infilled by a clear calcitecement.

A.



(x1·4)

B.

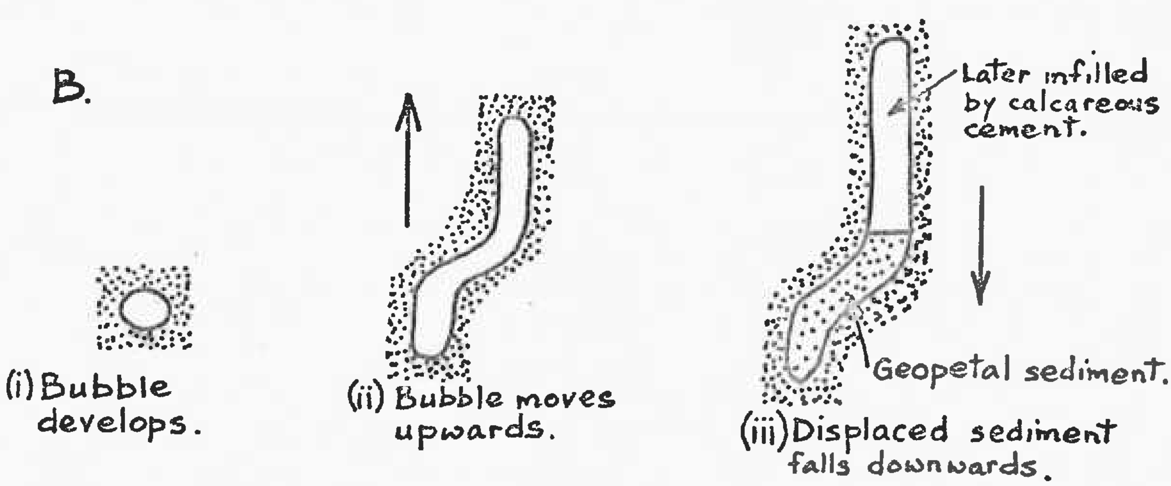


FIGURE 57 A) Birdseye mudstone showing gas bubble birdseye structures with geopetal sediments (La Plogne Mb., Larnagol).

B) The mechanism of generation of geopetal sediment in gas bubble birdseyes.

Examples of this lithofacies are exposed in the quarry at 251992 on the D24 near Saint Martin-Labouval and also by the roadside at 044262 on the N662 near Larnagol.

No fauna has been found in this lithofacies.

The Significance of Birdseye Structures

Birdseyes are voids which sometimes occur within fine grained calcareous sediments and they may or may not be filled by calcitic cement. A perusal of the literature has indicated that it is possible to distinguish two types of birdseyes:

1. desiccation birdseyes (Shinn, 1968)
2. gas-bubble birdseyes (Hodgson, 1958; Cloud, 1960, 1962; Shinn, 1968).

Desiccation birdseyes are irregular in shape and they are thought to be produced when a sediment becomes dried out and differential shrinking occurs (Shinn, 1968). This most commonly happens in upper intertidal or supratidal environments. Multer (1971) noted that the shape of the cavities and an association with mud cracks probably confirms that this type of birdseye originates as a result of desiccation. Perkins (1963) described an ancient example of desiccation birdseyes from some laminated Devonian dolomites. These were associated with typical supratidal deposits, but apart from these, no other diagnostic features were present. Using a Recent example from the Persian Gulf, Shinn (1968) pointed out that birdseyes may occur in a sediment with no other diagnostic features whatsoever, and although these deposits came from an upper intertidal to supratidal environment, there was nothing to indicate this, except for the desiccation birdseyes.

Gas-bubble birdseyes are spherical or oval in shape and sometimes they may form irregular trails resembling burrows or rootlets. These are thought to form under water, if gas happens to be generated in the sediment while it is still soft. The gases coalesce to form bubbles which displace the sediment and if they become big enough they move through the sediment leaving thin and sometimes intermittent trails. Hodgson (1958) produced these structures experimentally by passing gas through a soft sediment under water. Independently, Cloud (1960, 1962) found actual examples of this in some recent, subtidal lagoonal muds from the Bahamas.

Shinn (1968) has also described another kind of gas-bubble birdseye, which probably forms only in an upper intertidal or supratidal environment. This structure is thought to be formed when gas bubbles are trapped, at the sediment/water interface, while the sediment is being deposited. Typically the bubbles do not coalesce or form trails. This is probably because the sediment rapidly becomes dried out after it has been laid down.

Thus, the different kinds of birdseyes are quite distinct, and they form in completely different situations. Care must be taken, therefore, in making a thorough examination of birdseyes before they are used to diagnose an environment of deposition.

The Environment of Deposition of the Birdseye Mudstones

Most of the examples of birdseye structures that have been found in the Cajarc Formation are gas bubble types, similar to those described by Hodgson (1958) and Cloud (1960, 1962). A few examples of desiccation birdseyes are also known, but these only usually occur in the algal boundstone and disrupted boundstone lithofacies. Both types, however, are nearly always present in sediments that are closely associated with upper intertidal and supratidal deposits such as laminated calcareous mudstones and lignitic marls. Besides occurring in this lithofacies, gas bubble birdseyes have also been seen in laminated calcareous mudstones and ostracod wackestones.

Following Hodgson and Cloud, the gas bubble birdseye structures of the Cajarc Formation are considered to have formed under water, in soft sediment. To some extent, the close association with upper intertidal and supratidal sediments argues against this conclusion, because frequent exposure and desiccation would have taken place and this might have dried out and hardened the deposits. But even in this situation temporary pools of water might have existed, where gas could have formed in soft sediments. In one example a laminated calcareous mudstone has been found with mud cracks, and also gas bubble birdseyes and minor slump structures. This is interpreted as an upper intertidal deposit that suffered desiccation, but where for some time at least the sediment remained soft enough for the birdseyes and slumps to form. The most logical explanation of this is that temporary pools of water existed in the upper intertidal environment.

Other birdseye mudstones may have been deposited in permanent fresh or brackish lakes, similar to those postulated for the ostracod wackestones (figure 64). Indeed, the two lithofacies are very similar and in one example an ostracod wackestone has been found that passes laterally into a birdseye mudstone. Both the lithofacies possess birdseye structures and the only difference between them is that the ostracod wackestones contain the abundant remains of ostracods. Furthermore, in these lakes, some of which might have been stagnant, hydrogen sulphide could easily have been generated in the sediment, and this gas may have been responsible for the production of the birdseyes.

With regard to the petrology of the gas bubble birdseyes of the Cajarc Formation, some of the larger ones have been partially infilled with geopetal sediment. This feature has been described from some Dinantian limestones in Britain by Hodgson (1958), who considered that the geopetal sediments had been precipitated within the cavities. However, a more likely explanation is that as the gas bubbles formed and coalesced, and were expelled upwards, small quantities of the host sediment became displaced and fell back into the cavities and gas trackways to produce geopetal sediments (figure 57).

In the birdseye mudstones the geopetal sediments are slightly coarser in grain size than the host sediment. This is probably the result of much looser packing, because there would have been no compaction within the cavities and also of the overgrowth of sediment grains during cementation. These features are very similar to those that have been found in the geopetal sediments inside pseudomorphs of secondary anhydrite (p.316) in the Cajarc Formation.

4.14 The Ostracod Wackestone Lithofacies

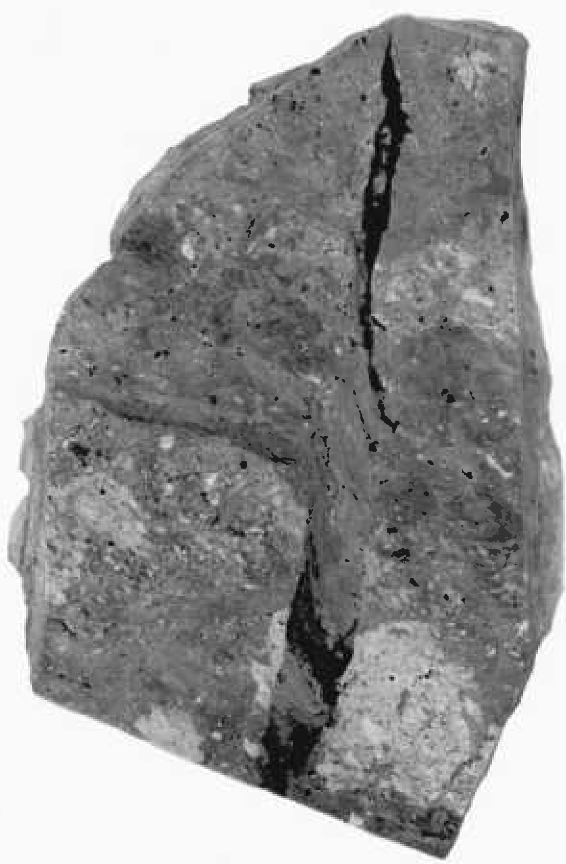
This lithofacies can be seen in the quarries at 075262, on the N662 just below La Plogne, and also at several levels in the section which has been measured at 064260 on the N662 near Cajarc. It is composed mainly of light grey ostracod wackestones which in places pass into calcareous mudstones. These have a chalky appearance on fractured surfaces and they are very porous in comparison with the calcareous mudstones of the Cajarc Formation. Occasionally birdseye structures are developed, and also the ostracod fauna may be associated with charophyte debris and various gastropods (figures 58,59 and 105).

Two types of ostracod wackestone have been distinguished; mottled wackestone and even-coloured wackestone (figure 58). The mottled types are characterised by disrupted sedimentary structures which are emphasised by variations of colour

A.

(x1·4)

B.



(x2)

FIGURE 58 Ostracod wackestone lithofacies.

A) Even coloured wackestone with charophytes, ostracods, Neritina sp. and Viviparus sp. (La Plogne Member, quarry below La Plogne).

B) Mottled wackestone with root structures, showing disrupted nature (La Plogne Member; roadside exposure at 135283 near Montbrun).

from light and dark grey to white or buff. Despite the apparent variations, acetate peels have shown that the mottled examples have an even grained micritic texture. This suggests that the mottling is due entirely to colour variations.

Even coloured ostracod wackestones form the bulk of the sediments of this lithofacies. They do not display any colour or grain size variations. It is interesting, however, to note that some of the laminated calcareous mudstones of the Cajarc Formation pass into laminated sediments with abundant ostracods (figure 75). Strictly these should be included in this lithofacies; in which case it would also be possible to distinguish a third laminated type of ostracod wackestone that displayed both colour and grain size variations. However, because these are thought to represent the highest parts of upper intertidal marshes they have been included in the laminated calcareous mudstone lithofacies (p.153).

The Fauna of the Ostracod Wackestones

The following fauna and flora has been recovered from the sediments of the ostracod wackestone lithofacies:

Charophyta:	Chara bleicheri (Saporta)
Gastropoda:	Viviparus bulbiformis (Sandberger)
	Nertina bidens (Sandberger)
	Planorbis calculus (Sandberger)
	?Pseudomelania (or ?Oonia) (Pietet&Campiche)
Ostracoda:	Fabanella bathonica (Oertli)
	?Timeriasevia sp. (Mandelstan)
	?Bisulcolcypris sp. (Pinto & Sanguinetti)

The gastropod fauna (figure 59) was first described from the Bathonian limestones of the Cajarc area by Sandberger (1870-75), who considered all the species listed above to

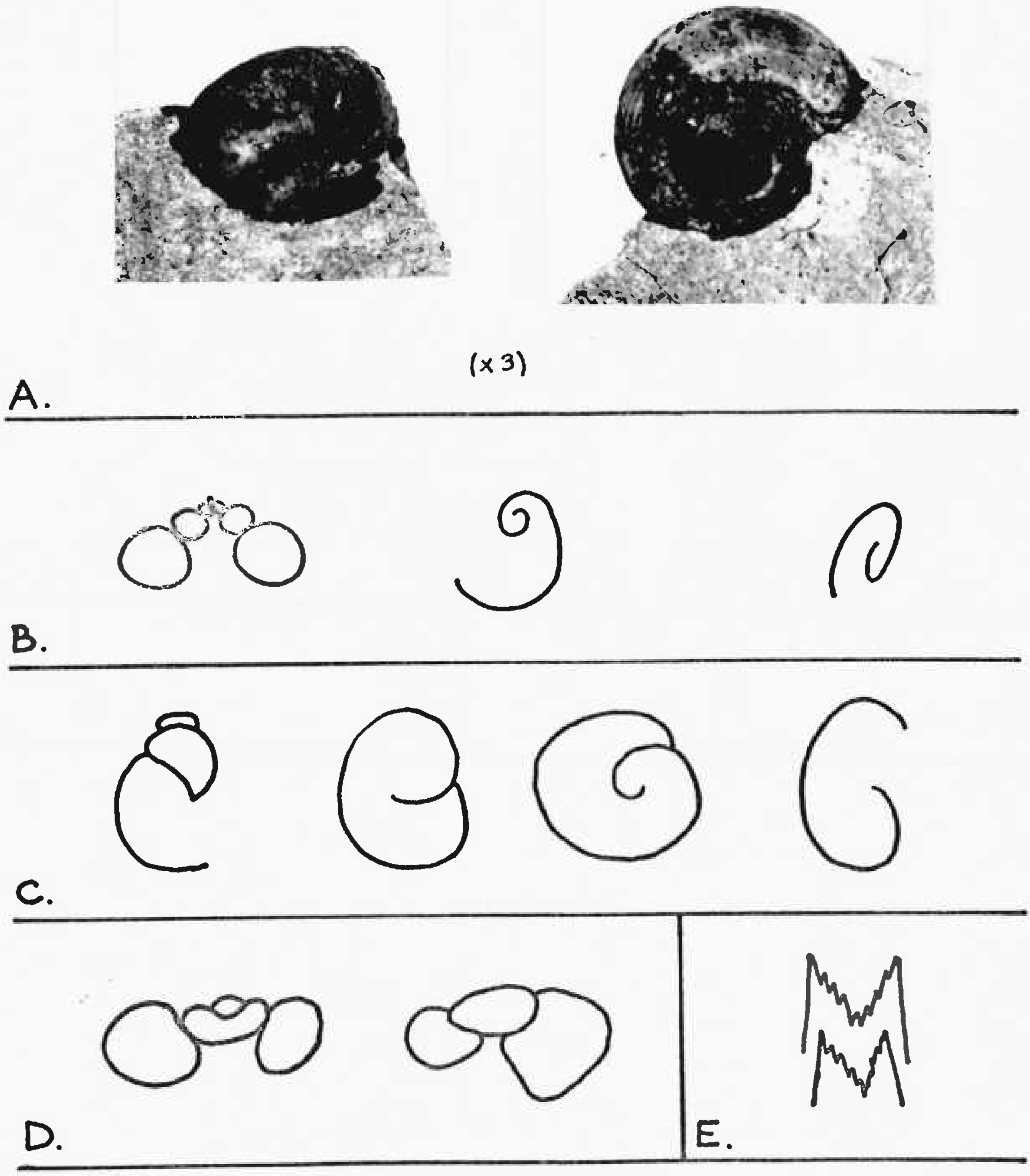


FIGURE 59 The gastropods of the ostracod wackestone lithofacies:

A) Photograph of Viviparus bulbiformis.

B,C,D) The appearances in thin section of V. bulbiformis, Neritina bidens and Planorbis calculus, respectively.

E) The ornamentation of N. bidens.

be fresh or brackish water forms. Following Sandberger, Bleicher (1871) concluded that the fauna was indicative of fluvio-lacustrine conditions. This idea has persisted, even to this day, in Notice Explicative for the geological map of Gourdon (194), which mentions a 'fauna d'eau douce de Cajarc'. This is probably a reference to one or two beds in the quarries at 075262, on the N662 just west of Cajarc which contain the fauna and flora listed above. The writer has discussed the possible modes of life of the gastropods with Dr. N. Morris of the British Museum of Natural History and he considers that Sandberger's ideas are probably correct.

With regard to the ostracod fauna, marine forms are notably absent in the ostracod wackestones. Moreover the range of species is small and smooth shelled unornamented forms are dominant (figure 105). Dr. R. Bate of the British Museum of Natural History is of the opinion that this assemblage is typical of fresh or brackish water conditions. Moreover Bernard et al (1956) described a similar ostracod assemblage from some Bathonian limestones in the region of Poiton in the Paris Basin and they concluded that it was typical of a lacustrine environment, ecologically similar to the 'mangrove coasts' of tropical regions (mesohaline; 5-9‰ NaCl).

It is possible that the ?Timeriasevia sp. and ?Bisulcocypris sp. forms, which have been identified in the ostracod wackestones, might be the same species as Gomphocythere, n.sp. (Oertli) and Bisulcocypris teniumarginata (Oertli), respectively, which were described by Bernard et al (op.cit.).

As in the ostracod wackestones, Bernard et al (op.cit.) noted the association of ostracods and charophytes in the Bathonian limestones. Modern charophytes live entirely submerged in shallow, quiet, slow moving bodies of fresh or brackish water (Peck 1957, p.4). Most workers believe that charophytes have never lived in marine habitats and Carozzi

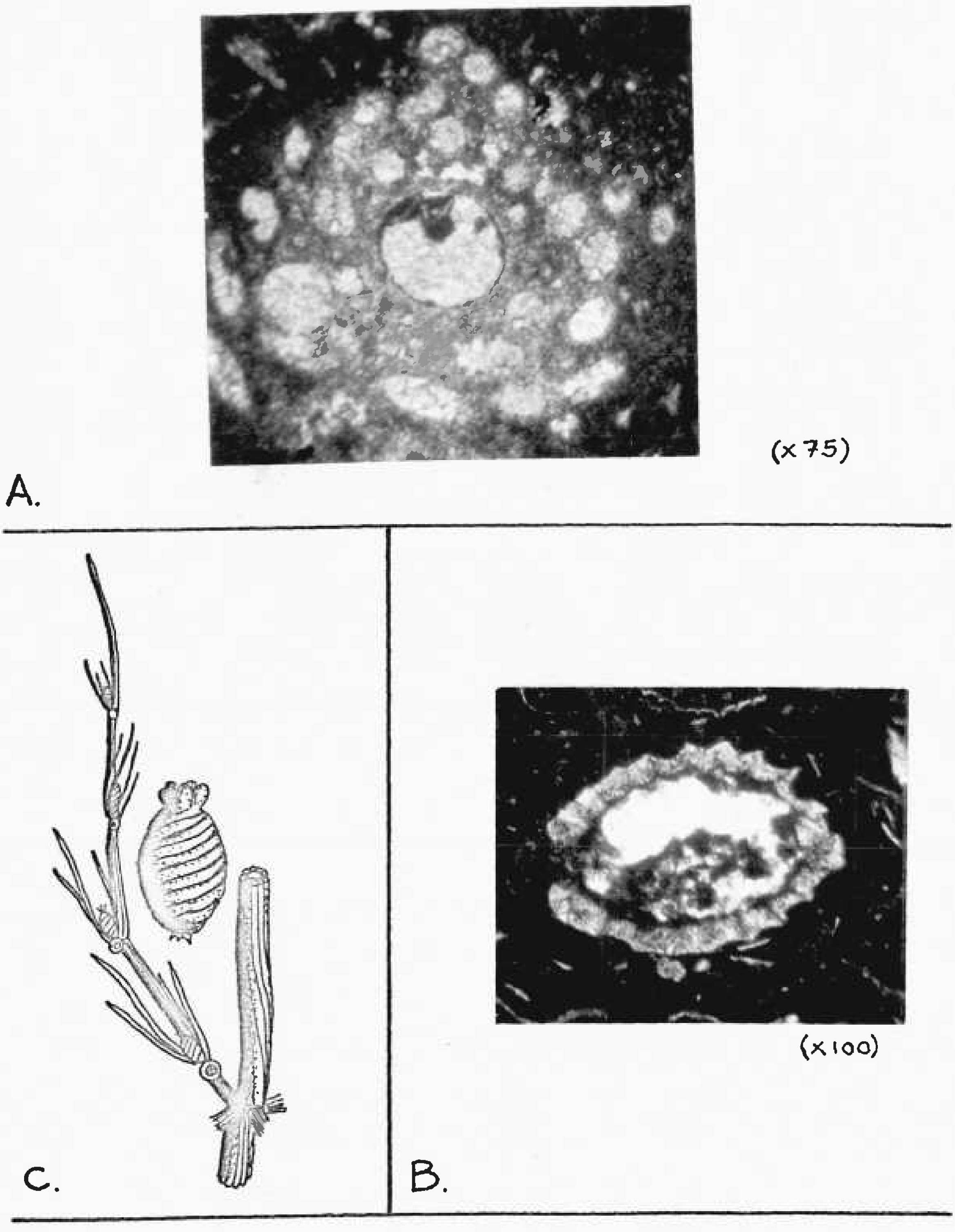


FIGURE 60 Charophytes in the ostracod wackestone lithofacies:

A) photomicrograph showing a cross-section of a stem;

B) photomicrograph of an oogonium with a geopetal sediment.

C) a reconstruction of a charophyte from Cayeux (1916, p.XXII, fig.4).

(1961, p.505) suggested that a source for charophyte debris should be looked for in emergent areas that enclosed fresh-water ponds. Perkins (1963) also noted that in the Devonian, charophytes are associated with mud cracks and desiccation breccias, which indicate subaerial exposure.

Both the oogonia and the stems of charophytes (figure 60) have been found in the ostracod wackestone lithofacies, but the oogonia are much more common than the stems. Sometimes oogonia have been reworked into oolitic grainstone beds which overlie ostracod wackestones, where they occur in a very much abraded condition (p.104). In some examples within the ostracod wackestone lithofacies, the hollow interiors of a few oogonia have been partially infilled by geopetal sediments.

The Environment of Deposition of the Ostracod Wackestones

The fauna and flora of the ostracod wackestones probably lived in a fresh or brackish water environment and it is reasonable to assume, therefore, that the sediments were not deposited in any lagoonal situations which would have been continuously affected by sea water. Although it is difficult to distinguish between the three types of ostracod wackestone in thin section, their relationships with other sediments together with the gross sedimentological features of each, suggest that they have originated in different ways.

1. The laminated ostracod wackestones - thin layers of laminated ostracod wackestone, approximately 10 cm. in thickness, have often been bound to be resting on laminated calcareous mudstones that are present towards the upper parts of some sedimentary rhythms (figure 72). They have often been disturbed and disrupted by mud cracks, and they possess a fauna and flora of disarticulated ostracods, charophyte oogonia, and occasionally

?Pronoella raristriata (Sandberger).

The laminated calcareous mudstones have already been interpreted as upper intertidal and supratidal deposits so it is probable that the laminated ostracod wackestones represent the uppermost areas of the upper intertidal flats where fresh or brackish water marshes might have existed and where rain water may have formed temporary pools (figure 63a) (also see page 168).

The influence of fresh and brackish water on the uppermost reaches of the upper intertidal marshes of the Wash has already been noted (p.152), and similar influences of calcareous sedimentation. Shinn et al (1969) and Multer (1971) observed that in the Bahamas and in Florida Bay in high upper intertidal and supratidal zones, depressions sometimes become flooded with rain water and temporary, fresh or brackish ponds are formed. Although the biota of these pools was not studied, the authors suspected that fresh or brackish faunas and floras might 'bloom' sporadically.

Moreover, Kesling (1961, Q19) noted that ostracods often live in ephemeral ponds of water, and that their eggs can withstand long periods of desiccation. Likewise, the ostracods in the laminated sediments of the Cajarc Formation might have lived in ephemeral pools of water and each time the uppermost tidal flats were flooded during storms and spring tides, it is possible that they may have become disarticulated and redistributed. Charophytes probably also lived in these pools and they too would have been reworked during influxes of the sea.

If prodgradation of the intertidal flats took place, it is possible that some of the larger pools could have become established as permanent fresh or brackish lakes. However, when coastal lagoonal sediments prograde seawards, an extensive lowlying supratidal coastal plain is left (Evans et al, 1973). On Andros Island storm surges penetrate deep inland, so it is possible that the Bathonian lakes were still influenced by the sea, even when they were some distance from the coastline. Storms may have been an important factor in redistributing the fauna and flora of the temporary pools and lakes over the high intertidal flats and coastal plains.

2. <u>The mottled ostracod wackestones</u> - these are only developed in minor amounts. Usually they are closely associated with laminated ostracod wackestones, and often they are succeeded by rooted lignitic marls. All gradations between disturbed and disrupted laminated sediments and mottled ostracod wackestones, have been found.

Shinn et al (1969) and Multer (1971) noted that in the Recent upper intertidal and supratidal areas of the Bahamas and Florida Bay, disrupted and mottled sediments are often produced from laminated sediments by the formation of mud cracks and birdseyes, as a result of progressive desiccation. They figured box cores showing laminated upper intertidal deposits passing into mottled sediments (Shinn et al, 1969; fig.21, 22A, 22B), which are very similar in appearance to the mottled ostracod wackestones of the Cajarc Formation (figure 58b).

Thompson (1968) also described an example of what he called chaotic mud deposits, which were considered to have been produced by the progressive desiccation of laminated upper intertidal and supratidal sediments. However, the growth of evaporitic minerals helped to disrupt the deposits in latter example.

It is probable, therefore, that the mottled ostracod wackestones of the Cajarc Formation have also been produced by the progressive desiccation of laminated upper intertidal and supratidal sediments which contain a fauna of fresh or brackish water origin (figure 60a). Furthermore, it is also possible that the roots which later grew down from the succeeding lignitic marl layers may have helped to disrupt the sediments (figure 58b).

3. The even-coloured ostracod wackestones - again these are usually associated with probable upper intertidal and supratidal deposits, such as laminated calcareous mudstones and rooted lignitic marls. However, they form much thicker and more massive deposits than the previously described types of wackestone, but individual beds are not always continuous along the strike. For example, a bed 1 m. in thickness is present in the Larnagol section (044262) but it pinches out in the section (064260) near Cajarc, where it is represented only by a thin lignitic marl, and it reappears in the La Plogne sections (075262).

Unlike the laminated and mottled ostracod wackestones, the beds of even-coloured ostracod wackestone are too thick to be explained in terms of a prograding intertidal flat sequence. The faunal and floral assemblages are also quite different; ostracods and charophyte oogonia are still abundant, but the stems of charophytes and four types of fresh and/or brackish gastropods are also common. Moreover, the conditions of deposition seem to have been much more tranquil because many of the ostracods have remained articulated and geopetal sediments have sometimes been deposited within these tests, whereas in the laminated and mottled wackestones the ostracods are mostly disarticulated. Gas bubble birdseyes are also present and occasionally ostracod wackestones pass laterally into birdseye mudstones. Probably, therefore, the sediments remained soft and submerged for long

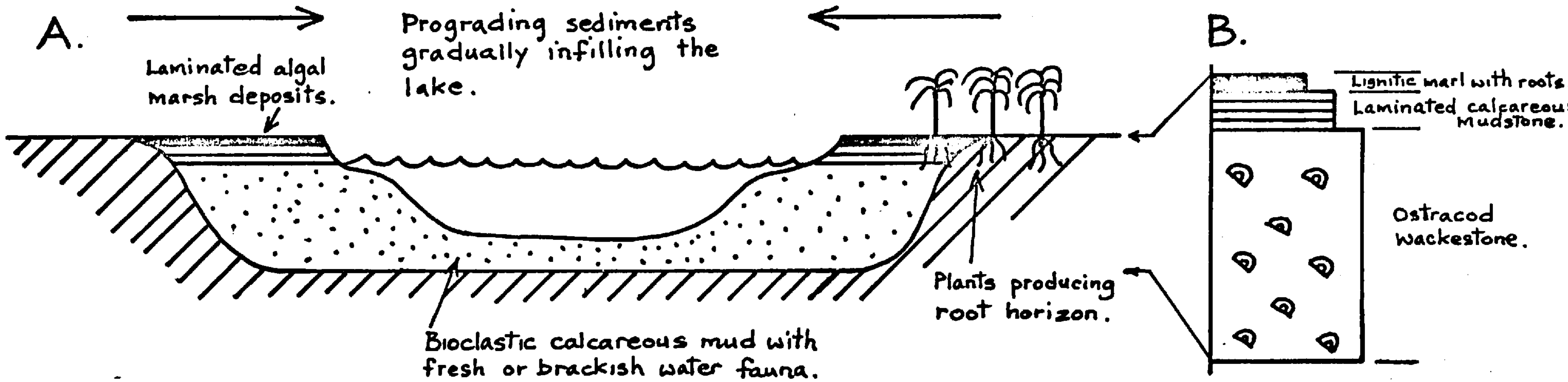


FIGURE 61 A) Depositional model for fresh or brackish inland lakes, e.g. Lake Forsythe, Andros Island (Black, 1933);

B) A possible equivalent in the Cajarc Formation.

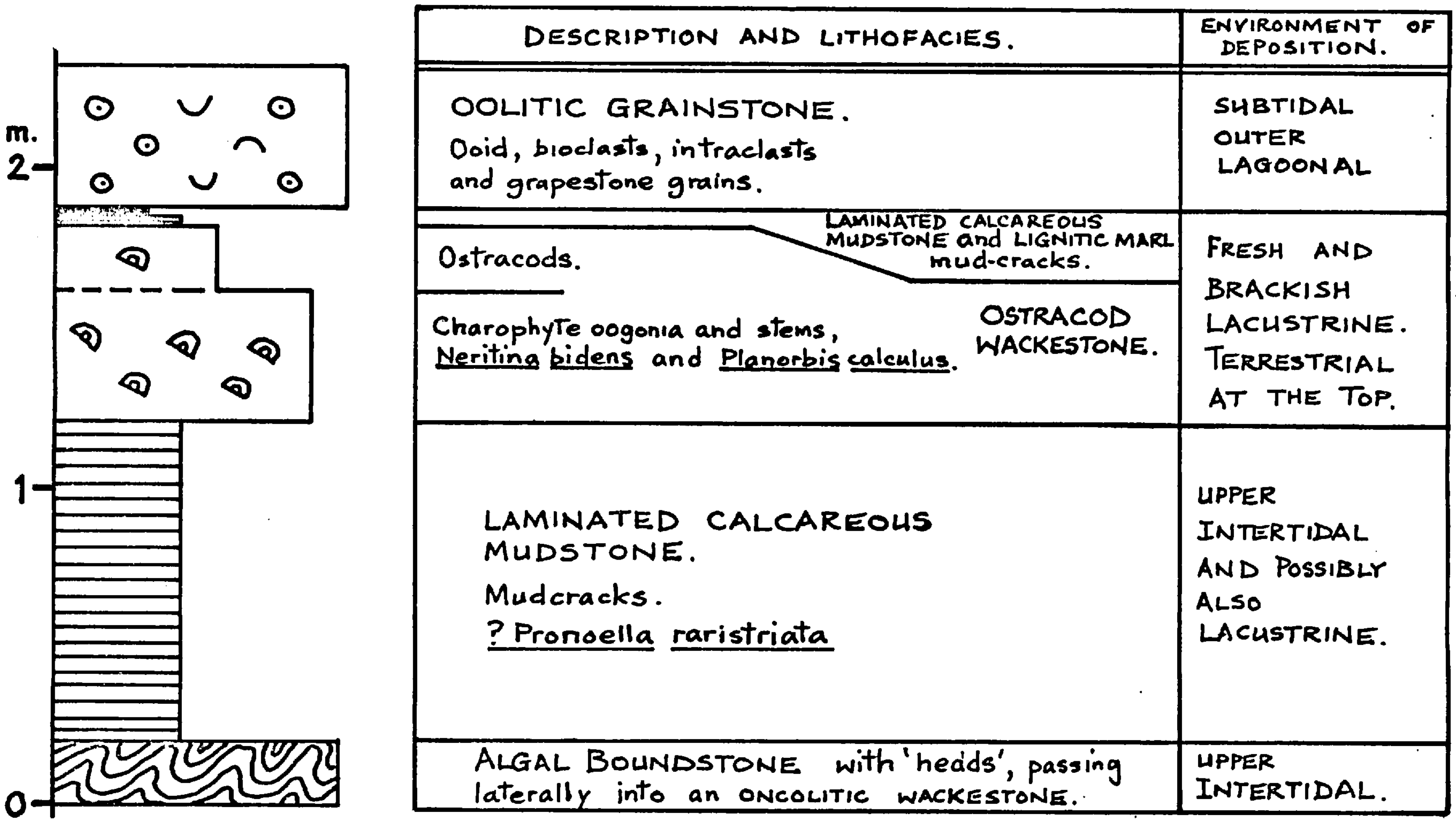


FIGURE 62 Section log showing the relationship of an ostracod wackestone bed with other sediments (cf. figure 60); note the layered fauna of the ostracod wackestone (La Plogne Member, 064260 near Cajarc).

periods of time.

This evidence suggests that the even-coloured ostracod wackestones have been deposited in bodies of water of considerable size, that were some distance away from the influence of marine waters. These might have been permanent fresh or brackish lakes, which were apparently important areas of deposition at certain times during the development of the Cajarc Formation.

Black (1933) described a Recent example of some permanent fresh and brackish lakes from Andros Island. He noted that the brackish lakes are intermittently influenced by the sea during storms, but that the fresh water ones are completely isolated from the sea. All the lakes are being infilled with calcareous mud and they support fresh or brackish faunas. Around the shores, flat laminated algal sediments are accumulating and prograding into the lakes (figure 61). If such sequences became preserved, they would be very similar to some which have been found associated with the even-coloured ostracod wackestones (figure 61 & 62).

Black (op.cit.) also noted that in Lake Forsythe on Andros Island, there are two different layers of fauna preserved in the sediment which possibly represent slight changes in condition, such as a sudden influx of the sea (turning the water brackish) or the shallowing of the lake as it became infilled. A similar feature has also been found in an ostracod wackestone in the section at 064260 near Cajarc (figure 62). Here the fauna is composed of a lower layer of gastropods and charophyte debris, and an upper layer with abundant ostracods. This could be an ancient analog of Lake Forsythe.

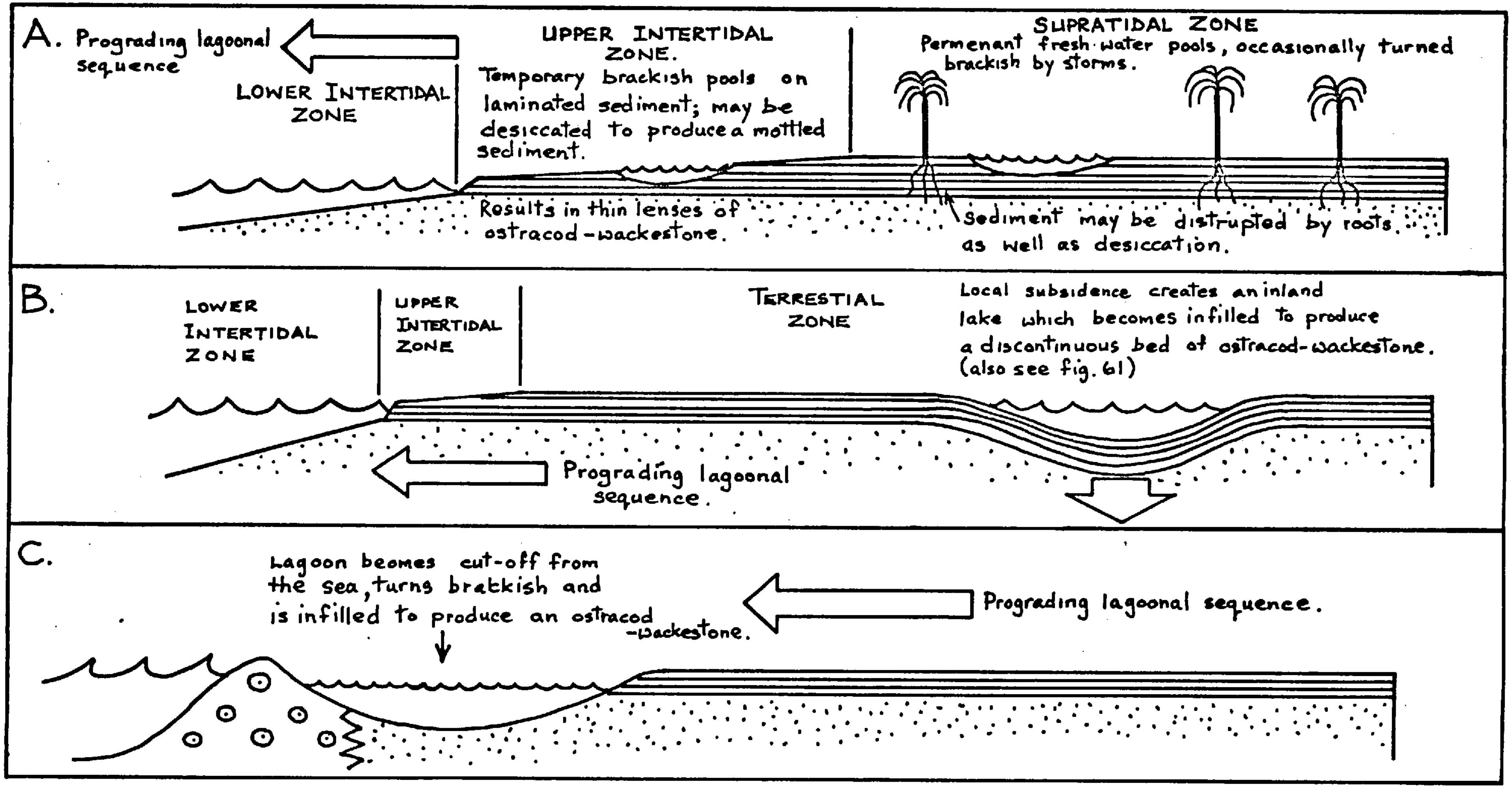


FIGURE 63 Depositional models for the ostracod wackestone lithofacies.

A) Temporary pools in upper intertidal zone.

B) Inland lake.

C) Cut-off lagoon.

The lake deposits of the Cajarc Formation have probably originated in two ways; either as inland lakes or as coastal lakes. If a lagoonal area of sedimentation is considered, which is prograding and thereby forming an extensive supratidal coastal plain, any local subsidence that might occur would probably result in the creation of large inland lakes (figure 63b). Under suitable climatic conditions these would be filled with fresh or brackish water.

Another alternative is that the coastal lagoons could, at some stage, have become cut-off from the influence of the sea by the formation of a barrier (figure 63c), or merely by the uneven growth of the prograding intertidal flats. Under these conditions it is possible that the lagoon might eventually become brackish or even fresh. A Recent example of this is, of course, the Fleet near Abbotsbury in Dorset, which is separated from the sea by Chesil Beach.

Some of the thicker laminated calcareous mudstone deposits, especially those with a ?Pronoella raristriata ostracod fauna, may represent coastal lagoons which became fresh or brackish and were infilled by lacustrine sediments; but in some instances these could possibly even represent inland lake deposits.

Finally, Carozzi et al (1972, p.314) identified some ostracod wackestone deposits from boreholes which passed through Middle Jurassic limestones in Southern Aquitaine. These were interpreted as lagoonal-lacustrine (hypersaline) deposits. While the present writer agrees with the first part of the interpretation, it is unlikely that the environment was hypersaline at any time because of the presence of fresh and brackish fossils. Certainly calcitised evaporitic minerals have been observed in some ostracod wackestones towards the top of the Cajarc Formation, but these are thought to have grown, during early diagenesis in a sabkha environment, after the deposition of the sediments (p223). Another possibility is that the fauna in these evaporitic deposits represents the influxes of fresh water into a sabkha environment, after which temporary pools of fresh or brackish water became established and fresh or brackish organisms flourished briefly until the pools dried out.

4.15 The Marl Lithofacies

Thin beds of marl, 5-20 cm. in thickness, are developed throughout the Cajarc Formation. In most cases they are composed of millimetre-laminated marls or lignitic marls, but occasionally the original depositional structures have been destroyed by tectonic activity (i.e. differential movement of limestone beds using marls as planes of décollement). In the Larnagol and La Plogne Members of the formation the marls are grey and usually lignitic, but in the Brengues and Marcilhac Members they are more cream in colour and are nearly always free of lignite.

Usually the marls show only a thin development but in Larnagol and La Plogne Members they have sometimes infilled old channels, and in these situations the marls reach thicknesses of up to 1 m. (figure 64). A good example of this can be seen by the roadside at 112264 on the north bank of the Lot, opposite Cadrieu. Here, however, much of the sediment is lignitic. Another example of a deposit of lignitic marl (figure 85) is exposed at 044262 on the N662, near Larnagol, where the lignite forms thin bands and lenses in a laminated bed of marl.

Lignitic root structures are occasionally developed in the marl beds of the Larnagol and La Plogne Members. These penetrate downwards from the upper surfaces of the marls,

FIGURE 64 Some lignitic marl deposits which have infilled old channels, or solution hollows on an ancient karst surface. A log of this section is given in figure 39. (La Plogne Member; roadside exposure at 112264, on the north bank of the Lot, opposite Cadrieu).

FIGURE 65 Root structures which are possibly Equisetum sp., that pass down from a lignitic marl into a calcareous mudstone; sometimes these reach 50 cm in length (location as above).

sometimes even into underlying beds of calcareous mudstone (figure 65).

Root structures and lignites have not been found in the marl horizons within the Marcilhac and Brengues Members. Instead, the marls are associated with calcareous mudstones which bear calcitised evaporitic minerals. Good exposures of these can be seen on the D17 road between 023350 and 020359, to the north of Marcilhac and also at 075364 just to the south of Brengues.

Marl is much more frequently developed in the Brengues Member than it is elsewhere in the Cajarc Formation.

The Fauna and Flora of the Marls

No fauna or flora has been recovered from the marls of the Marcilhac and Brengues Members, but the lignitic marls of the Larnagol and La Plogne Members have yielded the following assemblage:

Plantae:	?Equisetum sp. aff. maximum (Lamark)
Charophyte:	Chara bleicheri (Saporta)
Ostracod:	Fabanella bathonica (Oertli)

Both the stems and oogonia of C. bleicheri have been found in the marls.

The root structures are associated with beds of lignitic marl have been attributed to an indeterminate species of the horsetail Equisetum. Bleicher (1871) identified similar material from Bathonian lignites in the Larzac area, near Millau (Aveyron), as Equisetum maximum; the horsetails in the Cajarc Formation are probably of the same species.

Individual roots are about 1 cm. in diameter and up to 50 cm. in length (figure 65). Often they pass vertically

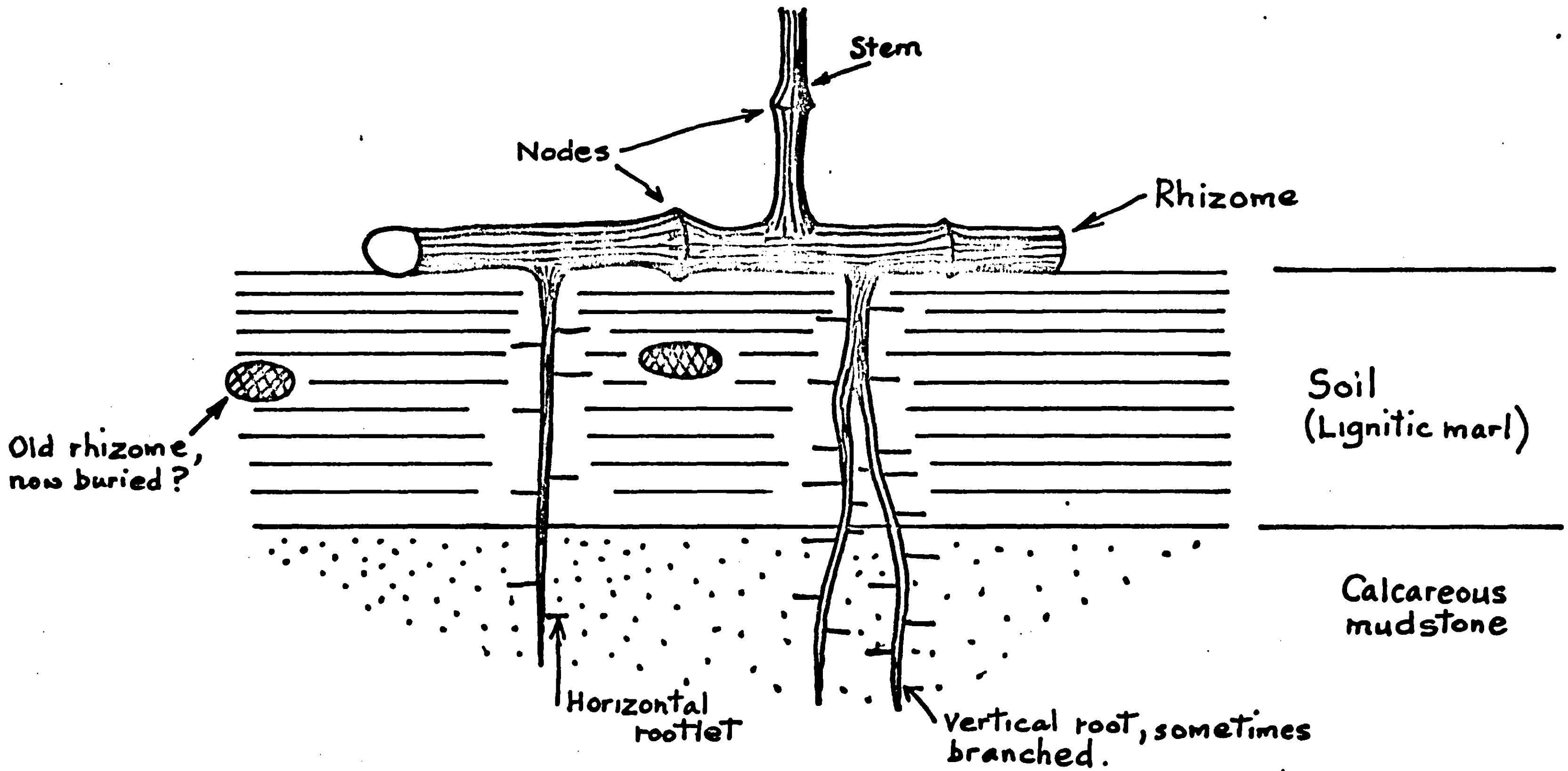
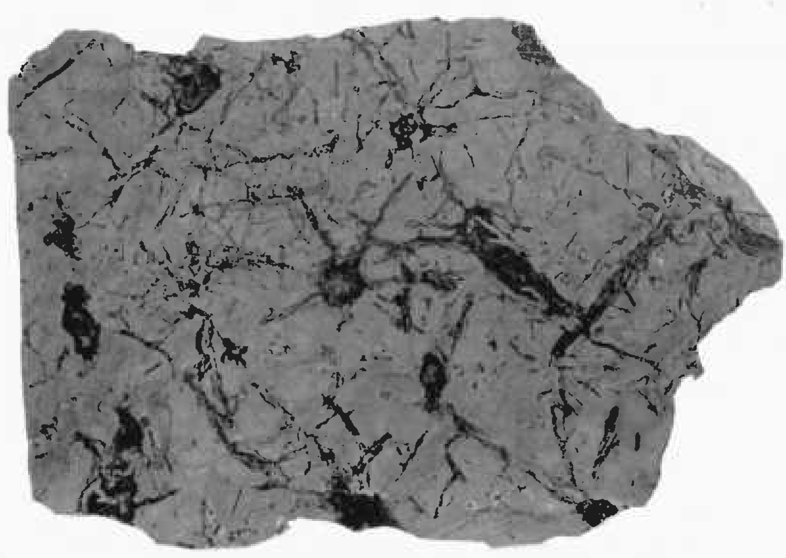


FIGURE 66 Reconstruction of ? *Equisteum*.

A.

(x0·4)

B.



(x0·8)

FIGURE 67 A) Vertical root structures of ? Equisetum sp.

B) Section across the roots, showing some radiating (or spiralling?) horizontal rootlets.

(La Plogne Member; roadside exposure at 112264, on the north bank of the Lot opposite Cadrieu).

downwards from marl horizons into underlying beds of calcareous mudstone, and sometimes they may be branched (figures 65,66,67). There are always numerous radiating (or spiraling?) horizontal rootlets associated with the vertical roots (figure 66 & 67b). Rooted horizons can be examined most easily at 044262, near Larnagol (figure 85), at 112264, near Cadrieu (figure 65 & 67) and at 1532288 near Ambeyrac.

In some of the marl beds, flattened horizontal lignitic structures have been found. These are probably the compacted remains of the rhizomes of Equisetum sp. (figure 66). Bleicher (op.cit.) also described some possible rhizomes from Bathonian lignitic deposits.

Lignite beds are well know from the Bathonian limestones of Aquitaine. Bleicher (op.cit.) noted that these were being exploited in the region around Larzac. The flora of these beds was listed by Bleicher (1871, 1872) and figured and described by Saporta (1872-3). It included Equisetum maximum, Otoyamites, Zamites, Sphenoyamites, Pteris and Ginko biloba; but as no subsequent work has been found it is possible that these names are in need of revision.

Apart from Equisetum sp. none of these forms have been observed in the Cajarc Formation by the present writer. Bleicher (op.cit.) also found some dental pallets of the fish Sargus sp. and some scales identified as Lepidotus sp. The latter were supposedly recovered from beds of lignitic marl that crop out near Cadrieu, in the Lot Valley, but the writer has found no evidence of these. However, the marls are packed with shiny lignitic fragments which Bleicher may have misidentified as fish scales.

Bulk macerations, carried out by Dr. C. Hill of the British Museum (Natural History), have indicated that the lignites of the Cajarc Formation are composed almost entirely of woody axes (i.e. the stems and branches of woody plants), and not as expected of the debris of Equisetum plants. It has not been possible to identify any of the woody plants because no recognisable cuticle was recovered from the macerations.

Occasionally lignitic debris is present in laminated and massive calcareous mudstones which underlay beds of lignitic marl. This debris consists of water-worn woody axes (with rounded ends), Equisetum branches and fusain pebbles (Harris, 1958), that have probably been transported from vegetated terrestrial areas into a lagoonal environment.

The water-worn fusain pebbles are composed of charcoal and not lignite. This can be established by rubbing fragments of the pebbles on paper; lignite will not mark the latter whereas charcoal does. When subjected to burial and diagenesis, wood is transformed into lignite and eventually into coal. Charcoal is never formed. Moreover, Harris (1958) argued that the latter can only be produced by the burning of wood. Therefore, the presence of fusain pebbles in the limestones of the Cajarc Formation implies that, even in Jurassic times, forest fires were probably occurring quite naturally.

Karst Surfaces Associated with the Marls

Sometimes horizons have been found in close association with solution/erosion surfaces. A good example of this is exposed in the road (N662) section between Larnagol and Cajarc (figure 85), and also at 135280 near Montbrun (figure 68), where an irregular weathered surface occurs above a bed of peloidal grainstone. This surface cuts across the cross-stratification of the grainstone and in places solution puts up to 40 cm. deep have been formed. It is succeeded by a rooted lignitic marl.

The features of this surface suggest that it has been

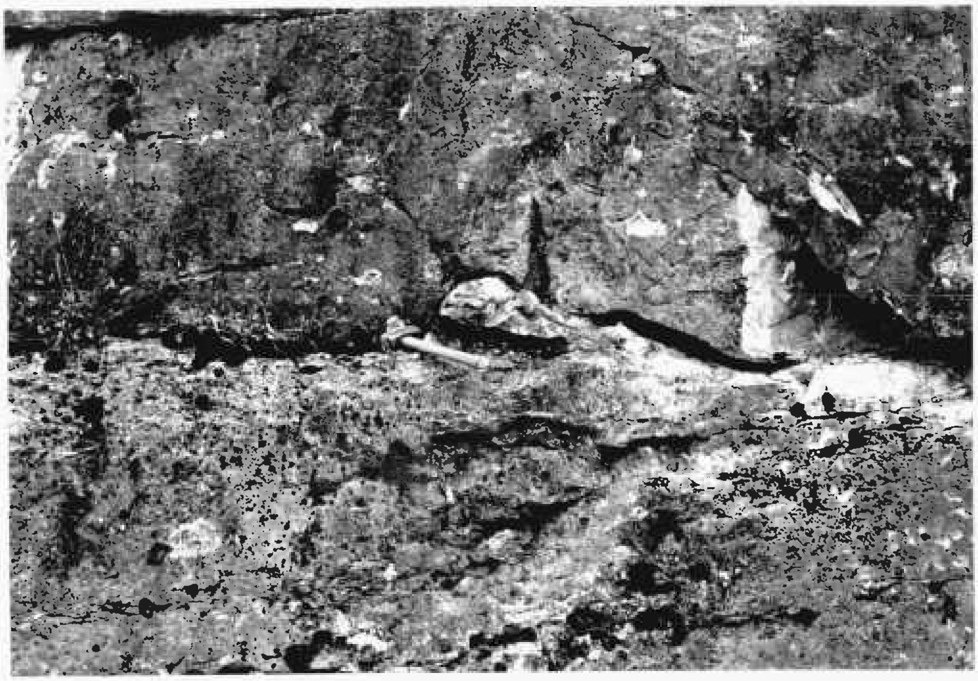
A

B.

FIGURE 68 A) A karst surface in the La Plogne Member, overlaid by a lignitic marl with roots.

B) Detail of a solution hollow (N662 roadside exposure at 135280, near Montbrun).

The succession at this outcrop is the same as the outcrop near Cadrieu (shown in figure 39).



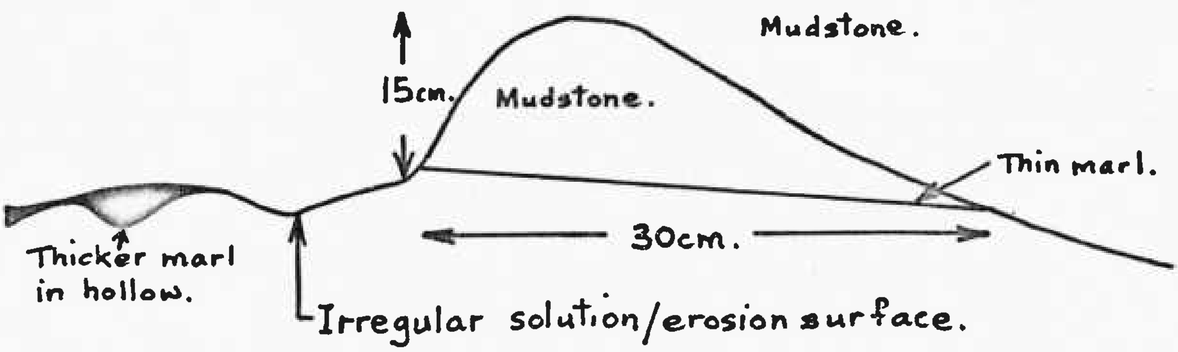


FIGURE 69 Photograph and explanatory sketch of a karst surface associated with a very thin marl horizon. Note the eroded remnant of a previously overlying bed. (La Plogne Member; N662 roadside exposure, at 133278 near Montbrun).

formed by solution/erosion processes. Furthermore, on page 119 it was concluded that the bed in question became cemented in a subaerial environment, soon after it was deposited. This is exactly where solution/erosion might be expected to have taken place. Thus it appears that this horizon probably represents an ancient karstic surface.

Other examples have also been found. In the roadside exposure (N662) at 133278, near Montbrun, several irregular solution/erosion surfaces are present. These are associated with very thin marl horizons (1-2 cm. in thickness) (figure 69). At first sight they looked like stylolites, but a closer examination has shown that they do not have the typical sutured morphology of the true stylolites of the Cajarc Formation and in some cases it can be demonstrated that the surfaces have resulted from periods of contemporaneous erosion.

Roehl (1967) noted that modern karst surfaces are formed in terrestrial environments. He observed that detached blocks are commonly found above these surfaces and organic matter and soil tends to accumulate in topographic lows. Similar features have been observed in the Cajarc Formation at 135-283, near Montbrun, where an old channel has been infilled by lignitic marl and large rounded limestone fragments. The underlying limestone has also been intensely weathered and disturbed.

The organic matter in the lignites of the Cajarc Formation may have provided the acidic leaching solutions necessary to produce the karst surfaces. Also the rooted horizons may have assisted in the disturbance and eventual weathering of the underlying limestones. Another point made by Roehl (op.cit.) was that many of the fossil soils that he studied were enriched with iron-oxide. Again this has been observed in some of the lignitic marls of the Cajarc Formation which have been cemented by iron-oxide (these might even represent old iron pans).

The frequent associations of marls with karst surfaces has suggested that the marls might have been derived, in part at least, as solution residues by the weathering of underlying limestones. Evidence of this can be found at 135283 near Montbrun, where a weathered and disrupted ostracod (figure 58b) wackestone underlies a lignitic marl.

Karstic surfaces probably represent long periods subaerial exposure, and they imply that contemporaneous uplift and erosion must have occurred. In the future, if these prove to be regionally developed, they could form useful datum horizons in rocks which are otherwise difficult to correlate.

The Environment of Deposition of the Marls

It has been difficult to accurately determine the environment of deposition of this lithofacies, but it is generally thought that the marls are of supratidal or terrestrial origin.

Laminated lignitic marls often pass upwards from laminated calcareous mudstones, deposited in an upper intertidal environment (p.153), and the microfossils C. bleicheri and F. bathonica which have been recovered from the marls are thought to have lived under fresh or brackish water conditions (p198). Therefore, like some of the laminated calcareous mudstones, it is possible that the lignitic marls have also been deposited on fresh or brackish marshes, just above an upper intertidal zone (figure 70).

Although the fossil content and the laminated nature are very similar, there is marked change in composition from laminated calcareous mudstone to lignitic marl, because there is a drastic upward reduction in the calcareous content of the sediment. This probably corresponded to a

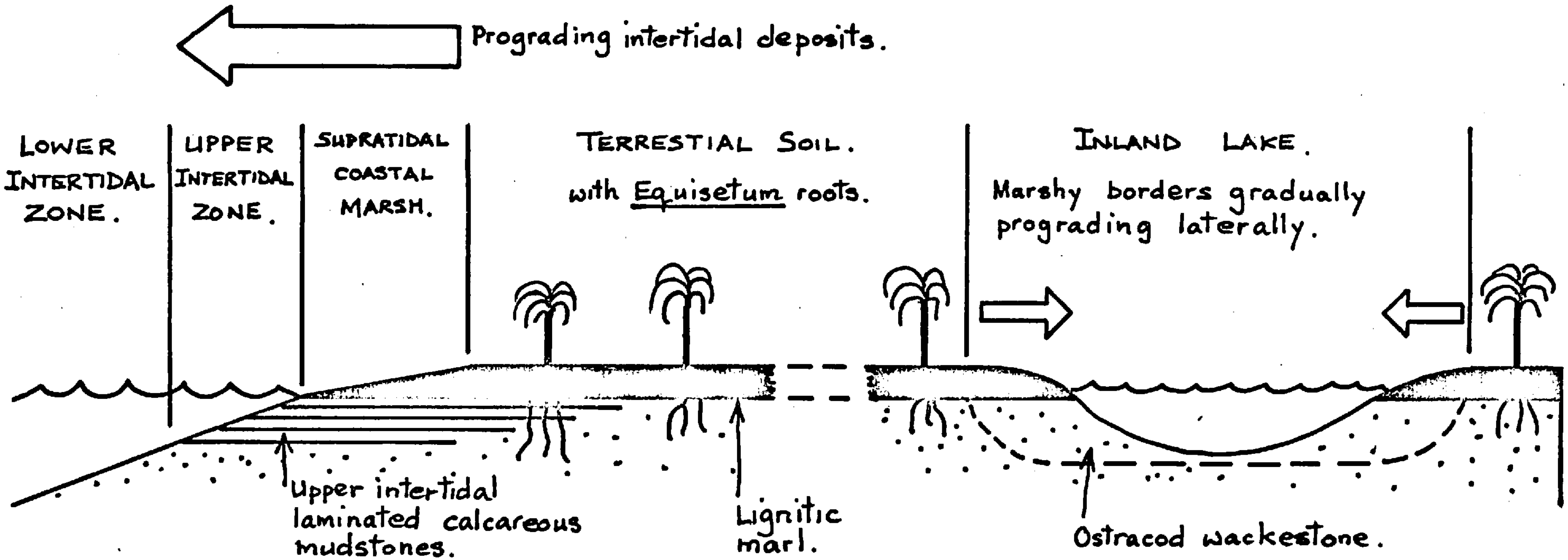


FIGURE 70 Summary of the possible environments of deposition of the lignitic marls. A depositional model for the non-lignitic marls of the Upper Cajarc Formation is given in figure 80.

change in the environment of deposition. If this change was from upper intertidal to supratidal, it can be explained in terms of a reduction in the supply of calcareous sediment due to a lack of influence of sea water in supratidal situation.

Some ostracod wackestones also pass upwards into laminated lignitic marls. As wackestones have probably been deposited in a fresh or brackish lacustrine environment (p.200) it is possible that the marls represent the last stages of the infilling of the lakes when fresh or brackish marshes became established (figure 61a & 70). Although this was probably a similar microenvironment to the coastal fresh and brackish marshes described above, the situation of deposition might have been slightly different; it could also have been a coastal or inland, bordering fresh or brackish water bodies instead of sea water (figure 70).

A few of the lignitic marls have been pervaded by the roots of ?Equisetum sp. Modern species of Equisetum sp. are terrestrial plants which prefer shady, moist conditions, and sometimes they live in, or at the margins of still or moving bodies of fresh water. Dr. C.N. Page of the Royal Botanical Garden (Edinburgh) has informed the writer (pers.comm.,1975) that modern examples of Equisetum sp. frequently occur around bodies of fresh water but only infrequently around brackish water. They also occur in coastal situations, but probably only where any salt has been leached away. In tropical regions, as far as it is known, Equisetum sp. occurs much further away from the sea in temperate areas, and it only lives in fresh water marshy habitats that are never inundated by the sea.

Hence, the presence of ?Equisetum sp. in some of the marls of the Cajarc Formation suggests a terrestrial environment of deposition, very probably under marshy conditions. This is not inconsistant with the evidence presented previously.

Some of the marls with rooted horizons might also represent fossil soils. This is supported by their infrequent association with karst surfaces and also by the presence of iron-oxide cements which may have been produced by 'iron-pan' conditions. It is possible that as the deposition of lignitic marl commenced, either in a coastal supratidal or inland marsh situation and lateral progradation took place, eventually terrestrial conditions could have become established and thus many of the marls may have ended up as 'soils' (figure 70).

The lignitic marls of the Cajarc Formation are possibly the tropical lagoonal equivalent of brackish water clays and peats which Reineck (1972) has described from the supratidal zone of regressive intertidal flat sequences in temperate regions.

The lignite-free marls of the Marcilhac and Brengues Members also occur at the tops of intertidal sequences, usually in association with algal boundstones and calcitised evaporitic deposits such as nodular anhydrite (p223). As with the lignitic marls it is possible that the relative lack of calcareous sediment may have been due to the lack of influence of marine waters. Furthermore, the close association with algal boundstones (upper intertidal; p176) and evaporites has suggested that the marls have been deposited in a supratidal sabkha environment (figure 80). It is also possible that these marls were once rich in evaporitic minerals but these are no longer present.

4.16 Sabkha Environments in the Cajarc Formation

In the Marcilhac and Brengues Members much evidence has been found to suggest that evaporitic minerals have formerly been present in the limestones. Calcareous pseudomorphs of the folloiwng minerals have been observed:

1. primary nodular anhydrite.
2. secondary replacement anhydrite.
3. primary discoidal gypsum.
4. laminated primary gypsum.
5. celestite(?).

These pseudomorphs occur with spherules of lutecite and also with single beds of microdolomitic rocks in a mostly undolomitised succession.

The petrology and significance of the pseudomorphs will be discussed in Chapter 6; it will suffice to note here that these are considered to indicate the establishment of supra-tidal sabkha conditions during the deposition of the Cajarc Formation and although very little sediment was deposited in this environment, some subtidal and intertidal deposits underwent considerable disruption and diagenesis as a result of sabkha processes (figure 80).

Good examples of sediments that have been modified by sabkha diagenesis can be seen in the road section (D17) between 023350 and 020359, just north of Marcilhac (enclosure 3).

4.17 The Crystalline Carbonate Lithofacies

Most of the lower part of the Cajarc Formation is made up of decimetre or centimetre-bedded crystalline limestones. These rocks have been leached and weathered to produce red, brown or yellow cavernous and rubbly looking beds, known as the Calcaire Cargneuliform (p.370).

Unweathered crystalline limestones are composed of anhedral crystals of calcite which may be up to 8mm. in diameter. Petrological and X-ray analyses have shown that these rocks are almost entirely calcareous, but sometimes 1 or 2% of dolomite may be present.

In Chapter 7 these rocks are interpreted as calcareous sediments which have been dolomitised and dedolomitised, and it has been possible to trace some beds laterally into unaltered sediments. Moreover, some of the crystalline rocks possess ghosts of grainstone textures, but the majority have no recognisable depositional textures. These sediments are thought to have originally been calcareous mudstones.

4.18 The Age of the Cajarc Formation

On the geological maps for Gourdon (194) and Cahors (206) rocks equivalent to the Cajarc Formation were considered to be Lower to Middle Bathonian in age. Daukoru (1970) has also dated the lateral equivalent of the Cajarc Formation in the Dordogne region as Lower to Middle Bathonian and Delfaud (1972) and Bourollec et al (1973, fig.9) have dated the top half of Rhythm JA (which is equivalent to the Cajarc Formation), in the Cajarc area, as being 'Bathonian inferieur'.

It would appear therefore, that the Cajarc Formation is Bathonian in age and the fossils that have been found by the present writer have tended to support this date. In particular, the ostracod F. bathonica, the terebratulid O. sp. aff. bathonica, and the echinoid Acosalenia are typical Bathonian forms. Moreover, the gastropod assemblages that have been recovered from beds of ostracod wackestone near Cajarc, have been described as Bathonian fossils by Bleicher (1871) and Sandberger (1870-75).

These fossils have only been recovered from the La Plogne Member and above. It has not been possible to date the Larnagol Member because of extensive recrystallisation.

4.19 The History of Deposition of the Cajarc Formation

A summary of the main lithofacies types of the Cajarc

LITHOFACIES	ENVIRONMENT OF DEPOSITION	% OF SUCCESSION (Discounting recrystallised sediment)
1) Oolitic Grainstone	Subtidal, outer lagoonal	9%
2) Calcareous Mudstone	Subtidal to lower intertidal, inner lagoonal	56%
3) Laminated Calcareous Mudstone	Upper intertidal, and possibly also lacustrine	24.5%
4) Algal Sediments	Upper intertidal, and possibly also lacustrine	
5) Marls	Terrestrial, supratidal marsh and sabkha	2.5%
6) Ostracod Wackestone	Fresh or brackish water lacustrine	8%
7) Calcitised Evaporitic Deposits	Sabkha environment superimposed on sediments deposited in other environments.	-
8) Crystalline Carbonate	Diagenetically altered rocks	-

FIGURE 71 Summary of the main lithofacies and their environments of deposition, in the Cajarc Formation.

Formation and their relative abundances, is given in figure 71. Discounting rocks which have been diagenetically altered, calcareous mudstone is the dominant lithology of this formation and upper intertidal sediments are about half as important.

In figure 71 it can be seen that about 70% of the sediments have probably been deposited under subtidal to intertidal, inner lagoonal conditions. Outer lagoonal conditions only became established on five or six occasions, and these resulted in the deposition of thin beds of oolitic grainstone. However, it should be stressed that no oolitic barrier sediments have been observed in the Cajarc Formation. Four episodes of lacustrine accumulation also took place, during which beds of ostracod wackestone were formed.

Therefore it appears that inner lagoonal sedimentation dominated the history of the Cajarc Formation and thus in lower and middle Bathonian times a tropical coastal lagoon probably existed in the Quercy region. This conclusion is in agreement with palaeogeographical reconstructions that have been made by other workers such as Delfaud (1971, 1973) and Winnock et al (1973) (summarised in figure 6). These reconstructions have also suggested that the landmass of the Massif Central laid to the east of the lagoon, and a coastal barrier existed to the west. The latter has been described from boreholes in the Aquitaine Basin (Winnock et al, 1973) and throughout the lower and middle Bathonian this barrier remained well to the west of Cajarc.

The Cajarc Formation is characterised by a rhythmic pattern of sedimentation in which groups of lithofacies repeatedly succeed one another. This can be seen in the quarry at 075262, on the N662 near Cajarc (figure 72a), where each bed is a distinct rhythm, composed of three or four lithofacies. An actual example of one of these beds, which crops

FIGURE 72 A) Quarry at 075262 on the N662, near Cajarc, showing the La Plogne Member of the Cajarc Formation. Each bed represents a distinct sedimentary rhythm, composed of three or four different lithofacies; details of the bed (1) at the base of the quarry are given in figures 72B and C. The section log of this exposure is given in enclosure 6.

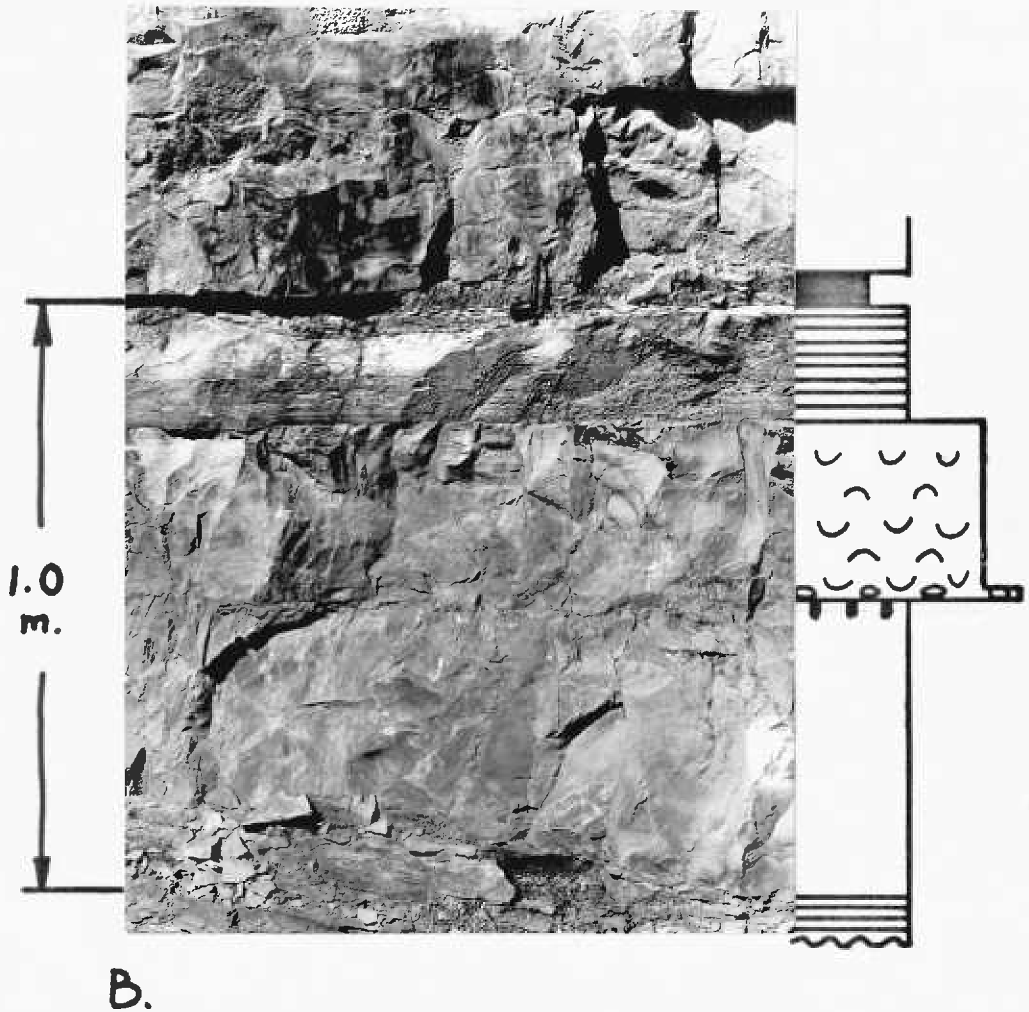
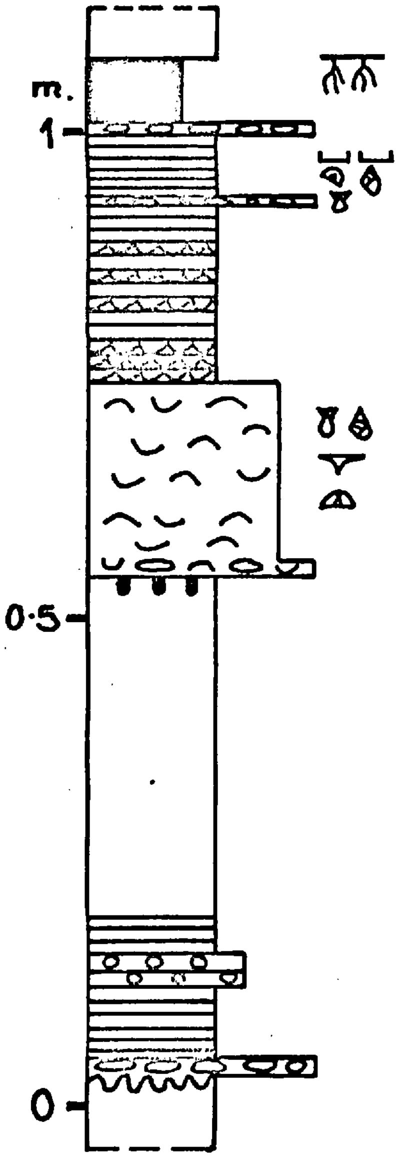


FIGURE 72

B) A typical sedimentary rhythm which is developed at the base of the quarry (figure 72a) at 075262 on the N662, near Cajarc.

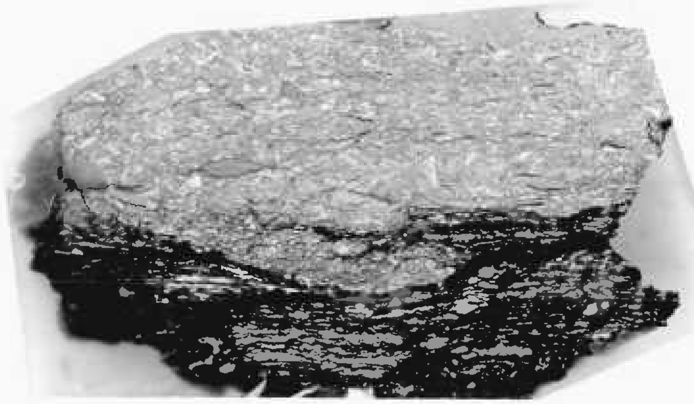
C) A detailed section log of this bed: deposition probably started with a transgressive phase and finished with a regressive or progradational phase (see figure 76).



DESCRIPTION		LITHOFACIES	ENVIRONMENT OF DEPOSITION.
Laminated marls with lignitic layers and occasional root structures. (fig 75a)		MARL	TERRESTRIAL OR SUPRATIDAL
Wavey laminated organic intraclastic packstone.	cut and fill structures	LAMINATED CALCAREOUS MUDSTONE.	FRESH OR BRACKISH SUPRATIDAL MARSH
Laminated ostracod-charophyte-wackestone with well developed polygonal mud-cracks (129/74; fig. 75B).			
Peloid-intraclast-packstone with oysters and intraclasts.			UPPER INTERTIDAL
Flat, lenticular and wavey laminated calcareous mudstones, peloid-siltstones and packstones; some trough cross-lamination at the base.			
Bioturbated, mottled, or sometimes trough cross-laminated bioclast-intraclast-wackestones and calcareous mudstones (130/74; fig. 74).		CALCAREOUS MUDSTONE	LOWER INTERTIDAL
Bored hardground surface overlain by a concentration of bioclasts, and intraclasts derived from below (128/74; fig. 74)			SUBTIDAL INNER LAGOONAL
Bioturbated or trough cross-laminated peloid-siltstones; some burrows infilled with sand sized peloids. (131/74; fig. 74)			LOWER INTERTIDAL ?
Calcareous mudstone with ramifying, organic-rich laminations.		ORGANIC LAMINATED LIMESTONE	UPPER INTERTIDAL (erosion surface TERRESTRIAL) ?
Peloid-bioclast-packstone with ramifying, organic-rich layers (132/74; fig. 73C)			
Fissile, laminated calcareous mudstone, with dark, organic-rich laminations (133/74; fig. 73B); some peloid bands.			
Blackened erosional base, overlain by bioclastic intraclastic band (134/74; fig. 73A).			

FIG. 72c.

A.



(x 1)

B.

(x 1·8)

FIGURE 73 Lithologies at the base of the sedimentary rhythm described in figure 72.

A) A peloidal bioclastic packstone with ramifying organic-rich laminations (132/74).

B) A fissile, organic laminated limestone, with calcareous mudstone and peloidal grainstone layers (133/74).

C) An underlying bed of trough cross-laminated peloidal siltstone, with a blackened erosion surface (1) and a layer of bioclasts and intraclasts which have been draped by organic-rich algal laminations (2) (134/74). (See next page).

(x1·3)

FIGURE 73 C

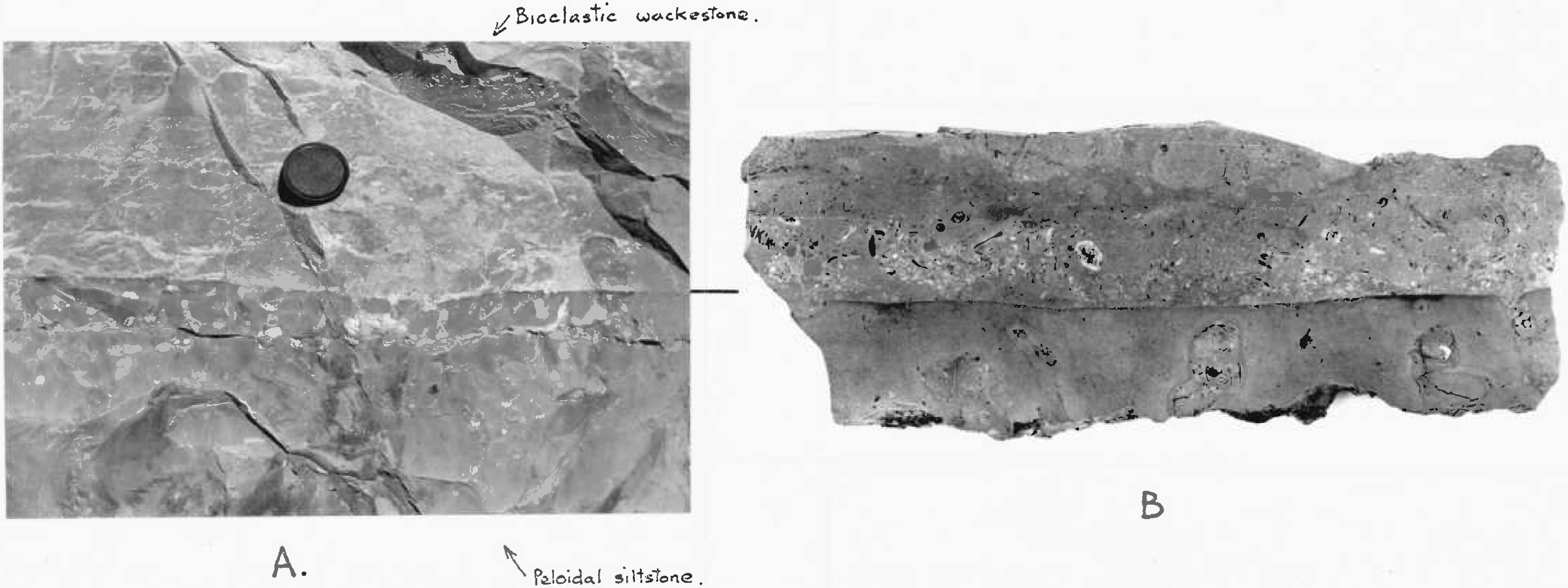
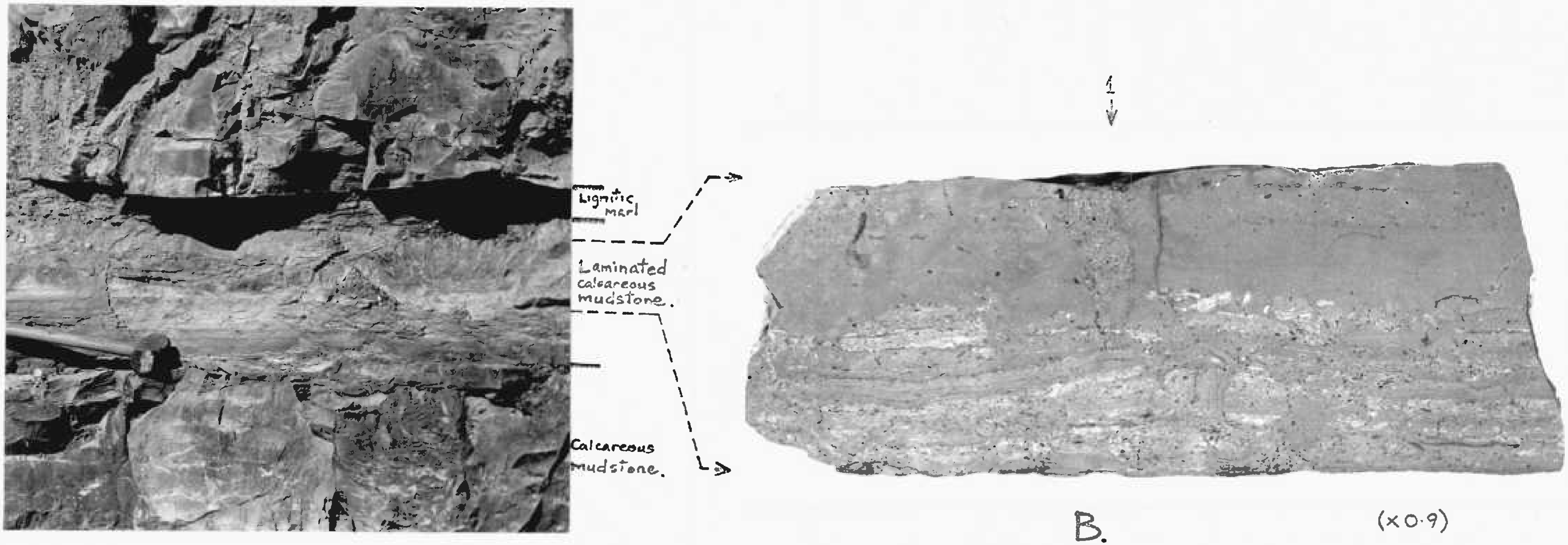


FIGURE 74 Lithologies developed in the middle of the sedimentary rhythm described in figure 72.

A) A detail of the field outcrop showing a bored hardground (1)

B) A polished slab of the hardground surface (128/74), with a concentration of bioclasts and intraclasts above.



B.

A.

FIGURE 75 Lithologies developed at the top of the sedimentary rhythm described in figure 72.

A) A detail of the field outcrop.

B) A polished slab of laminated ostracod charophyte wackestone (129/74) showing disrupted laminations and mud-cracks (1).

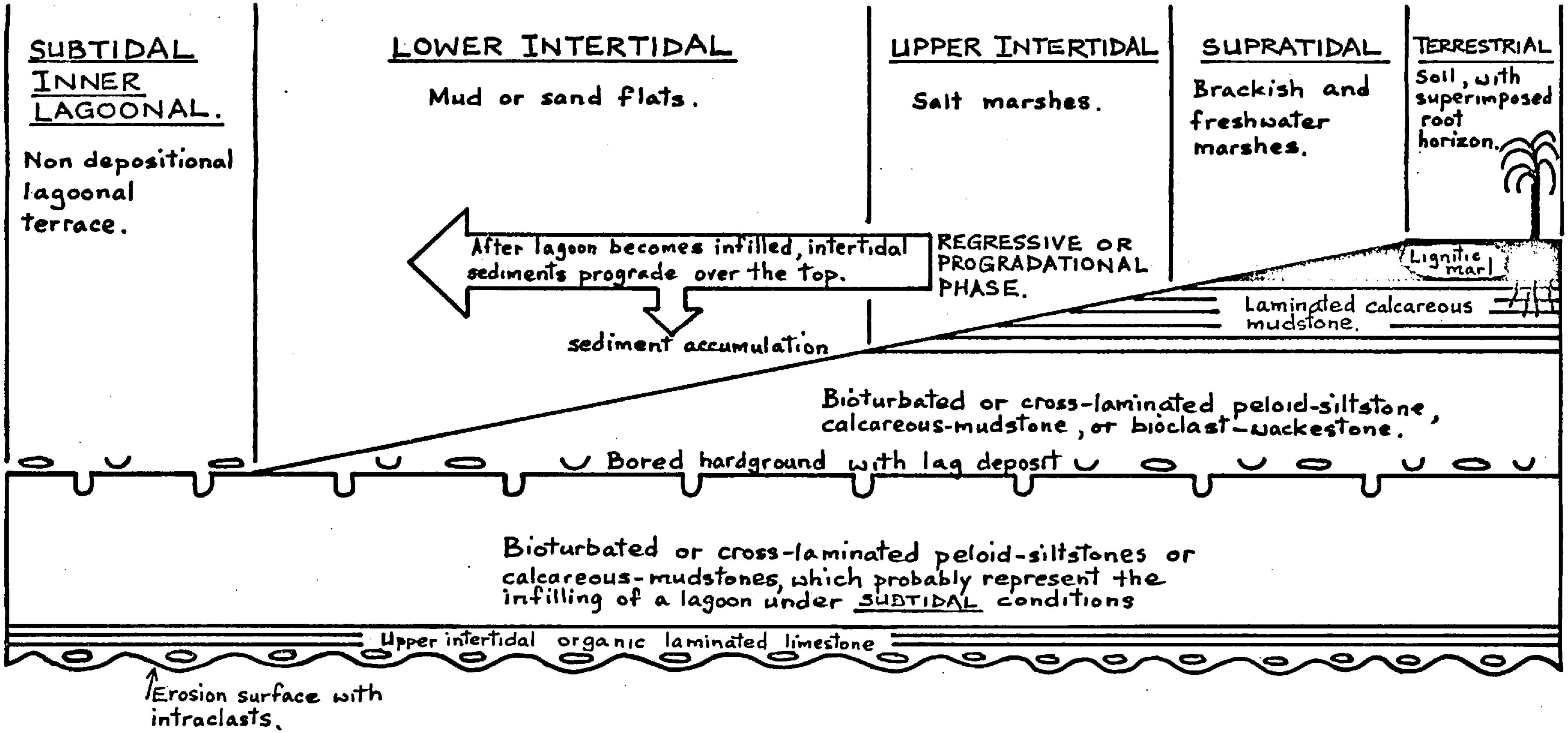
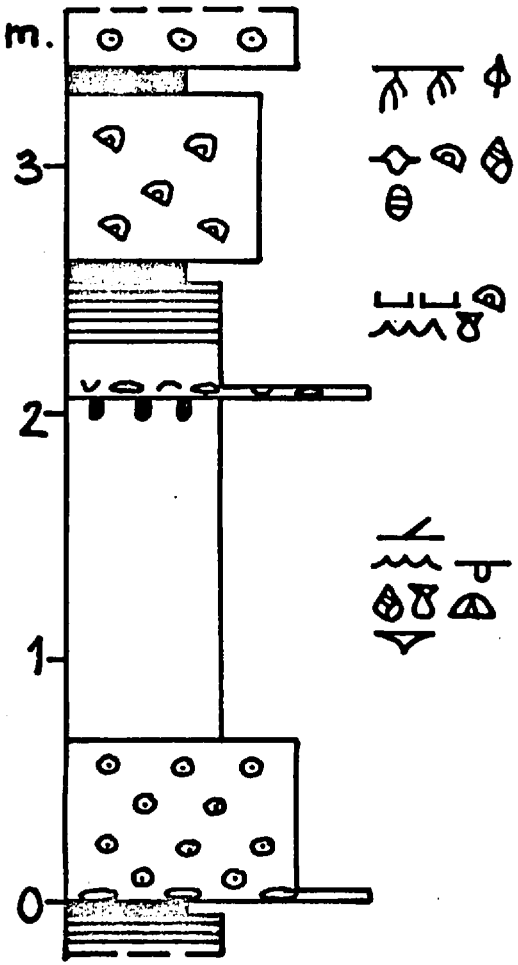


FIGURE 76 Depositional model for the sedimentary rhythm described in Figure 72.

out at the base of the quarry, is given in figure 72b & c. By comparing the lithofacies with Recent sediments it has been possible to interpret this bed and also to construct a model of deposition for it (figure 76). Although the base of the bed is erosive and a thin layer of transgressive sediments overlays this, the bulk of the deposit probably accumulated during a progradational or regressive phase. An initial transgression resulted in the deposition of a thin veneer or upper intertidal sediments and this was followed by the establishment of subtidal inner lagoonal conditions. The lagoon then began to infill and eventually intertidal and supratidal sediments prograded out into it, to complete the depositional rhythm.

An 'ideal' rhythm has been composed for the La Plogne and Marcilhac Members, which takes into account all the lithofacies that are present (figure 77), and a model of deposition which might result in the sequence is given in figure 78. According to this, sedimentation would have started with a transgression and the establishment of outer lagoonal conditions, during which a sheet of oolitic grainstone would have been deposited, possibly with a slightly erosive base. The lagoon would have then gradually become infilled and inner lagoonal calcareous muds would have begun to spread into it. Eventually intertidal and supratidal sediments would have prograded into, and completely infilled the lagoon. Sometime after this had occurred, perhaps after the shoreline had migrated a considerable distance local subsidence may have resulted in the formation of fresh or brackish lakes in which ostracod wackestones could have been deposited. Finally another rhythm of deposition would have been instigated by a renewed transgression phase.

In the upper part of the Marcilhac Member and in the Brengues Member, laminated calcareous mudstones are largely replaced by algal boundstones and calcitised evaporitic minerals became abundant. Hence the ideal succession of litho-



DESCRIPTION	LITHOFACIES	ENVIRONMENT OF DEPOSITION
Lignitic marl with *Equisetum* roots.	MARL	TERRESTRIAL
Ostracod-charophyte-wackestone with *Viviparus bulbiformis* and *Neritina bidens*. Gas-bubble birdseyes sometimes developed.	OSTRACOD WACKESTONE	LACUSTRINE
Lignitic marl.	MARL	SUPRATIDAL
Laminated calcareous-mudstone or peloid-siltstone with Ostracods and ?*Pronoella caristriata*.	LAMINATED CALCAREOUS MUDSTONE	UPPER INTERTIDAL
Massive, mottled and bioturbated, or trough cross-laminated calcareous-mudstones or peloid-siltstones, with bivalves, *Nerinella* sp., *Acrosalinia* sp., and *Ornithella* cf. *bathonica*. Occasional hardgrounds.	CALCAREOUS MUDSTONE	LOWER INTERTIDAL SUBTIDAL INNER LAGOONAL.
Ooid-peloid-bioclast-rhodolith-grainstone with slightly erosive base; fossils and sedimentary structures generally absent.	OOLITIC GRAINSTONE	SUBTIDAL OUTER LAGOONAL.

FIGURE 77. An 'ideal' sedimentary rhythm in the Middle Cajarc Formation.

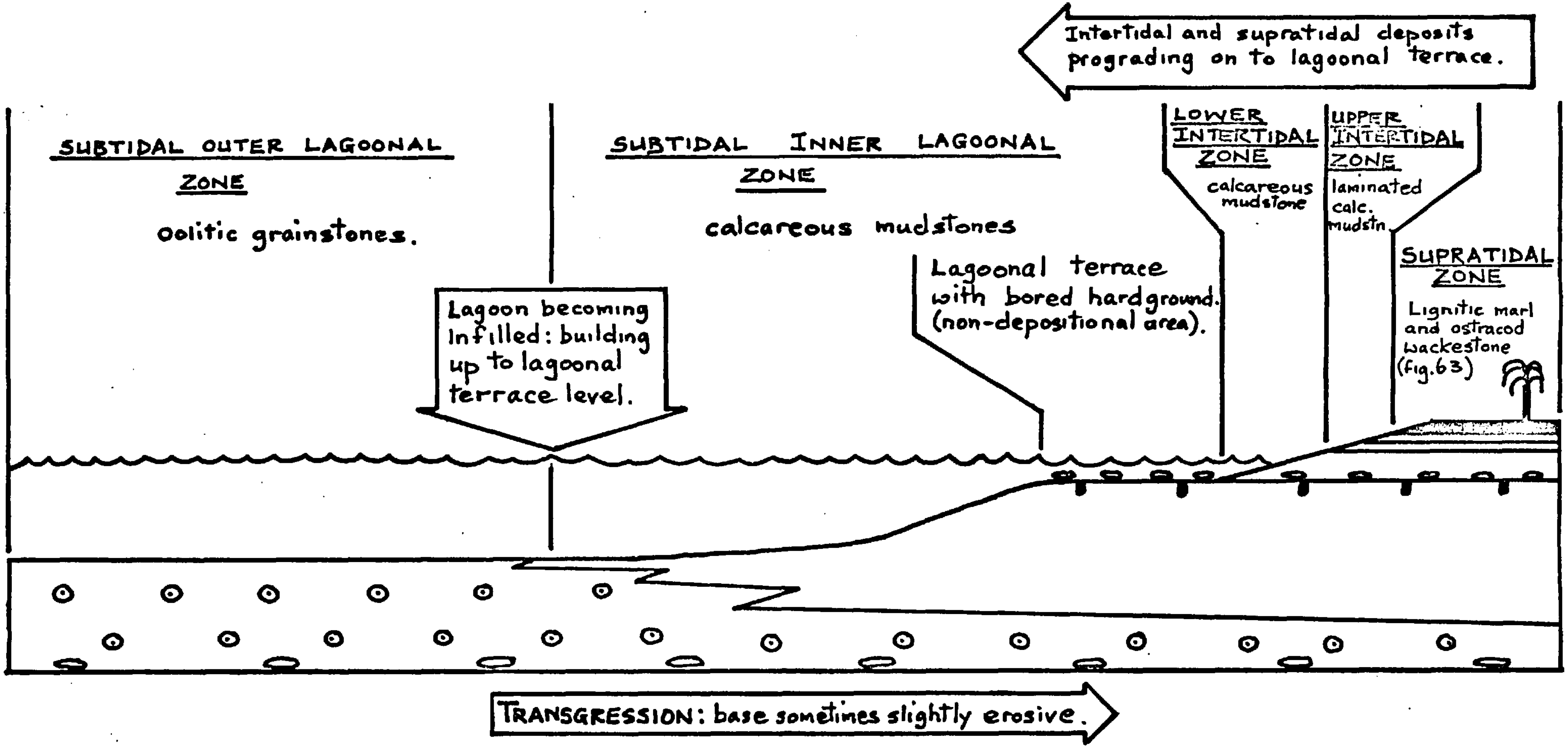
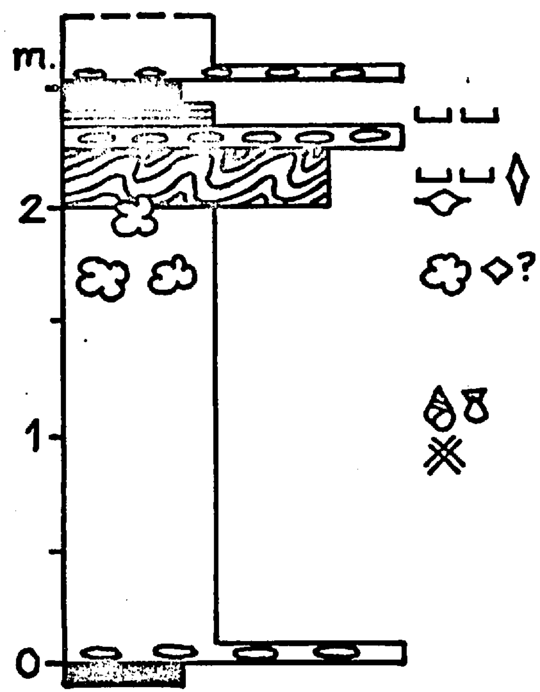


FIGURE 78 Depositional model for the Middle Cajarc Formation.

facies (figure 79) is slightly different from the one already discussed and to explain this, it is necessary to use a modified model of deposition (figure 80) in which upper intertidal algal mats replace laminated calcareous muds and a supratidal sabkha environment replaces the supratidal marshes and terrestrial soils of the previous model.

A typical succession of lithofacies in the middle Cajarc Formation is given in figure 81 and although very few of the rhythms are 'ideal' nearly every bed represents a prograded series of lagoonal sediments. Each bed can be considered as a first order rhythm of deposition. Second order rhythms, which are composed of series of first order rhythms, are also evident (figure 81). The succession of lithofacies implies that each second order rhythm probably commenced with a more major transgressional phase, which resulted in the deposition of an oolitic grainstone in an outer lagoonal environment. As the lagoon became infilled calcareous mudstones, upper intertidal and supratidal sediments were deposited. A series of less well developed transgressional/progradational phases then followed during which outer lagoonal conditions did not become established, and finally an important regressive phase was reached when inland lakes were formed and ostracod wackestones were deposited. Generally this pattern is repeated in each second order rhythm.

The Cajarc Formation is about 110-120 m. in thickness and it is composed entirely of sediments that, by analogy with Recent environments of deposition, have probably accumulated in less than 15 m. of water. Obviously, therefore, these limestones did not simply infill an existing basin of deposition 120 m. in depth, but the history that is preserved in the rocks does indicate that each time a lagoon was created it became infilled by sedimentation. To account for this the level of the sea must have risen periodically,



DESCRIPTION	LITHOFACIES	ENVIRONMENT OF DEPOSITION
Laminated marl.	MARL	SABKHA
Laminated calcareous mudstone.	LAM. CALC. MUDSTN.	UPPER INTERTIDAL
Intraclastic grainstone / packstone.	ALGAL BOUNDSTONE	
Algal boundstone, with 'heads', desiccation birdseyes, and gypsum pseudomorphs.		
Calcitised band of nodular or entrolithic anhydrite, sometimes in association with celestite pseudomorphs.	CALCAREOUS MUDSTONE	LOWER INTERTIDAL ? — — — ?
Massive, mottled or cross-laminated calcareous-mudstone with bivalves and Nerinella sp; pseudomorphs after secondary anhydrite; varying degrees of dolomitisation (now often dedolomitised).		SUBTIDAL INNER LAGOONAL
Intraclastic base.		

FIGURE 79 An ideal sedimentary rhythm in the Upper Cajarc Formation.

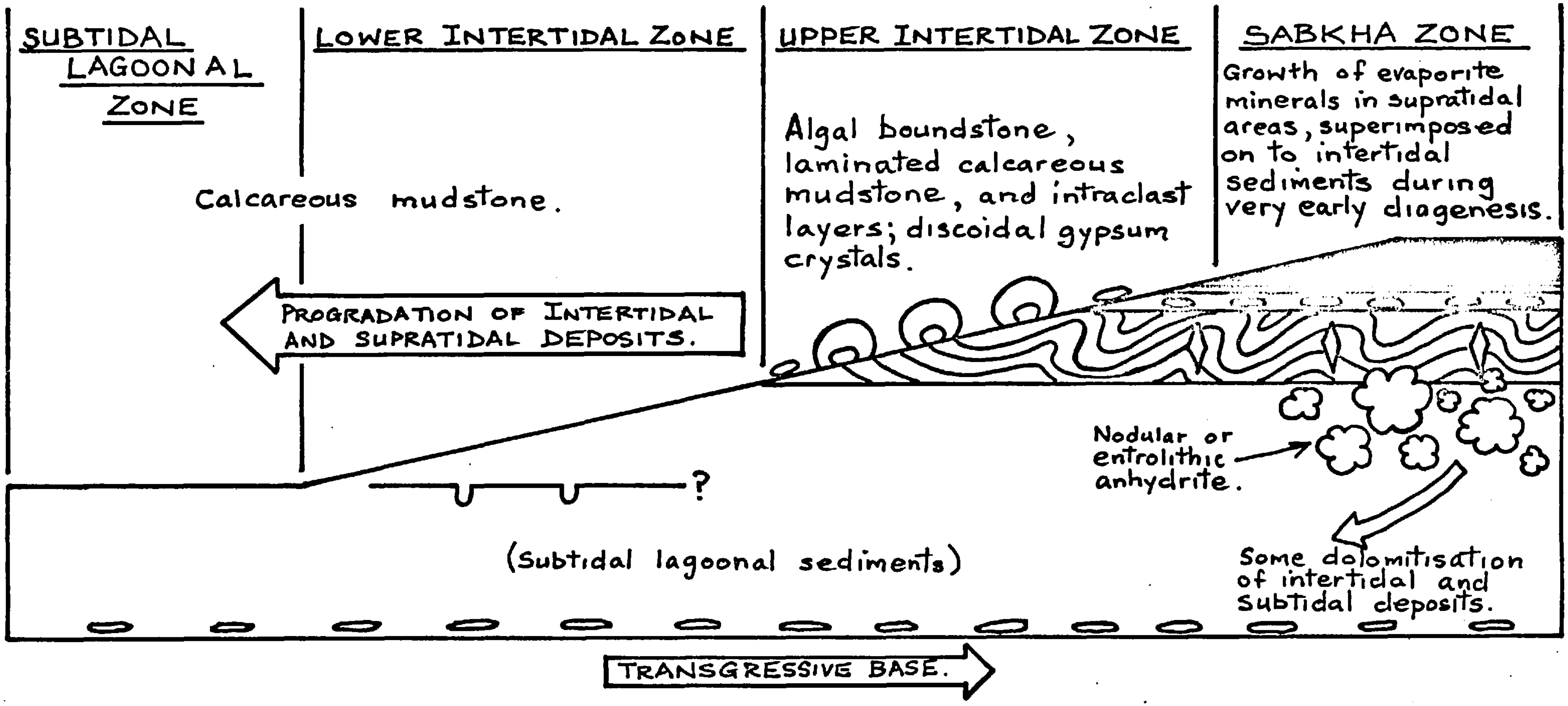


FIGURE 80 Depositional model for the Upper Cajarc Formation.

by a small amount, in relation to the depositional surface of the sediment. This can be explained in two ways; firstly, by eustatic changes in sea level and secondly by small but periodic amounts of subsidence.

Eustatic changes in sea level are difficult to prove, but if they have been responsible for the pattern of sedimentation in the Cajarc Formation, then they should be visible on a worldwide scale. A subsidence mechanism is more easily considered because all over Northwest Europe and the surrounding continental shelf, Jurassic sedimentation seems to have been dominated by a series of 'basins' and 'highs' which were probably controlled by faulting. Within the basins vast thicknesses of sediment have accumulated, mainly in response to subsidence. As Cajarc area is situated on the edge of the Aquitaine Basin, where large amounts of subsidence took place in the Jurassic Period, it seems reasonable to infer that as the sediments of the Cajarc Formation were deposited, they were accommodated by subsidence.

Each time subsidence occurred, the resulting transgression would have probably formed as series of coastal lagoons which were eventually infilled by prograding beds of sediment. Moreover, a substantial amount of subsidence probably would have caused the development of an outer lagoonal environment in the area under consideration, which eventually would have been infilled (figure 82). If this was then followed by a smaller degree of subsidence, outer lagoonal conditions might not have become established and only calcareous mudstones would have been deposited (figure 82). Very small amounts of subsidence would have probably resulted in the repetition of only one or two lithofacies (figure 83); for example, repeated small transgressions could have resulted in a build-up of upper intertidal and supratidal deposits.

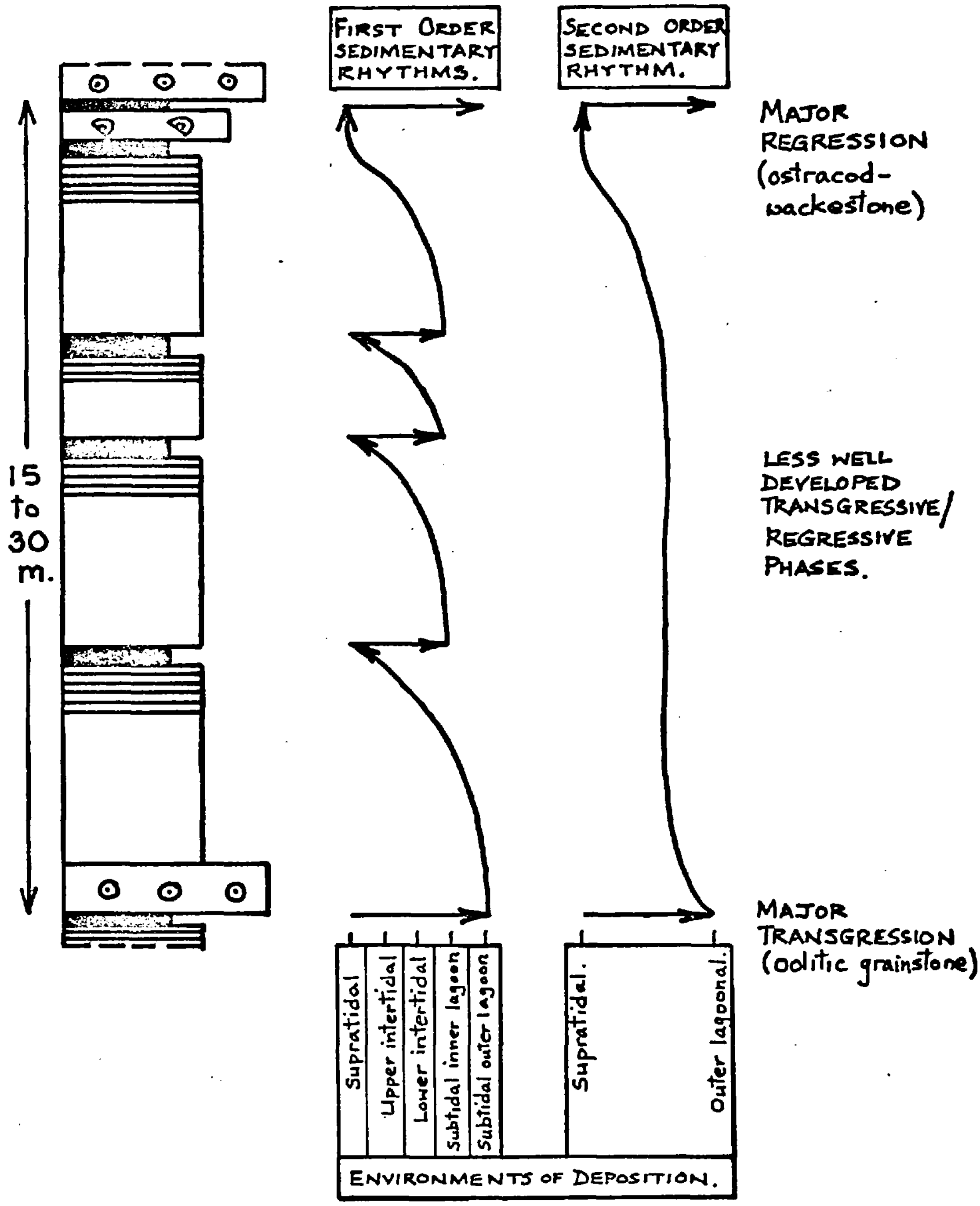


FIGURE 81. Typical succession of lithofacies in the Middle Cajarc Formation (La Plogne and Marcilhac Members), showing the development of first and second order sedimentary rhythms; note the variations in environment the of deposition.

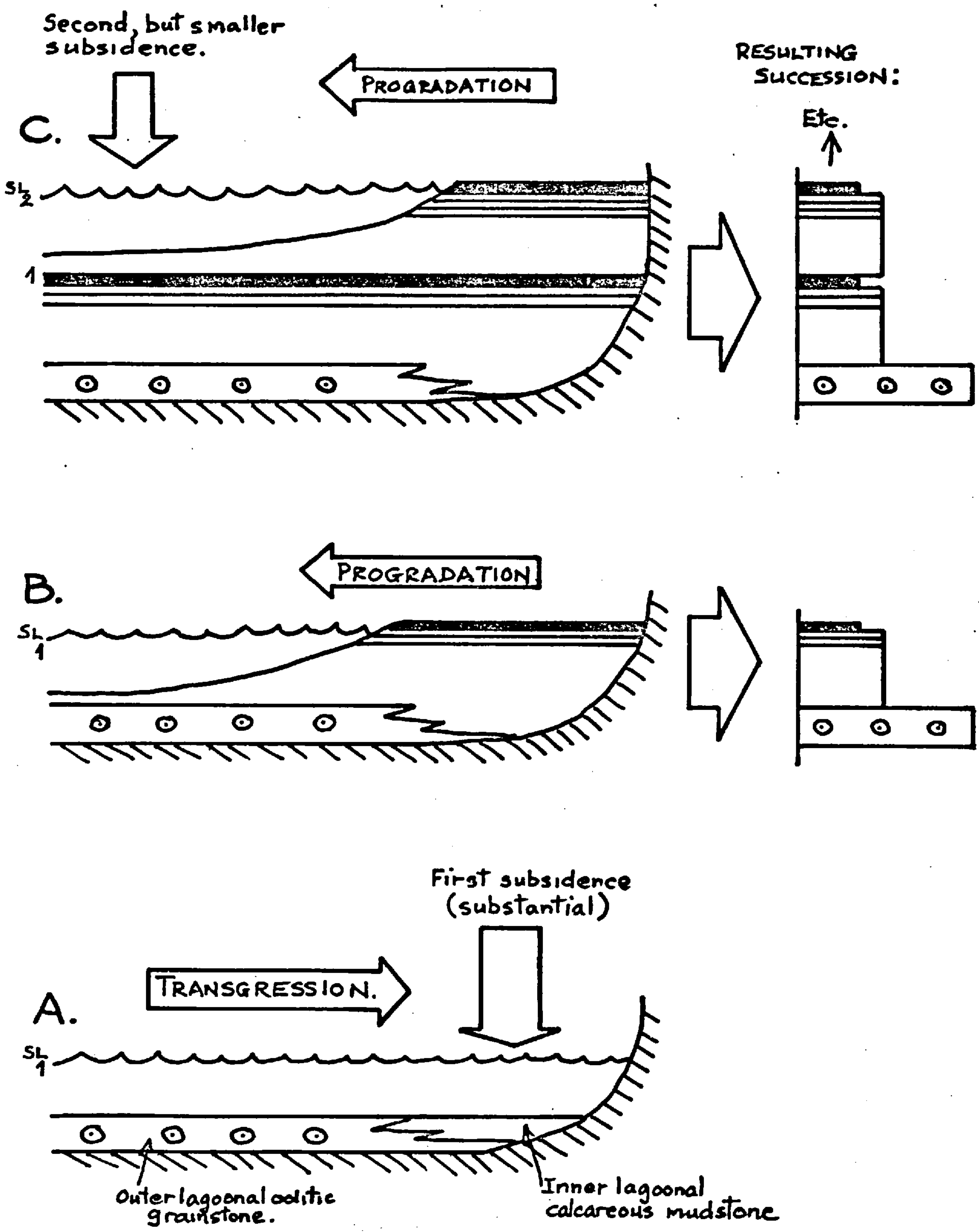


FIGURE 82 Subsidence and rhythmic sedimentation in the Cajarc Formation.

A) First subsidence accompanied by a substantial transgression, and the deposition of oolitic grainstones.

B) Lagoon infilled with sediment.

C) A second, but smaller subsidence and less substantial transgression, followed by infilling with sediment.

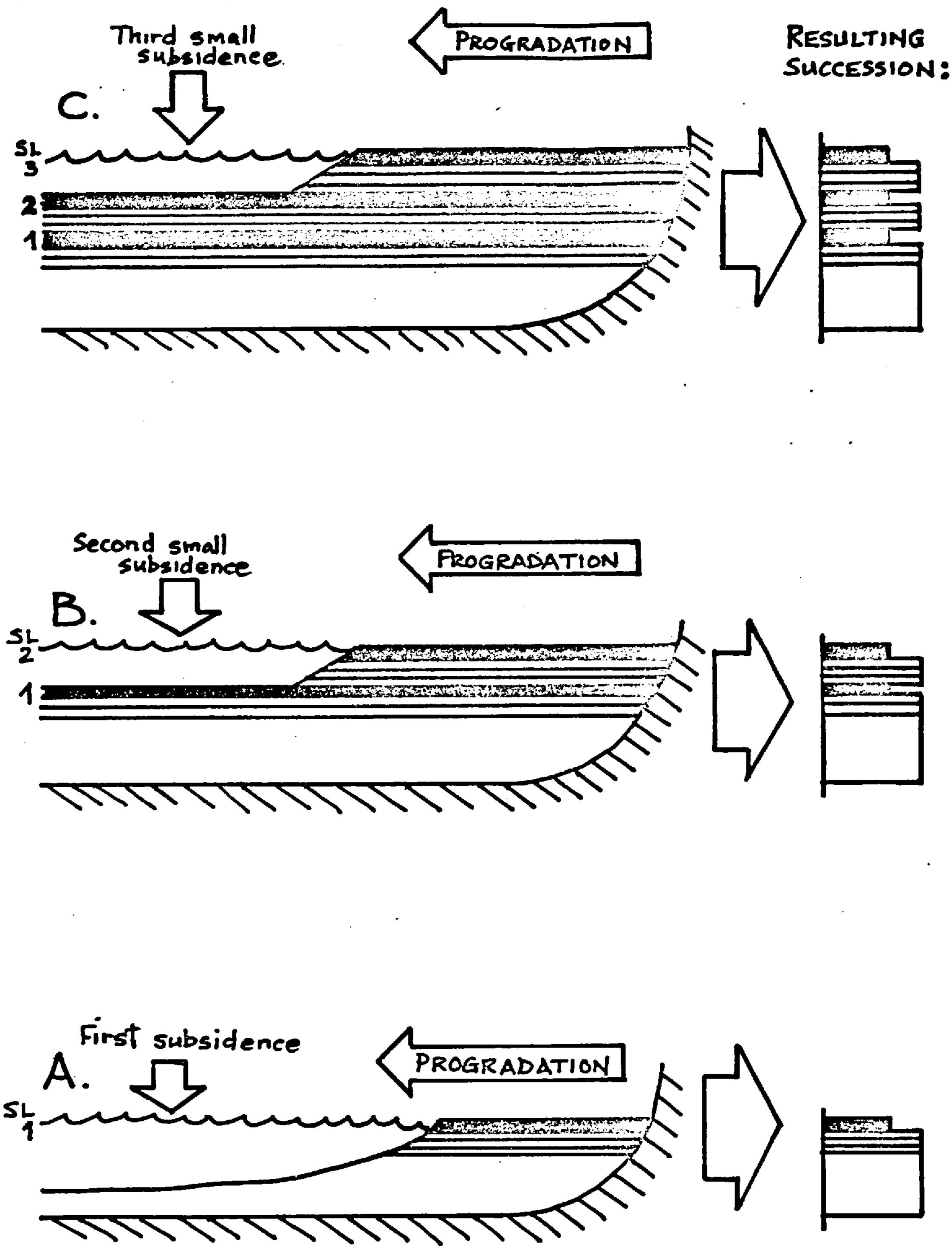


FIGURE 83 The effect of slight amounts of subsidence on the rhythmic patterns of sedimentation in the Cajarc Formation.

A) Subsidence followed by infilling of lagoon with a normal succession of sediments.

B) Second smaller amount of subsidence, followed by deposition of only two lithofacies.

C) Third subsidence, the same as B; resulting succession is a repetition of marls and laminated calcareous mudstones,

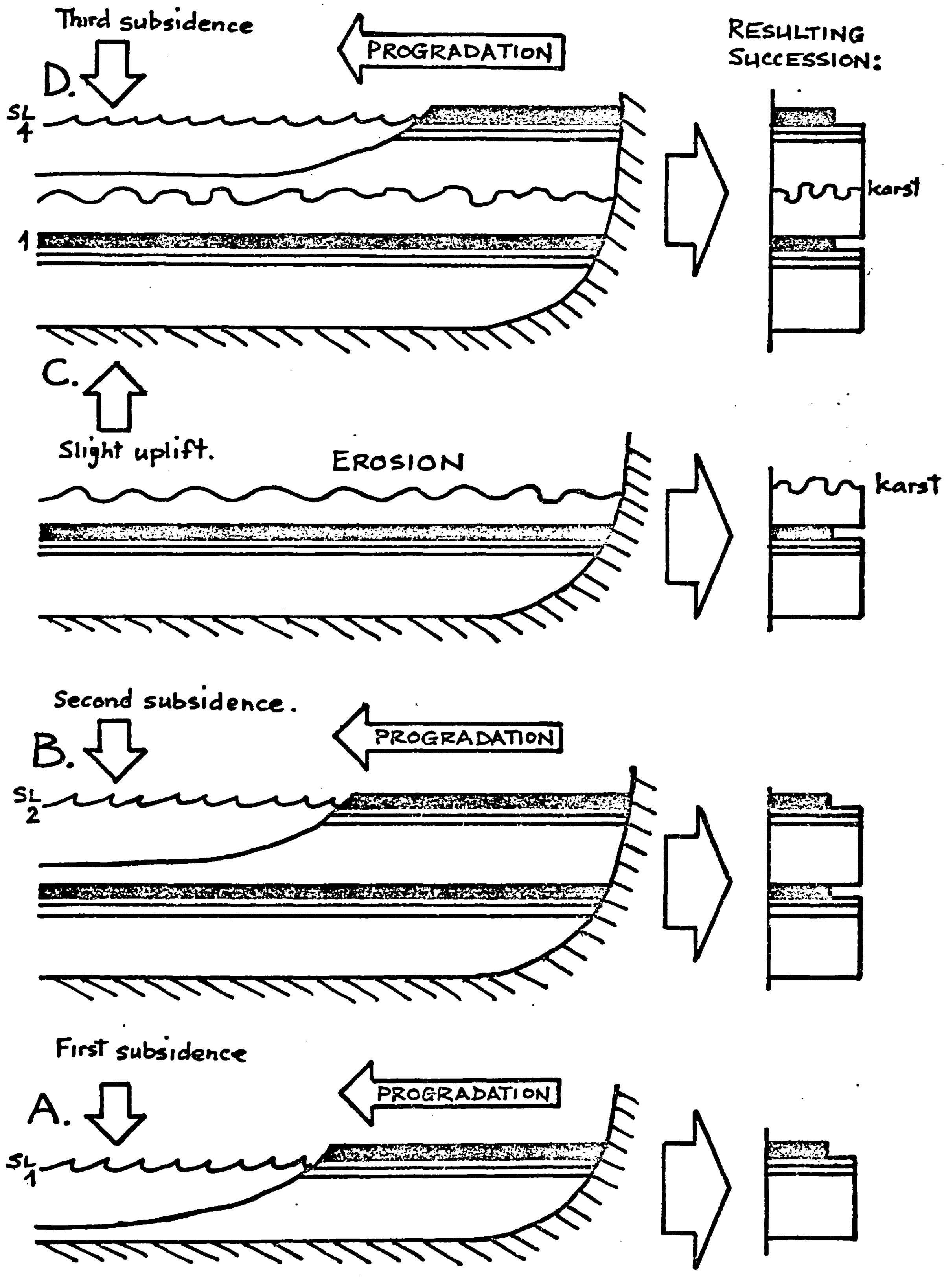


FIGURE 84 The effect of a slight amount of uplift on the rhythmic patterns of sedimentation in the Cajarc Formation.

A) and B) Two phases of subsidence followed each time by the infilling of the lagoon.

C) Sight uplift into subaerial environment, causing erosion: a karst surface develops.

B) Renewed subsidence, followed by the inflling of the lagoon.

The sequences of these models are very similar to the actual ones in the Cajarc Formation. Therefore it is probable that the rhythmic patterns of sedimentation in the formation have developed in response to periodic but small amounts of subsidence. Differing degrees of subsidence can also be used to explain the presence of first and second order rhythms; the latter can be considered as a phase of subsidence made up of a series of smaller pulses (first order rhythms) which gradually lose momentum upwards, until no subsidence takes place and a general regression occurs.

The effect that a small amount of uplift may have had on this pattern is considered in figure 84. Uplift into a subaerial environment would have probably resulted in certain lithofacies not being deposited and also in the removal of some sediment by erosion, leaving karst surfaces and/or fossil soils. However, these are infrequent in the Cajarc Formation, suggesting that actual uplift was rare.

Similar to the Saint Martin Formation, each member of the Cajarc Formation represent a distinct period in the history of the unit. Generally it may be said that the formation becomes more regressive upwards, with upper intertidal and supratidal sediments becoming more abundant. Towards the end of the history of deposition of the Saint Martin Formation, in upper Bajocian times, lagoonal conditions prevailed in the Cajarc area and a horizon of rootlets that is present in the Corn section suggests that a supratidal environment may even have become established.

The deposition of the Cajarc Formation probably began in early Bathonian times, but unfortunately the lowest or Larnagol Member has been recrystallised at most locations, so it has been difficult to fully understand the early history. However, enough evidence has been found in the sections at Saint Martin and Montbrun to suggest that the

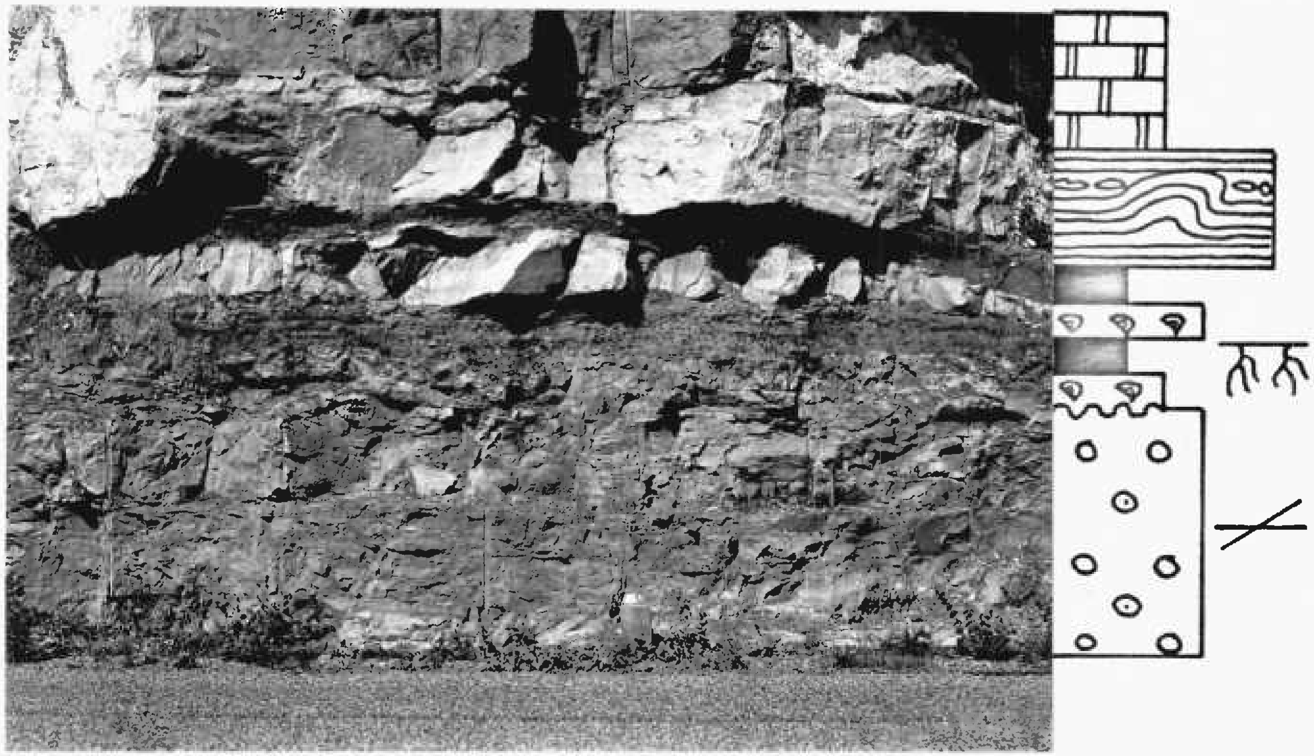
Larnagol Member originally consisted of calcareous mudstones, deposited in an inner lagoonal environment and upper intertidal, supratidal and lacustrine sediments; the latter group may even have dominated the deposition of this member. Calcitised pseudomorphs after secondary and anhydrite are also present at a couple of horizons, indicating, perhaps, that sabkha conditions became established on two occasions (p.355).

The deposition of the La Plogne Member started under outer lagoonal conditions with the accumulation of a cross-bedded peloidal oolitic grainstone (figure 85 and 86a). Almost immediately this bed was uplifted and cemented in a subaerial environment and a karst surface became developed above it (figure 85). A thick fossil soil (lignitic marl) with ?Equisetum sp. roots, and a lacustrine ostracod wackestone with gas-bubble birdseye structures were then deposited. This horizon probably represents a general regression of the sea, caused by slight uplift (figure 85).

The regressive sediments are succeeded by a laminated algal boundstone (figure 86b) and then a calcareous mudstone, which probably accumulated in response to a renewed transgressive phase. The remainder of the La Plogne Member comprises three second order sedimentary rhythms, as depicted in figure 81. Lignitic marls with rooted horizons are typical, and the various lithofacies are developed in the following proportions:

Lignitic marl	2.5%
Ostracod wackestone	2.0%
Upper intertidal deposits	22.5%
Calcareous mudstone	70.0%
Oolitic grainstone	3.0%

The history of this member finished with a general regression and the deposition of an ostracod wackestone in a

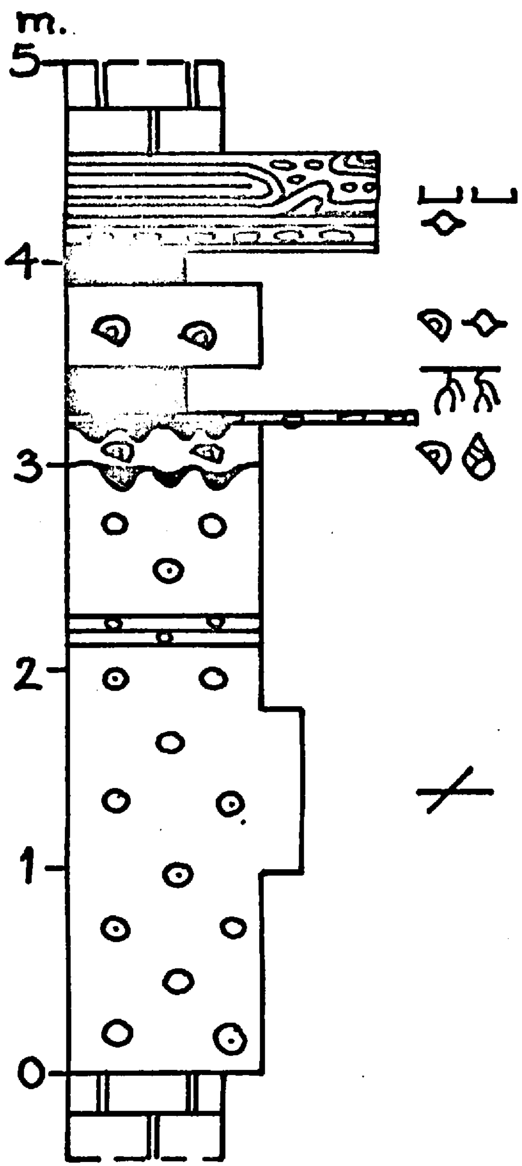


A.

FIGURE 85

A) A roadside (N662) exposure of the basal beds of the La Plogne Mb. of the Cajarc Formation at 044263 near Larnagol.

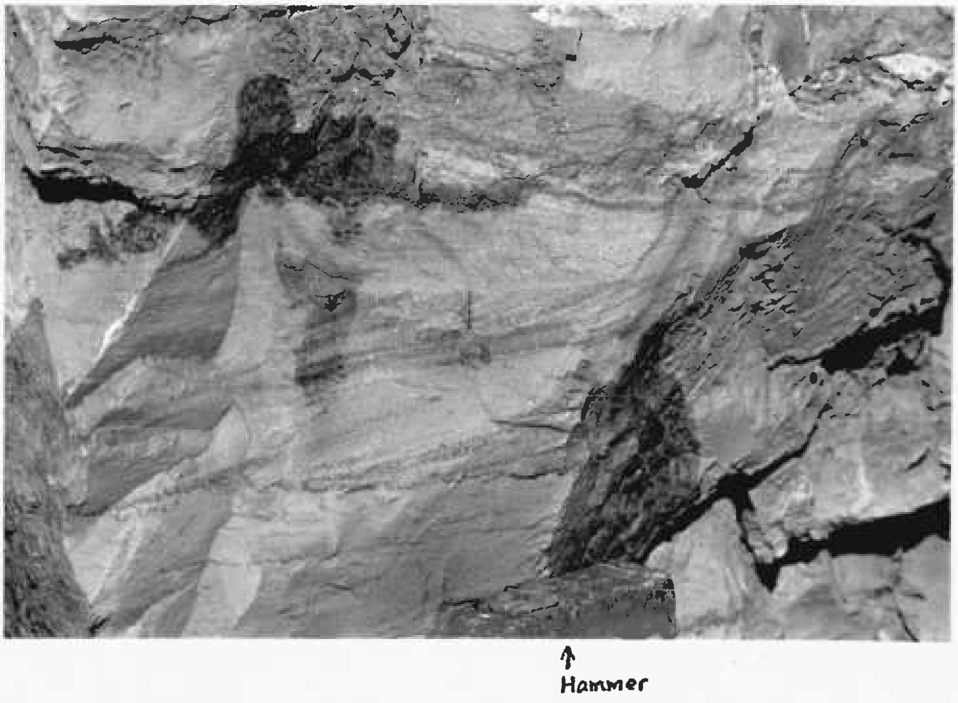
B) A detailed log of this exposure.



DESCRIPTION	LITHOFACIES	ENVIRONMENT OF DEPOSITION
Crystalline limestone with dedolomitic texture; passes laterally into calcareous mudstone with peloid lenses.	CRYSTALLINE CARBONATE	? LAGOONAL
Laminated algal boundstone (99D/73; fig. 86B); partly dolomitised and dedolomitised; mud-cracks, crinkles, over-fold structures, intraclast layers, birdseyes, and ostracods near base.	LAMINATED ALGAL BOUNDSTONE	UPPER INTERTIDAL
Laminated and sometimes lignitic marl.	MARL	SUPRATIDAL TO TERRESTRIAL
Ostracod wackestone with gas-bubble birdseye structures (99c/73).	OSTRACOD WACKESTONE	FRESH OR BRACKISH LACUSTRINE.
Laminated lignitic marl with ?<u>Equisetum</u> roots; thin organic laminated limestone near the top.	MARL	TERRESTRIAL
EROSION SURFACE		
Structureless, dark grey ostracod wackestone with <u>Neritina bidens</u> (101/73)	OSTRACOD WACKESTN.	LACUSTRINE
EROSION SURFACE with solution hollows; cuts across cross-bedding of underlying grainstone bed; thin marl infilling depressions.		
Flat, organic laminated peloid grainstone – fossil algal mat? Cross-bedded peloid-ooid-grainstone (fig. 86A) with foraminifera; partial dolomitisation/dedolomitisation in some places. Low angle (< 10°) cross-sets dipping mainly westwards; some troughs present; megaripples?	OOLITIC GRAINSTONE	SUBTIDAL OUTER LAGOONAL
Crystalline limestone with dedolomitic texture.	CRYSTALLINE CARBONATE	MODIFIED DURING DIAGENESIS ?

FIG. 85B

A.



B.

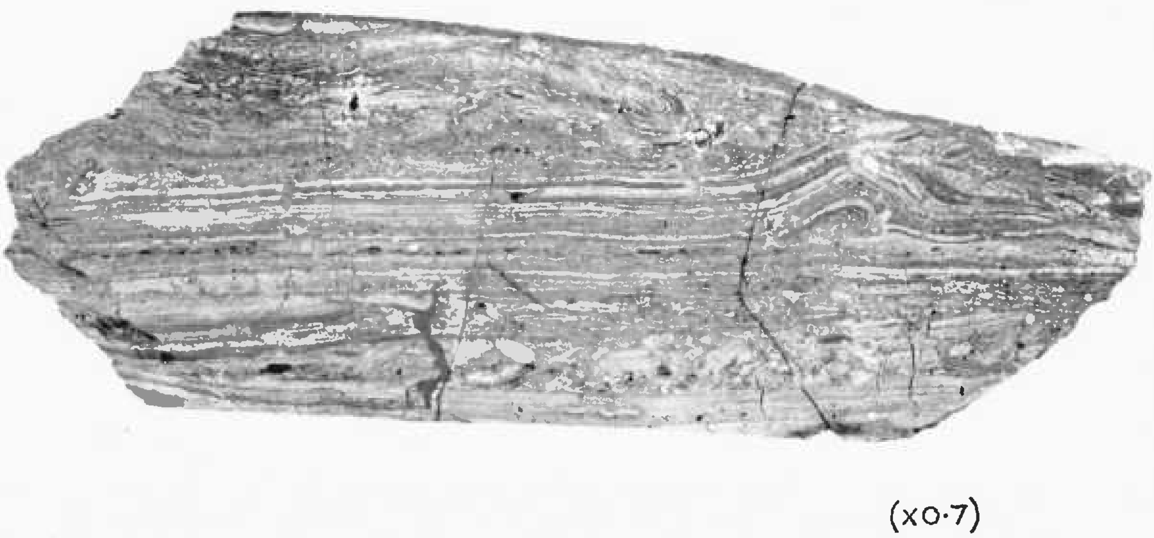


FIGURE 86 A) An outcrop of the basal peloidal oolitic grainstone of the La Plogne Member at 044263, near Larnagol showing cross-bedding structures.

B) A polished slab of laminated algal boundstone (99D/73) showing mud cracks (1) crinkles (2), intraclast horizons (3) and overfold structures (4) (La Plogne Mb. Larnagol).

lacustrine environment.

The Marcilhac Member also commences with an outer lagoonal oolitic grainstone deposit and the pattern of sedimentation was similar to that of the La Plogne Member. However, no lignitic marls are developed but instead calcitised evaporitic mineral became abundant suggesting that sabkha conditions had started to occur. Two second order sedimentary rhythms are present in this unit.

Although calcitised evaporitic minerals are also well developed in the Brengues Member, the most interesting feature of this unit is the greater abundance of upper intertidal, supratidal and lacustrine sediments, when compared with the rest of the Cajarc Formation. The succession is made up in the following proportions:

Marl	12%
Ostracod wackestone	45%
Upper intertidal deposits	30%
Calcareous mudstone	10%
Oolitic grainstone	3%

This is thought to indicate a general regression of the sea towards the end of the period of deposition of the Cajarc Formation and as it might have been expected, a thick deposit of lacustrine ostracod wackestone is developed at the very top of the formation.

Besides the increasingly regressive nature of the Cajarc Formation upwards, there also appears to have been a change in the conditions of deposition of the supratidal sediments at the being of the history of the Marcilhac Member. In the upper Larnagol and La Plogne Members the marl lithofacies is often lignitic. Moreover, horizons of roots are common and plant debris abounds at some levels. None of these features has been found in the Marcilhac and Brengues

Members. Instead, the marls are associated with algal boundstones and calcitised evaporitic deposits.

It is as if the climate suddenly changed from moist, pluvial conditions to an arid desert environment. However, the cause of the change is obscure, but whatever it was, it must take into account that the whole of eastern Aquitaine appears to have been effected.

Furthermore, as well as influencing the environments of deposition, the climatic change also seems to have altered the pattern of early diagenesis of the sediments; in the La Plogne and Larnagol Members prograding beds were probably only affected by the growth of roots and possibly fresh water influxes, but in the Marcilhac and Brengues Members the beds have been subjected to sabkha type diagenesis, during which evaporitic minerals grew and dolomitisation took place. It is also possible that refluxing brines from the sabkhas caused the dolomitisation of the lower parts of the Cajarc Formation and the Saint Martin Formation (p.376).

CHAPTER 5

THE MONTBRUN FORMATION

The Montbrun Formation succeeds the Cajarc Formation and is the uppermost unit of the rocks that have been studied in the Lot Valley area. It has been so named because of the occurrence of easily accessible and freshly cut exposures near the Château at Montbrun, on the road to Greálou. It crops out along most of the Lot Valley between Montbrun and Tour de Faure, and also in the Célé Valley between Espagnac and Sauliac. Detailed logs of the stratigraphic succession of this formation have been measured at Tour de Faure, Larnagol, La Plogne, Montbrun, Marcilhac and Espagnac (figure 87).

The Montbrun Formation varies in thickness from 25.25 m. at Marcilhac to 35.25 m. at Larnagol. It has been divided into two members: the lower or Château Member is composed of massively bedded limestones which are well exposed above the Château at Montbrun; the upper or St. Suplice Member consists of interbedded marls and limestones which may be seen in the D73 road section at 046353, near St. Suplice. The massive limestones of the lower unit usually form impressive cliffs which rise above the stepped slopes so characteristic of the exposure of the Cajarc Formation, and the marls and limestones of the upper member normally form a vegetated slope above the cliff (figure 91).

FIGURE 87. Lithostratigraphic subdivision and general interpretation of the Montbrun Formation.

Many of the limestones of this formation have suffered severe diagenetic alteration including dolomitisation, and later dedolomitisation (p.357). Also, at most localities, the whole unit has been fractured or brecciated. These features have made it difficult to determine the original lithologies of the rocks and to understand the history of deposition of the Montbrun Formation.

On the geological maps for Gourdon (194) and Cahors (206) the equivalent of the Montbrun Formation was mapped by the French geologists as'Bathonien Superieur (J_I)'; it was described as 'calcaires compact a Rhynchonella elegantula' on the Gourdon Sheet, and 'calcaires massifs' on the Cahors Sheet. In the Dordogne region to the north Daukoru (1970) named the lateral equivalent of these rocks the Blagour Formation. Bouroullec et al (1973) named the unit as 'Rhythm JB1'; they also called the lower, or massive limestone member, the 'Series Inferieures de Rocamadour' and the upper, or marl and limestone member, the 'Series Inferieures de Lacave'.

5.1 The Sediments of the Montbrun Formation

Fracturing, brecciation and diagenetic alterations have made it difficult to ascertain the original lithological characters of the rocks of this formation. The succession is composed entirely of limestones with some beds of marl or argillaceous limestone near the top. Although no dolomite, gypsum, anhydrite nor celestite have been found in the rocks, textural evidence has suggested that all of these minerals were probably formerly present.

By the use of polished slabs and thin sections of the fractured-brecciated limestones, the original depositional fabrics of the rocks may be reconstructed. Moreover, with the assistance of ghost textures and lateral passages into unmodified sediments, it has been possible to infer the initial lithologies of many of the diagentically altered limestones. Consequently, the original succession of lithogies that was probably deposited in the Lot Valley area during upper Bathonian times (p.260), can be compiled. In addition a suprisingly good correlation has been achieved between the various section logs measured in the region (figure 87).

Although most of the lithofacies that were recognised in the Cajarc Formation are also present in the Montbrun Formation, because of the intense diagenetic modification, a similarly detailed subdivision of the succession has not been accomplished.

The most commonly developed lithofacies in the Montbrun Formation is crystalline limestone. These sometimes possess ghost sedimentary fabrics, and they have been interpreted as originally being calcareous sediments which were dolomitised, and later dedolomitised to produce fine to coarsely crystalline limestones with dedolomitisation textures (p.360). Confirmation of this can be seen in figure 87 where crystalline limestone, with ghosts of original grainstone fabrics and dedolomitisation textures, can be seen to pass laterally into unaltered oolitic grainstones.

Most of the unaltered rocks are either calcareous mudstones or oolitic grainstone. The latter are composed of varying proportions of ooids, peloids, bioclasts grapestone grains and rhodoliths. The calcarous mudstones sometimes contain peloids and bioclasts, and often are associated with algal boundstones and calcitised evaporitic deposits.

At some levels ostracods are abundant in the rock and they form ostracod wackestones or packstones. In the St. Suplice Member these are interbedded with marls, algal boundstones and calcareous mudstones.

Calcareous pseudomorphs after various evaporitic minerals are also present at various levels in the rocks of the Montbrun Formation. These originally consisted of primary nodular or enterolithic anhydrite, secondary anhydrite, primary discoidal gypsum, primary laminated gypsum and celestite (?). Presumably these became calcitised at a later stage during the subsequent diagenesis of the rocks (p.353).

At St. Suplice up to 50% of the limestones of the St. Suplice Member have been replaced by secondary anhydrite (which is now calcitised). This suggests that perhaps nodular anhydrite was much more abundant than indicated by the evidence that remains today.

<u>The Fauna and Flora of the Montbrun Formation</u>

The Montbrun Formation has only yielded a very poor faunal and foral assemblage, but the following forms have been recovered:

Charophyta -	indeterminate Charophyte oogonia.
Brachiopoda -	<u>Burmirhynchia</u> sp. indet. (Buckman)
Gastropoda -	<u>Neritina</u> sp. indet. (Lamark)
	<u>Planorbis</u> sp. indet. (Guettard)
	<u>Viviparus</u> sp. indet. (Montfort)
Ostracoda -	<u>Bisulcocypris</u> sp. indet. (Pinto & Sanguinetti)
	<u>Darwinula</u> sp. indet. (Brady & Robertson)

Burmirhynchia sp. has only been recovered from the basal oolitic grainstone bed of the Montbrun Formation at 021359, on the D17 just north of Marcilhac. Indeterminate fragments of bivalves, gastropods echinoids and calcareous algae have also been found, and a few calcareous algal balls or rhodoliths are present. Some of the calcareous algal fragments may belong to the genus Emscheria sp.

Smooth shelled, unornamented ostracods are abundant in some beds of ostracod wackestone, and occasionally these are associated with fresh water gastropods such as Neritina sp. and Viviparus sp. The marl beds of the St. Suplice Member at La Roque (078278) contain a fresh or brackish water assemblage consisting of Darwinula sp. a juvenile form of Bisulcocypris sp., Planorbis sp. and some indeterminate charophyte oogonia. The fresh water gastropods of this formation are probably of the same species as those described from the Cajarc Formation.

The fauna and flora of the Montbrun Formation can be divided into two distinct groups: one which probably lived in a subtidal lagoonal environment, and another which lived in a fresh or brackish lacustrine environment. Ager (1965) argued that the genus Burmirhynchia is indicative of a shallow water sublittoral coastal habitat with a sandy bottom. In the Montbrun Formation, the occurrence of this form in oolitic grainstones supports this conclusion; these sediments were probably deposited in an outer lagoonal environment. Although calcitised evaporites are sometimes associated with the fresh and brackish water fossils, they are considered to represent lacustrine conditions.

The Environments of Deposition of the Sediments of the Montbrun Formation

The lithofacies that are developed in this formation are comparable with those of the Cajarc Formation. Therefore the Montbrun Formation can probably be interpreted in a similar way. It is likely that those sediments have been deposited in situations which included subtidal outer and inner lagoonal, lower and upper intertidal, supratidal sabkha and fresh or brackish water lake environments. However, because the original nature of the sediments has often been obscured by diagenetic processes, it has only been possible to apply a general interpretation of either inner or outer lagoonal (figure 87) to these deposits.

The outer lagoonal deposits consist of oolitic - peloidal - bioclastic - grainstone with occasional grapestone grains and rhodoliths. These are similar to the rhodolithic - grainstones and oolitic - grainstones of the St. Martin and Cajarc Formations, respectively. Likewise they are thought to represent a subtidal, outer lagoonal habitat.

The inner lagoonal deposits include calcareous mudstones, algal boundstones, marls, calcitised evaporites and ostracod wackestones. By comparison with the Cajarc Formation, these were probably deposited in a range of environments which included subtidal inner lagoonal, intertidal and supratidal habitats.

An interesting feature of the Montbrun Formation is the alternation of fresh and brackish water deposits with layers of calcitised evaporitic minerals, especially in the St. Suplice Member. At first this was thought to be unusual, but studies which have been made of some Recent sabkhas on the coast of Libya (Sherif 1975, pers com.), have revealed that the sabkha areas are intermittently flooded with fresh water, and fresh or brackish animals may flourish for periods of up to 3 to 4 months. These processes are depositing an evaporitic sediment of discoidal and laminated gypsum, with thin lacustrine layers. The evaporitic and lacustrine beds of the Montbrun Formation might be an ancient analog of the Libyian sabkhas, but some of the thicker beds of ostracod wackestone probably represent permanent fresh or brackish lakes which formed inland during phases of general regression (p.238).

5.2 The Age of the Montbrun Formation

This formation has been difficult to date because very few fossils have been recovered from it. The indeterminate species of Burmirhynchia which has been found in the basal oolitic grainstones of the Montbrun Formation at Marcilhac, might be the B. elegantula (Deslongchamp) described in the legend of the Gourdon Sheet. This would date the unit as upper Bathonian, but as the species cannot be determined the range of the genus, Bathonian to Callovian, must be used instead. A similarly unsatisfactory date has also been obtained from the ostracod fauna found in the upper part of the St. Suplice Member at La Roque, because the genera Bisulcocypris and Darwinula are found in both Bathonian and Callovian strata.

However, a more accurate date has been obtained by considering the conclusions of other workers. Daukoru (197) argued, by using macrofaunal evidence, that the Blagour Formation which he described was uppermost Bathonian in age. Furthermore, Bouroullec et al (1973) also dated the same unit at Marcilhac and La Plogne as Upper Bathonian, on the basis of the foraminifera Trocholina sp. They also indicated that the formation immediately above was Callovian in age; these dates were established at the Centre de Recherches de Pau - S.N.P.A., and currently they are being used by petroleum companies that are prospecting for hydrocarbons in Aquitaine. Therefore, as the Montbrun Formation is equivalent to the units discussed above (p. 255), it can also be assigned an Upper Bathonian age.

5.3 The History of Deposition of the Montbrun Formation

The period of deposition of the Cajarc Formation ended with a general regression of the sea, probably towards the close of Middle Bathonian times. A renewed transgression and the establishment of outer lagoonal conditions, probably in the early Upper Bathonian, marked the beginning of the history of deposition of the Montbrun Formation. The succession commences with an oolitic grainstone which is followed by six, or possibly seven, second order rhythms of sedimentation. Each of these starts with outer lagoonal sediments and passes upwards into inner lagoonal and supratidal deposits.

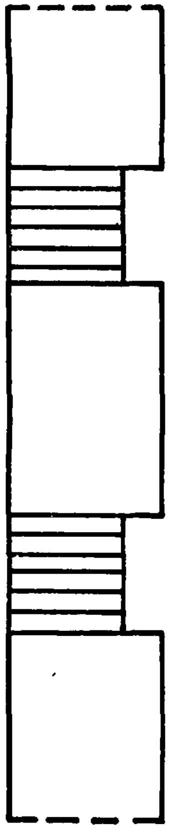
The outer lagoonal phases are better, and more regularly developed than in the Cajarc Formation, and the resulting grainstone beds are much thicker. Sabkha conditions prevailed in the supratidal environment, throughout the deposition of the Montbrun Formation. Also, during the more pronounced regressive phases at the end of each rhythm of deposition, lacustrine conditions became established and beds of ostracod wackestone were deposited.

The rhythms of deposition probably occurred in response to repeated phases of subsidence. As in the Cajarc Formation, the second order rhythms generally became more supratidal towards the later part of the period of deposition of the Montbrun Formation, until finally towards the end of Upper Bathonian times, there was a general regression of the sea. The succession of this unit culminates in a series of upper intertidal and supratidal sediments, including marls, which are lignitic at the very top, lacustrine deposits, and calcitised nodular anhydrite and laminated gypsum which probably formed in supratidal sabkhas.

During the burial and diagenesis of the formation, much of the sediment was dolomitised, and later this became dedolomitised during uplift and erosion (p.368). Also, at some stage during the burial of the unit, fracturing and brecciation took place.

5.4 The Brecciation of the Montbrun Formation

The Montbrun Formation overlies about 10 m. of bedded marls and limestone of the Brengues Member of the Cajarc Formation, and is succeeded by the massively bedded limestones of the Series de Rocamadour Superieur (JB2) Bouroullec et al, 1973). The measured sections through the Montbrun Formation (figure 87) show that, effectively, the massive limestones of the Château Member (21 - 35 m. in thickness) are sandwiched (figure 88) between the less competent units of the Brengues (10 m.) and St. Suplice Members (3 - 5 m.); both of which are composed of decimetre - bedded successions of marls and limestones.



UNIT	LITHOLOGY	DEGREE OF BRECCIATION
SERIES DE ROCAMADOUR SUPÉRIEUR (JB_2)	Massive limestones.	Largely unaffected but fractured and faulted near base (fig. 92).
ST. SUPLICE MEMBER	Marls and limestones.	Disturbed and broken into a blocky breccia with a marl matrix (fig. 92)
CHÂTEAU MEMBER	Massive limestones.	Fractured and brecciated (fig. 97).
BRENGUES MEMBER	Marls and limestones.	Disturbed and broken into blocky breccia; some minor shear planes (fig. 90).
MARCILHAC MEMBER	Bedded limestones.	Largely unaffected

FIGURE 88 The stratigraphic relationship of the brecciated limestones of the Cajarc and Montbrun Formation.

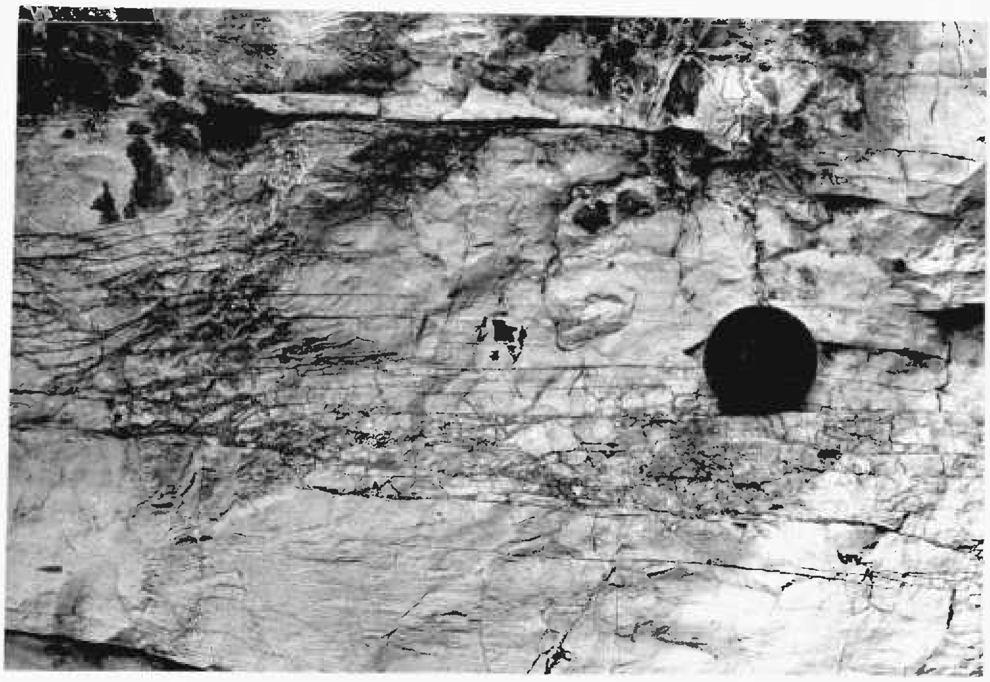


FIGURE 89 A rare example of fracturing and incipient brecciation in the La Plogne Member of the Cajarc Formation, at 134287 near the Montbrun railway tunnel (lens-cap = 6 cm).

The Château Member is extensively fractured and brecciated where it crops out in the Lot and Célé Valleys. Daukoru (1970) noted that the massive limestones of the lateral equivalent of the Montbrun Formation in the Dordogne Valley (which he called the Blagour Formation) are also extensively fractured and brecciated. Likewise, the equivalents of the marls and limestone units above and below the Château Member, are disturbed and brecciated in the Lot, Célé and Dordogne Valleys.

Sometimes the upper parts of the Cajarc Formation (apart from the Brengues Member) have been fractured or brecciated, but the limestones below have only rarely been affected (figure 89). The sediments at the base of the Series de Rocamadour Superieur are often fractured and rarely brecciated, but this dies out rapidly upwards and rarely extends more than 10 m. above the base of this unit.

Therefore, considering the whole of the Middle Jurassic succession, intense brecciation seems to be restricted to the massive limestones of the Montbrun Formation, and to the marl and limestone units above and below. Furthermore brecciation seems to have taken place on a regional scale.

The Breccias of the Marls and Limestones.

At some localities the marls and limestones of the Brengues and St. Suplice Members form bedded sequences that show only slight disturbance. More often, however, these units have been intensely disrupted, and horizons of blocky limestone - clasts, embedded in a matrix of marls, have resulted.

FIGURE 90 Disrupted marls and limestones of the Brengues Member of the Cajarc Formation:

A) A blocky breccia at La Plogne (074263) where the marly matrix has been removed by weathering to leave a cemented jumble of limestone blocks.

B) The roadside section at 072364 near Brengues showing a blocky limestone breccia with a marly matrix and some relatively undisturbed limestones beneath. Just above the breccias, out of the field of the photograph there is a cliff formed by massive limestones of the Château Member of the Montbrun Formation.

A.

(lens-cap = 6cm)

Disrupted marls and limestones of the Brengues member : blocky breccia with a marly matrix.

B.

Bedded limestones of the Marcilhac Member.

Brecciated examples of the Brengues Member are exposed in the road section at 072364, near Brengues (figure 90 a), and at La Plogne (072364)(figure 90 b), and a disturbed and brecciated outcrop of the St. Suplice Member can be seen at 046353, on the D73 near St. Suplice (figure 92 c).

The Mechanism of Brecciation of the Marls and Limestones

The bedded nature of the Brengues and St. Suplice Members at some localities suggests that the sediments of these units were originally deposited as normal layered sequences, which were later disrupted and brecciated. Within these disturbed zones thin beds of limestone have been broken-up to form blocky breccias, and beds of marl have become contorted, sheared, pinched-out, and sometimes low-angled thrusts have developed.

From a distance, at St. Suplice, the successive sedimentary units are apparently horizontally bedded and undisturbed (figure 91). However a closer examination has shown that the base of the Series de Rocamadour Superieur is crumpled and faulted, and in places it even has a stepped appearence (figures 92 a & b). This basal faulting may have been responsible for much of the shearing, contortion and brecciation in the underlying marls and limestones of the St. Suplice Members (figure 92 c), and as very similar features are present in the Brengues Member, the same mechanism may also have operated within this unit.

Price (1975) noted that most sedimentary sequences are made up a mixture of competent and incompetent layers.

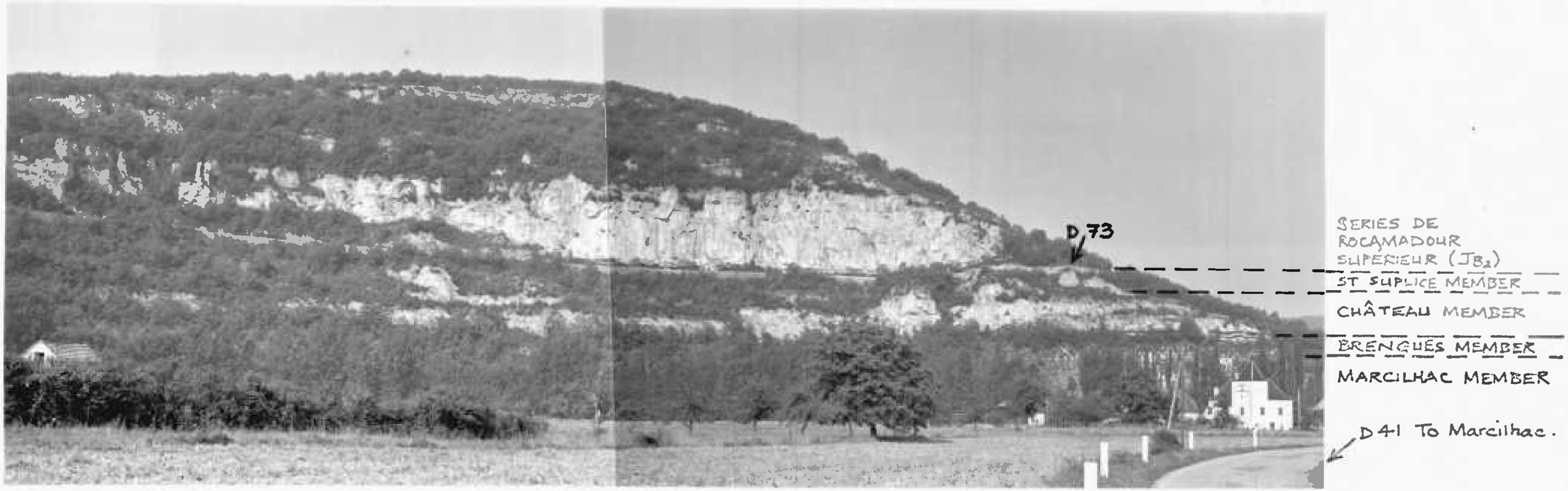
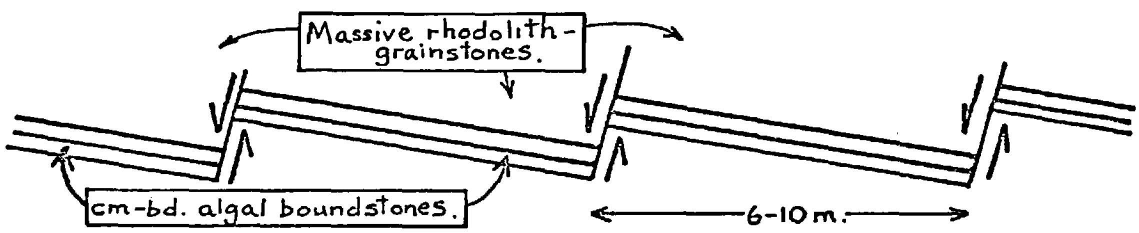


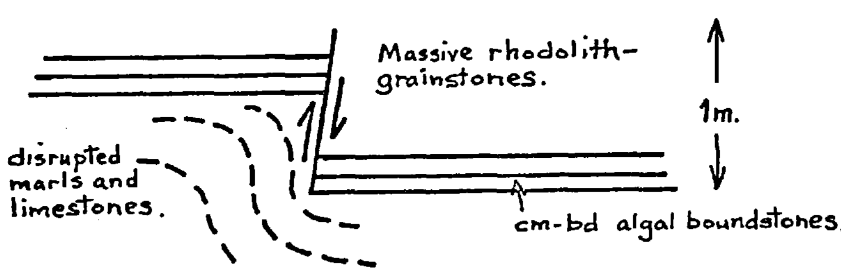
FIGURE 91 Panoramic view looking westwards from Vazac (054354) in the Célé Valley. This shows the overall undisturbed and bedded nature of the Cajarc and Montbrun Formations, and the Series de Rocamadour Superiéur. The D73 road can be seen clinging to the base of the cliff formed by the latter unit (more detailed photographs of the base of the Series de Rocamadour are given in figure 92.

FIGURE 92

A) Outcrop of the Upper St. Suplice Member and Lower Series de Rocamadour Superieur on the D73 at 046353, near St. Suplice. Note stepped nature of the base of the massive limestone unit.



B) Detail of the base showing a fault, and also the disruption of the underlying marls and limestones of the St. Suplice Member.



C) Detail of Suplice Member showing the brecciation and disruption of the marls and limestones.

Series de Rocamadour Supérieur.

St. Suplice Member.

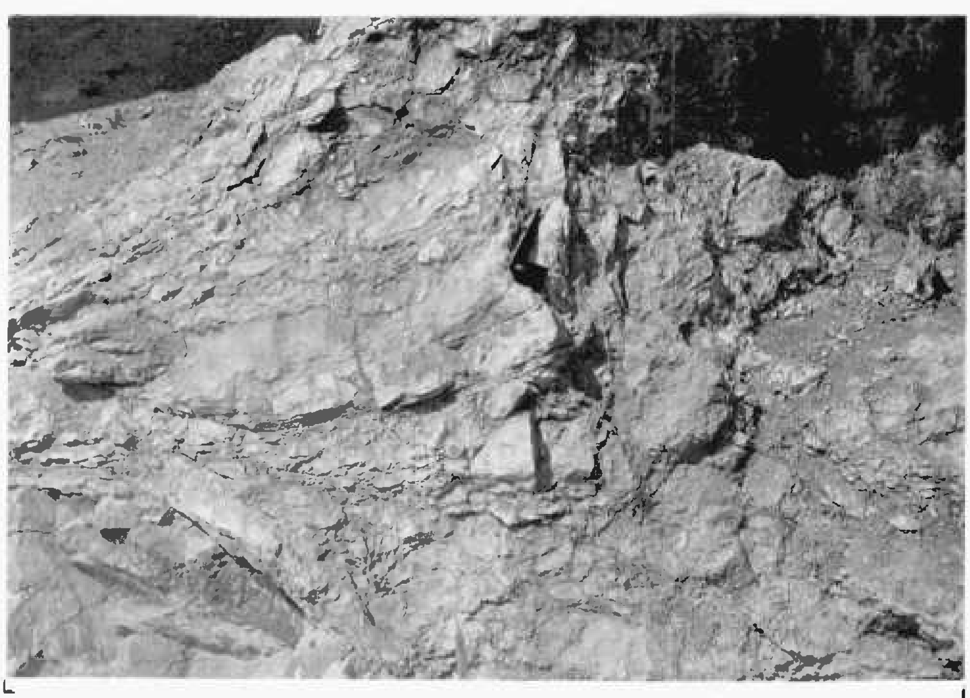
←D73

A.

Series de Rocamadour Superieur

St. Suplice Member.

B.



C.

He also noted that when such a sequence is induced to deform by the application of buckling stresses, a 'flexural slip' mechanism of folding occurs where the competent beds slide relative to one another, using the incompetent beds as 'lubrication'. Consequently, the latter horizons may become sheared and deformed, and one could imagine that if these were composed of interbedded limestones and marls, that a breccia might be created that would be similar to the ones which have been observed in the Middle Jurassic of the Lot Valley.

Furthermore, small step - like faults, comparable to those visible at St. Suplice, could also be envisaged to have formed at the bases of thicker, more competent units, if they became folded by a buckling mechanism (figure 93). Therefore, the disruption of the marls and limestone units of the Middle Jurassic may have been caused by a combination of flexural slipping and basal faulting which developed because of the growth of the gentle WNW - ESE folds that are found in the area; the latter probably grew in response to buckling stresses that were set up by the uplift of the Massif Central (p. 23).

More evidence of flexural slipping can be seen in the bedded limestones of the Larnagol, La Plogne and Marcilhac Members of the Cajarc Formation. Occasionally in these units, thin beds of marls or lignitic marl have been deformed, sheared and tectonically thinned or thickened in places, yet the beds of limestone above and below are undisturbed; these features could only have been produced by the sliding of one bed of limestone over another, using the marls as a lubricating medium.

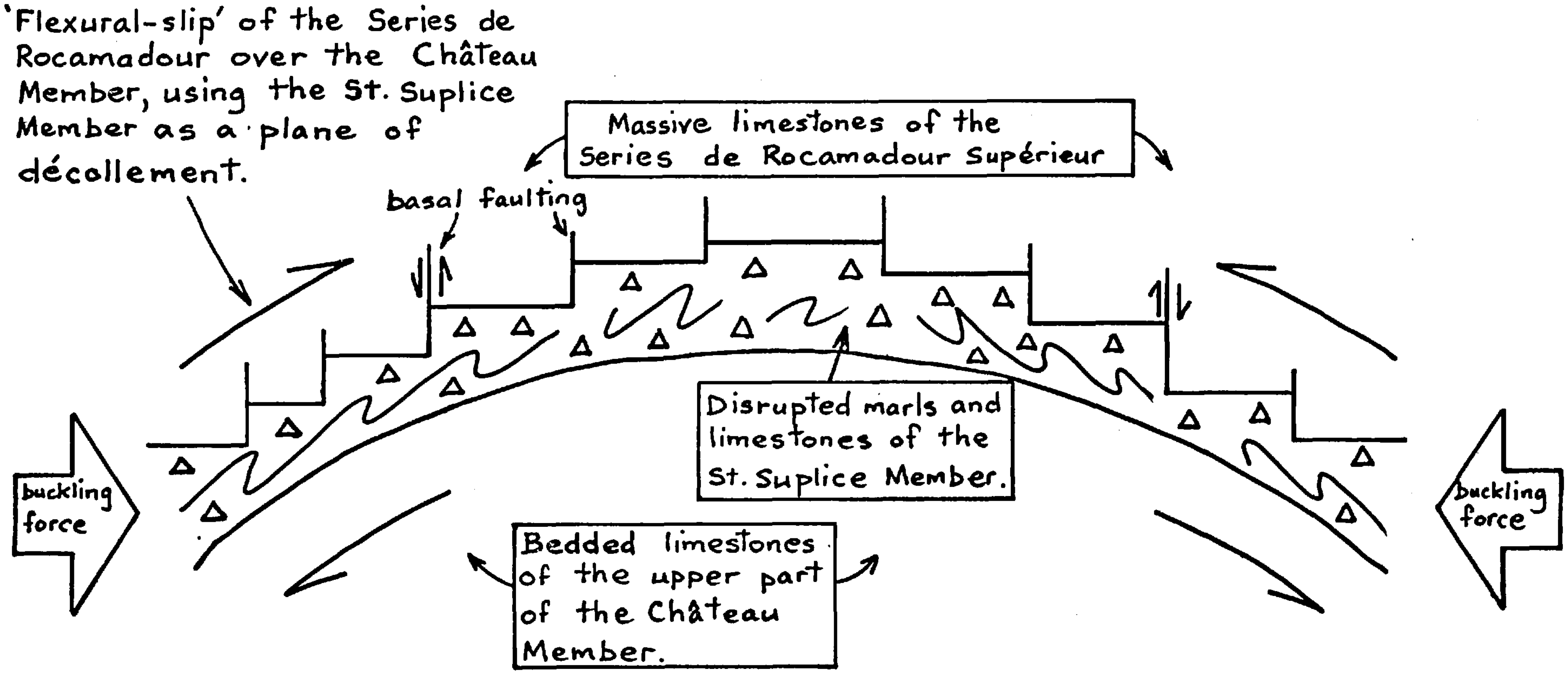


FIGURE 93 Development of basal faults in the Series de Rocamadour Superieur, and the mechanism of disruption of the marls and limestones of the St. Suplice Member of the Montbrun Formation.

Hence it seems that the Brengues and St. Suplice Members may have acted as incompetent horizons because of the occurrence of included beds of marl. If evaporitic deposits were also originally present in these units, then their relative incompetency would have probably been even greater, and it is of interest in this respect to note that evidence has been found to indicate the former presence of nodular anhydrite and laminated gypsum. Moreover, in the St. Suplice Member secondary anhydrite (now calcitised) originally replaced up to 50% of some of the beds of limestone, and following the arguments outlined on p. 355, it is possible that substantial quantities of primary anhydrite may have previously been interbedded with the marls and limestones.

The Breccias of the Massive Limestones

The study of the brecciation of the massive limestones has been made difficult because the outcrops of the Château Member usually form heavily weathered and inaccessible cliffs. Consequently most of the data has been derived from thin sections and polished slabs that have been made from samples which were collected while stratigraphic sections were being measured through the unit. Nevertheless, it has been possible to examine the brecciated limestones in a strike - section at La Plogne, and in some fresh road cuttings at Montbrun and Rocamadour.

At La Plogne (074263), the fractured basal crystalline grainstone of the Château Member passes laterally into zones of blocky breccia with clasts of the same lithology (figure 94 a) and there is no change in the overall thickness of the bed. Within the disrupted zones, blocks of

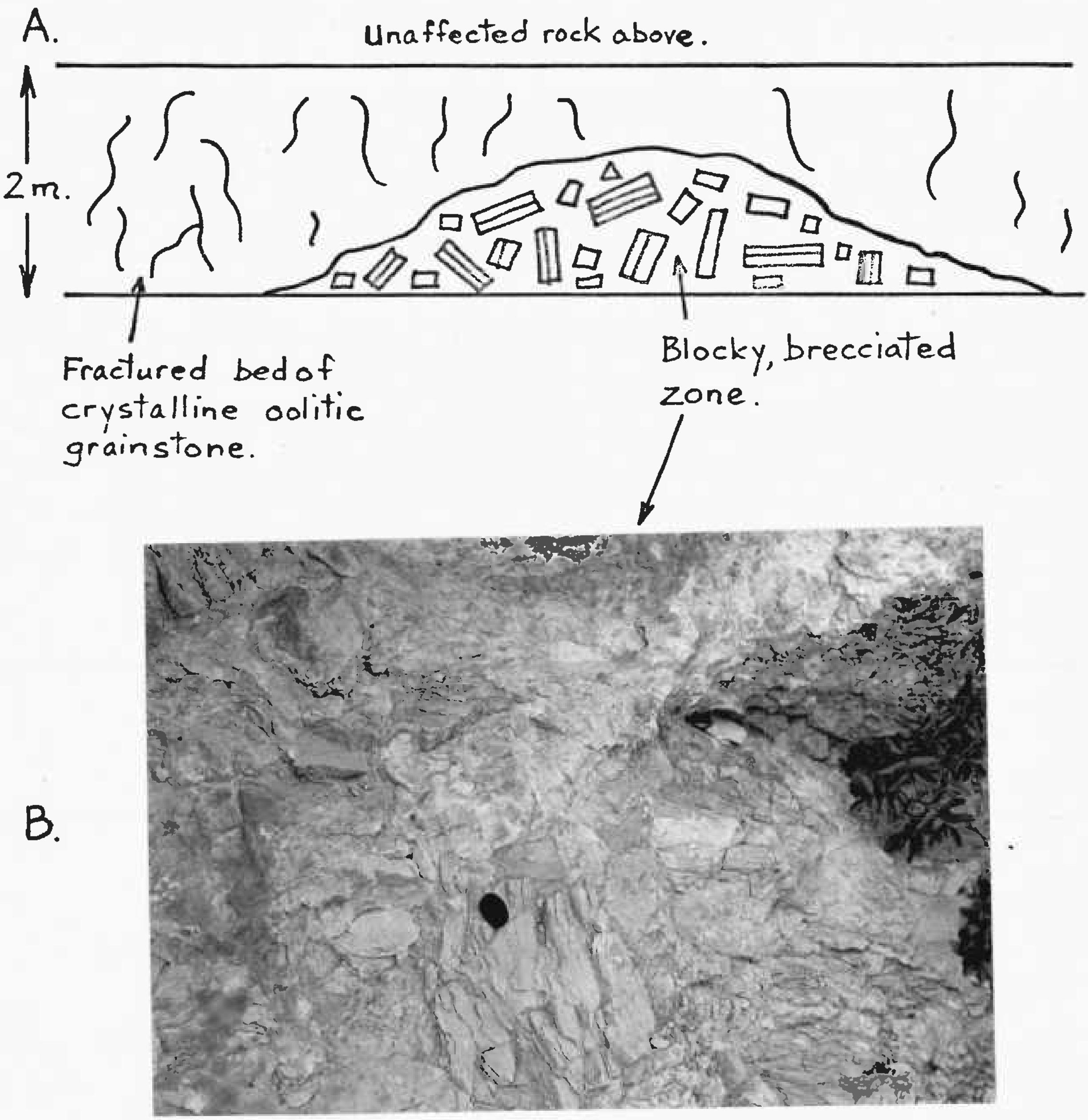


FIGURE 94 A) Sketch of the crystalline oolitic grainstone bed of the Château Member of the Montbrun Formation at La Plogne (074263), showing lateral passage from unbrecciated into brecciated rocks.

B) Detail of brecciated zone, showing a block resting prependicular to bedding (lens-cap = 6 cm.).

limestone now result at varying angles to their original positions (figure 94 b).

At Montbrun (126292) and Rocamadour the overall horizontally bedded nature of the Château Member is preserved, but individual beds have been disrupted and displaced, and fractured limestones pass laterally into shattered and brecciated rocks with no apparent variations in thickness. One particularly distinctive bed at Montbrun has been broken into a series of slabs, and some of these have dropped up to 25 cm. below the others (figure 95).

In some cases in the road section near Rocamadour, unaffected beds pass laterally into breccias, and in other cases zones of brecciation cut across the bedding at angles. Also certain horizons, such as those adjacent to bedding planes, have sometimes been intensely shattered. Relatively flat lying beds may become sharply upturned, with dips suddenly increasing by up to 45°; yet in the rocks above and below there are no such variations.

All gradations from incipient fracturing (figure 96) to intense brecciation have been recognised in the Château Member. When two fractures meet, small patches of breccia have often developed, and where they have become opened-up angular rock fragments have fallen between to form thin 'veins' of breccia (figure 96 b & 97). More intense disruption has caused the complete shattering of some beds, and chaotic breccias have resulted. All these types pass laterally into one

FIGURE 95 A roadside exposure of the Château Member at 072364 near the Château de Montbrun, showing a darker coloured bed which has been broken into a series of slabs.

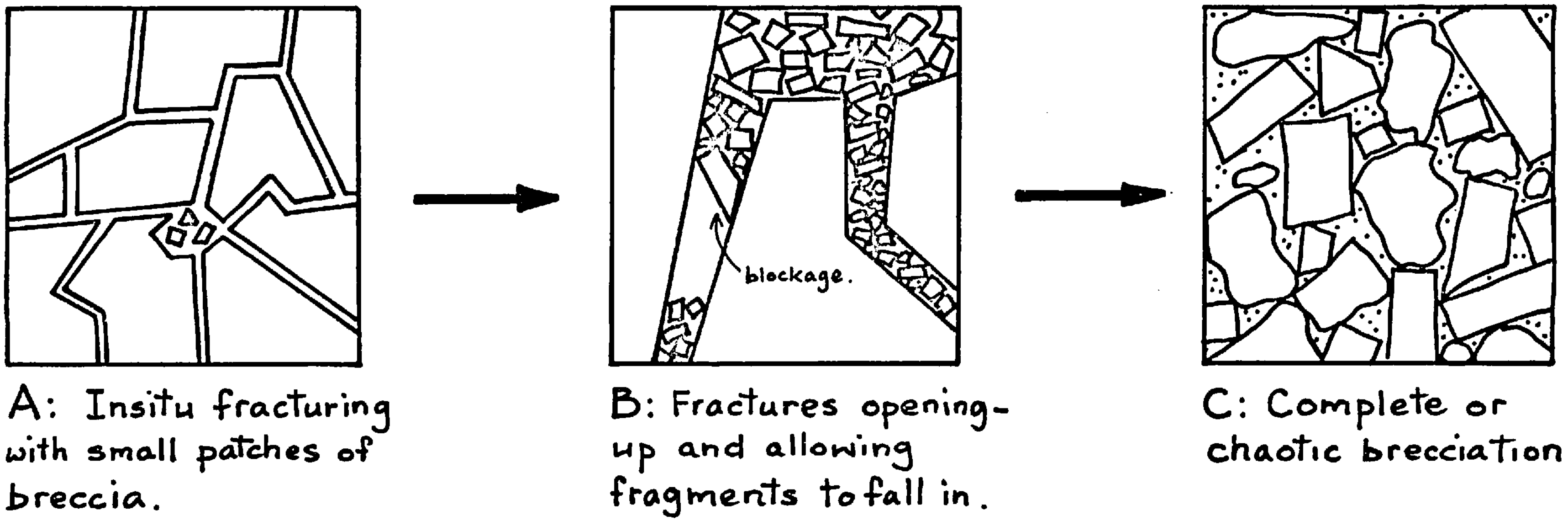


FIGURE 96 Progressive stages of brecciation in the massive limestones of the Montbrun Formation.

(x0·8)

FIGURE 97 Fractured calcareous mudstone with 'veins' of orthobreccia (Château Member; roadside exposure near Rocamadour).

another at outcrop and they probably represent the progressive stages of brecciation of the limestones.

Where intense brecciation has occurred the resulting rocks are mostly orthobreccias (Pettijohn 1957), and the individual fragments are angular or blocky in shape. The components range from sand grade up to huge detached bedded units, several metres across. The composition of the breccias is usually monomictic. This is probably because most of them appear to have been generated in situ from rocks whith no lithological variations. However, some oligomictic and polymictic breccias are also present where brecciation has cut across bedding planes. In these cases the lithological mixture seems to have resulted by fragments dropping down from overlying horizons; at Rocamadour some of the components have fallen by as much as 2m. below their original stratigraphic positions. The effect of gravity is also quite noticeable where small rock fragments have become wedged in open fractures. Empty spaces have been preserved below them and these have now been filled by calcite cement (figure 96 b).

Most of the fractured and brecciated rocks have been cemented by coarse crystalline calcite, but at some levels monomictic or oligomictic Parabreccias (Pettijohn 1957) are evident in which angular limestone fragments are supported by a calcareous matrix (figure 98). The latter is relatively fine grained, and texturally it resembles the calcareous replacement mosaics that have been found in some pseudomorphs after secondary anhydrite (figures 104 and 110).

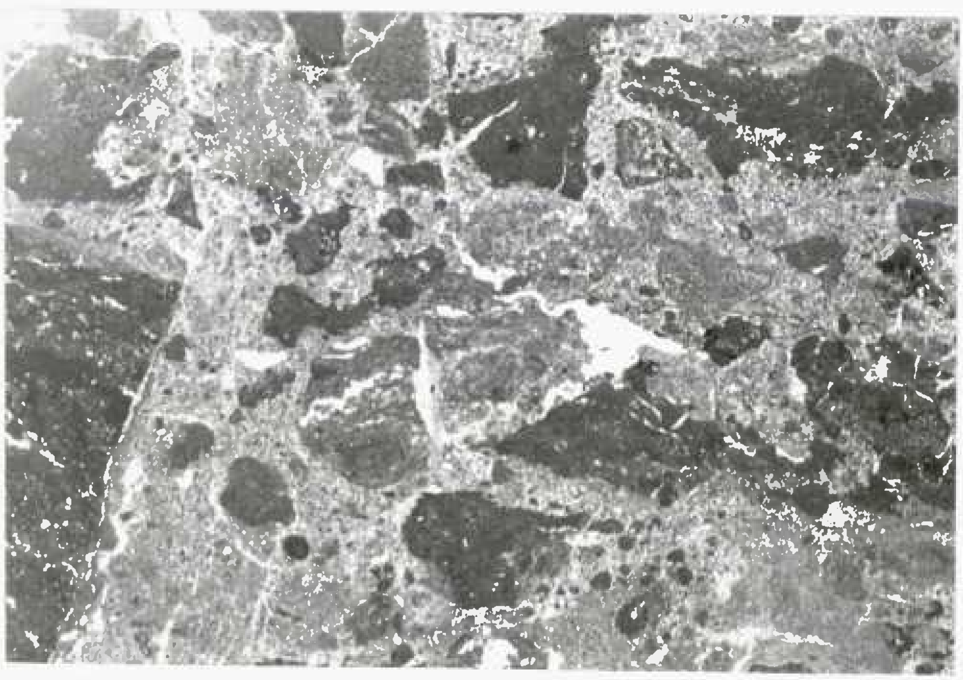
The Mechanism of Brecciation of the Massive Limestones

To summarise briefly, the Château Member comprises a

A.

(x1·5)

B.



(x6·5)

FIGURE 98 A) Parabreccia with a calcareous matrix: note that the fragments are supported by matrix.

B) Photomicrograph showing the texture of the matrix of the parabreccia in figure 98a (Château Member, roadside exposure at 073-364, near Brengues).

massively bedded limestone sequence which is sandwiched between sequences of marls and limestones that appear to have been tectonically disturbed. Brecciation seems to be restricted mainly to these units, and the sediments above and below are relatively unaffected.

Even when brecciation has been intense the stratigraphy of the massive limestones is preserved, and good correlations can be made from one location to another. Bedded and fractured limestones often pass laterally into brecciated zones with no apparent variations in thickness, and with unbrecciated rocks above and below, but sometimes the disruptions cut across bedding planes.

These features suggest that the brecciation of the massive limestones probably took place in situ, sometime after the deposition of the unit. Furthermore, the regional extent of the disrupted rocks, has convinced the writer that the brecciation has neither been the result of faulting nor of penecontemporaneous disruption during the deposition of the rocks. However, during the burial of the succession, several other mechanisms such as tectonic, solution - collapse or hydraulic brecciation, may have been important. These will now be considered separately.

(i) <u>Tectonic Brecciation</u>

Daukoru (1970) postulated a tectonic mechanism of brecciation for the Blagour Formation, which is the lateral equivalent of the Montbrun Formation in the Dordogne Valley. He concluded that the rocks had been fractured and brecciated while they were being folded. However his arguments do not seem to have been very realistic: firstly, the influence of an overburden pressure was not considered; secondly, the pattern of strain that probably would have developed in the folds was disregarded, therefore the fracture patterns that were infered seem unlikely; and thirdly no attempt was made to explain why the limestones above and below the brecciated horizon were largely unaffected (this would not have been expected if folding had been responsible for the brecciation).

If the disruption of the massive limestones has been caused by folding, there would probably be a relationship between the degree of folding and the intensity of brecciation. However a comparison of the pattern of brecciation (figure 87) with the fold axes developed in the Lot Valley area (figure 7), has shown that no obvious relationship exists.

(ii) Solution - Collapse Brecciation

Middleton (1961) showed that the brecciation of certain Mississippian limestones in S.W. Montana, might have been caused by the dissolution of evaporites, and the subsequent collapse of the overlying beds into the space so created. He proved that evaporites had formerly been present by making correlations with the same rocks in the subsurface, and he suggested that they were removed by the circulation of groundwaters, during uplift and erosion.

One of the problems with this interpretation is that for collapse to have taken place, it would have been necessary to maintain the space left after the removal of the evaporites, against the weight of the overburden. Stanton (1966) overcame this by suggesting that brecciation would probably take place concomitantly with dissolution, and that as removal occurred some of the remaining evaporitic material would flow into the disrupted limestones to form a matrix. Eventually, if all the evaporites were removed, only a residual breccia would remain.

A similar mechanism can also be postulated for the brecciation of the massive limestones of the Montbrun Formation, because there is ample evidence to indicate the former existence of evaporitic minerals. If these were present in reasonable quantities, their subsequent removal might have caused the brecciation.

Lucia (1972) noted that the best evidence for solution - collapse brecciation is the lateral passage of the surface breccias into subsurface sequences with abundant evaporites. Although no equivalent evaporites have been described from the subsurface rocks of mid - Aquitaine, this may be because these have been calcitised, and as yet have not been recognised as such. Therefore until the subsurface evidence is clarified the role that solution - collapse brecciation has played must be left open.

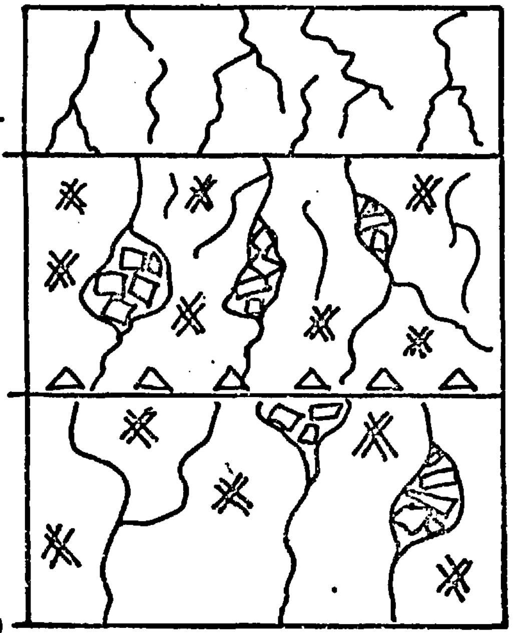
The origin of the matrices of the parabreccias is critical to this argument because it is possible that they have produced by the calcitisation of the anhydrite matrices of breccias. If this is so then it would suggest that solution - collapse brecciation has occurred. Also it would perhaps indicate that substantial quantities of evaporites have formerly been present. Another alternative, however, is that the matrices were formed as a 'rock - flour", which could have been generated by any mechanism of brecciation.

<u>The Origin of the Parabreccias</u>: Bouroullec et al (1973, p.15, figure 4) described a parabreccia from the Jurassic of Aquitain that is almost identical to those found in the Montbrun Formation. They interpreted it as a 'collapse breccia of tidal channel origin', but what exactly they meant by this is not clear to the present writer.

Middleton (1961) found some parabreccias with calcareous matrices in the Mississippian limestones of S.W. Montana. He suggested that the matrices had originated as 'rock - flour'. This was thought to have been generated by mechanical processes, when underlying evaporites were removed by leaching, and the overlying limestones collapsed into the space so produced. During cementation each of the minute grains of the matrix became overgrown by calcite, and a fine to medium grained mosaic of crystals was formed. Using Rosin's Law he also argued that mechanically generated breccias should contain up to 20% by weight, of material less than 0.0625 mm. in diameter.

The parabreccias of the Montbrun Formation are very similar in appearance to the ones described by Middleton. At outcrop they form thin horizontal layers, beneath beds which have been fractured or brecciated and although it has not been possible to estimate the amount of fine grained material present, the matrices could easily have accumulated as a 'rock - flour' derived from the brecciation of overlying limestones (figure 99).

Stanton (1966) described some parabreccias from borehole cores, that except for a matrix of anhydrite, were also similar, in many respects, to the parabreccias of the Montbrun Formation. As had Middleton, he considered these to have been produced by the removal



Description	Interpretation according to: Middleton (1961).	Stanton (1966).
Fractured bed.	Mechanical brecciation: fine material falling down to form a parabreccia.	Concomitant collapse, causing fracturing and brecciation.
Fracturing and orthobrecciation becoming more intense downwards. Pseudomorphs after seondary anhydrite. Thin band of parabreccia.		Solution of an evaporite band (now calcitised).
Fractured bed with patchy orthobrecciation. Pseudomorphs after secondary anhydrite.		

FIGURE 99 The possible origins of the parabreccias in the roadside exposure (D32) of the Château Member, near Rocamadour.

of evaporites but he thought that as dissolution progressed concomitant brecciation took place, and that the evaporites had flowed into the brecciated limestones.

The texture of the matrices of the breccias in the Montbrun Formation are very similar to those which have been observed in calcitised bands of nodular anhydrite, and in pseudomorphs after secondary anhydrite. Thus the parabreccia could have been formed by a similar mechanism to that proposed by Stanton, with the difference, however, that the matrix was later replaced by calcite. Moreover, the field evidence (figure 99) seems to agree with the processes suggested by Stanton, because if an evaporitic band were to become dissolved a thin parabreccia would develop and the overlying limestones would gradually collapse and become fractured and brecciated, and there is plenty of evidence to suggest that evaporites were formerly present.

As both the field and textural evidence can be interpreted in two ways, it is difficult to decide whether the matrices have been generated from a 'rock - flour', or by the calcitisation of anhydrite. Indeed, a breccia produced by solution and collapse would almost certainly contain some fine grained material, which according to Stanton's arguments, would become intermixed with anhydrite. If this matrix became calcitised, each of the calcareous inclusions would probably be overgown and the grain - size of the resulting mosaic would be dependant on the abundance of inclusions; widely spaced inclusions would form a coarse mosaic, whereas more densely packed ones would give finer mosaics. Thus a situation could be imagined where if all the inclusions were in contact, the resulting texture would be undistinguishable from that of a loosely packed, but cemented, fine - grained calcareous accumulation, such as a rock - flour or geopetal sediment.

(iii) Hydraulic Brecciation

When a pile of sediments is buried and compacted, or is tectonically compressed, the porosity of the rocks decreases and some of the pore-water is driven out. If this water is prevented from escaping by a relatively impervious barrier, the pressure would probably build up until it equalled that of the overburden. Any further increases in pressure may cause the overburden to be hydraulically floated-off, or jacked-up. Some water might also escape by fracturing the impervious barrier, and migrating upwards until the pressure once again became equal to that of the overburden.

Once a space has been created by hydraulic jacking, and the overpressured waters have begun to stope their way into the overburden, the resulting debris would probably fall downwards into the void and accumulate as a passive collapse breccia. By this mechanism, a susceptible horizon could become intensively fractured and brecciated while other parts of the succession remained relatively unaffected.

This is a very potent mechanism which has been given very little consideration by geologists in the past. Shearman et al (1972) recently realised this potential and they convincingly argued that hydraulic jacking had occurred in some Permian and Jurassic evaporitic sequences. Price (1975) also made some theoretical investigations and he concluded that hydraulic jacking and fracturing were possible important geological processes.

Actual evidience of the operation of hydraulic processes in rocks can be obtained by examining some practices in industrial geology. For example, in the Petroleum Industry the porosity of reservoir rocks is sometimes artifically increased by fracturing them with highly pressured water or gel. Also, when dams are being built, the sites are usually grouted by drilling a series of boreholes and pumping pressurised cement into them. However, great care must be taken not to exceed the pressure exerted by the overburden, as this may induce hydraulic jacking which could disturb the foundations of the dam and destroy the water sealing properties of the bed-rock.

Price (op cit.) noted that evaporitic deposits might form relatively impervious layers, especially in successions where pore-waters are overpressured. In the Montbrun Formation, evidence of the former existence of evaporites is much more abundant than in the rest of the Middle Jurassic sequence. Therefore it is possible that these may have formed a seal and thus have allowed selective hydraulic jacking and brecciation in the Montbrun Formation, while the remainder of the succession was unaffected.

(iv) <u>Generation of High Pore - Water Pressures</u>

In order to cause the hydraulic brecciation of the Montbrun Formation, high pore - water pressure must have been generated at some time during the history of development of the rocks. Two lines of evidence suggest that his may have occurred.

Firstly, thin 'beef' horizons of fibrous calcite are present in some of the lignitic marls beds of the La Plogne Member of the Cajarc Formation. Shearman et al (1972) argued that similar layers of gypsum 'beef' probably grew in spaces between bedding planes that were created by hydraulic jacking. When the hydraulic effect was removed, the full loading of the overburden was transferred to the gypsum crystals, and this imparted a vertical fibrous texture to them. An analogous process may have formed the calcite 'beef' layers in the Cajarc Formation.

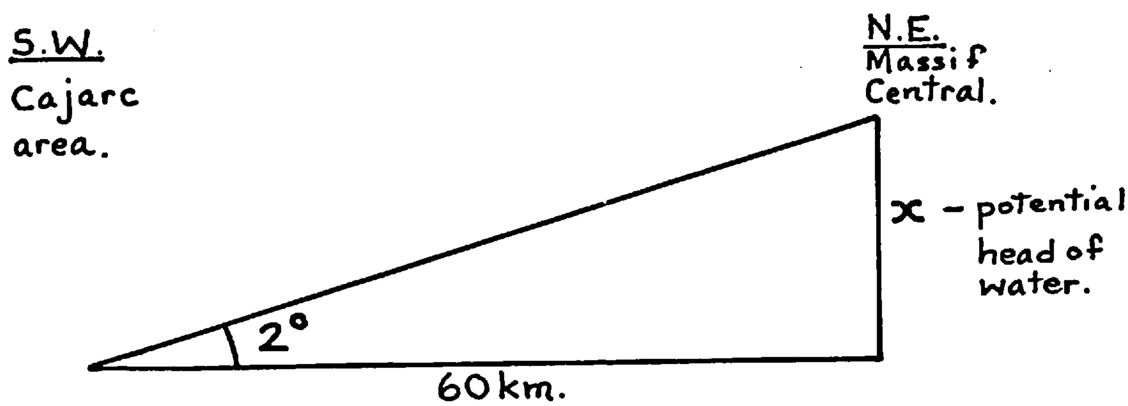
Secondly, buckling forces appear to have induced the Middle Jurassic rocks of the Lot Valley to be folded by a 'flexural slip' mechanism (p.272). This probably took place when the rocks were buried under at least 900 m. of overburden (p. 21) Price (1975) noted that for buckling forces to induce 'flexural slip' folding under the weight of an overburden, the frictional resistance between each bed must be overcome. He though that a high pore - water pressure would minimise this, and he concluded that for folding to commence the fluid pressure would almost certainly have to be equal to the lithostatic pressure.

The question which must now be asked is how these high pressures were generated. Price (op.cit.) argued that during the burial of sedimentary rocks the pore - water pressure should increase according to the hydrostatic head of water that is available. In theory, as the specific gravity of water is less than that of rock, the hydrostatic pressure should always be less than the lithostatic pressure which is due to the weight of the overburden. Under these conditions the ratio (λ) of the pore - water to lithostatic pressure would be about 0.4. However, in practice, sedimentary rocks are usually compacted during burial, and any water that is trapped in the pore - spaces may become highly pressured. Price showed that often the pore - water pressure can approach the lithostatic pressure, so that $\lambda \simeq 1$.

An increase in the pressure of the pore - waters of the Middle Jurassic rocks of Aquitaine, might have been influenced by three factors; folding, burial and compaction, and temperature.

Folding: This could have increased fluid pressures in two ways; firstly by creating a much higher hydrostatic head of water than would otherwise have been available; and secondly, by causing tectonic compression of the rocks.

Isopach maps published by the B.R.G.M. (1973) have indicated that Middle Jurassic sediments onlapped the Massif Central by about 50 or 60 km. Therefore, the uplift of the massif, which probably occurred in the late Jurassic - early Cretaceous, could have created a hydrostatic head of water of about 2100 m:



$$\text{Tan } 2° = \frac{x}{60 \times 100}$$

Therefore x = 2094 m.

Price (op. cit.) showed that hydrostatic pressure (p) can be calculated using the equation:

$$p = \rho g z_1 \ldots\ldots\ldots(i)$$

and the lithostatic pressure is given by:

$$\sigma = \rho_b g z_2 \ldots\ldots(ii)$$

where ρ is the density of water, ρ_b the bulk average density of rock, g the acceleration due to gravity, z_1 the head of water available, and z_2 the thickness of the overburden.

From equations (i) and (ii):

$$\lambda = \frac{p}{\sigma} = \frac{\rho g z_1}{\rho_b g z_2} \ldots\ldots(iii)$$

For hydraulic brecciation to have occurred in the Cajarc area, λ must have constantly been approaching unity.

Therefore $$\frac{\rho Z_1}{\rho_b Z_2} = 1$$

and the head of water that would have been needed to cause the necessary overpressuring is given by:

$$Z_1 = \frac{\rho_b Z_2}{\rho}$$

Now the thickness of the overburden (Z_2) in the Cajarc area at this point in time, was probably about 900 m. (p. 21), so taking $\rho = 1$ and $\rho_b = 2{\cdot}5$:

$$z_1 = 2.5 \times 900$$

$$= \underline{2250m}.$$

Thus, although the potential head of water (2100 m.) would almost certainly have raised the pressure of the pore - waters, it was probably not enough to cause hydrobrecciation on its own.

Besides the possibility of creating an increased hydraulic head of water, folding also causes internal strains to be set up in the rocks, and these probably decrease the porosity. If the tectonic strain increases at a faster rate than the pore - waters can escape, overpressuring may result (Price, op. cit.). However, no data is available to quantify this process, so its role in the brecciation of the Montbrun Formation cannot be assessed.

Burial and Compaction: If a layer of sediment becomes buried, stresses are imparted on to it by the weight of the subsequent overburden. This causes compaction to occur, and the resulting internal strains decrease the porosity of the rocks, and any excess pore - water is driven - off. However, if the burial was to be relatively quick, or if an impermeable barrier existed, the rate of strain would probably increase faster than the pore - waters could escape.

Consequently, the confinement of the latter would almost certainly cause the fluid pressure to increase, and under the right conditions it might even approach the lithostatic pressure (i.e. $\lambda \simeq 1$).

Price (op. cit) proposed a simple model for the dewatering of a horizontal sequence of sediments in which the vertical stress or lithostatic pressure at any particular depth, can be found using equation (i) on page 292 . The effective horizontal stress was assumed to be 80% of the vertical stress, and was initially everywhere assumed to be 0.7. The pore - water pressure at any particular depth was calculated using equation (iii).

Hence $$0{\cdot}7 = \frac{P}{h\rho_b g}$$

Therefore $$P = 0{\cdot}7 h \rho_b g$$

A slightly modified version of this has been used to construct a model for the Middle Jurassic sediments of the Aquitaine Basin (figure 100). The data for this has been taken from borehole logs and isopach maps published by the B.R.G.M. (1973). It represents a unit width of the basin, stretching from the Massif Central to the Atlantic coast, and it takes into account the state of burial at the end of the Lower Cretaceous, since when very little deposition has occurred.

The thick line A - B represents the Montbrun Formation. This is assumed to be an effective seal against the

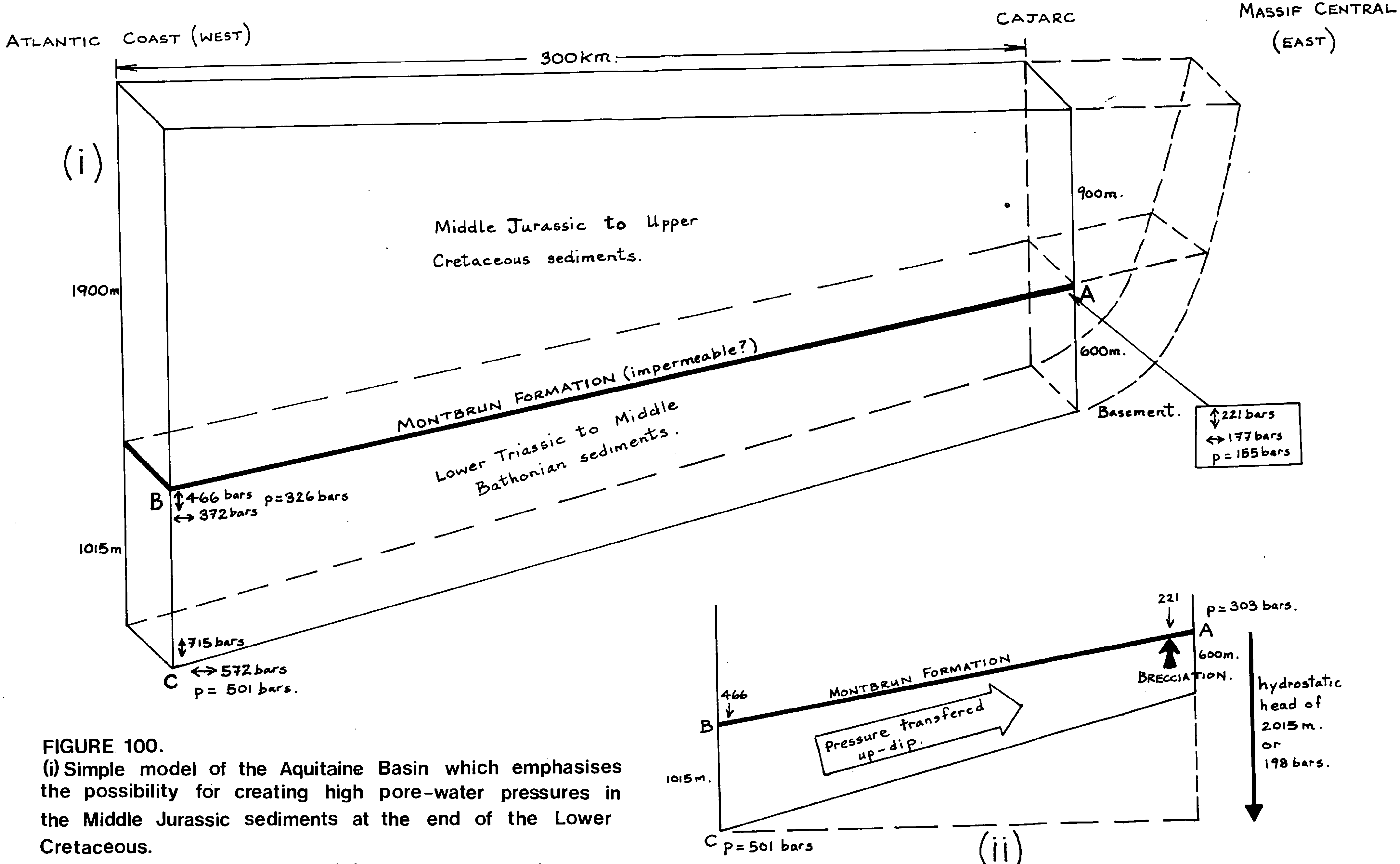


FIGURE 100.
(i) Simple model of the Aquitaine Basin which emphasises the possibility for creating high pore-water pressures in the Middle Jurassic sediments at the end of the Lower Cretaceous.
Theoretical values of vertical (↕) and horizontal (↔) stress, and pore-water pressure (p) are given at A, B and C. (calculated after Price 1975).

(ii) Diagram showing how the pore-waters may become overpressured at A, and escape by hydraulic brecciation. The effective pressure at A is 501−198=303 bars.

upward migration of pore - waters. Using Price's model, the theoretical values of vertical and horizontal stress, and the pore - water pressures have been inserted below the level of the Montbrun Formation.

The pore - water pressure that initially would have existed at C is 501 bars, and at B 155 bars. Assuming the system was closed and given the long period of time that was involved, if 501 bars was constantly available at C [figure 100 (ii)] ,then eventually the pressure at A would increase to 303 bars (501 minus 198 bars, which is the hydrostatic head, between A and C, acting against the pressure at C).

Theoretically, therefore, the pore - water pressure at A could have exceeded the lithostatic pressure by 82 bars (303 minus 221). In reality, however, every time the pore -water pressure approached the lithostatic pressure, hydraulic jacking and/or brecciation would probably have taken place, and the excess of 82 bars would have gradually been dissipated upwards; each time λ approached unity the pressure would have been released.

Temperature: As a sediment becomes buried, the temperature to which it is subjected can be expected to increase progressively. A unit volume of water that is buried to a depth of 3 km. would probably encounter a temperature in the order of 100^{o}C. To maintain its original pressure the unit would need to expand by 3% of its initial volume. However, during burial, the effect of compaction usually decreases the porosity of a sediment, and no expansion of the pore - water would be permitted; if anything it is compressed.

If the increase in volume of 3% was prevented, the fluid pressure would probably increase to about 1500 bars! Therefore to maintain λ at unity or just less, the increase in volume of the pore - waters must be accommodated by the constant dewatering of the sediments as temperature increases. If a relatively impermeable barrier was able to stop dewatering from occurring, the potential increase in pore - water pressure would probably be very great.

(v) A Model for Hydraulic Brecciation

Although many assumptions have been made in the foregoing mathematicl arguments, they do emphasise the potential that may have existed for the operation of hydraulic processes. If the Montbrun Formation did form a relatively impermeable barrier against the dewatering of the sediments, then it can be shown that high pore - water pressures would have resulted. However, the relative roles played by compaction, temperature and tectonic compression are difficult to assess, and they may even have been equally important.

The overburden in the centre of the Aquitaine Basin was much thicker than at the margin. Therefore the pore - waters probably only became overpressured at the basin margin, and it is only in these areas that hydraulic brecciation can be expected to have taken place.

At the same time that high fluid pressures were probably being created in the centre of the basin, the Massif Central was being uplifted, and the marginal Jurassic rocks were gradually being uplifted and eroded; the present state of erosion was probably reached in the early Tertiary times the weight of the overburden was being progressively released, so that the lithostatic pressure was gradually decreasing. This, in conjunction with a constant source of highly pressure pore - waters from the centre of the basin, would have probably maintained λ almost continuously at unity.

Under these conditions it might have been possible for hydraulic jacking, fracturing and brecciation to have operated throughout the time that uplift and erosion was occurring. Therefore hydrobrecciation must be considered as one of the possible causes of the disruption of the Montbrun Formation.

5.5 Conclusions on the Origin of the Breccias

Three mechanisms have been considered for the brecciation of the Montbrun Formation; tectonic, solution - collapse and hydraulic brecciation. tectonic mechanism has probably caused the disruption of the marl and limestone units, no conclusive evidence has been found to indicate which of these processes operated on the massive limestones.

It may even be possible that all three processes have some part in the deformation of the rocks. For example, the evaporitic bands in the Montbrun Formation could have formed an impermeable barrier and thereby caused pore - water pressures to build up. This would have allowed hydrobrecciation to take place. At the same time some solution - collapse brecciation could have been operating, because as dewatering progressed some of the evaporites may have been removed in solution.

Also, simultaneously, the uplift of the Massif Central was probably setting up buckling stresses, and as λ probably equalled unity, 'flexural slip' folding was initiated (Price, 1975). This caused the disruption of the marls and limestones, and it may even have deformed the massive limestones to some extent.

5.6 The Possible Economic Importance of the Montbrun Formation

Many workers now believe that Mississippi Valley - type lead - zinc ore bodies may have been formed entirely as a result of the diagenesis and dewatering of sedimentary rocks. Beales and Jackson (1966) noted that most of the known examples of this type of ore deposited have been found in the marginal areas of sedimentary basins, usually in carbonate host rocks. They considered that the metals were derived from clay minerals, during diagenesis. Dunsmore (1975) suggested that they may also be derived from carbonate and evaporitic minerals, and their co-existing brines.

Beales and Jackson thought that as dewatering progresses in response to compaction, metals might be carried towards the basin margin by the migrating pore - waters. Precipitation as metal sulphides was thought to occur when metal - rich waters came into contact with sulphide rich ores.

Shearman (1971) suggested that sulphides may be produced by the reduction of sulphates in the presence of hydrocarbons, and residual traces of hydrocarbons have sometimes been found in association with ore metals.

Moreover, sulphate is only usually abundant in carbonate evaporite successions. Therefore it is not suprising that lead - zinc ore bodies are usually found in carbonate host rocks, in situations where the accumulation of hydrocarbons might be expected to have taken place.

The same process of dewatering which concentrates hydrocarbons into suitable reservoir rocks, probably brings sulphate ions into contact with hydrocarbons. It also possibly causes metal enriched solutions to pass through the hydrocarbon reservoirs. Eventually this might create a commercial ore body.

Many important lead - zinc ore deposits have been described from host rocks of brecciated limestone or dolomite. One such deposit occurs just north of Figeac, in the Lot Valley, where some brecciated dolomitic rocks of Sinemurian age have been mineralised. In many ways these breccias are similar to those developed in the Montbrun Formation because:

(a) In both cases the textures are similar and they consist of monomictic or oligomictic orthobreccias, cemented together by coarsely crystalline calcite.

(b) The fragments making up the breccias are mostly dolomitic, or have been so at some time; the Sinemurian breccias are entirely dolomitic, but the brecciated rocks of the Montbrun Formation are mostly dedolomitised.

(c) Both examples have been generated from lagoonal deposits at the margin of the Aquitaine Basin, and the brecciated sequences pass basinwards into thick carbonate or carbonate evaporite successions (figures 101 and 102).

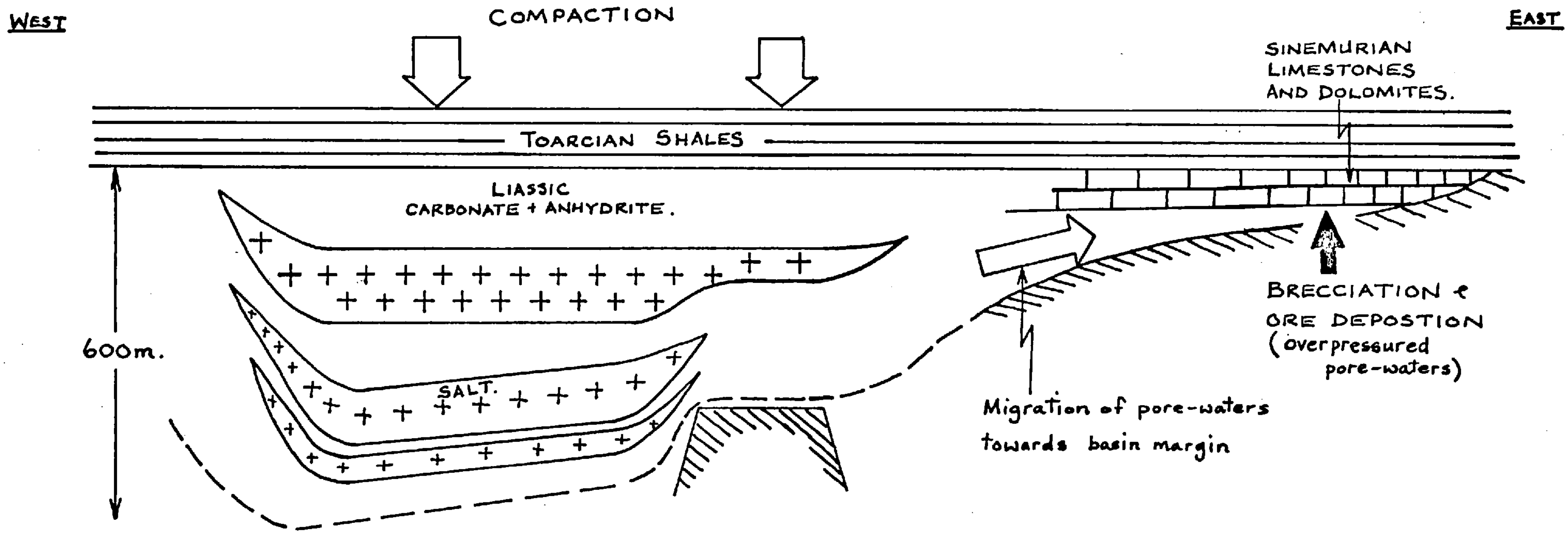


FIGURE 101. Cross-section of the Liassic rocks of the Aquitaine Basin, showing the migration of pore-waters; the brecciation of the marginal limestones, and the situation of ore deposition. (Based on Winnock et al, 1973).

These similarities suggest that the Montbrun Formation could also be a zone of potential lead - zinc mineralisation. This is emphasised by fitting the model of ore formation, suggested by Beales and his co - workers (1966, 1970) and Dunsmore (1985), to the Jurassic rocks of Aquitaine.

The compaction of the carbonate - evaporite succession within the basin probably caused the connate waters to migrate towards the basin margin (figure 101). Here, in response to the repeated build up of pore - water pressures, carbonate rocks have been brecciated, and these have acted as hosts for lead - zinc ore bodies. All the necessary ingredients, metals, sulphates and hydrocarbons, could easily have been derived from the sediments within the basin, and as dewatering progressed these were concentrated into the suitable host rocks, i.e. the breccias, to form ore deposits.

The same argument can also be applied to the brecciated rocks of the Montbrun Formation (figure 102). Compaction probably caused the generation of high pore - water pressures within the basin. This induced the migration of connate waters towards the basin margin, where they escaped by hydrobrecciation. Thus pore - waters rich in metals and sulphates may have been filtering through brecciated carbonate rocks. There are two reasons for believing that hydrocarbons were also in evidence; firstly lignitic beds occur in the Cajarc Formation and these may have been a source of methane, secondly all the calcium sulphate minerals in the succession have been replaced by calcite, which might have been achieved by reduction in the presence of hydrocarbons (p. 353).

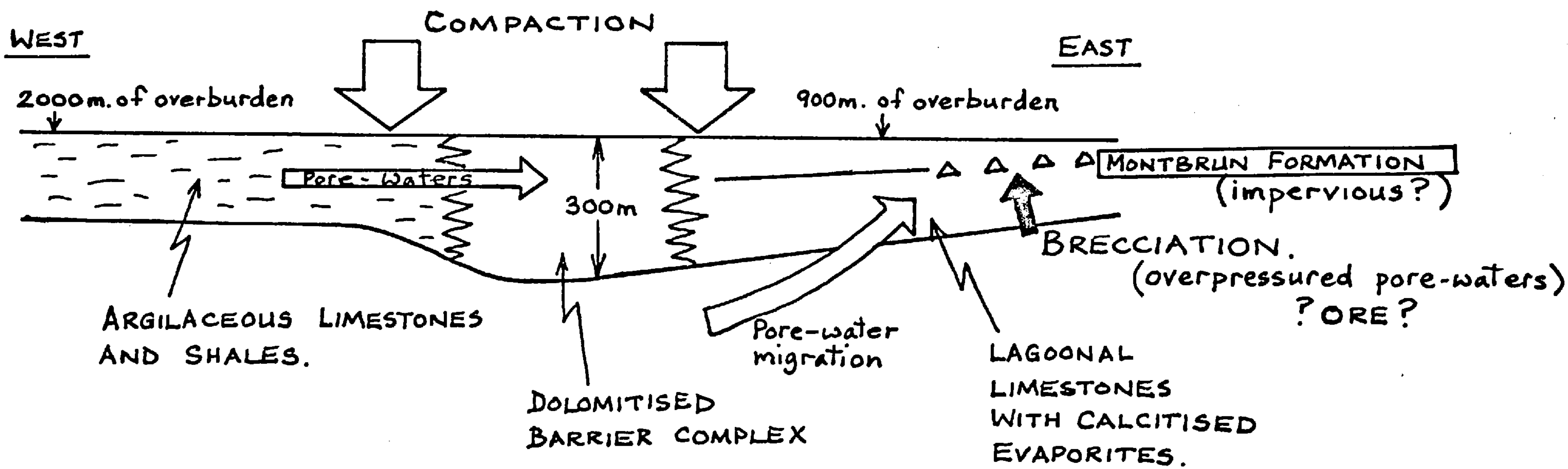


FIGURE 102 Cross-section (after Winnock et al, 1973) of the Middle Jurassic rocks of the Aquitaine Basin, showing the migration of pore-waters and the brecciation of the Montbrun Formation.

Thus, if hydrocarbons were present, ore deposits might be expected to have formed somewhere in the Middle Jurassic breccias on the eastern flanks of the Aquitaine Basin, but so far none have been found.

CHAPTER 6

VANISHED EVAPORITES

Calcareous and siliceous pseudomorphs after evaporitic minerals have been found in the Middle Jurassic rocks of the Cajarc area, in association with intertidal and supratidal sediments. Moreover, spherules of diagenetic lutecite are present and Folk and Pittman (1971) and West (1973) considered that these probably indicate that evaporitic deposits have formerly been present. This chapter is concerned with the description of the pseudomorphs and the identification of the original minerals which were present. An attempt will also be made to clarify some of the difficulties which have arisen with these identifications.

Five types of replaced evaporitic deposits have been recognised:

1. calcitised and silicified crystals of secondary anhydrite.
2. calcitised nodular or entrolithic deposits of primary anhydrite.
3. calcitised discoidal crystals of primary gypsum.
4. calcitised deposits of laminated primary gypsum.
5. calcitised crystals of celestite (?).

6.1 Secondary or Replacement Anhydrite

Shearman (pers.comm., 1975) demonstrated that in some borehole cores of Devonian and Mississippian limestones from Western Canada, the host rock has been partially replaced by patches of secondary anhydrite. In thin-sections these usually comprise single or groups of crystals which porphyroblastically enclose numerous unreplaced relicts of the host limestone. Often the presence of inclusions has preserved the original fabric of the limestones within the porphyroblasts and this can be seen most clearly when the anhydrite is at extinction (figure 106).

Secondary or replacement anhydrite is usually found in close association with nodular or entrolithic deposits of primary anhydrite. It is possible, therefore that the $CaSO_4$ which replaced the limestones may have been derived during diagenesis from adjacent layers of primary anhydrite.

Shearman recognised three types of secondary anhydrite which can be described as castellated, axe-head and vein types respectively.

The castellated types are composed of single or groups of several crystals which have an irregular appearance in hand specimen (figure 103). In thin-sections they are subhedral and they possess rectangular outlines with 90^{o} re-entrants (figure 104a).

The axe-head types comprise single euhedral crystals which are shaped like double axe heads (figure 115a). On fractured surfaces and in thin sections these exhibit a variety of cross-sections, depending upon the orientation of the crystals, which include lanceolate, truncated lanceolate, barrel and rectangular shapes (figure 113a).

The veins of secondary anhydrite (figure 117a) consist of irregularly outlined stripes made up of porphyrobastic crystals. The central zone of the veins is usually clear, but the outer zones are cloudy and packed with inclusions. The borders are often castellated in a similar way to the subhedral crystals. They are thought to originate when anhydrite replaces limestone on either side of fractures; the latter being usually preserved as clear central zones.

Calcitised and silicified pseudomorphs of these three types

FIGURE 103 Some limestones from Western Canada which have been replaced to varying degrees by castellated crystals of secondary anhydrite (left) and some comparable calcareous pseudomorphs (right), from the Brengues Member of the Cajarc Formation, near Brengues:

A) small patches (left) and similar calcareous pseudomorphs (right).

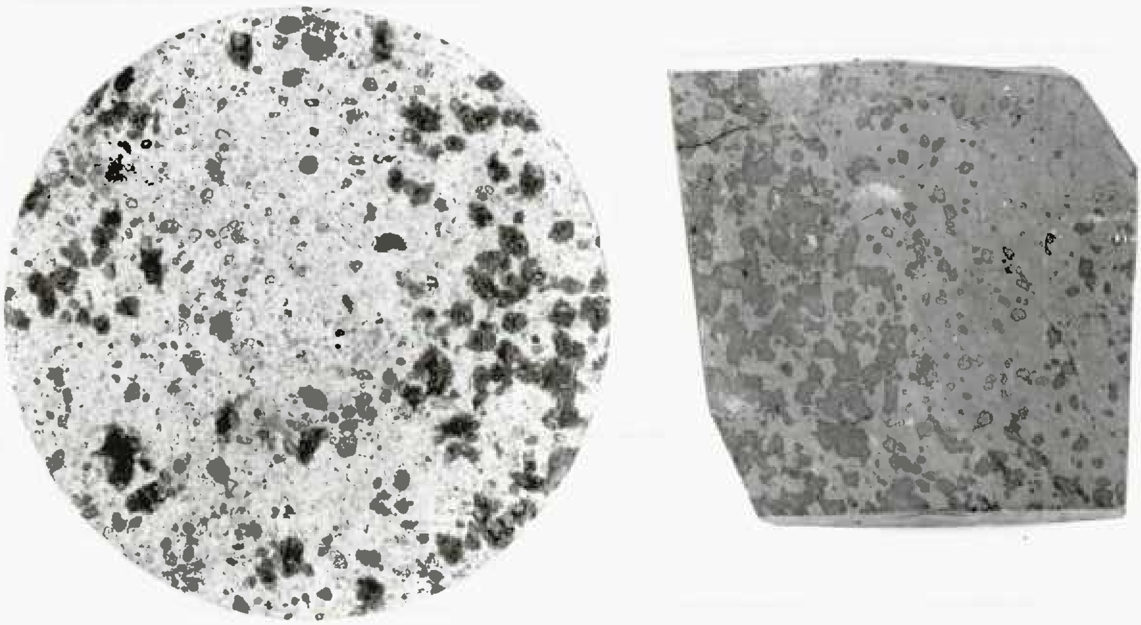
B) larger patches and the equivalent pseudomorphs.

C) extensive patches and some comparable pseudomorphs.

(All photographs are actual size; Canadian examples are courtesy of D.J. Shearman).

A.

B.



C.

of secondary anhydrite have been observed in the Cajarc and Montbrun Formations and in the Series de Rocamadour Superieur.

Calcitised Crystals of 'Castellated' Secondary Anhydrite

Some unusual mudstones have been found in the Cajarc and Montbrun Formation, with irregular, darker coloured patches or spots, which range upwards from 0.5 mm. in size. These rocks are entirely calcareous and in hand specimen there is no apparent textural variation between light and dark areas.

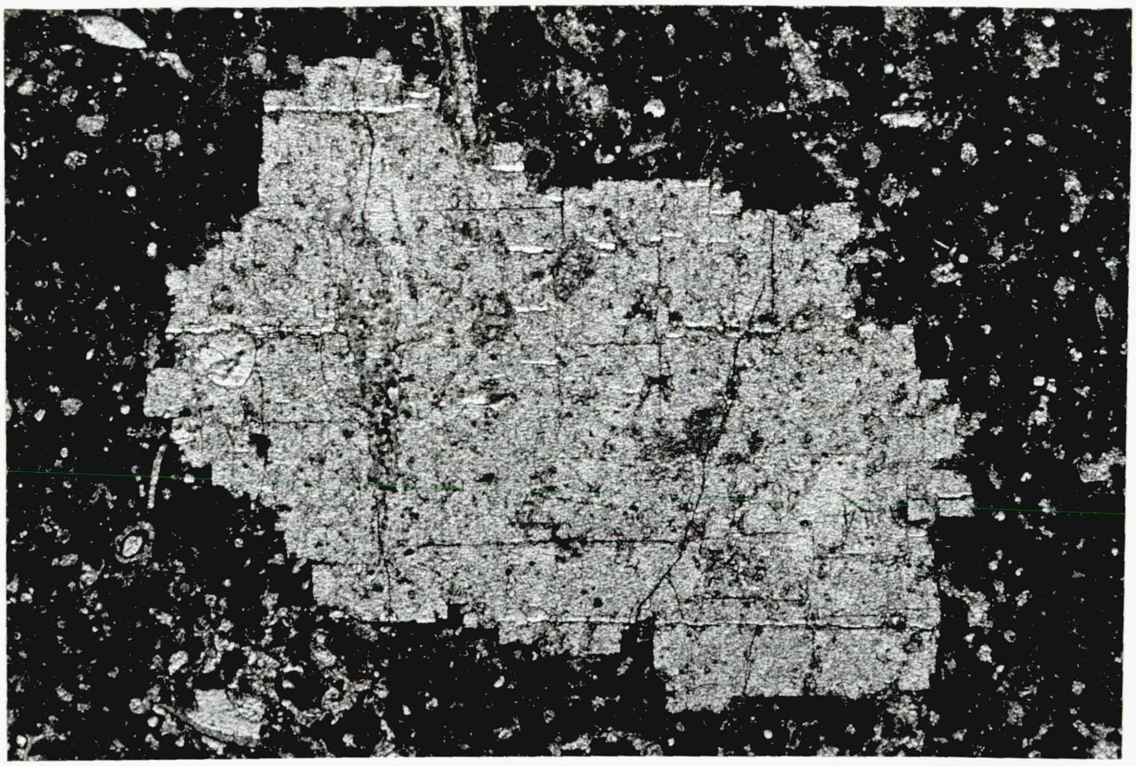
The sizes and scales of development of the patches are exactly comparable to the subhedral crystals of secondary anhydrite which have been described in the previous section (figure 103). Moreover, in thin sections, the patches have castellated outlines (figures 104b & 105) that are very similar to those of the subhedral crystals of secondary anhydrite (figure 104a). Therefore it is very probable that these patches and spots are calcareous pseudomorphs of subhedral crystals of secondary anhydrite.

Lucia (1961 and 1972, fig.32) and Armstrong (1968) recognised similar pseudomorphs as being either gypsum or anhydrite, but they were uncertain as to which mineral was responsible. Moreover, Bouroullec et al (1972, p.15, fig.4) considered identical pseudomorphs to be after gypsum. These can now be shown to be pseudomorphs after secondary anhydrite.

Three kinds of texture can be distinguished within the pseudomorphs; regenerated sedimentary textures, equigranular textures and geopetal textures.

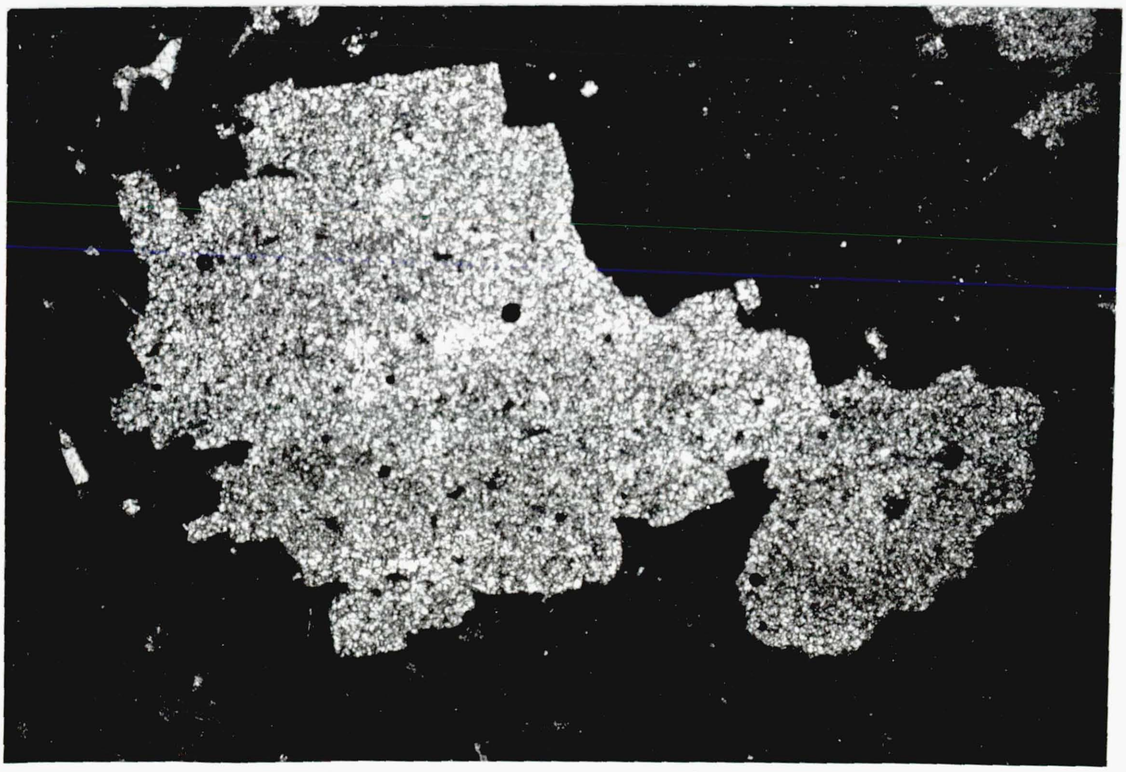
Figure 105 shows a photomicrograph of an ostracod wackestone which has been partially replaced by secondary anhydrite. Subsequently the latter crystals have been calcitised, and the original sedimentary texture has been regenerated within

A.



(x 20)

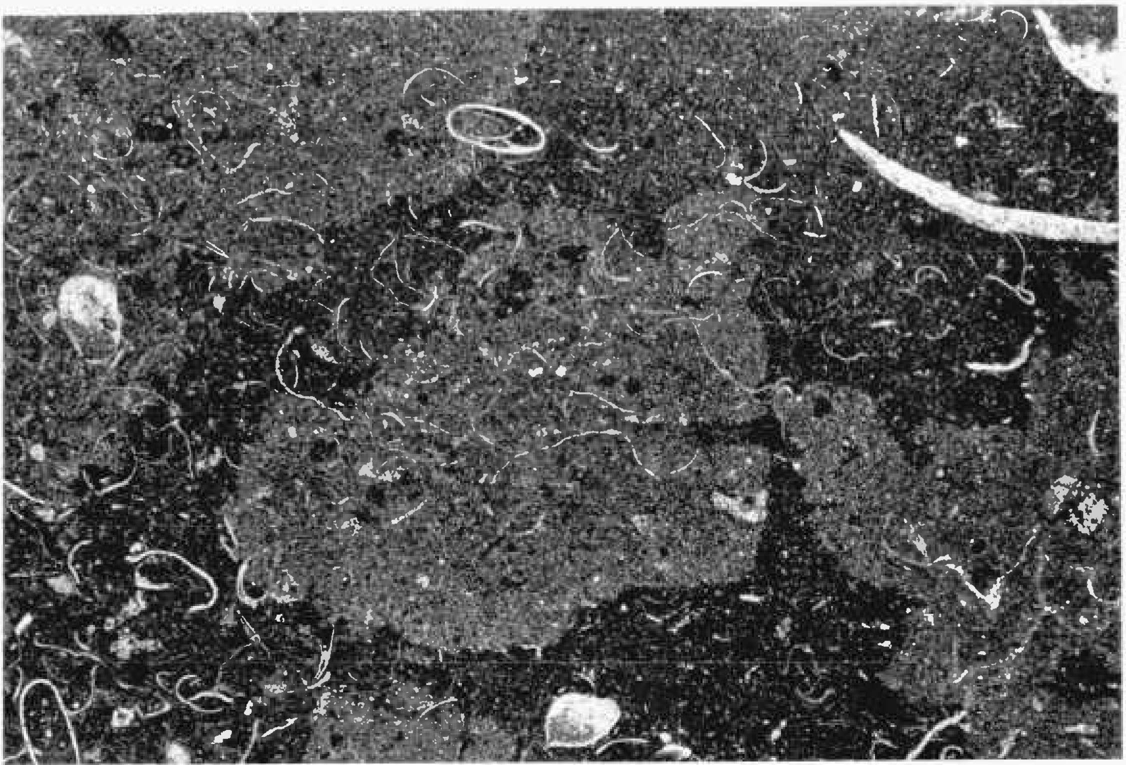
B.



(x60)

FIGURE 104 A) Photomicrograph of a crystal of secondary anhydrite with castellated outline (Western Canada, courtesy of D.J. Shearman).

B) Photomicrograph of a calcareous pseudomorph after secondary anhydrite, with a castellated outline (Montbrun Formation, Larnagol).



(x25)

FIGURE 105 Photomicrograph of an ostracod wackestone that has been partially replaced by secondary anhydrite and subsequently calcitised. Note the castellated outline of the pseudomorphs and the regenerated internal textures. Also note that geopetal sediments have accumulated in ostracods which remained articulated (Brengues Member, La Plogne).

the pseudomorphs; ostracod shells can be seen to pass, apparently unaltered, from the host sediment into the pseudomorphs.

The grain size inside the pseudomorphs is slightly coarser than that of the host sediment, and this may explain the lighter colour of the pseudomorphs in thin section. In hand specimens this variation is not discernable, but it has the effect of making the pseudomorphs appear to be darker in colour than the host.

Figure 104b is a photomicrograph showing a pseudomorph with an equigranular texture. The grain size is coarser than in the previous example and no obvious sedimentary fabric has been preserved.

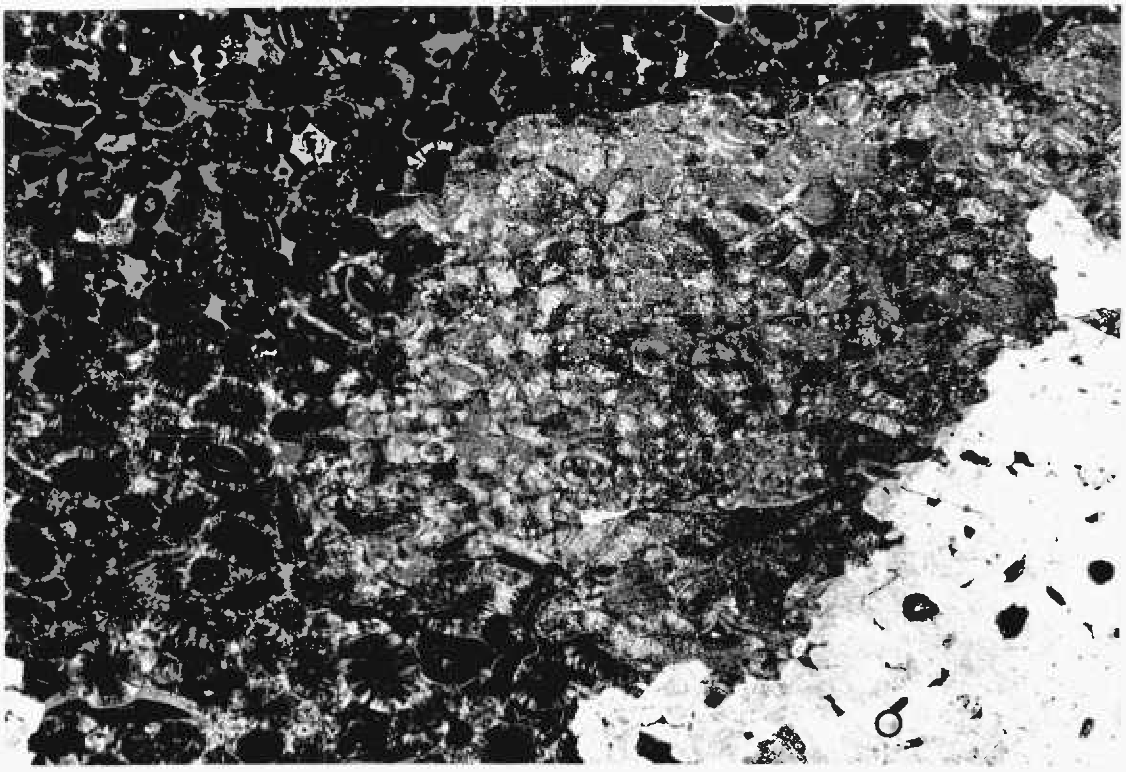
Figure 108d is a photomicrograph of a pseudomorph with a geopetal texture. A fine grained geopetal sediment occupies the lower half of the pseudomorph and the upper half has been infilled by a cement of calcite crystals.

These textures can be understood by examining a thin section of an actual crystal of secondary anhydrite. Figure 106a is a photomicrograph of such a crystal at extinction, and every point of light within it is an inclusion of calcite. The configuration of these, mimics the texture of the host sediment; two things can be inferred from this, firstly the inclusions are unreplaced relicts of the host rock; and secondly the anhydrite has partially replaced the limestone.

Figure 106b shows a photomicrograph of an axe head crystal of secondary anhydrite at extinction. This has partially replaced a calcareous mudstone and numerous unreplaced inclusions of calcite are preserved inside it.

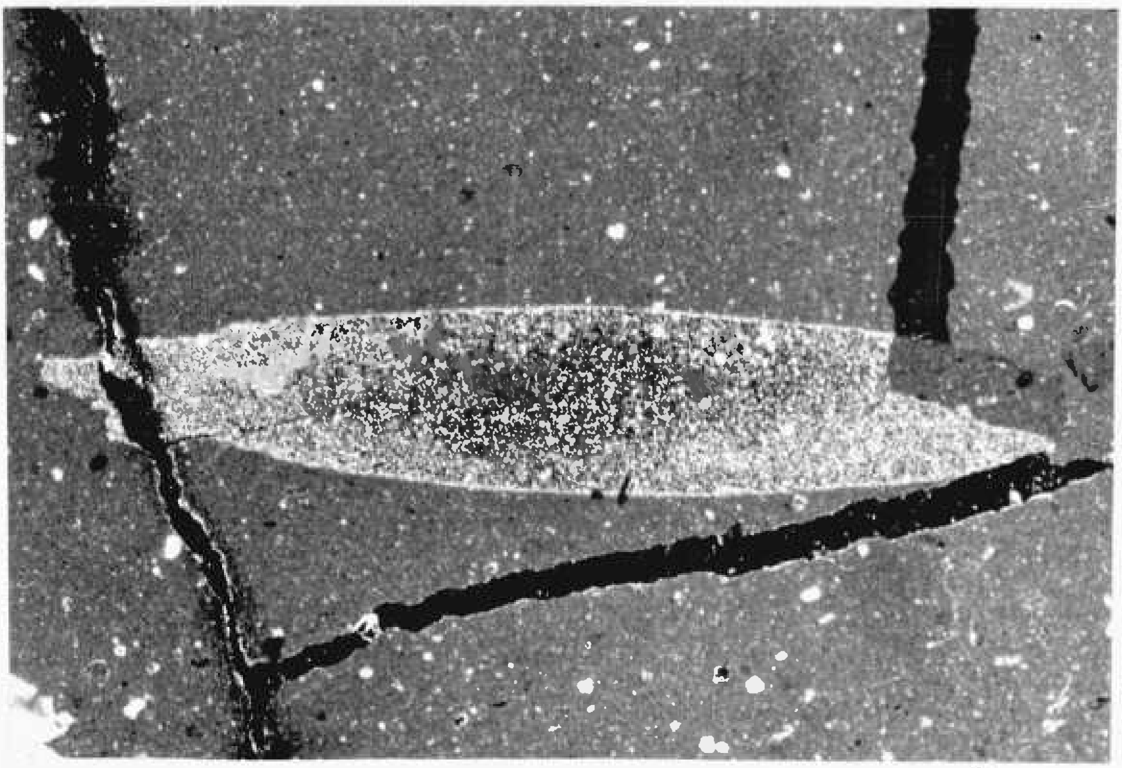
If these secondary anhydrite crystals were to become calcitised, two processes might operate whereby calcite replaces

A.



(x 20)

B.



(x 30)

FIGURE 106 Photomicrograph of a castellated (A) and axe-head (B) crystals of secondary anhydrite at extinction, which contain abundant ureplaced relicts of calcite that mimic the original fabric of the host limestone (Western Canada, courtesy of D.J. Shearman).

anhydrite to give textures similar to those described previously. Either piecemeal replacement takes place or all the anhydrite is removed by dissolution and the void is subsequently infilled by calcite.

During piecemeal replacement it is probable that only very small quantities of anhydrite are replaced by calcite at any one time. As calcitisation progresses, it seems likely that sub-microscopic volumes of anhydrite go into solution and calcite is precipitated concomitantly. Thus any unreplaced relicts of the original limestone are left undisturbed and these probably act as nuclei for the precipitation of calcite. Each inclusion is thought to be overgrown to form a larger crystal and eventually the resulting texture mimics the original fabric of the host rock. A similar argument was used by Evamy (1967) to explain the regeneration of textures when certain dolomites become calcitised.

As replacement gains momentum each inclusion is probably overgrown until it interferes with adjacent crystals of calcite at which stage all the intervening anhydrite would have been replaced (figure 107a). By this process a small number of widely spaced inclusions (i.e. extensive original replacement by anhydrite) might be expected to produce a coarser grained texture than would a large number of closely spaced inclusions (i.e. less extensive original replacement) (figure 107b). Moreover, because replacement by anhydrite is usually fairly complete, once calcitisation has occurred, the final texture of the pseudomorphs would nearly always be coarser than that of the host limestone.

Provided that unreplaced relicts are present, piecemeal replacement should always regenerate the original texture of the host limestone. However, if secondary anhydrite has replaced a rock with no distinctive sedimentary fabric, such as a calcareous mudstone, the texture which would be regenerated should be a slightly coarser version of that of the calcareous mudstone. Thus the resulting pseudomorph would

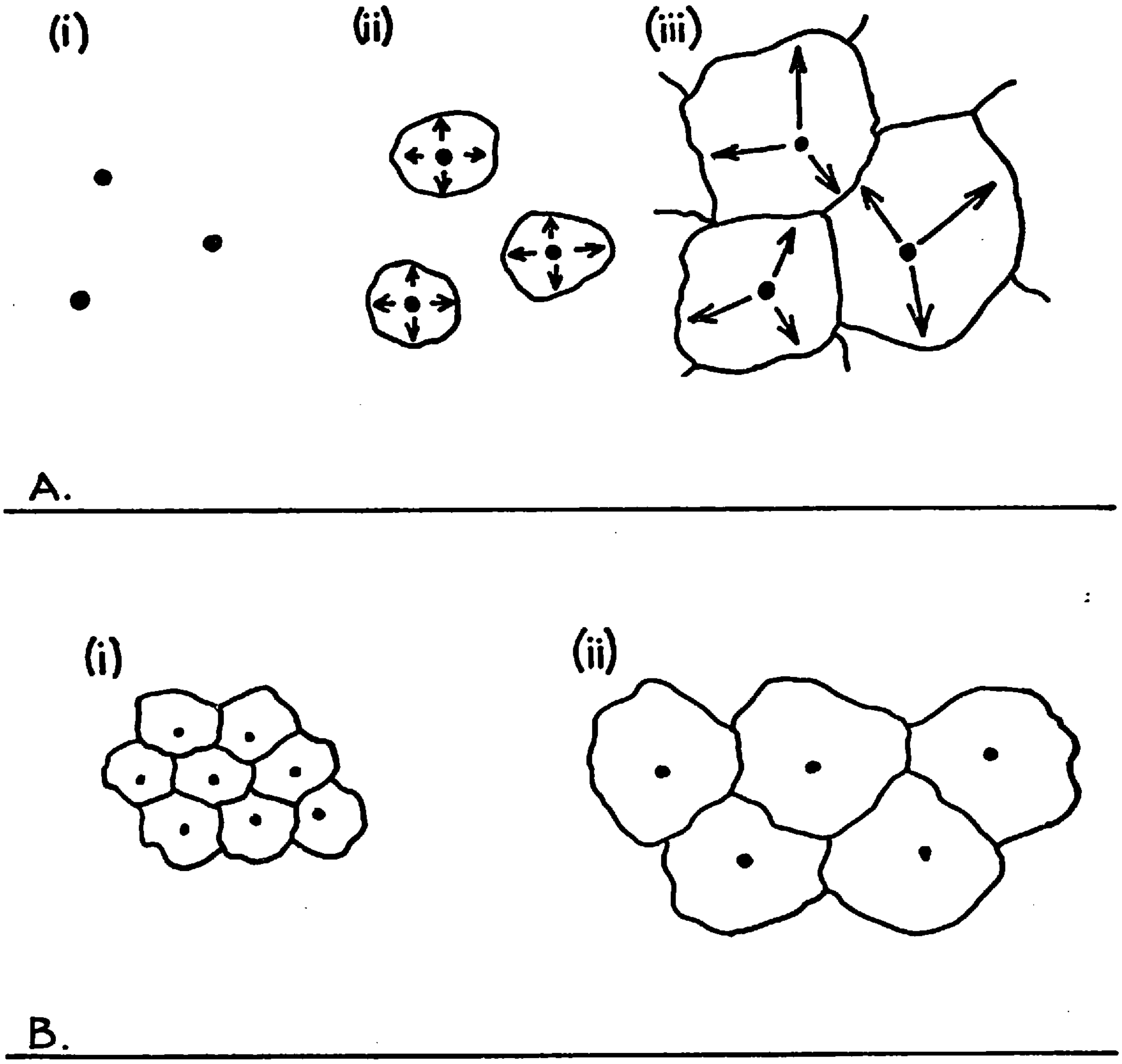


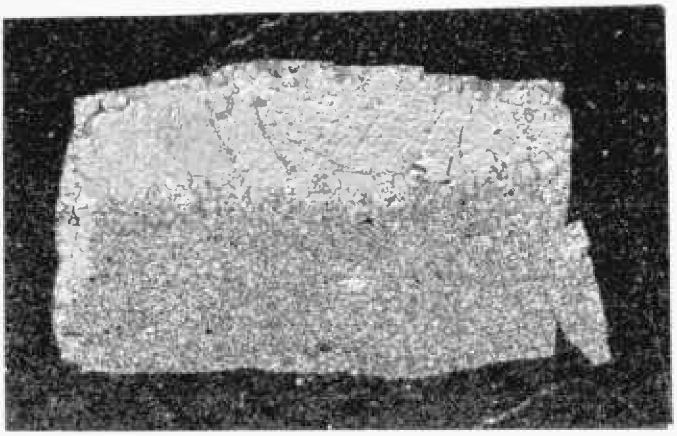
FIGURE 107 A) Piecemeal replacement of anhydrite by calcite: unreplaced relicts of calcite (i) in secondary anhydrite are gradually overgrown (ii) at the expense of anhydrite, until all the intervening anhydrite is replaced and a mosaic of calcite crystals results (iii).

B) Closely spaced inclusion produce a finer grained mosaic (i) and more widely spaced ones result in a coarser mosaic (ii).

be filled with a coarser grained, equigranular mosaic of calcite crystals (figure 104b), and although this does mimic the host rock, no obvious ghost fabric is apparent.

The other way by which calcareous pseudomorphs might be formed is if all the anhydrite were to be dissolved at once. Any unreplaced relicts of the host rock which might be present would fall downwards under the influence of gravity to form a geopetal sediment (figure 108). Initially the latter would probably consist of a loosely packed accumulation of calcite crystals. However, during cementation these could be overgrown until all the pore spaces had been infilled and an equigranular texture was created (figure 108). At the same time coarse crystals of calcite cement would probably grow into the overlying void which has been generated until the whole pseudomorph was filled by calcite (figure 108).

A peculiar feature of some larger pseudomorphs with geopetal sediments is the presence of 'roofs' of inclusions, above the cement filled voids (figure 109). Why some inclusions have apparently defied gravity and remained suspended after anhydrite has been removed, was initially a puzzle to the writer. However, an examination of some actual crystals of secondary anhydrite has shown that at the very edges, where replacement had only been slight, the unreplaced inclusion were still interconnected. Therefore, if the anhydrite became dissolved, these could be expected to remain suspended, while the more isolate inclusions towards the centre of the crystals dropped downwards to form geopetal sediments.



A. (x35)

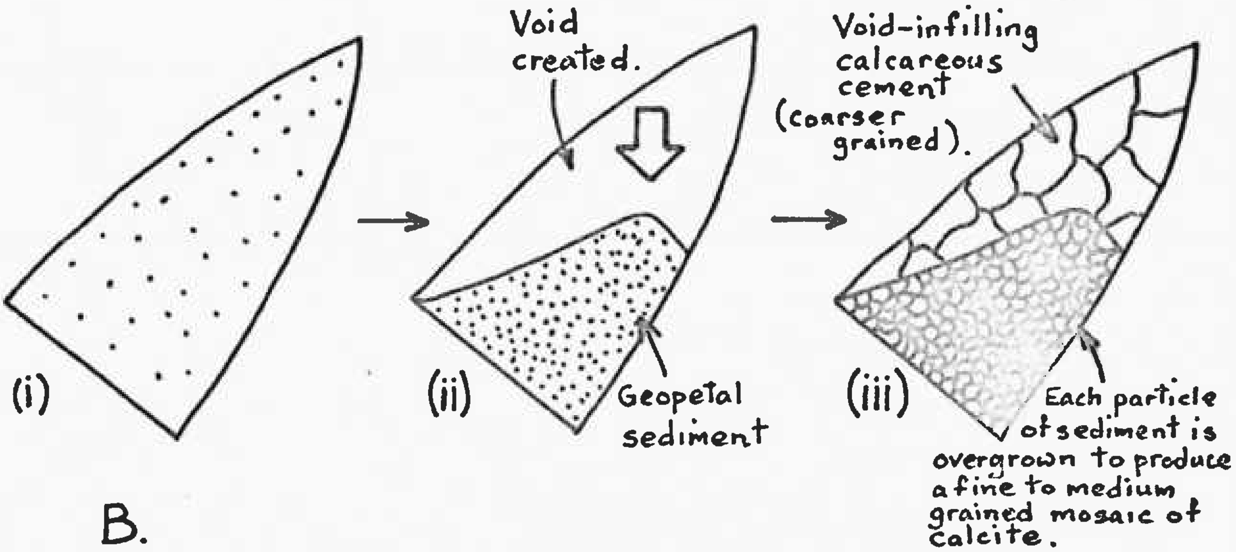


FIGURE 108 A) Geopetal sediment inside a pseudomorph after secondary anhydrite.

B) The development of the geopetal sediment: (i) unreplaced relicts in anhydrite; (ii) anhydrite is removed and inclusions fall downwards; (iii) geopetal sediment is cemented and the void is infilled to produce a calcareous pseudomorph.

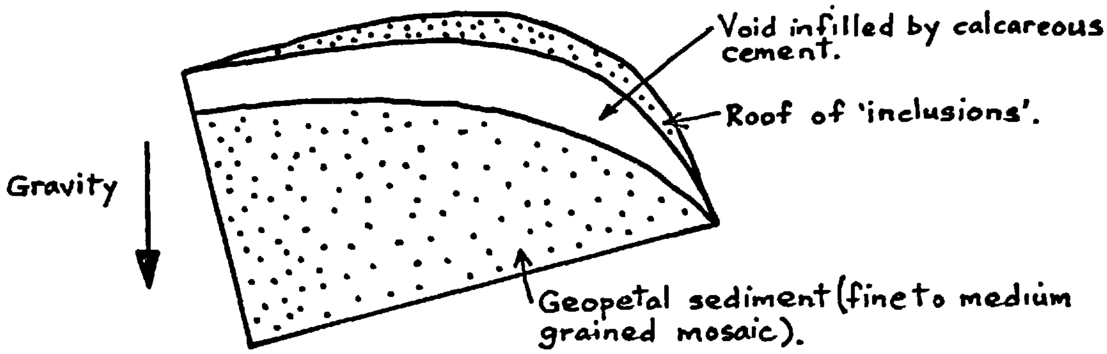
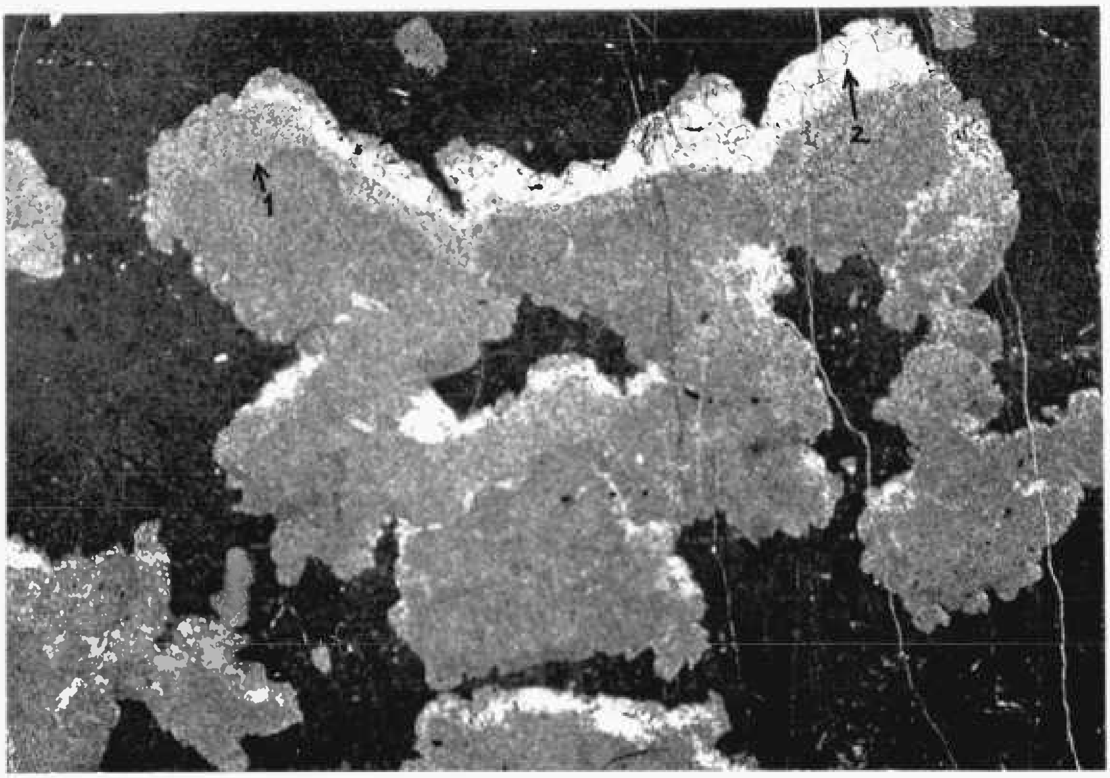


FIGURE 109 Pseudomorph with a 'roof' of unreplaced relicts.

Another unusual feature which has been observed is that some of the geopetal sediments are layered (figure 110). The reason for this is not clear, but it might have resulted from stronger compaction in the lower layers.

Silicified Crystals of 'Castellated' Secondary Anhydrite

Crystals of secondary anhydrite have also been found which have been replaced by one or two crystals of quarty, with sharp extinction. These have typical castellated outlines but they are more elongated than those described in the previous section (figure 111). Using acid, it has been possible to dissolve out some of the pseudomorphs, whereupon it was found that they have a platy habit.



(x11)

FIGURE 110 Photomicrograph of some pseudomorphs after secondary anhydrite with layered geopetal sediments (1) and voids which have been infilled by calcareous cement (2). A thin roof of unreplaced relicts is also preserved (3). (Marcilhac Member, near Cajarc).

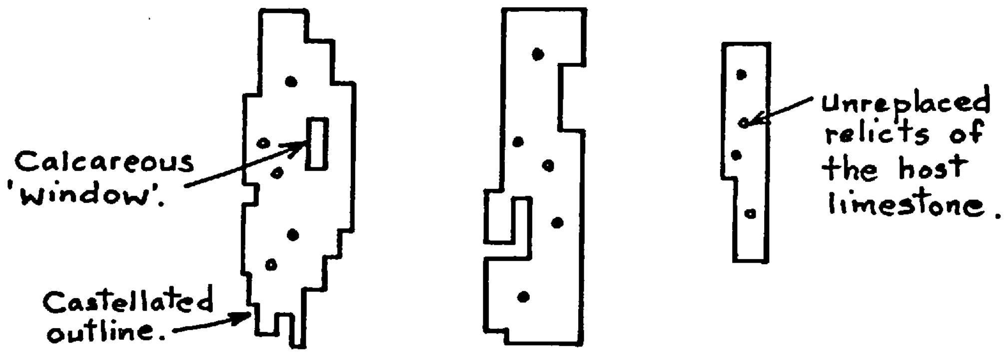
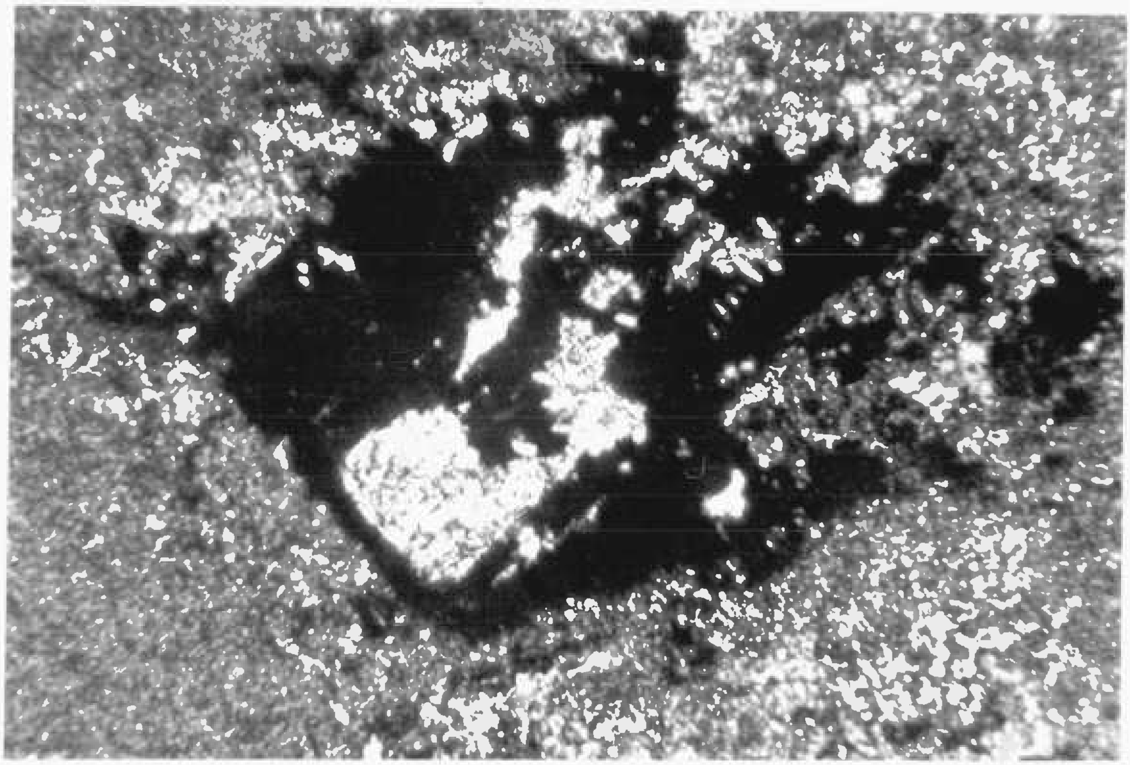


FIGURE 111 Silicified lath-shaped pseudomorphs after secondary anhydrite.

In thin sections, small anhedral and large rectangular calcareous inclusions are present inside the pseudomorphs. The latter are probably the re-entrants of the original crystals of anydrite, which because of the position of the section, appear to be trapped within the pseudomorph. The smaller anhedral inclusions are possibly unreplaced relicts of the host limestone.

Staining the pseudomorphs with Alizerine red-S has revealed that some of the inclusions are not calcareous (figure 112). These possess high birefringence colours (yellows and blues) and a rectangular cleavage which is parallel to the outlines of the pseudomorphs. Moreover, in any particular pseudomorph, all the non-calcareous inclusions go into extinction simultaneously and the extinction is always parallel to the shape of the pseudomorph. This suggests that



(x150)

FIGURE 112 Photomicrograph showing some unreplaced inclusions of anhydrite in a silicified pseudomorph after secondary anhydrite (Brengues Member, near Larnagol).

at one time all the inclusions were part of the same crystal which has subsequently been replaced by quartz.

The optical properties of the inclusions strongly suggest that they are relicts of larger crystals of anhydrite. Furthermore, as the unreplaced relicts are still in optical continuity with each other, silicification must have occurred on a piecemeal basis. Finally, the presence of unreplaced relicts confirms that the castellated pseudomorphs were once crystals of secondary anhydrite.

Calcitised Crystals of 'Axe-head' Secondary Anhydrite

In a few polished slabs and thin sections, some more regularly shaped pseudomorphs have given rise to lanceolate, truncated lanceolate, barrel shaped and rectangular cross-sections (figures 113 and 114). These have been reconstructed into an orthorhombic pseudomorph, shaped like a double 'axe-head' (figure 115a) and on the basis of this, they have been identified as calcareous pseudomorphs after axe-head crystals of secondary anhydrite.

It is possible that similar pseudomorphs have often been misidentified as being after gypsum (for example see Bouroullec et al, 1973, pl.2, figs.3,4; pl.3, fig.3). However gypsum crystals are monoclinic and when they are present in sediments they are usually discoidal in habit. Therefore in thin sections they would only produce lanceolate shapes (figure 115b) so they can easily be distinguished from anhydrite pseudomorphs which form a range of shapes.

The internal textures of the axe-head pseudomorphs are identical to those of the castellated types.

Calcitised Veins of Secondary Anydrite

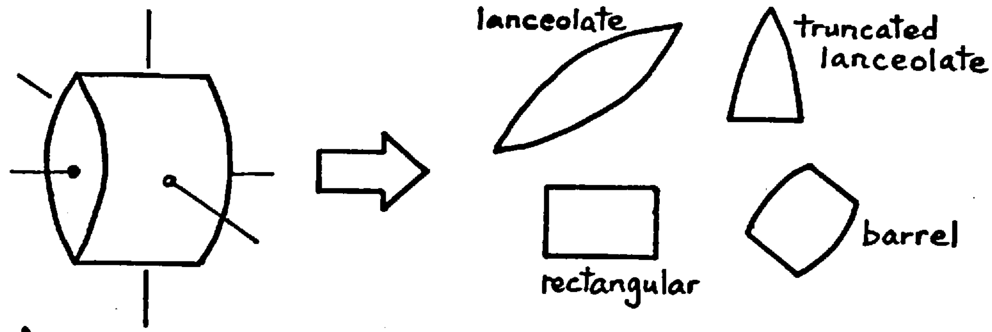
In the Brengues Member of the Cajarc Formation a few cal-

FIGURE 113 A) 'Axe-head' crystals of secondary anhydrite which have partially replaced a limestone from Western Canada (courtesy of D.J. Shearman).

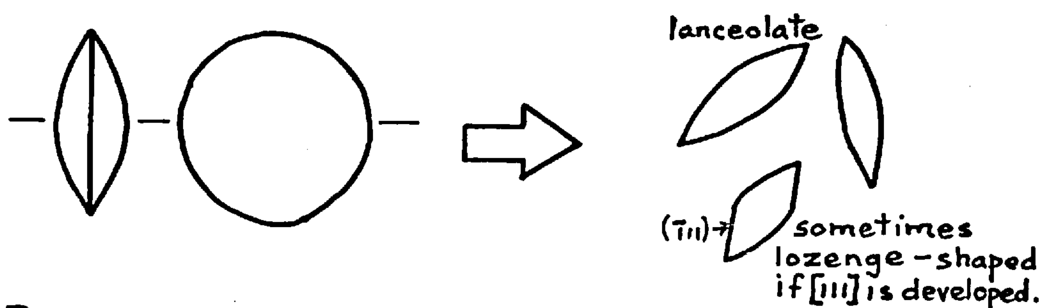
B) Comparable calcareous pseudomorphs from the Middle Jurassic of the Dordogne. Note the range of shapes that are developed and also the presence of geopetal sediment inside the pseudomorphs (courtesy of E.M. Daukoru). (Both photographs are actual size).

(x10)

FIGURE 114 Photomicrograph of some calcareous pseudomorphs after 'axe-head' secondary anhydrite crystals, showing the range of shapes which are developed: lanceolate, truncated lanceolate, barrel and rectangular. Geopetal sediments are also in evidence (Middle Jurassic of the Dordogne; courtesy of E.M. Daukoru).



A.



B.

FIGURE 115 A) A double 'axe-head' crystal of anhydrite and the range of cross-sections which can be drived from it.

B) A discoidal crystal of gypsum, and the cross-sections which can be obtained from it. Note that only lanceolate shapes are possible.

careous mudstones have been pervaded by numerous thin, parallel stripes which are darker in colour than the host sediment (figure 116). These are orientated either parallel, perpendicular or at 45^{o} to bedding planes. The colour and texture of the stripes in hand specimens is identical to that of the pseudomorphs of castellated secondary anhydrite which have already been described.

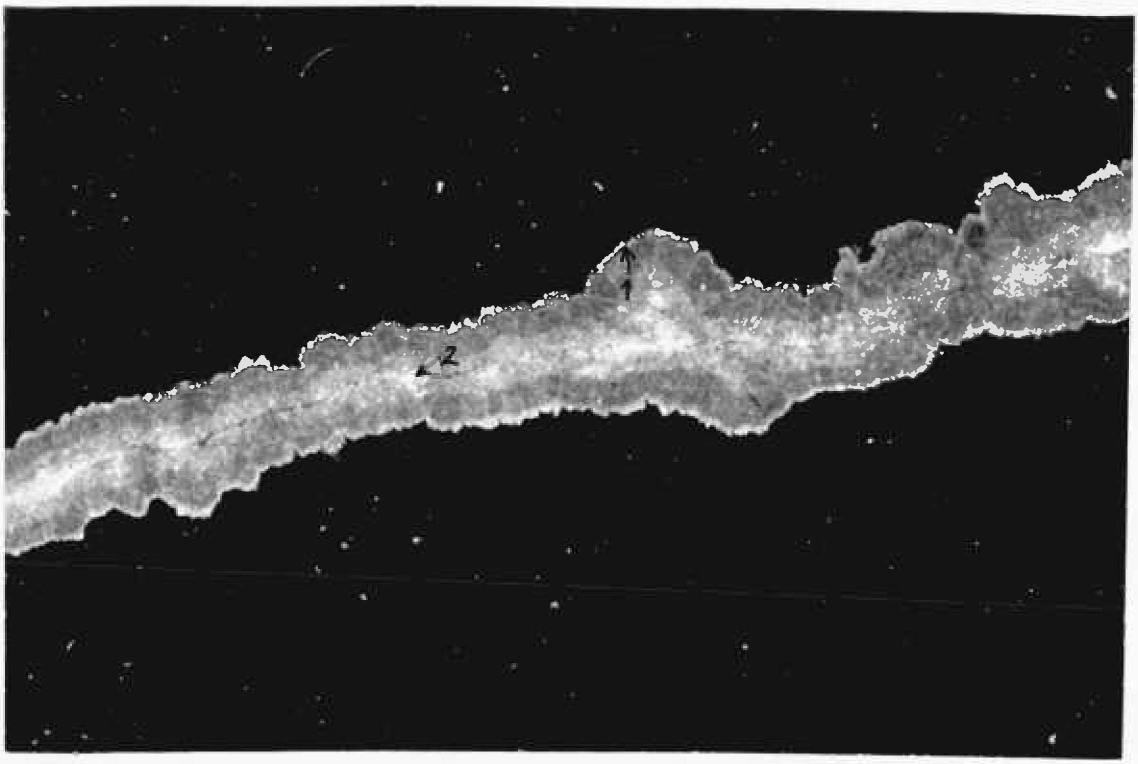
Hairline fractures sometimes run through the stripes and in thin sections they have castellated outlines (figure 117b). These features are very similar to those found in veins of secondary anhydrite (figure 117b) therefore the stripes are interpreted as calcitised pseudomorphs of the veins.

The original factures of the veins are now filled by coarser crystals of calcite. Bordering the fractures, the texture of the stripes is either equigranular (figure 117b) or it mimics the sedimentary fabric of the host limestone. These textures are exactly the same as the ones found in the pseudomorphs which have been formed by piecemeal calcitisation. No examples of complete dissolution have been seen.

The marginal zones of the stripes probably represent areas where anhydrite originally replaced the host limestone. Numerous unreplaced relicts would almost certainly have remained (figure 117a) and during calcitisation these are thought to have been overgrown so as to regenerate the original texture of the host. In contrast, the lines of the fractures were probably initially filled with inclusion-free anhydrite (figure 117a). Therefore, it is possible that only a few sites of nucleation were available and as replacement progressed only a small number of larger crystals were able to grow. Thus the textural differences created during the formation of the anhydrite veins have been preserved in the calcareous pseudomorphs.

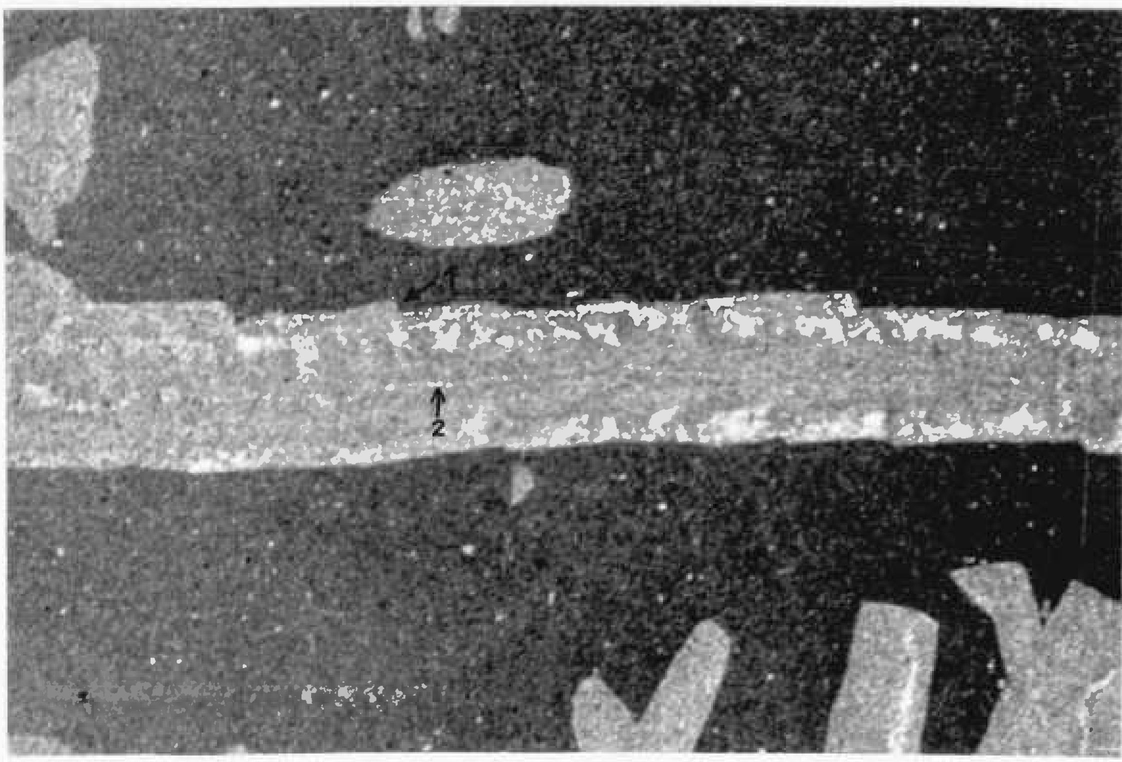
FIGURE 116 Calcitised veins of secondary anhydrite in a calcareous mudstone (Brengues Member, near Brengues) (actual size).

A.



(x15)

B.



(x25)

FIGURE 117 A) Photomicrograph of a vein of secondary anhydrite with a castellated outline (1) and a clear central zone (2), which probably represents the line of the original fracture. Either side of the latter the anhydrite is crowded with unreplaced relicts of the host limestone (Western Canada, courtesy of D.J. Shearman).

B) Photomicrograph of a calcitised vein of secondary anhydrite with a castellated outline (1). A clear central zone (2) is preserved and on either side of this an equigranular mosaic of calcite crystals is developed (Larnagol Member, near Saint Martin-Labouval).

6.2 Calcitised Nodular or Entrolithic Deposits of Primary Anhydrite

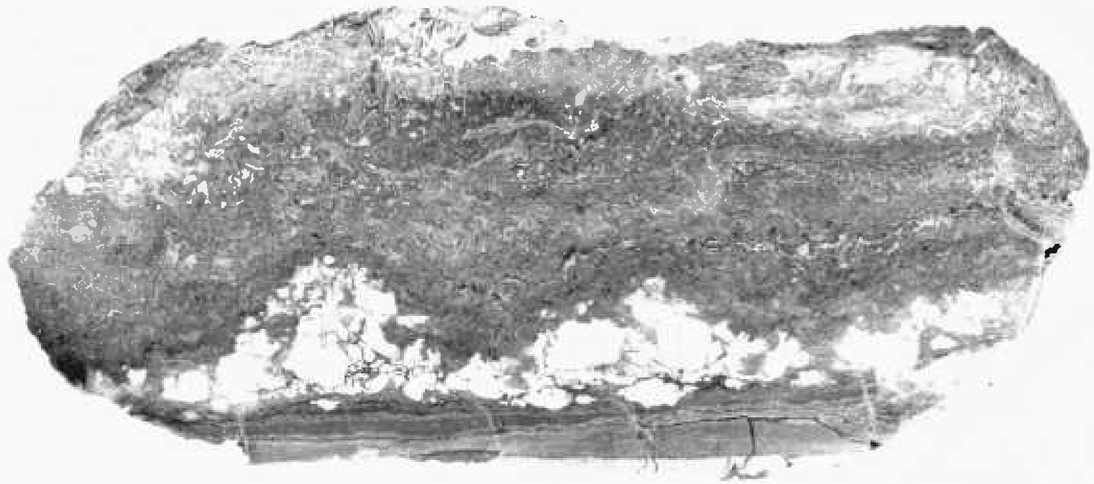
In the intertidal and supratidal sediments of the upper Cajarc and Montbrun Formations, white, coarsely cryatalline calcareous bands are sometimes developed. These may take the form of lines of isolated nodules, layers of coalesced nodules (figure 119), entrolithic bands (figures 118 & 121) or 'chicken-wire' agglomerations of small nodules (figure 120).

All of these morphologies have been described from the Recent deposits of primary anhydrite in the Trucial Coast area of the Persian Gulf (Shearman, 1966; Butler, 1969 and Kendall and Skipwith, 1969), and the sizes and scales of development of the calcareous bands are very similar to the evaporitic layers. Also, polished slabs of the calcareous nodules (figure 119) bear a strong resemblance to the bands of primary anhydrite which Shearman (1966) described from Purbeckian rocks in the IGS borehole at Warlingham.

Lucia (1972) noted that nodules of primary anhydrite often have lobate of mamillated external surfaces which could be used to identify pseudomorphed nodules. He also noted that lines of vugs or cavities might be left behind if nodules of anhydrite were to be leached away. Both these features have been observed in the Middle Jurassic limestones of the Cajarc area (figures 118 & 119).

Furthermore, Shearman and Fuller (1969) observed that as nodules of anhydrite grow, gradually they coalesce and entrolithic folds may develop which 'tend to bulge upwards and outwards into tightly compressed cumulous forms that are sometimes flattened along the basal surface of the layer'. Exact analogs of this have been found in some of the white calcareous bands of the Brengues Member of the Cajarc Formation.

FIGURE 118 A band of calcitised nodular and entrolithic primary anhydrite in a calcareous mudstone. Some of the larger nodules are now preserved as voids or as geodes, lined with calcite crystals (Marcilhac Member, D17 roadside exposure at 022359 near Montbrun).



(x 0·4)

FIGURE 119 A polished slab showing a calcitised band of nodular anhydrite with a flat lower surface and a diapiric upper one (Marcilhac Member, near Cadrieu).

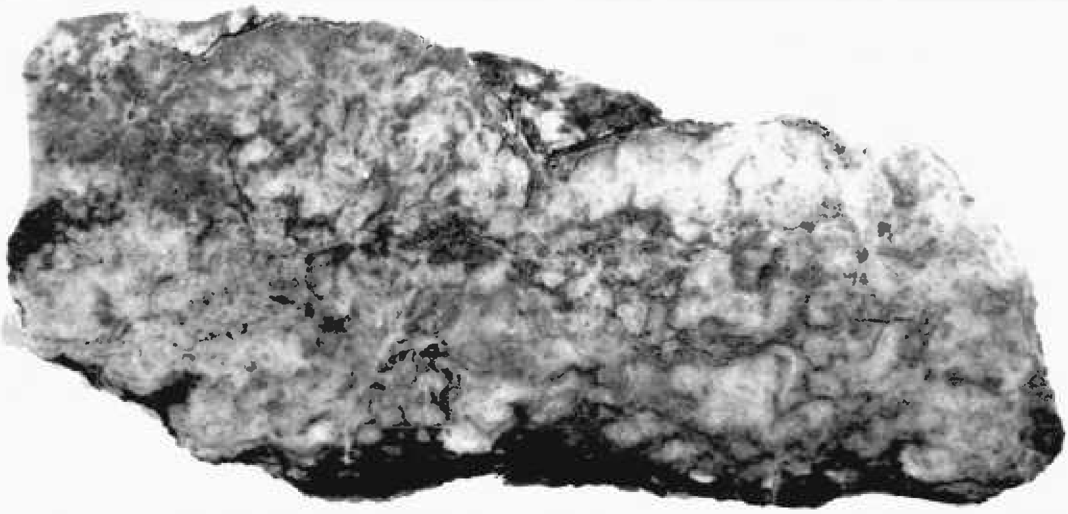


FIGURE 120 A polished slab composed almost entirely of coalesed nodules of primary anhydrite which have been calcitised. On freshly fractured surfaces this lithology looks more like a crystalline limestone than a former evaporitic rock (Brengues Member, Marcilhac).

Therefore the morphology of the calcareous bands suggests that they may have originally been layers of primary anhydrite and the fact that they occur in what appear, on other grounds, to be intertidal and supratidal sediments, supports this conclusion. Furthermore, Shearman (pers.comm., 1975) observed that secondary anydrite is usually found in close proximity to layers of primary anhydrite. So as pseudomorphs after secondary anhydrite are abundant, it seems reasonable to infer that the white bands were originally primary anhydrite which was subsequently calcitised.

An examination of the textures of the bands has tended to confirm this interpretation. Figure 121b is a photograph of an acetate peel which has been made from a calcitised layers (figure 121a) in the Brengues Member near Montbrun. It shows a well developed entrolithic structure which has probably resulted from the growth and coalescence of anhydrite nodules. The outline is picked out by a concentration of insoluble material. The area inside the outline is filled mainly by coarse crystals of calcite, with patches of medium and fine grained calcite and occasional isolated lumps of the host sediment (figure 121c). What little insoluble material is present within the entrolithic shape is concentrated into the lumps of host sediment.

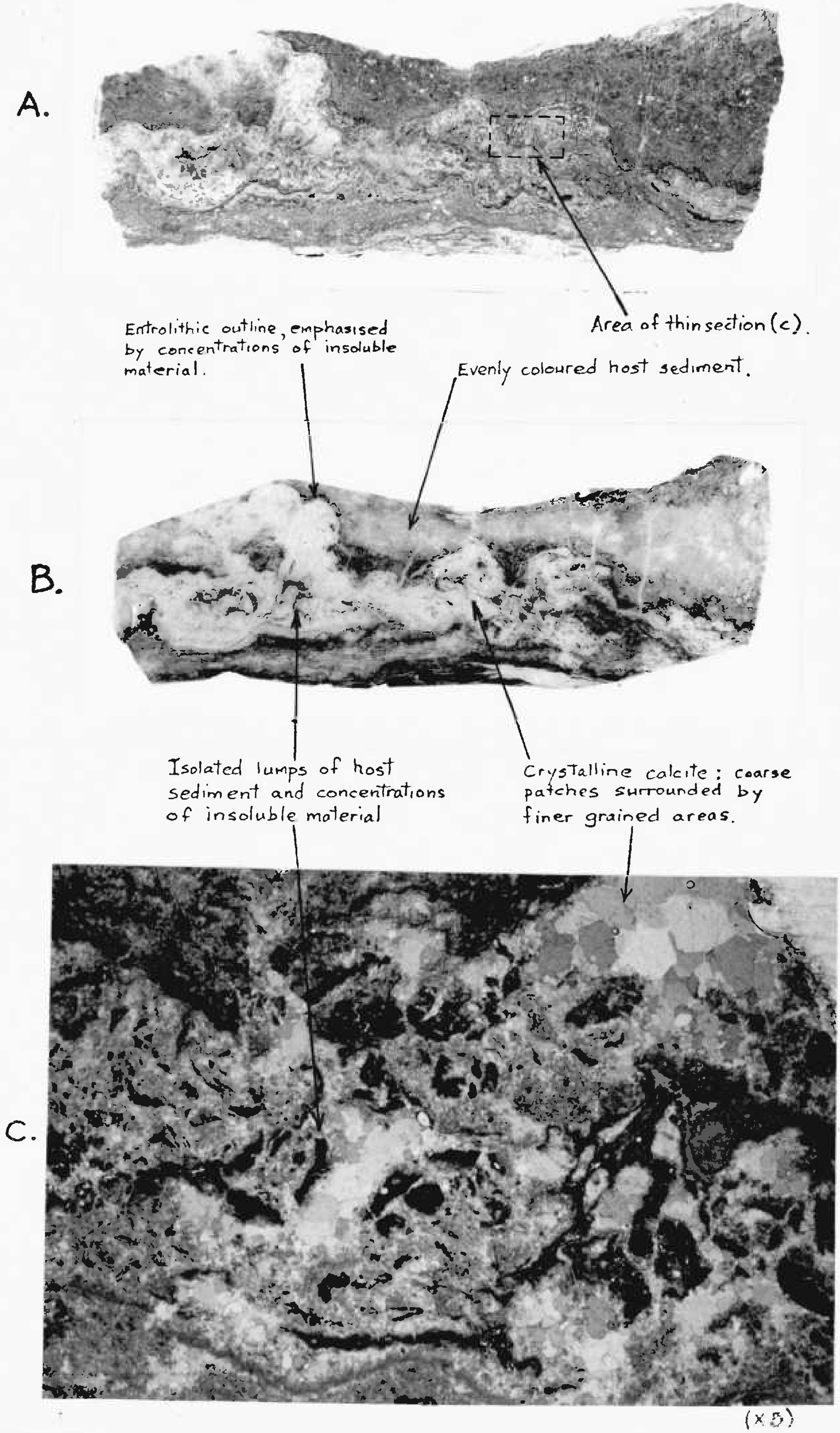
Shearman and Fuller (op.cit.) observed that as anhydrite nodules grow, they displace the host sediment outwards. Such a mechanism might also be expected to push organic matter and other insoluble particles towards the edges of the nodules. This probably accounts for the concentrations of insoluble matter that are in evidence around the borders of many calcitised bands of primary anhydrite. Presumably these insolubles include clay minerals and iron oxides as well as organic matter.

As nodules grow and coalesce it is likely that volumes of sediment may become isolated within the increasing mass of

FIGURE 121 A) Polished slab of a calcitised band of primary anhydrite (actual size).

B) Acetate peel of the same slab, which emphasises the outline of the calcitised band (actual size).

C) Photomicrograph of a thin section of a part of the band, showing the texture of the calcitised areas and also some isolated lumps of the host sediment. (38/74; Brengues Member, near Montbrun).


A.
Area of thin section (c).
Entrolithic outline, emphasised by concentrations of insoluble material.
Evenly coloured host sediment.
B.
Isolated lumps of host sediment and concentrations of insoluble material
Crystalline calcite : coarse patches surrounded by finer grained areas.
C.
(x5)

anhydrite. Similar isolated patches are preserved in the calcitised entrolithic bands, suspended in matrices of coarse crystalline calcite. They are angular and irregular in shape and sometimes they form long streaks or wisps which follow the general outline of the bands. Lucia (op. cit.) recorded similar structures in calcareous nodules which he called internal septae.

When the bands of primary anhydrite became calcitised, the internal textures of the individual nodules seems to have been preserved, and now the isolated patches of sediment are suspended in a calcareous matrix. If replacement was effected by a dissolution and void infilling mechanism, the inclusions should have fallen downwards to form geopetal accumulations. As this did not happen it appears that calcitisation took place on a piecemeal basis, thus preserving the original textures of the nodules.

The calcareous matrix which has replaced the anhydrite is composed of cells of coarse crystals of calcite, surrounded by areas of finer crystals (figure 121c). The latter also form streaks and wisps, together with sediment inclusions, which follow the general outlines of the nodules. These textures can be understood by considering the pattern of growth of nodules of primary anhydrite.

Shearman and Fuller (op.cit.) showed as individual crystals of anhydrite developed within a nodule, they force the host sediment away from the centre of growth and concentrate it towards the margin (figure 122a). However, if a number of growth cells were to develop side by side, within a nodule (figure 122c) any sediment inclusions would be pushed to the margins of each cell (figure 122b). Thus areas of inclusion-free anhydrite would be surrounded by inclusion-rich bands.

During any subsequent calcitisation, if a piecemeal mechanism

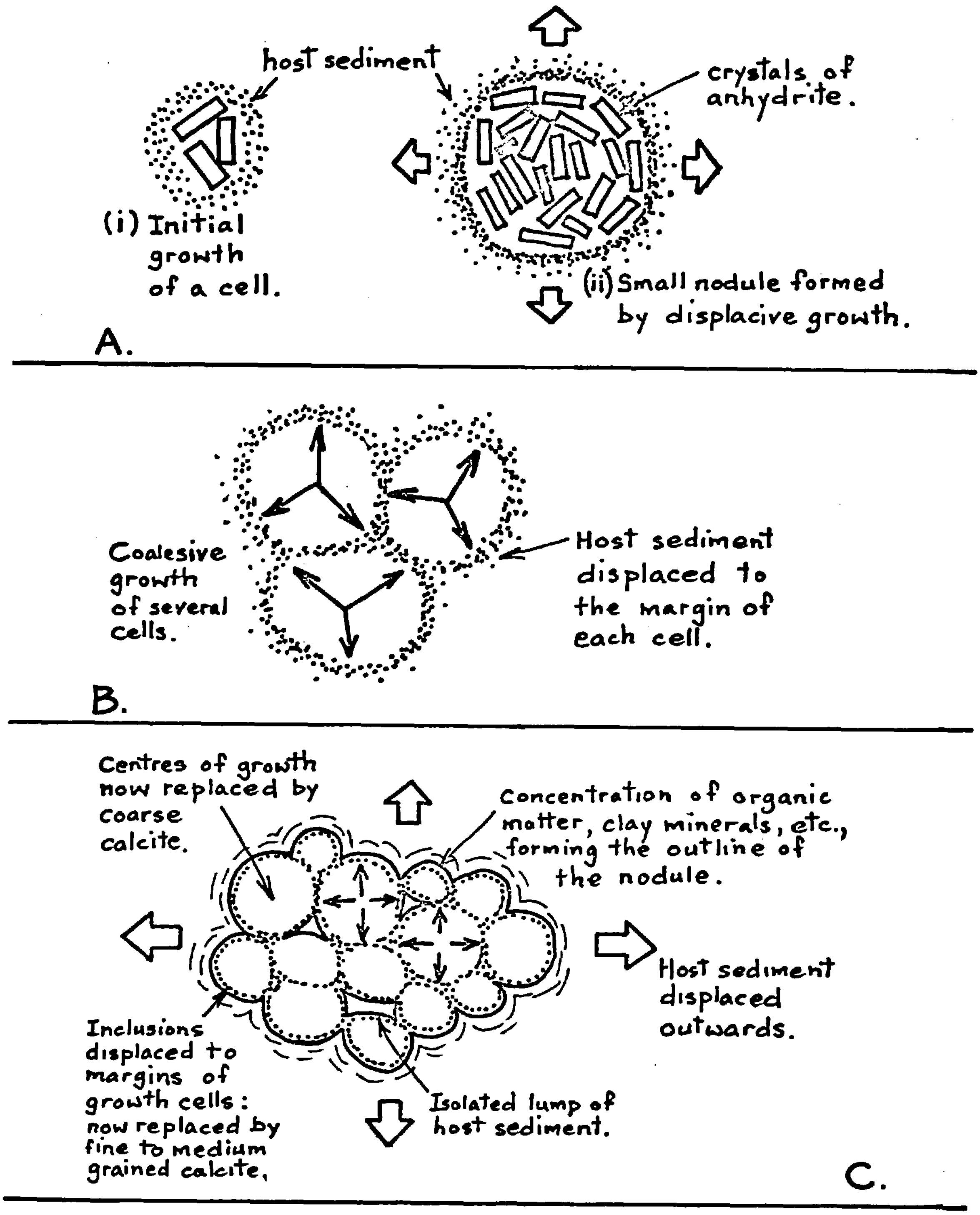


FIGURE 122 A) The displacive growth of a nodule of anhydrite (after Shearman and Fuller 1969).

B) The coalesive growth of several cells.

C) The texture of a calcitised nodule of anhydrite in relation to the original growth pattern of anhydrite.

were to operate, the inclusion-rich areas could give rise to a fine or medium grained mosaic of calcite crystals, and the inclusion-free areas a coarse grained mosaic. This is possibly how the cellular pattern of the calcitised anhydrite bands originated (figure 122c).

Some of the textures that are described in this section have previously been observed in the Middle Jurassic limestones by Bouroullec et al (1972). In particular, a photomicrograph (pl.1, fig.5) which they described as 'des plages amygdaloides' with stylolites or organic and argillaceous material, is the exact analog of figure 121. They thought that this texture had been produced by the compaction and recrystallisation of a stromatolitic deposit. However, the evidence presented in this thesis suggests that these features are more likely to be calcitised nodules of primary anhydrite. Furthermore, the 'stylolites' which they describe are probably not true stylolites at all because they appear to have formed in response to the displacive growth of nodular anhydrite.

6.3 Calcitised Crystals of Discoidal Gypsum

Lanceolate and lozenge shaped pseudomorphs have been observed in some upper intertidal and supratidal limestones in the upper parts of the Cajarc Formation and in the Montbrun Formation. Typically these occur in algal boundstones and ostracod wackestones, andalso in association with calcitised layers of nodular anhydrite. The pseudomorphs vary in size from silt to fine sand grade and they are infilled by either a single or several crystals of clear calcite, which bear no optical relationship to the lanceolate outlines.

Using the random cross-sections that are present in thin sections, it has been possible to reconstruct the three-dimensional shape of the pseudomorphs which is discoidal (figure 115b). The only crystal which is known to the writer that has this habit is gypsum (Masson, 1955; Shearman, 1966; Butler, 1969 and Kendall and Skipwith, 1969). These crystals grow displacively in soft sediments during their very early diagenesis in upper intertidal and supratidal sabkha environments.

Masson (1955) described the growth of discoidal crystals of gypsum. He noted that the crystals, which are monoclinic, are flattened perpendicularly to their c-axes. The discoidal shape is due to the irregular convex development of the $(\bar{1}02)$ faces at the expense of the $(\bar{1}11)$ pyramid faces. If the $\bar{1}11$ face does not become completely supressed the crystals retain a lozenge shaped cross-section (figure 123a), but if it is completely supressed, a lanceolate cross-section results (figure 123b).

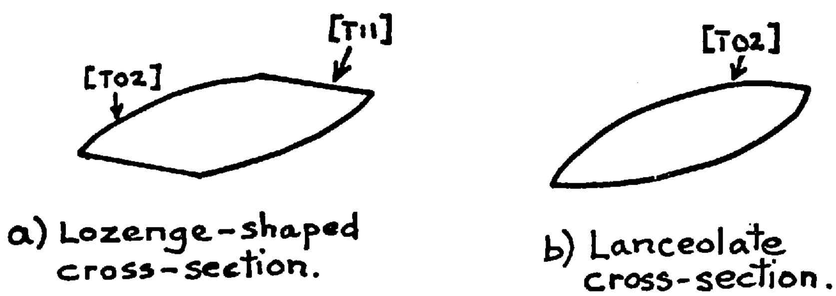


FIGURE 123 Cross-sections of gypsum pseudomorphs.

Unlike the pseudomorphs of secondary anhydrite, no geopetal or regenerated sedimentary textures are visible in the gypsum pseudomorphs. This is hardly surprising because when gypsum grows in Recent algal mats or fine grained sediments, it displaces most of the host and it remains relatively free of inclusions (Kendall and Skipwith, op.cit.). Therefore, during calcitisation very few nucleation sites would be available, so coarse grained mosaics of calcite would probably result.

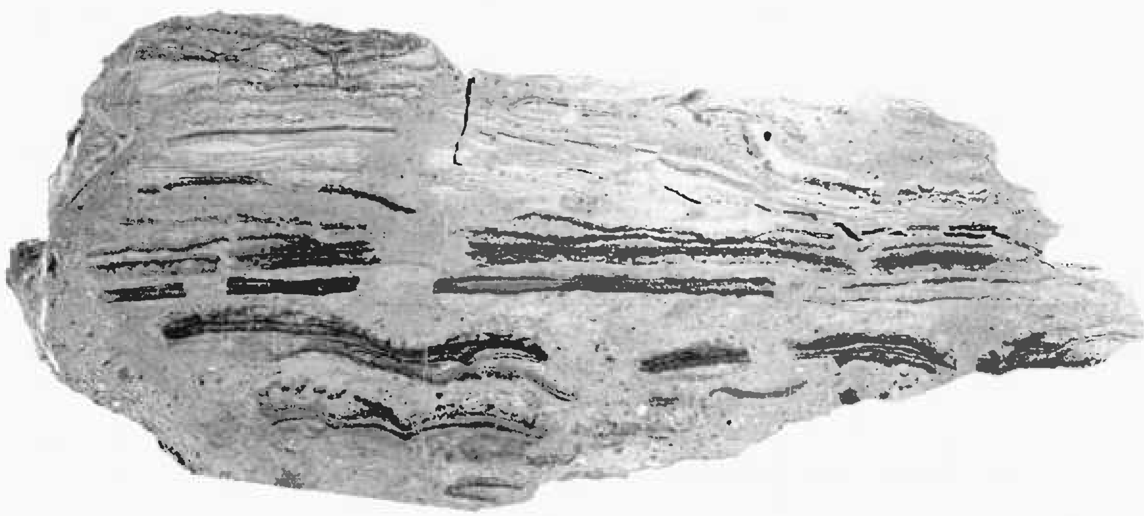
6.4 Calcitised Deposits of Laminated Gypsum

In the upper part of the Saint Suplice Member at La Roque (078278), some interesting light and dark grey, centimetre and millimetre laminated calcareous sediments (figure 124) have been found to be interbedded with ostracod-charophyte-wackestones and marls. At first sight these rocks looked like laminated algal deposits, but thin sections and acetate peels have revealed that originally they may have been composed of up to 60% of primary crystals of discoidal gypsum. These have since been replaced by calcite.

The darker layers are composed almost entirely of calcareous pseudomorphs after discoidal crystals of gypsum, which are mostly orientated with their c-axes approximately parallel to bedding (figure 125). The layers are discontinuous and birdseye cavities, filled with calcareous cement, are sometimes developed beneath them; these were probably caused by mud cracks and gas blisters which formed in response to desiccation.

The lighter coloured layers are composed of approximately equal amounts of calcareous mudstone and discoidal pseudomorphs of gypsum. The latter are rarely larger than silt grade and they are randomly orientated. Occasionally, immediately above the dark layers, a few sand sized pseudomorphs may be arranged with the c-axes perpendicular to the bedding (figure 125). A small number of sand sized intraclasts, which are sometimes blackened, are also present in these layers and very thin and irregular laminations of insoluble material, probably composed of organic matter and clays, usually occur just above the darker layers.

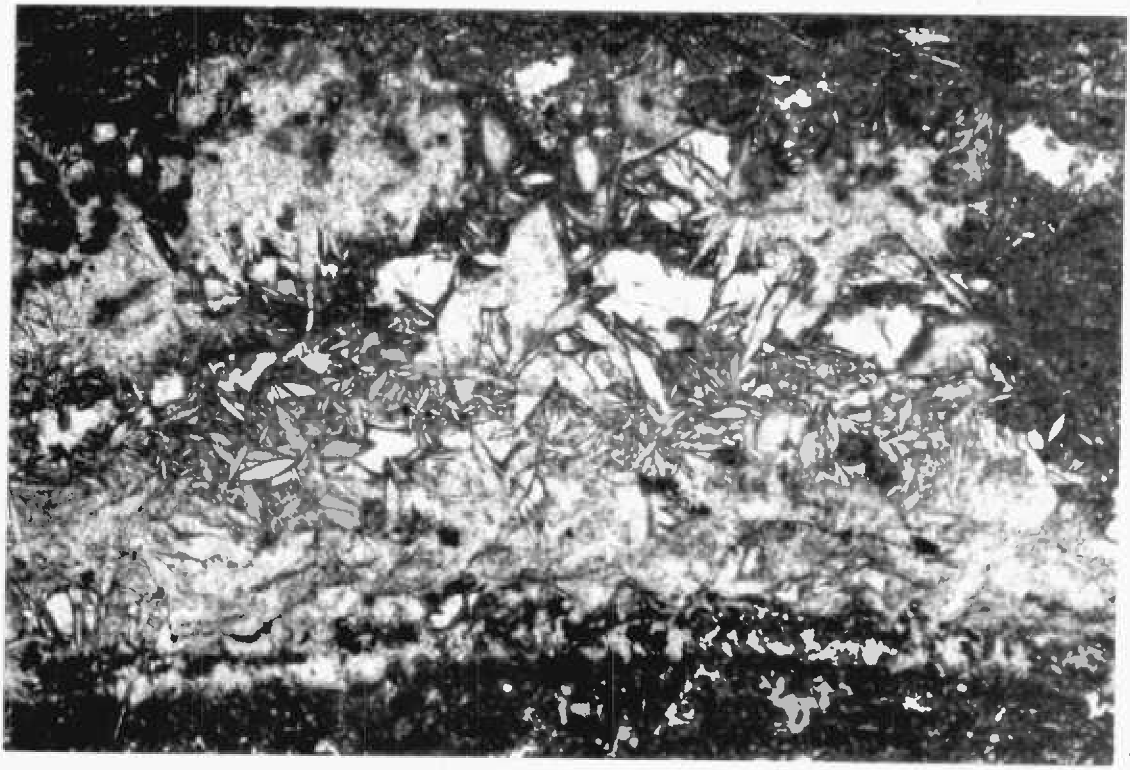
A number of examples of laminated gypsum sediments are known which are comparable to the layers of pseudomorphs in the



(x0·9)

FIGURE 124 A calcitised deposit of laminated gypsum with mud-cracks (Saint Suplice Member, La Roque).

A.



(x15)

B.

(x15)

FIGURE 125 Photomicrographs of a calcitised deposit of laminated gypsum in which, originally, the crystals grew upwards (A) from a base with their C-axes approximately parallel to the bedding and where the layers of crystals sometimes became truncated (B) (Saint Suplice Member, La Roque).

Saint Suplice Member. These have been found in the Tertiary successions of the Paris Basin (Shearman, pers.comm., 1975), the Çankiri Çorum Basin in Turkey (Ergun, pers.comm., 1975) and near Alicante in Southern Spain (Orti, pers.comm., 1975). Similar Recent examples occur in Laguna Mormona, in Baja California (Shearman, pers.comm., 1975) and in the sabkhas on the west coast of the Gulf of Sirte in Libya (Sherif, pers.comm., 1975).

In the latter case, Sherif observed that swallow-tail and discoidal habits of gypsum are growing displacively in the sediments of the sabkhas, to form layered deposits. He also noticed that sometimes bands of sediment have been displaced and layers of inclusions have become trapped as the gypsum crystals grew. Orti (op.cit.) also observed similar features in the Tertiary evaporites near Alicante, where layers of primary discoidal crystals of gypsum have grown displacively with their c-axes approximately parallel to bedding.

Sherif showed that in the Recent sabkhas of Libya, laminated gypsum deposits are actively forming below the sediment surface in the realm of highly saline groundwaters. Desiccation probably has no effect on these sediments. Shearman, however, observed that crusts of primary discoidal crystals of gypsum are also growing in supratidal brine pools in Laguna Mormona, with their c-axes approximately parallel to the surface of the sediment. These crusts are strongly influenced by desiccation and water or gas-filled blisters often form below them. Mud cracks were not seen, though these could easily develop if the brine pools were to dry out.

Both of these types of deposit are formed in supratidal sabkha environments, and once they have been preserved they superficially appear to be similar. However, the presence of swallow-tail twins, disrupted layers of sediment, lines of inclusions and the lack of desiccation features, can be used to distinguish the groundwater types from those formed in brine pools, which should characteristically be relatively free of inclusions and also intensely affected by desiccation.

In the pseudomorphed layers, the original gypsum crystals did not disturb the sediment and very few inclusions seem to have been trapped, so perhaps the host sediments was not deposited until after the gypsum had grown. Also, the crystals look as if they have grown upwards from a free surface and in some cases they appear to have been truncated by erosion (figure 125b).

Furthermore, the layers have frequently been broken, apparently by mud cracks, and large birdseyes have formed underneath them; these were probably due to desiccation at the sediment/air interface. Therefore, by analogy with Laguna Mormona, the darker layers of pseudomorphs are interpreted as gypsum crusts which have grown in supratidal brine pools.

The lighter coloured bands are considered to represent layers of sediment that were carried into the supratidal zone by wind, or by the sea during storms. Once deposited these probably came under the influence of sabkha conditions and while brine pools may have formed on the sediment surface, the bulk of the accumulations would have probably been subjected to the circulation of highly saline groundwaters. It is in this situation that minute, randomly arranged discoidal crystals of gypsum are thought to have grown displacively in the sediment.

6.5 Calcitised Crystals of Celestite

A few examples of calcareous pseudomorphs have been found in the Cajarc and Montbrun Formations which produce an unusual range of shapes in thin section (figure 126a and 127a). The simplest possible habit from which these can be derived is an orthorhombic crystal (figure 126b) that is elongated parallel to its b-axis and in which the following forms are developed: macrodome (h01), brachydome (0kl), orthorhombic prism (hk0) and sometimes a basal pinacoid (001) (after Bishop, 1967).

This is a typical habit of celestite and also sometimes of barytes and anhydrite (Dana, 1892; West, 1960 and Deer et al, 1966). The mode of occurance and the habit of the pseudomorphs are identical to those of the celestite crystal in the Purbeckian Hard Cap Limestones of the Isle of Portland. In each case the sizes are similar and the crystals are arranged in thin layers with their b-axes parallel to bedding. Moreover, after dissolving out some of the celestite crystals using acid, it was found that their growth habit is identical to the one which has been inferred for the pseudomorphs. Therefore it is possible that the latter have been produced by calcitisation, from crystals of celestite.

In thin section some pseudomorphs have displaced layers of organic matter. This may have resulted from compaction but it seems unlikely since calcareous sediments usually become cemented fairly rapidly, thus preventing substantial compaction from occurring. The other possibility is that the original crystals grew displacively in soft sediment.

Beales (1965) noted that celestite may grow either in a soft sediment or it can replace an already lithified limestone. If replacement took place in the Middle Jurassic limestones, there should be some regenerated textures or geopetal sediments in the pseudomorphs. As neither of these has been observed it seems reasonable to infer that possibly the original crystals grew in an unlithified host and all the particles of sediment were displaced outwards.

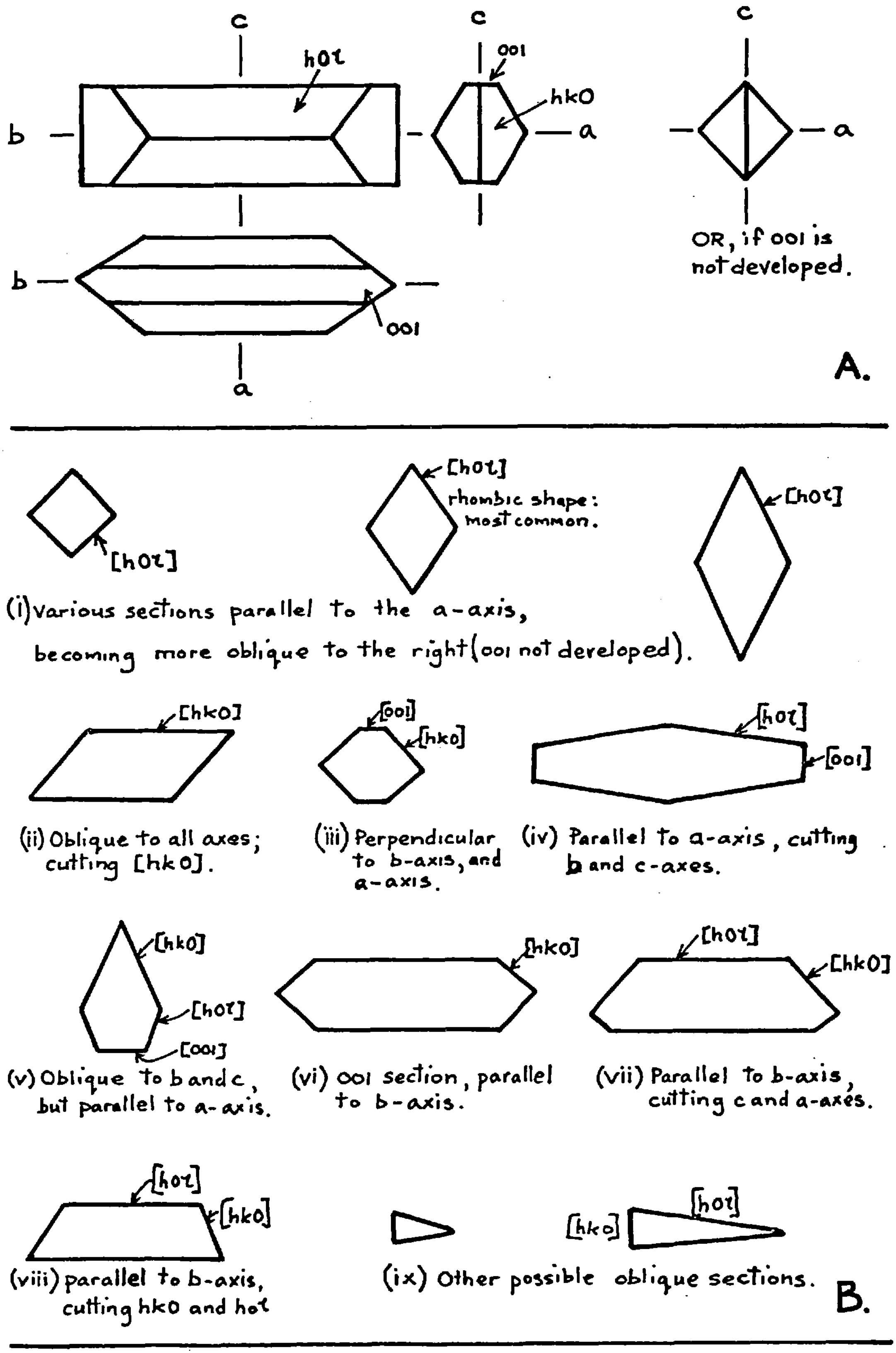


FIGURE 126 A) Common orthorhombic habit of celesite.

B) The range of cross-sections which can be obtained from this habit.

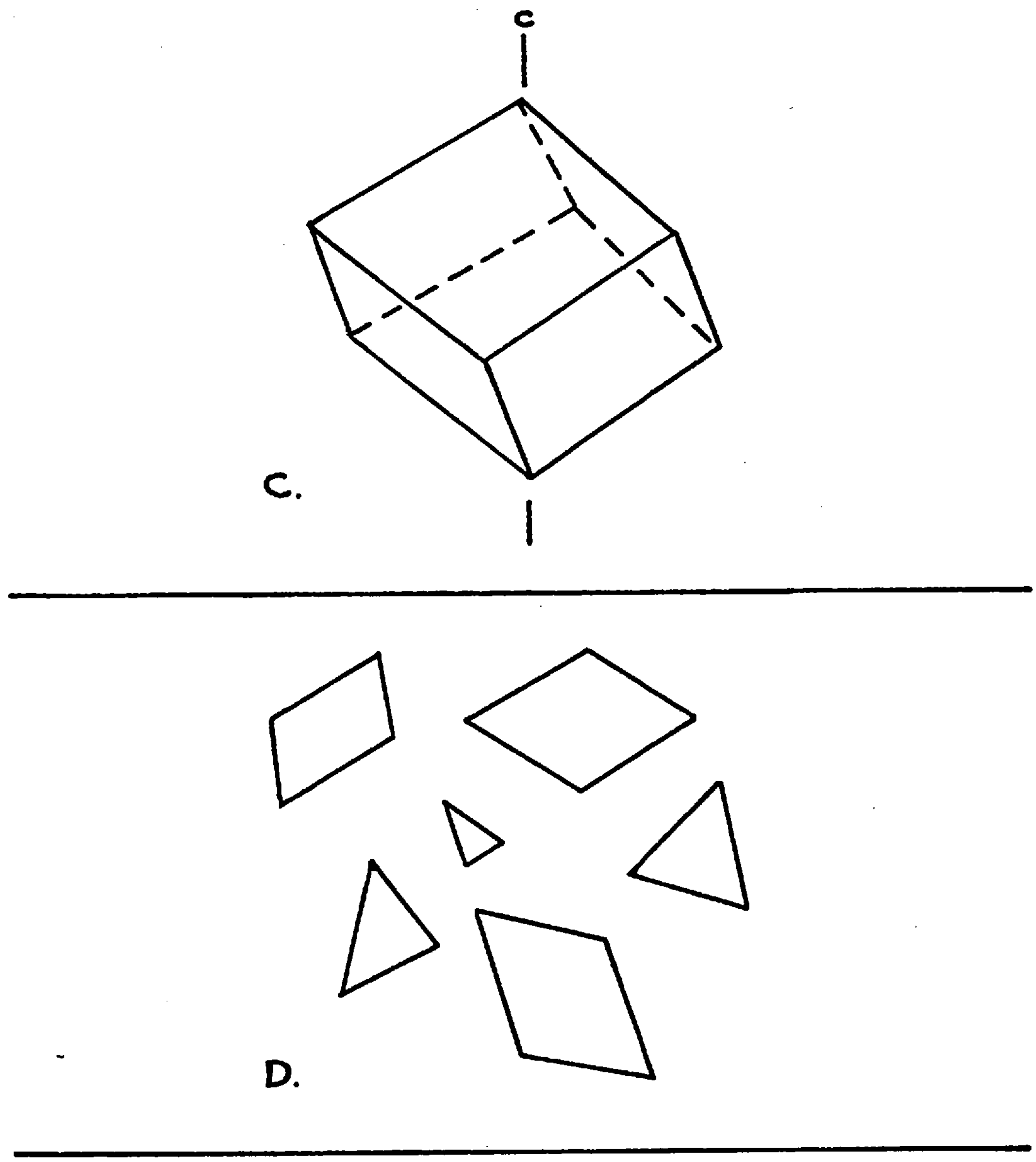


FIGURE 126 C) Typical rhombic habit of dolomite.

D) The cross sections which can be obtained from this habit; these are only rhombic and triangular in shape.

For these particular crystals of celestite to have grown in the first place, two things would have been necessary; firstly the host sediment should have been unconsolidated and secondly a ready supply of SO_4 and Sr ions would have been needed. One situation where these requirements might have been fulfilled is in a sabkha environment. Indeed, Evans and Shearman (1964) have recorded celestite from coastal sabkhas of the Persian Gulf. Moreover, Bush (1973) noted that SO_4 is plentiful in these sabkhas because Ca SO_4 is actively being precipitated and Sr is also available because it is being released by the dolomitisation and calcitisation of aragonite. Therefore it is not surprising that the pseudomorphs have most commonly been found, together with calcitised nodules of anhydrite, in sediments which were modified in a sabkha environment.

All the pseudomorphs are now filled by medium to coarse grained mosaics of calcite crystals. They often occur adjacent to masses of nodular anhydrite which have been calcitised on a piecemeal basis. Furthermore, where large numbers of pseudomorphs are grouped together, patches of host sediment are now suspended in a calcareous matrix and no geopetal structures have developed. Therefore, like the anhydrite, the celestite crystals probably became calcitised in a piecemeal fashion.

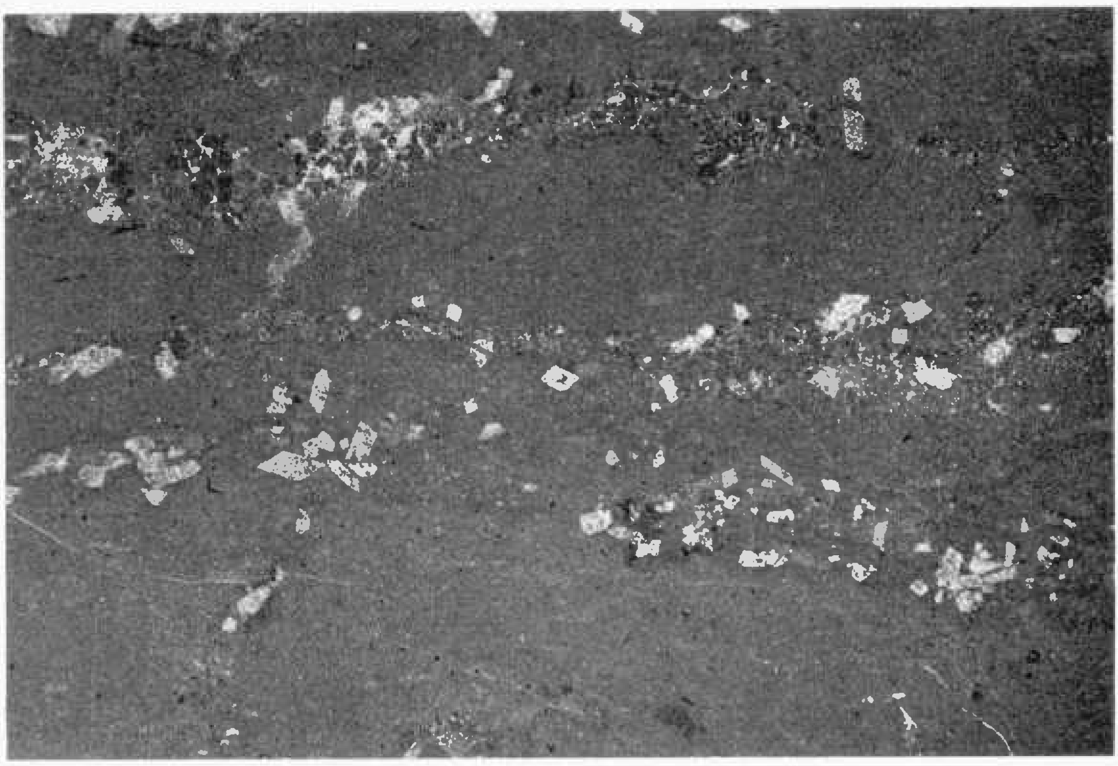
The most commonly developed cross-section of celestite pseudomorphs in thin sections is a rhombic shape (figure 126b). It is difficult to distinguish this from dolomite pseudomorphs such as those which were described by Evamy (1967), and it is possible that in the past many celestite pseudomorphs have been wrongly identified as dolomites.

However, these can easily be distinguished from one another if the habits of the original crystals are considered. For instance, dolomite typically forms a rhombohedral crystal, and if a number of random cross-sections of this are made,

A.

(x20)

B.



(x10)

FIGURE 127 A) Photomicrograph of some calcareous pseudomorphs after celestite (La Plogne Member, near Larnagol).

B) Photomicrograph of some calcareous pseudomorphs after barytes from the Jurassic of Northern Spain (courtesy of A. Sbeta).

only triangular and rhombic shapes can be produced (figure 126d). Celestite, in contrast, is orthorhombic and a much greater range of shapes can be derived from it, which could not be obtained from dolomite (figure 126c).

Another problem which has become apparent is that barytes and anhydrite crystals sometimes grow in exactly the same habit as celestite, making it almost impossible to distinguish between pseudomorphs of the three types. As an example, figure 127b is a photomicrograph of some pseudomorphs from the Jurassic of Northern Spain. As their habit is identical to the celestite of the Hard Cap Limestones, initially they were also identified as celestite. To confirm this, some unreplaced relicts of the original mineral which are present inside the pseudomorphs, were analysed using an electron microprobe. To the writer's surprise these turned out to be relicts of barytes and not celestite!

Hence it is possible that the orthorhombic pseudomorphs in the Middle Jurassic rocks of the Cajarc area could be relicts of barytes, but after a consideration of the environments of deposition of the sediments a source of Ba could not be envisaged. Therefore, that these were composed entirely of celestite seems to be the most reasonable interpretation.

6.6 Lutecite

Spherulitic aggregates of length-slow chalcedony or lutecite, have been found together with calcitised evaporitic deposits in the Brengues Member of the Cajarc Formation. These rarely exceed one centimetre in diameter. They occur either in patches of calcite which have replaced anhydrite or in the host sediment, or sometimes at the boundaries of the host and calcitised anhydrite.

Schreiber (1974) showed that spherules which are broken, or have pitted and abraded outlines, might have originated as detrital grains. No evidence of this has been found in the Brengues Member. Instead, the outlines of the lutecites are sharp and still concentric with internal growth lines.

There is also no indication that the lutecites grew displacively in the host sediment before it became lithified. On the contrary, numerous inclusions of calcite can be detected inside the spherules which suggests that they have grown by replacing the host.

Folk and Pittman (1971) considered that spherulitic lutecite is usually indicative of evaporitic deposits; it either coexists with the evaporites or it can remain as a residual mineral after evaporites have been removed. They also observed that lutecite can replace either calcite, or evaporitic minerals such as anhydrite, gypsum, celestite and barytes, and sometimes unreplaced relicts may remain in the spherules.

In the Brengues Member, the lutecites in the host sediment are considered to have grown during diagenesis by replacing the limestone, and many unreplaced calcareous relicts have been preserved in the spherules. However, the majority of the lutecites occur in patches of coarse crystals of calcite which have replaced anhydrite. Initially these lutecites were thought to have replaced the original anhydrite, but all the inclusions in these spherules are calcareous and no anhydrite relicts have been detected. Therefore it is probable that the lutecites have replaced calcite, which itself had already replaced anhydrite.

Some lucetite has also formed pseudomorphs after celestite crystals. Again these were initially interpreted as having replaced celestite, but a closer examination revealed that calcareous inclusions are ubiquitous. Some of the pseudomorphs even possess cores of calcite crystals with similar textures to the calcareous pseudomorphs. It would seem, therefore, that these were also replaced by lutecite after they had been calcitised.

Thus the evaporitic deposits seem to have been removed before replacement by lutecite commenced. Folk and Pittman (op.cit.) noted that this might be induced by the presence of formation waters which were enriched in sulphates. If this was the case, the changes must have occurred before uplift and erosion started to modify the composition of the pore-waters. However, one thing that has remained a mystery is why the lutecites preferentially replaced coarsely crystallised patches of calcite after anhydrite, and not more of the host limestone, especially if the pore-waters were in general circulation. Perhaps the calcite which replaced the sulphates is slightly different, in composition or structure, to normal calcite?

6.7 The Replacement of the Evaporitic Minerals

All the pseudomorphs in the Middle Jurassic rocks of the Cajarc area are after sulphate minerals. Two types of replacement have become evident; piecemeal and complete dissolution with subsequent infilling of the void.

With piecemeal replacement, the internal features of the original crystals are often preserved or occur as ghost structures, which suggests that it occurred on a molecule for molecule basis. However, this seems unlikely, especially when calcite or quartz replaces a sulphate mineral, because the difference in lattice structure and the changes in volume which would be involved, would probably make it impossible. Nevertheless, what could take place is that very small volumes of say $Ca\ SO_4$ might go into solution and correspondingly small amounts of $Ca\ CO_3$ could be precipitated concomitantly. Thus any internal textures or inclusions would be undisturbed.

The rate at which this occurs could govern whether piecemeal replacement or complete dissolution takes place. A slow rate of dissolution would probably result in piecemeal replacement, whereas a fast rate would probably completely remove the original mineral to leave a void.

A controlling factor in the rate of dissolution might be the porosity of the rock. In this respect it is interesting that pseudomorphs formed by both mechanisms, usually occur in close proximity to one another. In these cases it is almost certain that the same processes have operated on the original minerals, but the rate may have varied with differences in the porosity of the host.

The geochemistry of calcitisation is far from understood and no evidence has been found which suggests how it has occurred. Shearman and Fuller (1969) and Kinsman (1969) considered that sulphate may become reduced by bacteria, in the presence of organic matter of hydrocarbons so that calcite is precipitated and H_2S gas is given off:

$$Ca\,SO_4 + CH_4 \text{ (i.e. methane)} \rightarrow Ca\,CO_3 + H_2S + H_2O$$

This process could have taken place in the Middle Jurassic limestones because lignitic deposits are fairly abundant and they may have acted as sources of methane.

Another possibility was suggested by Lucia (1972) who thought that circulating fresh water could cause calcitisation. This might easily have occurred in the Middle Jurassic rocks especially during the Pleistocene when the ground waters were very much colder and therefore the CO_2 content was probably higher.

Obviously this is a near surface process. Yet Carozzi et al

(1972, pl.91) found castellated calcareous pseudomorphs after secondary anhydrite, which contained unreplaced relicts of the latter at a depth of 1300 m. below the surface in Aquitaine. Therefore calcitisation may also be occurring at depth.

It would be interesting, however, to look for evidence of an unconformity or discontinuity above this particular level, because a period of calcitisation may have occurred during a break in deposition. Calcitised evaporitic deposits might even tell the same story as do some dedolomites in the subsurface (Evamy, 1967).

6.8 The Significance of the Evaporitic Pseudomorphs

Until the present study only so-called pseudomorphs after gypsum had been described from the Middle Jurassic limestones of the Cajarc area. However, in the previous sections it was suggested that most of the 'gypsums' are in fact pseudomorphs after secondary anhydrite. Moreover, pseudomorphs after nodular and entrolithic bands of primary anhydrite, discoidal crystals of primary gypsum, laminated deposits of primary gypsum and celestite crystals have also been recognised. Thus a whole suite of evaporitic minerals appears to have formerly been present in the Middle Jurassic rocks.

Apart from secondary anhydrite which was replacive, these minerals probably grew displacively in an unconsolidated host sediment, at a very early stage in diagenesis. Most of them occur in mud-cracked supratidal and intertidal deposits such as algal boundstones, laminated calcareous mudstones, calcareous mudstones and ostracod wackestones, and sometimes both the host and adjacent sediments have been dolomitised (now usually dedolomitised).

All of the minerals, except for secondary anhydrite, can be found in the Recent sabkhas of the coastal plains of the

Persian Gulf (Bush, 1973). These have a very low, flat topography and they are gradually prograding seawards (Evans, 1970 and Evans et al, 1973). Thus areas which were formerly intertidal are becoming stranded in the supratidal zone. Here the arid climate of the region causes the ground waters to evaporate, and they are probably replenished by sea water from the nearby lagoons. As this continues the chemical composition of the ground water becomes more and more concentrated until a brine is formed.

Eventually, minerals such as gypsum, anhydrite, celestite and halite start to precipitate and these grow displacively in sediments which were originally deposited in both intertidal and supratidal environments. Furthermore, the composition of the brines is changed and this causes the host sediment to become dolomitised to varying degrees. Thus as the coastal plain extends seawards it induces the onset of early diagenetic processes and sediments that were originally deposited in non-sabkha environments may become modified both by chemical replacement and by the disruptive growth of new minerals.

Secondary anhydrite is a product of later diagenesis. Usually it can be shown to have grown replacively in limestones after they have been lithified. This probably takes place, subsequent to burial, when circulating formation waters become supersaturated with respect to $Ca\ SO_4$. Needless to say, unlike primary evaporitic deposits, secondary anhydrite is not confined to sediments laid down in any particular environments. Nevertheless, it often occurs in close proximity to primary anhydrite deposits, which probably grew under sabkha conditions.

Occasionally, castellated and axe-head pseudomorphs of secondary anhydrite have been misidentified as being after gypsum (e.g. Bouroullec et al, 1973, p.15, fig.4). They have also been used as indicators of supratidal conditions, but as they are actually after secondary anhydrite this interpretation is clearly incorrect.

Palaeogeographical interpretations of the Middle Jurassic rocks of the Aquitaine Basin (figure 6) have shown that two lagoonal complexes became developed in the Middle Jurassic (Winnock et al, 1973). Substantial deposits of evaporites have been found in the southern lagoon (Faber, 1972), but up to now, none has been described from the northern one.

The sequence in the southern lagoon, which is known as the Formation de Saint Menard, has been interpreted as a restricted, intertidal to supratidal lagoonal succession (Faber, 1972; Carozzi et al, 1972 and Winnock et al, 1973). It is composed of about 300 m. of alternating deposits of anhydrite and dolomite, interbedded with occasional thin ostracod-charophyte-rich limestones. In the Cajarc area of the northern lagoon, the equivalent succession is made up of limestone with calcitised evaporitic minerals, calcitised dolomites and thin ostracod-charophyte-rich beds. This suggests that similar conditions of deposition may have existed in each lagoon. Furthermore, although the aerial extent of the northern lagoon was greater than the southern one, the thicknesses of the Middle Jurassic sediments in each case is alike, therefore the rates of deposition were probably about the same.

Thus, since the rate of sedimentation and the conditions of deposition were apparently similar, it is possible that substantial quantities of evaporites might also be present in the subsurface rocks of the northern lagoon. As yet, none has been recognised, but it could be that, as have the evaporites at outcrop around Cajarc, the subsurface deposits could also have been calcitised, thereby making them difficult to detect in borehole cores.

CHAPTER 7

DOLOMITISATION AND DEDOLOMITISATION

Winnock et al (1973) and Carozzi et al (1972) showed that the lagoonal limestones of the Cajarc area pass laterally westwards into lagoonal limestones and dolomites, and eventually into completely dolomitised oolitic limestones of the barrier (figures 5 and 6), in the subsurface. Moreover, in the area of the southern lagoon (figure 6), the Middle Jurassic succession consists almost entirely of interbedded dolomitic and evaporitic rocks.

Dolomite is only rarely developed in the Middle Jurassic rocks of the Cajarc area. This is suprising since they were probably deposited under similar conditions to the rest of the Middle Jurassic sediments of Eastern Aquitaine. Also this is even more suprising as calcitised evaporites are common in these limestones, and dolomite usually occurs with evaporites in other parts of Aquitaine. However, although dolomitic rocks are rare, considerable portions of the St. Martin, Cajarc and Montbrun Formations are composed of crystalline limestones, and in this chapter it will be shown that these were once dolomitic rocks which have subsequently been calcitised.

7.1 The Dolomitic Rocks

Dolomite has only been found at a few levels in the Middle Jurassic succession of the Cajarc area. The lowest and most abundant occurrence is in the micaceous shales at the top of the Larroque Formation, and in the lowermost few metres of the rocks of the overlying St. Martin Formation (figure 11c). At this horizon most of the dolomite is iron - rich, and therefore it should really be called ankerite (p. 44).

In the Brengues Members of the Cajarc Formation several thin beds of dolomitic - mudstone and dolomitic - calcarous - mudstone, have been found, but no dolomite is present in the Montbrun Formation.

7.2 The Crystalline Limestones

Both fine and coarsely crystalline limestones have been observed in the Cajarc area. The finer types are sucrose in appearence, and in thin - section the boundaries between the crystals comprising the rocks, are simple. Some of these rocks are equigranular in texture, but others possess ghosts of original depositional textures and occasionally these pass laterally into more coarsely crystalline limestones with no such textures.

The coarser types are composed of much larger crystals, up to 8 mm. in size, and on fractured surfaces they usually display a mass of cleavage planes. In thin - section, the crystal boundaries are sutured and interpenetrating (figure 128). At extinction, the crystals seem to be full of inclusions which are usually less than 100 microns in size; staining with alizerine - red S has revealed that

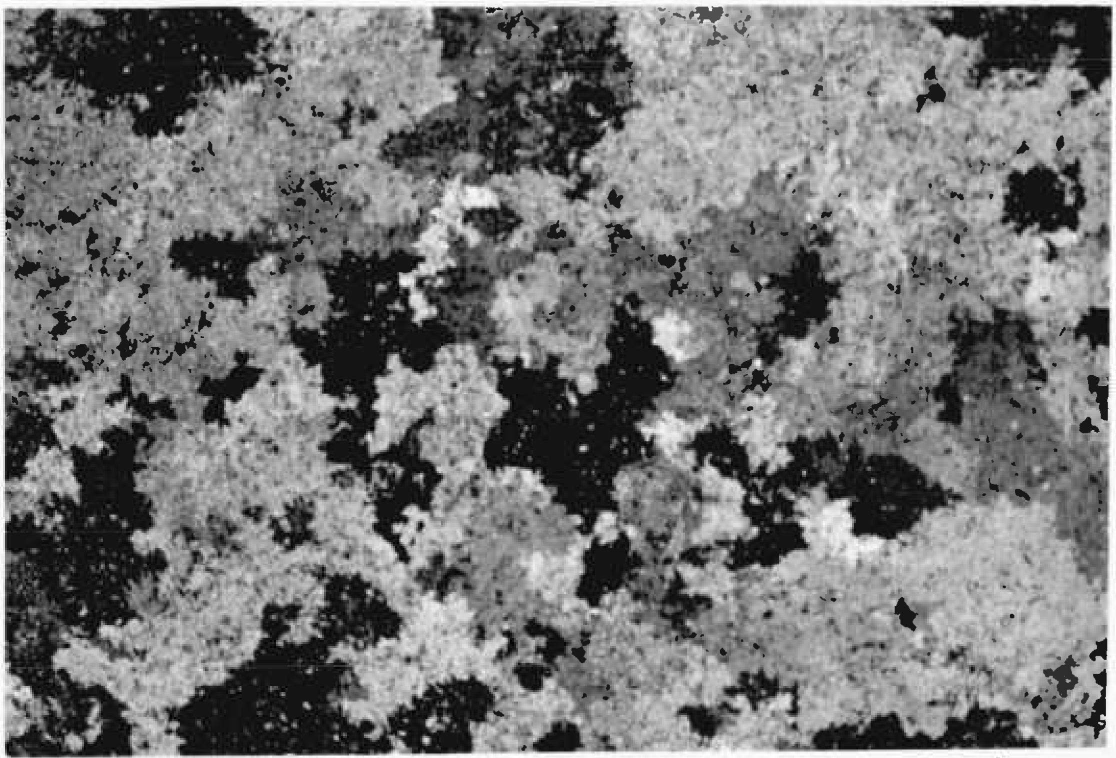


FIGURE 128 Photomicrograph of a coarsely crystalline limestone under crossed-polarisers, showing large poikilitic crystals of calcite with complex and interpenetrant boundaries (20/72; Larnagol Mb, N662 road section at 064259).

these are either calcareous or dolomitic in composition. Moreoever, the latter types often appear to be corroded rhombic shapes (figure 129), similar to those described by Shearman et al (1961, pl.1., c and d) and Lucia (1972, figure 31), whereas the calcareous ones are usually anhedral.

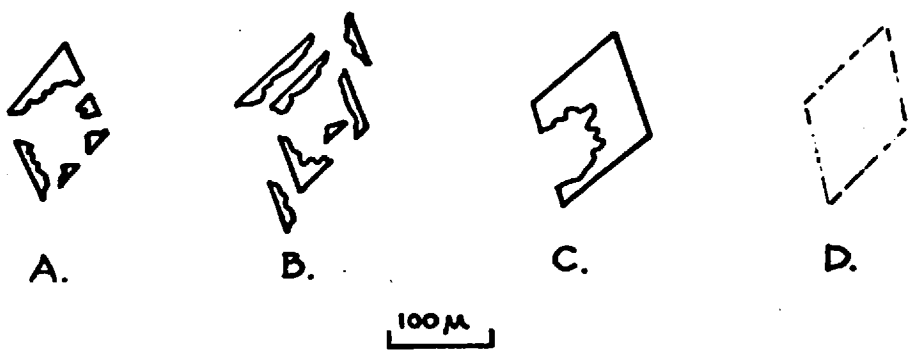


FIGURE 129 A, B and C) Corroded microrhombs of dolomite, and D) and iron-oxide ghost. Note the preservation of zones in B.

Shearman et al (op cit.) noted that if a dolomitic rock becomes replaced by large crystals of calcite, the resulting texture is typically equigranular, and the crystal boundaries are complex. They also noted that if calcitisation has been incomplete, the large crystals of calcite would probably poikilitically enclose unreplaced, corroded relicts of dolomite crystals which were originally rhombic in shape. Therefore following Shearman et al, the coarsely crystalline limestones of the Cajarc area are interpreted as calcitised dolomitic rocks (or dedolomites).

Further evidence of this is provided by the fact that crystalline limestones possess rhombic ghosts of iron-oxide which Shearman et al (op. cit., figures 5 and 6) suggested may be left behind if iron - rich dolomite has been calcitised. Furthermore, in one of the more coarsely crystalline types with no inclusions of dolomite, acetate peels have revealed a ghost - like microrhombic texture within apparently homogeneous crystals of calcite. Presumably this has resulted from the preservation of dust lines or slight variations in composition within individual crystals, which were inherited from an original microdolomite - rock, and have now been picked out by etching with acid.

The more finely crystalline limestones with ghost textures have also probably been formed by the calcitisation of dolomitic rocks, because they are usually interbedded with the coarser poikilitic types, and rarely they pass laterally into dolomitic rocks (figure 11) e.g. at the base of the St. Martin Formation. In one or two cases rhombic ghosts of iron oxide, and corroded dolomite relicts have also been observed in these rocks.

With regard to the origin of the ghost textures, Evamy (1967) showed that sometimes a limestone may be incompletely dolomitised, leaving unreplaced relicts of the host limestone within crystals of dolomite. During any subsequent calcitisation these remnants could act as 'seeds' or nuclei, thus enabling replacement to progress by overgrowth of the inclusions until the original texture of the limestone is completely regenerated.

In the example described by Evamy (op. cit) only occasional patches of the limestone had been dolomitised, so that after calcitisation had occurred, only small areas possessed regenerated textures. However, in the Cajarc area, entire beds of limestone have probably been dolomitised and dedolomitised in this manner, and these now remain as ' recrystallised' limestones with ghosts of the original depositional textures.

Some of the finely crystalline limestones apparently do not possess ghost fabrics, but have equigranular textures instead; nevertheless, these can still be explained in terms of a process of regeneration, during dedolomitisation. Perhaps if a calcareous mudstone became incompletely dolomitised so that numerous unreplaced relicts of the limestone remained, and if this subsequently became replaced by 'seeded' crystals of calcite, a slightly coarser version of the fabric of the original limestone would be regenerated and a crystalline equigranular textured rock would probably result.

Many of the slightly coarser grained calcareous mudstones of the Cajarc Formation may have been subjected to dolomitisation followed by calcitisation and the regeneration of their original fabrics (p.128). Also many pseudomorphs after secondary anhydrite have internal textures which have been regenerated from unreplaced inclusions of calcareous mudstone (p. 314). Some workers might interpret these as neomorphic textures, but the petrological evidence clearly shows that they have resulted from a double process of replacement followed by calcitisation.

The calcitisation of the dolomites of the Middle Jurassic of the Cajarc area has probably taken place on a piecemeal basis (p. 314), because ghost textures are occasionally preserved, and unreplaced relicts of dolomite have sometimes remained undisturbed. Whether the dolomite has been replaced poikilitically, or by a regenerated mosaic of crystals, probably depended on the density of the unreplaced relicts of the original limestone in the dolomite crystals. If these were numerous, each one would be probably grown at the expense of the surrounding dolomite, until the latter was completely replaced and the fabric of the original limestone had been regenerated on a slightly coarser scale. However, if only very few unreplaced relicts were available, large crystals of calcite would have probably been able to replace considerable numbers of dolomite crystals, and at the same time possibly poikilitically enclose a few incompletely replaced rhombs.

The crystal boundaries generated by these two processes are also different. In cases where the original fabric has been regenerated, each unreplaced relict was probably overgrown by calcite until it met and mutually interfered with adjacent crystals (figure 130a). This resulted in the development of simple compromise boundaries (Bathurst, 1971, P.421). However, where poikilitic replacement has occurred, the growing crystals of calcite would have probably engulfed whole crystals of dolomite. As two crystals approached one another, it seems reasonable to expect that some dolomite rhombs would have been replaced by one crystal of calcite, and the remainder by the other crystal (figure 130b).

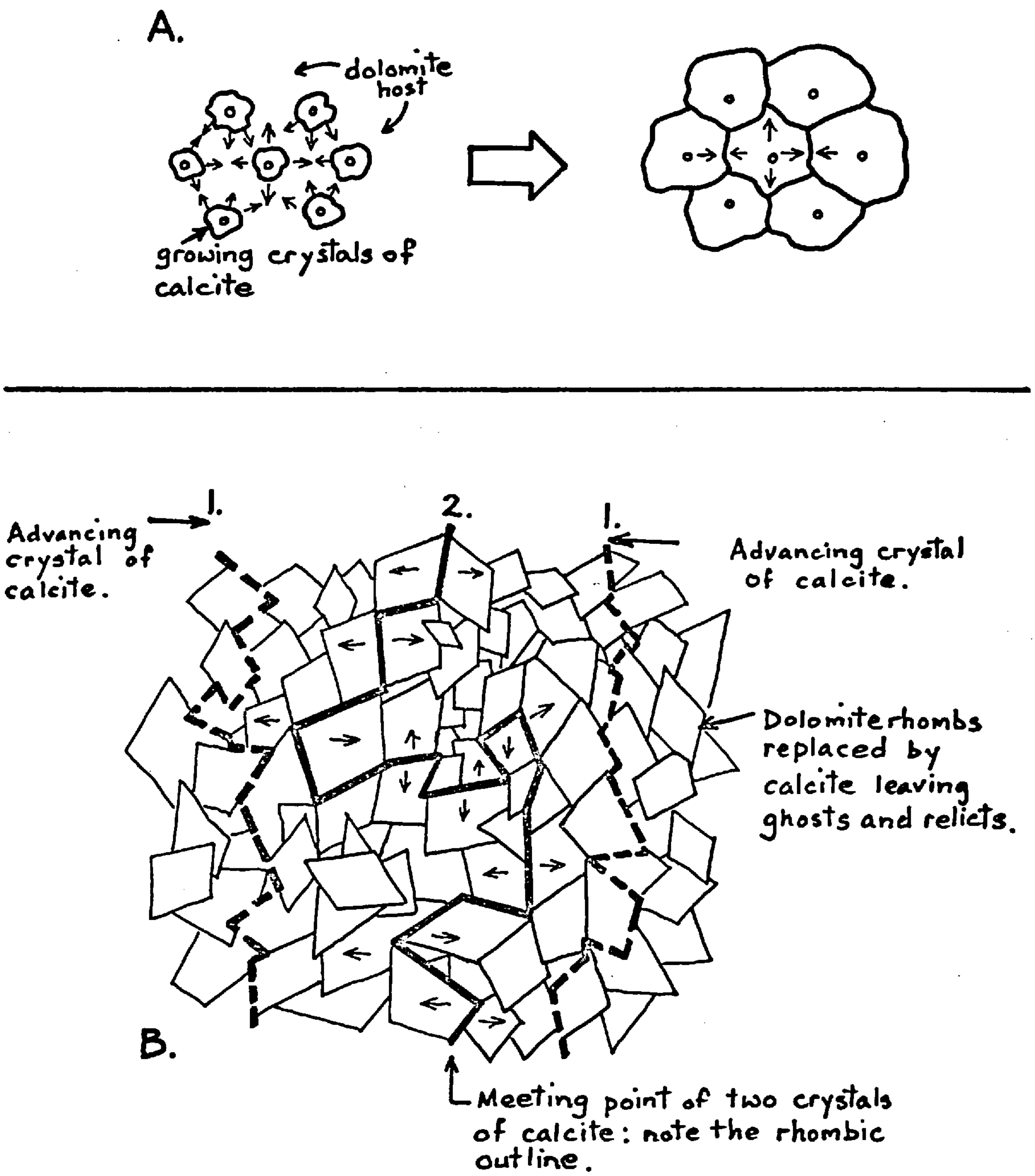


FIGURE 130 The development of grain boundaries in dedolomitised rock:

A) Simple compromise boundaries caused by the overgrowth of unreplaced inclusions of the original limestone.

B) Complexed, interpenetrating boundaries, caused by the poikilitic replacement of dolomite rhombs by large crystals of calcite.

Thus when they eventually met, the boundary between the crystals should have taken the form of the outlines of the rhombic crystals which had been replaced (figure 130b). This is exactly what has been found in the coarse crystalline limestones of the Cajarc area, where the crystal margins are angular and interpenetrating, and they often follow parts of the original outlines of the now removed dolomite rhombs.

Therefore, it would seem that the textures which have developed in the crystalline limestones were controlled by the density of unreplaced relicts of the original limestone, that remained in the dolomite - rocks prior to their calcitisation. Of course this would have been dependent on the degree of dolomitisation, because almost complete dolomitisation followed by calcitisation would have resulted in coarsely crystalline limestones, whereas incomplete dolomitisation followed by calcitisation would have given rise to a finely crystalline rocks with regenerated fabrics.

7.3 Partial Dolomitisation/Dedolomitisation Textures

So far, in all of the rocks discussed, the whole volume of the original limestones has been affected by dolomitisation and subsequent calcitisation. However, sometimes inter-bedded with these completely crystalline rocks are limestones in which only small volumes of sediment were replaced by dolomite. Subsequent calcitisation has often regenerated the original fabric of the limestone in these areas, and it has resulted in small, coarser

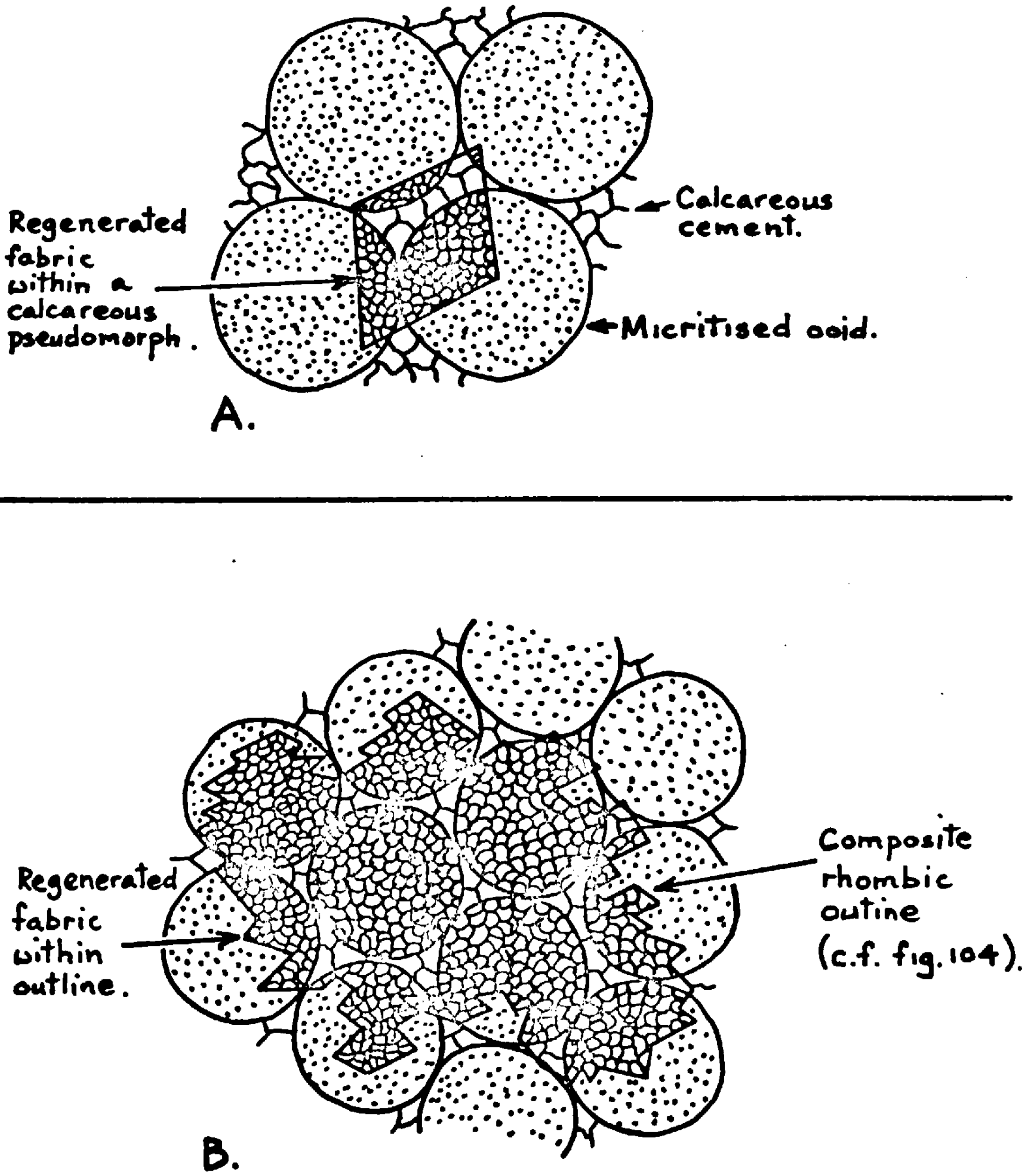


FIGURE 131 Partial dolomitisation/dedolomitisation textures in grainstones:

A) A rhombic calcareous pseudomorph after dolomite.

B) A patch of calcitised dolomite crystals.

grained patches with ghost textures, being surrounded by unaffected limestone. Evamy (1967) described some very similar rocks from the Upper Oxfordian of the Yonne Valley in France.

Varying degrees of original dolomitisation have been observed. Sometimes solitary dolomite rhombs have partially replaced oolitic grainstones in the St. Martin Formation, and subsequent calcitisation has regenerated the original fabric of the rock within the now calcareous pseudomorphs (figure 131a). Care must be taken, however, in distinguishing these rhombs from pseudomorphs of celestite or barytes (p. 344).

Occassionally groups of rhombs have also developed within host limestone, and calcitisation has regenerated the original fabric of the host within these patches. Usually they can easily be recognised because they have composite rhombic boundaries (figure 131b), but caution must be exercised to distinguish them from castellated pseudomorphs of secondary anhydrite which have rectangular margins. Furthermore, if this patchy replacement has been fairly extensive, it can cause the rock to look like a breccia, whereas in fact no mechanical fracturing has ever occurred. Dixon and Vaughan (1911) called similar dolomitic rocks as pseudo - breccias, but in the case under consideration the dolomitic patches have been completely calcitised.

Finally, in a few of the rhodolithic and oolitic grainstones of the St. Martin Formation, the cement has been dolomitised and the grains have remained relatively unaffected. Moreoever, subsequent calcitisation has resulted in the texture of the cement being regenerated, and the only evidence to indicate that dolomitisation has ever occurred are the now angular boundaries of the grains, which are composed of numerous rhombic indentations where the dolomite crystals just began to encroach into the grains (figure 17c).

7.4 The Cause of Dedolomitisation

At this stage it is pertinent to inquire why almost all of the dolomitic rocks of the Middle Jurassic of the Cajarc area have been calcitised. Evamy (1967) discussed the possible causes of dedolomitisation and he concluded that it is a near - surface process, which takes place when solutions with high Ca/Mg ratios are allowed to react with dolomite, thereby producing calcite. He also indicated that outcrops of dedolomitised rock should pass into dolomitic rocks in the subsurface.

This is exactly the situation that exists in the Aquitaine Basin, where dedolomitised rocks of Middle Jurassic age, can be correlated with dolomitic rocks in the subsurface (figure 5). Therefore, following Evamy (op. cit.), the crystalline limestones of the Cajarc area are considered to have resulted from the calcitisation of dolomitic rocks in a surface, or near - surface situation, after the rocks had been uplifted in response to the erosion of the overburden.

The present plateau surface of the Causse du Quercy probably dates from the Early Tertiary (p.23), and the only change which has occurred since then has been the incision of the east - west valleys, by rivers such as the Lot. Furthermore, during the Tertiary, a desert environment probably existed over Quercy (p. 21), so it is possible that ground waters rich in $CaSO_4$ may have been generated. By percolating down - dip, these might have caused surface and near - surface dolomitic rocks to become calcitised by a leaching process. Evidence of this can be found by examining the sections exposed in the valleys, because as the dedolomitised rocks approach the Tertiary land surface they become more and more weathered and cavernous, as if they have been increasingly severely leached at some time.

An interesting feature which has also been observed is that in some dedolomitic rocks, large poikilitic crystals of calcite have enclosed both anhedral and corroded rhombic calcareous inclusion. As calcite does not normally grow in a rhombic habit, the latter inclusions are almost certainly corroded rhombs of dolomite which have become calcitised. The anhedral inclusions may also be calcitised dolomite relicts, but on the other hand they might be unreplaced inclusions of the original limestone.

The presence of calcitised dolomite relicts implies that two separate phases of calcitisation must have occurred, because a single phase would have probably replaced the relicts in optical continuity with the poikilitic crystals. The first phase was probably due to leaching, in a near - surface environment, where large poikilitic crystals of calcite developed and enclosed corroded relicts of dolomite. The second phase, during which the corroded relicts were calcitised, probably occurred after exposure when the rocks were subject to subaerial weathering. All the specimens that have been examined have been collected from the sides of the Lot Valley, so it is possible that the second phase of calcitisation was caused by exposure produced by the incision of the rivers.

7.5 The origin of the Calcaire Cargneuliform

There are some unusual beds of crystalline limestone in the St. Martin Formation, and in the lower parts of the Cajarc Formation, which the early French geologists have mapped as ' calcaire cargneuliform'. This lithology is red, yellow or orange in colour and it has a rubbly and cavernous appearance at outcrop (figure 132). Good exposures can be seen in the D24 road section near St. Martin-Labouval.

In road cuttings along the D24, and the N662 between Lar nagol and Cajarc, crystalline limestones and dedolomitic textures, pass laterally into cargneuliform beds. Often this passage is up-dip, and the rubbly lithology occurs where the beds crop out at the present land surface. Also, within crystalline limestone, the cargneuliform lithology is sometimes developed along joints, fractures and bedding planes.

Furthermore, petrological examinations have shown that coarsely crystalline limestones have been recrystallised to yellow stained, fine grained mosaics less than 100 microns in average size,in the cargneuliform beds. The yellow stain usually just preceeds the advancing front of degrading recrystallisation, and it is thought to be due to iron-oxides which were originally derived from dolomite, before the crystalline limestone was generated by processes of calcitisation. Yellow, fine grained, calcareous geopetal sediments are also developed in some solution cavities in the rocks.

These features suggest that the calcaire cargneuliform has been formed by leaching processes related to the present day land surface. This probably commenced along joints and bedding planes, and as it progressed it eventually pervaded the whole rock to produce cavernous, rubbly lithologies, stained red, yellow or orange by iron-oxides.

An interesting point is why the crystalline limestones have been preferentially leached, while interbedded calcareous mudstones have remained unaffected. Evamy (1967) showed that calcite after dolomite may be enriched in Mg. He also suggested that this would be more soluble than low - Mg calcite. However this does not account for the preferential leaching of the crystalline limestones because x-ray analysis has shown that they are composed of low-Mg calcite, as are the interbedded mudstones.

Another possibility, which seems more likely, is that leaching was enhanced by the well developed cleavage planes that are present in the crystalline limestones; in contrast the mudstones are composed of very small crystals with no visible cleavage planes. Therefore groundwaters may have been able to attack the larger crystals much more effectively along the planes of weakness, which would probably have encouraged both the chemical and mechanical removal of $Ca\ CO_3$.

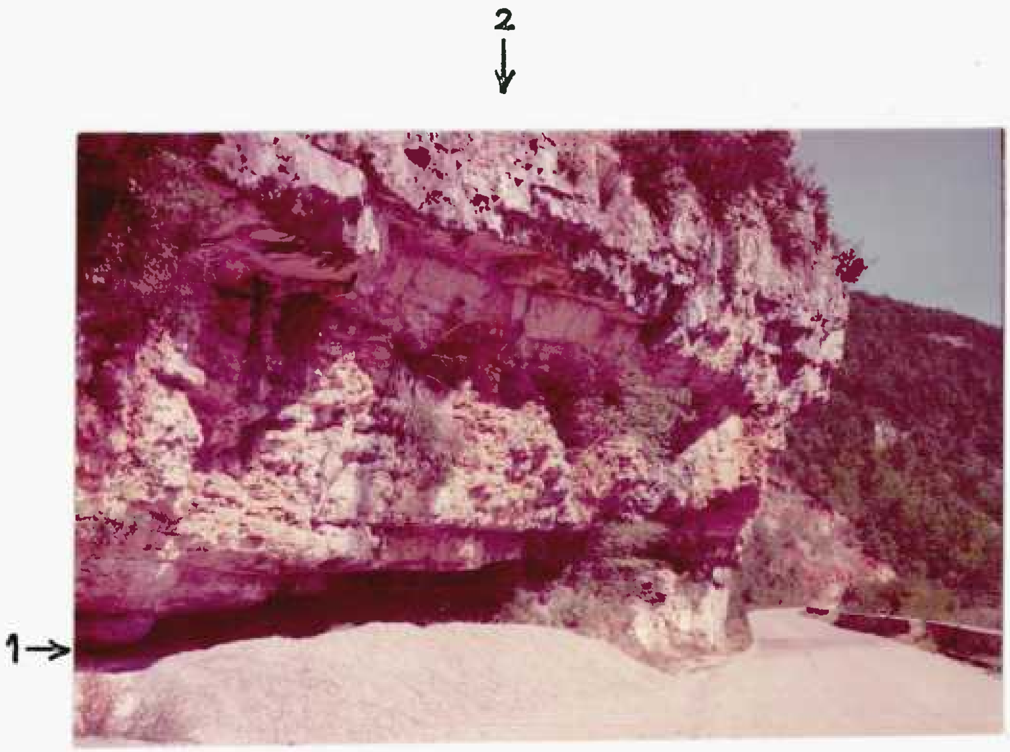


FIGURE 132 An outcrop of 'Calcaires Cargneuliform' on the N662 near Larnagol, showing the yellow colouring and the rubbly cavernous appearance of the lithology. This occurs at the base of the La Plogne Member, just above a thick lignitic marl (1), and it is overlaid by calcareous mudstones (2). Laterally it passes westwards into a coarse crystalline limestone with a dedolomitic texture and eventually into unaffected calcareous mudstone near Cajarc (072259).

Thus the calcaire cargneuliform has probably been produced from crystalline limestone, by surface leaching or weathering processes. It is suggested that the diagenetic evolution of this lithology is as follows:

(1) DEPOSITION
As a mudstone or grainstone

↓

(2) DOLOMITISATION
During diageneis to produce a microdolomite - rock

↓

(3) DEDOLOMITISATION
Due to leaching during uplift and erosion, producing a crystalline limestone

↓

(4) WEATHERING
Weathering or leaching at ground level to produce a cavernous, rubbly lithology, or calcaire cargneuliform

7.6 The Cause of the Original Dolomitisation

The presence of crystalline limestones and calcaire carneuliform at outcrop, together with the lateral passage of the Middle Jurassic sediments into dolomitic rocks in the subsurface, implies that dolomitic rocks were formerly present in the Cajarc area. Hence, in the Aquitaine Basin there exist, or have formerly existed, considerable volumes of dolomitic rocks of Middle Jurassic age.

Friedman and Saunders (1967) noted that most dolomitic rocks have probably been generated by the replacement of pre - existing limestones, and a perusal of the literature has shown that this may take place in various ways:

1) Upper Intertidal - Supratidal Dolomitisation (Shinn et al 1965 and 1969): this occurs in humid, tropical areas where the laminated calcareous sediments may become penecontemporaneously dolomitised in an upper intertidal to supratidal environment.

2) Sabkha Dolomitisation -(Shearman, 1963; Illing et al, 1965; Bush, 1973): this occurs in an arid, supratidal sabkha environment, where Mg - enriched brines can cause intertidal and supratidal calcareous sediments to become penecontemporaneously dolomitised.

3) Seepage Reflux Dolomitisation (Adams and Rhodes, 1960; Deffeyes et al, 1965; Friedman and Saunders, 1967; Bush 1973): this is later stage diagenetic dolomitisation probably caused when Mg - rich brines (possibly produced in sabkhas) seep downwards and basinwards into previously deposited sediments. It is influenced by the porosity of the sediments, and it can affect limestones which have been deposited in any environment. Usually it cuts across bedding planes and facies boundaries, therefore it is not stratigraphically controlled.

4) Late Stage Dolomitisation (Friedman and Saunders, 1967): this occurs along faults, joints, etc. due to circulating Mg - rich ground waters, and it usually shows a relationship to the structural features of the rocks.

Evidence of penecontemporaneous and seepage reflux types of dolomitisation has been found in the Middle Jurassic rocks of the Cajarc area, but no late stage, structurally controlled dolomites are known.

In the La Plogne Member, mud cracked, laminated calcareous mudstones (p. 153), deposited in an upper intertidal to supratidal environment and associated with lignitic marls, have sometimes been dolomitised (laminated microdolomite - rock) and occasionally dedolomitised (laminated finely crystalline limestone). These are only thinly developed and usually restricted to particular horizons. Furthermore no evaporites are present. Thus they are thought to have been dolomitised penecontemporaneously in an upper intertidal to supratidal environment, similar to the one described from the Bahamas by Shinn et al (1969).

In the Brengues and Marcilhac Members, thin beds of microdolomite or dedolomite occur together with calcitised evaporites which probably originated in a supratidal sabkha environment (p. 354). Again these are thinly developed and restricted to particular stratigraphic horizons. In this case dolomitisation probably took place penecontemporaneously, in a supratidal sabkha environment similar to that found in the Persian Gulf (Bush, 1973).

However, these small scale processes do not explain the former development of massive beds of dolomite in the St. Martin, Lower Cajarc and Montbrun Formations. Textural evidence such as the presence of ghost fabrics, suggests that the dolomites were formed by the replacement of pre-existing limestones and sometimes crystalline limestones pass laterally into unaffected sediments. Furthermore, most of the former beds of dolomite have apparently been generated from limestones which were originally deposited in environments where penecontemporaneous dolomitisation would not be expected to have occurred e.g. the crystalline limestones of the St. Martin Formation, which pass laterally into oolitic grainstones deposited in an outer lagoonal or barrier situation. Another example is also present at the base of the St. Martin Formation, where unaffected beds of open marine, bioclastic packstone pass laterally into both dedolomitised crystalline limestone, with ghost textures, and microdolomite - rock (figure 11).

Moreoever, the original zones of dolomitisation appear to have cut obliquely across bedding planes and stratigraphic boundaries, and the regional extent of dolomitisation seems to have varied: northwards in the Dordogne, the equivalent Middle Jurassic limestone are relatively unaffected, whereas westwards into the subsurface, the Middle Jurassic is almost completely dolomitised.

Thus the overall impression given by the former beds of dolomite is that they were created after burial had occurred, and that dolomitisation was probably caused by a seepage reflux mechanism. Bathurst (1971) reviewed this process, but he thought that the evidence for it was inconclusive. However, in the opinion of the writer, no other mechanism can satisfactorily explain the occurrence, or former occurrence, of massive dolomites in Aquitaine.

By this process Mg - enriched brines which formed in a sabkha environment, may have been able to seep basinwards and dolomitise the limestones as they went. This seems to have been controlled to some extent, by the porosity of the sediments, because grainstones have been most strongly affected. Also, impervious horizons appears to have encouraged the dolomitising brines to flow along certain levels, and the limestones immediately above have often been more intensely modified.

In conclusion, penecontemporaneous and later diagenetic dolomites (see footnote) have been recognised in the Middle Jurassic succession of the Cajarc area, but they have been almost completely calcitised.

Footnote: Some workers, eg. Rhodda and Fisher (1969) might call these stratal and massive dolomites, respectively.

SUMMARY

At the end of Toarcian times a complex of coastal lagoons became established to the west of the Massif Central. After conditions had stabilised, three general environments of deposition were in existence in the Aquitaine region: an open marine zone in the west; a coastal barrier zone in the middle; and a lagoonal zone in the east. These have given rise to successions which pass laterally into one another; these successions are dominated respectively by: shales and limestones with cephalopods; dolomitised oolitic rocks; and calcareous mudstones that are also sometimes dolomitic.

In the Cajarc area the lowest rock unit which has been studied is the Larroque Formation. Only the upper part of this unit was examined in detail where it is composed entirely of soft micaceous-ankeritic-shales with a sparse fauna of ammonites and belemnites. Using the ammonites it has been possible to date the formation as Upper Toarcian in age. A thin band of ferruginous-oolitic shale is present at the top of the unit, which is of the same age as the famous Minette ores of Lorraine. The sediments of this formation are thought to have been deposited in an offshore, open marine shelf environment.

The siliciclastic sediments of the Larroque Formation are succeeded by the limestones of the Saint Martin Formation, which is approximately 60 m. in thickness. The lower, or Latoulzanie Member of this unit, is composed of a thin succession of bioclastic and rhodolithic packstones which have been extensively dolomitised and dedolomitised. They contain a rich fauna of ammonites, belemnites, bivalves, gastro-

pods, brachiopods, echinoids and foraminifera, which indicate a lower Bajocian age for the rocks. These sediments are thought to have been deposited in a nearshore, open marine shelf environment, and they appear to represent a condensed sequence.

The middle or Ceneviers Member is composed of poorly fossiliferous oolitic grainstones and crystalline limestones, with a few thin beds of rhodolithic grainstone. The crystalline rocks sometimes account for more than 50% of the succession and they were probably formed during diagenesis by the dolomitisation and dedolomitisation of oolitic limestones. The sediments of this member are considered to have originally been deposited in a coastal barrier environment, with occasional periods when open marine or outer lagoonal conditions existed.

The upper or Corn Member is composed mainly of crystalline limestones (or dedolomites), interbedded with rhodolithic grainstones, calcareous mudstones and peloidal oolitic grainstones. These were probably deposited in a subtidal, outer lagoonal environment.

The succession of the Saint Martin Formation suggests that in early Bajocian times an oolitic coastal barrier became established around the Massif Central. This gradually migrated westwards into Aquitaine and it passed through the Cajarc area in late Middle to Upper Bajocian times; almost certainly it did not reach central Aquitaine until the late Bajocian or early Bathonian.

The rocks of the Saint Martin Formation are succeeded by the limestones of the Cajarc Formation, which is over 110 m. in thickness. The lowest, or Larnagol Member, is made of crystalline limestones, sometimes interbedded with calcareous mudstones. Originally the former were probably also calcareous mudstones, but they have since been dolomitised and dedolomitised to produce coarsely crystalline rocks. They were probably deposited in a subtidal to supratidal coastal lagoonal environment.

The remaining units of the Cajarc Formation, the La Plogne, Marcilhac and Brengues Members are composed mainly of massive calcareous mudstones, interbedded with laminated calcareous mudstones, algal boundstones, ostracod wackestones, lignitic marls and oolitic grainstones. The latter are considered to have been deposited under outer lagoonal conditions. The remainder probably accumulated under subtidal lower intertidal or upper intertidal conditions, with the exception of the lignitic marls which represent a supratidal or terrestrial environment and the ostracod wackestones which were possibly fresh or brackish lacustrine deposits.

Calcitised evaporites have also been recognised in the Marcilhac and Brengues Members. These indicate the establishment of sabkha conditions, under which the growth of nodular anhydrite, discoidal gypsum and celestite took place in a supratidal environment. During diagenesis, some of the limestones became partially replaced by secondary anhydrite and at a later stage all the evaporites were calcitised.

Six second-order rhythms of deposition have been recognised in the Cajarc Formation, each of which started with a transgression and the deposition of outer lagoonal oolitic grainstones and finished with a general regression and the deposition of lacustrine ostracod wackestones. Individual second-order rhythms are usually made up of a number of first-order rhythms which are composed of subtidal lagoonal calcareous mudstones which pass up into upper intertidal laminated calcareous mudstones and finally into supratidal lignitic marls.

Brackish water ostracods and marine terebratulids that have been found, indicate that the Cajarc Formation is Bathonian in age.

The uppermost unit which has been studied in the Cajarc area is the Montbrun Formation. This varies from 25-35 m. in thickness and it is composed almost entirely of crystalline limestones that have suffered dolomitisation and dedolomitisation. The formation has also been intensively fractured and brecciated over wide geographical areas. Three mechanisms of brecciation have been considered: tectonic brecciation, solution-collapse brecciation and hydraulic brecciation. It is possible that all three of these have played a role in the deformation of the Montbrun Formation.

Despite the intensive diagenetic alteration which has occurred, it has still been possible using standard petrological methods to determine the original deposition characters of the Montbrun Formation. Thus the history of deposition of the formation has been understood and six rhythms of sedimentation have been recognised; each one of which commences with outer lagoonal oolitic grainstones that passes upwards into inner lagoonal calcareous mudstones, sometimes with brackish water ostracods and calcitised supratidal evaporites.

The Montbrun Formation is probably upper Bathonian in age.

Throughout the Bajocian and Bathonian, the Cajarc area appears to have undergone gentle subsidence. This may have controlled the pattern of sedimentation and the first-order rhythms have possibly been cause by small, but repeated phases of subsidence. This has allowed considerable thicknesses of sediment to accumulate without any major transgressions or gross environmental changes.

Superimposed on the first-order rhythms is a second-order pattern. Furthermore, each formation also becomes more regressive upwards therefore they can be considered as third-order rhythms, superimposed on the first and second-order patterns.

Four main diagenetic processes appear to have operated on the Middle Jurassic sediments: dolomitisation, dedolomitisation, the replacement of limestones by secondary anhydrite, and the replacement of evaporites by calcite. Pseudomorphs after nodular anhydrite, secondary anhydrite, discoidal gypsum, lenticular gypsum, celestite and dolomite have been observed. Two main mechanisms of replacement have become evident: piecemeal replacement, and dissolution and the later infilling of the remaining voids.

Although very little dolomite has been found in the Middle Jurassic sediments, of the Cajarc area, it can be shown that the extensively developed beds of crystalline limestone and 'calcaire cargneuliform' have probably been formed by the calcitisation of dolomitic rocks as they pass laterally into dolomitic rocks in the subsurface. Originally, dolomitisation may have taken place in two ways: firstly in a sabkha or upper intertidal environment, where calcareous deposits became penecontemporaneously dolomitised; and secondly by a seepage reflux mechanism, during later diagenesis.

Thus the present study has revealed that the Upper Toarcian to Upper Bathonian rocks of the region have probably been deposited in a shallow water marine to brackish water area, which sometimes became completely exposed. Intense diagenesis has affected the rocks of the area and has obliterated many of their primary characters. Careful petrological studies have yielded sufficient evidence to enable the original depositional characters of the deposits to be recognised and the possible environments of deposition to be determined.

An understanding of the geological history of the area has indicated aspects of possible economic importance, some of which might be profitably pursued in the future. In this respect the potential of the Montbrun Formation, being either an oil reservoir or a zone of lead/zinc mineralisation is particularly outstanding.

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APPENDIX

The Location Of The Measured Sections

Tour de Faure Section (enclosure 1)

This section was measured from 961253 on the track just north of Tour de Faure, to 959257 at the top of the cliff which overlooks the town.

Saint Martin-Latoulzanie Section (enclosure 2)

The first 10 m. (i.e. the Latoulzanie Member) was measured in the N662 roadside section at 003249, just west of Latoulzanie. The next 50 m. (i.e. the Ceneviers and Corn Members) was measured up the valley side, from 995246 immediately north of Saint Martin-Labouval, to the D24 road at 994248. The remaining part of the section was measured along the D24 from 994248, finishing in the quarry at 999-253.

Marcilhac Section (enclosure 3)

The first 45 m. of this section (i.e. the Marcilhac and Brengues Members) were measured along the D17 road section just north of Marcilhac, from 022350 to 019359. The last 30 m. (i.e. the Montbrun Formation) was measured in the cliff section immediately south of Marcilhac from the roadside (D17) at 025341 to 026349.

Larnagol Section (enclosure 4)

This section was measured from the roadside (N662) at 045-263, just east of Larnagol up the valley-side to 0444264. The last 35 m. (i.e. the Montbrun Formation) was measured slightly more towards Larnagol, from 042261 to 041262.

Section at 064259, near Cajarc (enclosure 5)

This section was measured from the railway line at 063258 to the N662 road at 064258 about 2 km. west of Cajarc, and then from the roadside at 064259, up the valley-side to 064264.

La Plogne Section (enclosure 6)

The lower part of the section was measured in the quarry at 975261 on the N662 just south of Cajarc, and also along the road from 975261 to 975259. The upper part, including the Montbrun Formation was measured from 974260 to 974263, near La Plogne.

Espagnac-Brengues Section (enclosure 7)

All of this section apart from the Brengues Member was measured from 090388 on the D41 about 1.5 km. ENE of Espagnac, up the valley-side to 090396. The Brengues Member was measured along the roadside, just south of Brengues, from 075364 to 072364.

Corn Section (enclosure 8)

The lowest part of this section (i.e. the Latoulzanie Member) was measured along the roadside (D41), from 130144 to 133405 just west of Corn. The remainder of the section was measured up the valley-side from 133405 to 133407. A more detailed exposure of the Corn Member was measured to the SW of Corn along the road to Crayssac, between 123393 and 125396.

Montbrun Section (enclosure 9)

The lowest part of this section was measured along the road side (N662) at or near Montbrun, between 124290 and 128287. The La Plogne Member was measured along the railway cutting from the entrance to the tunnel at 134287, to 136289. The Marcilhac and Brengues Members and the Montbrun Formation were measured in the section along the road from Montbrun to Grealou, just above the Château, between 126289 and 126294.

Larroque-Toirac Section (enclosure 10)

The lowest part of this section was measured at the base of the cliff, actually in Larroque-Toirac at 159306. The remainder (i.e. most of the Saint Martin and lower Cajarc Formations) were measured up the valley-side just SW of Larroque-Toirac, from 157304 to 157307.

LEGEND

LITHOLOGY

- Calcareous mudstone.
- Laminated calcareous mudstone.
- Algal boundstone.
- Crystalline limestone.
- Marl.
- Shale.

FAUNA

- bivalves
- gastropods
- ammonites
- belemnites
- brachiopods
- corals
- echinoids
- charophytes
- ostracods
- plant debris
- roots

GRAIN TYPES

- bioclast
- ooid
- peloid
- grapestone
- rhodolith
- intraclast

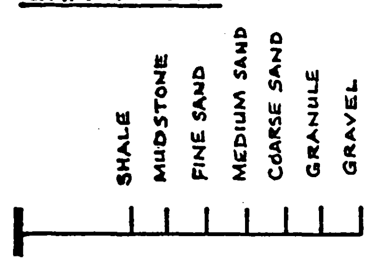
DEGREE OF BRECCIATION

- none
- fracturing
- brecciation

SEDIMENTARY STRUCTURES

- burrows
- borings
- cross-lamination
- cross-bedding
- ripples
- trails
- birdseye structures
- mud-cracks

GRAIN SIZE



(for comparison with section logs)

EVAPORITE PSEUDOMORPHS

- nodular or entrolithic anhydrite
- secondary anhydrite
- discoidal gypsum
- celestite

Enclosure 1

TOUR DE FAURE SECTION

DESCRIPTION	LITHOFACIES	ENVIRONMENT OF DEPOSITION
Rhodolith-peloid-grainstone.	RHODOLITH GRAINSTONE	OUTER LAGOONAL.
Algal boundstones and peloid-grainstone/packstones, with calcitised layers of nodular anhydrite.	ALGAL BOUNDSTONE	UPPER INTERTIDAL AND SABKHA
Marl	MARL	SUPRATIDAL
Unexposed	?	?
Algal boundstone with calcitised evaporites – parabreccia	ALGAL BOUNDSTN.	U. INTERTIDAL
Peloid-bioclast-packstone/wackestone, with foraminifera, bivalves, gastropods, calcareous sponges(?); bioturbated.	CALCAREOUS MUDSTONE	SUBTIDAL INNER LAGOONAL
Ooid-peloid-bioclast-grapestone grainstone; partially dolomitised and dedolomitised.	OOLITIC GRAINSTONE	OUTER LAGOONAL
Finely crystalline calcareous mudstone with microdolomite ghosts	CALC. MUDSTONE	INNER LAGOON
Algal boundstone and intra-packstone; calcitised evaporites – parabreccia	ALGAL BOUNDSTN.	U. INTERTIDAL AND SABKHA
Finely crystalline calcareous mudstone with echinoid debris bioturbated; dolomitised/dedolomitised – microrhomb ghosts; extensive replacement by secondary anhydrite (now calcitised) near the top.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
peloid-grapestone-grainstone	OOLITIC GRAINSTONE	OUTER LAGOONAL
peloid-bioclast-ooid-rhodolith-packstone.		
ooid-peloid-bioclast-grapestone-grainstone; partially dolomitised/dedolomitised.		
peloid-packstone; calcitised evaporites; parabreccia.	CALCAREOUS MUDSTONE	INNER LAGOONAL, INCLUDING SABKHAS.
Crystalline limestone with dedolomitic texture; calcitised evaporite	CRYSTALLINE CARBONATE	
Unexposed	?	
Crystalline limestone with dedolomitic texture; ghost grainstone fabric.	CRYSTALLINE CARBONATE	
Ooid-peloid-bioclast-grapestone-grainstone; calcareous algae fragments; partially dolomitised/dedolomitised to give a "pseudobreccia" texture.	OOLITIC GRAINSTONE	OUTER LAGOONAL
Finely crystalline limestone with "structure grumeulese" dedolomitic texture.	CRYSTALLINE CARBONATE	INNER LAGOONAL
Crystalline calcareous mudstone with microrhombic ghosts		
Peloid-bioclast-grapestone-grainstone.	OOLITIC GRAINSTONE	OUTER LAGOONAL
Finely crystalline limestone with dedolomitic texture; possibly originally calcareous mudstone; calcitised evaporites.	CRYSTALLINE CARBONATE	INNER LAGOONAL ?
Crystalline limestones with dedolomitic textures and ghost sedimentary fabrics. parabreccia. peloid ghosts. angular parabreccia. peloid ghosts.		OUTER LAGOONAL ? / INNER LAGOONAL ? / OUTER LAGOONAL ?
Algal boundstones with calcitised evaporites.	ALGAL BOUNDSTN.	U. INTER. + SABKHA
Crystalline limestone with dedolomitic texture. angular parabreccia.	CRYSTALLINE CARBONATE	LACUSTRINE ?
Peloid-grainstone/packstone with layer of calcitised evaporites.	CALCAREOUS MUDSTONE	INNER LAGOONAL
Massive calcareous mudstone		
Algal boundstone and peloid-grainstone/packstone with layer of calcitised evaporites.	ALGAL BOUNDSTONE	U. INTERTIDAL AND SABKHA
Crystalline limestone; probably dedolomite.	CRYSTALLINE CARBONATE	SUBTIDAL, INNER LAGOONAL TO SABKHA.
Intraclast-peloid-grainstone	CALCAREOUS MUDSTONE	
Calcareous mudstone with calcitised evaporite layer and intraclast-bioclast horizon.		
Algal boundstone and intraclast-peloid-grainstone.	ALGAL BOUNDSTONE	UPPER INTERTIDAL
Ooid-peloid-grainstone	CALCAREOUS MUDSTONE	SUBTIDAL AND LOWER INTERTIDAL
Calcareous mudstone with calcitised evaporites		
Ooid-peloid-intraclast-grainstone.		
Laminated calcareous mudstone with two layers of calcitised evaporites; intraclastic at base.	LAMINATED CALCAREOUS MUDSTONE	UPPER INTERTIDAL AND SABKHA
calcitised evaporite layer Massive calcareous mudstones. ← Algal boundstone ← Laminated calcareous mudstone ← Algal boundstone	MAINLY CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL; SOME UPPER INTERTIDAL
Laminated calcareous mudstone with *P. raristriata* and *F. bathonica* and algal boundstones with introclast layers and "heads".	LAM. CALC. MUD. ALGAL BOUNDSTN.	UPPER INTERTIDAL
Peloid-ooid-bioclast-grainstone; intraclastic at the base.	OOLITIC GRAINSTONE	OUTER LAGOONAL
Laminated and massive calcareous mudstones	LAM. & MASSIVE CALC. MUD.	UPPER TO LOWER INTERTIDAL
Calcareous mudstone with peloids and intraclasts	CALCAREOUS MUDSTONE	SUBTIDAL LAGOONAL.
Unexposed	?	?
Laminated calcareous mudstone with *P. raristriata* and *F. bathonica*	LAMINATED CALCAREOUS MUDSTONE	UPPER INTERTIDAL
← Laminated calcareous mudstone Massive and cross-laminated calcareous mudstones with bioclast-intraclast layers and bored horizons; some bioturbation. ← *Acrosalenia* sp.	MAINLY CALCAREOUS MUDSTONE.	SUBTIDAL TO LOWER INTERTIDAL / U. INTERTIDAL. / SUBTIDAL INNER LAGOONAL TO LOWER INTERTIDAL

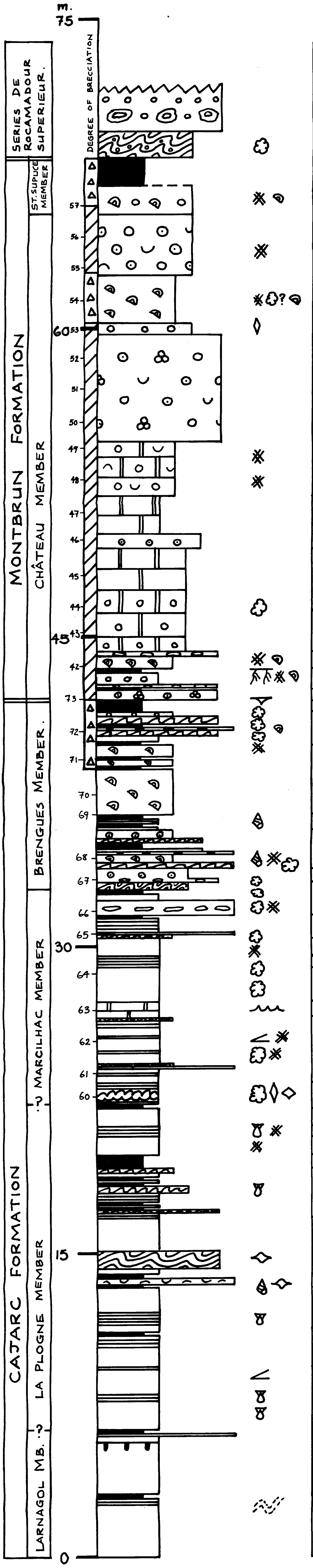
Enclosure 2

ST. MARTIN – LATOULZANIE SECTION

DESCRIPTION	LITHOFACIES	ENVIRONMENT OF DEPOSITION
Laminated calcareous mudstone.	LAM. CALC. MUD.	U. INTERTIDAL
Massive cdlcareous mudstone with a shaley biodastic band; orientated echinoid spines.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Shaley intraclastic band, followed by a thin marl and then a laminated calcareous mudstone (with microfaults).	LAMINATED CALC. MUDSTONE. / MARL	UPPER INTERTIDAL / SUPRATIDAL
Calcareous mudstone and bioclastic-wackestone.	CALC. MUDSTONE.	L. INTERTIDAL
Calcareous mudstone with birdseyes.	BIRDSEYE MUDSTONE	LACUSTRINE ?
Laminated calcareous mudstone with peloid layers and poorly developed argillaceous partings; intraclastic at base; laminated intraclast-bioclast-packstone at top.	LAMINATED CALCAREOUS MUDSTONE	UPPER INTERTIDAL
Lignitic marl with roots and plant debris; some lam. calc. mudstone layers.	MARL	SUPRATIDAL
Massive and cross-laminated calcareous mudstone.	CALCAREOUS MUDSTONE.	SUBTIDAL TO LOWER INTERTIDAL
Laminated calcareous mudstone.	LAM. CALC. MUD.	U. INTERTIDAL
Massive calcareous mudstone and bioclast-wackestone above bored horizon.	CALCAREOUS MUDSTONE	L. INTERTIDAL? / SUBTIDAL?
Wavey-bedded algal boundstone with "heads", birdseyes and "mud-chip" bands.	ALGAL BOUNDSTONE	UPPER INTERTIDAL
Wavey, organic laminated peloid-grainstone.	ORGANIC LAMINATED LTN.	UPPER INTERTIDAL
Laminated calcareous mudstone with mud-cracks and gas-bubble birdseyes; lignitic marl at the base.	LAMINATED CALC. MUDSTONE	LACUSTRINE ? / SUPRATIDAL.
Calcareous mudstone with birdseyes.	BIRDSEYE MUDSTONE	LACUSTRINE
Oncolitic? or Rhodolith? or intraclast? Wackestone.	?	?
Calcareous mudstone with intraclastic, bioclastic wackestone/packstone bands.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Laminated calcareous mudstone with lenticular and wavey peloid laminae (some starved ripples); ooid/intraclast layers.	LAMINATED CALCAREOUS MUDSTONE	UPPER INTERTIDAL
Calcareous mudstone with thin, wavey or lenticular-bedded, peloid-grainstone layers; sharp crested ripples; wavelength 10-18cm., and amplitude 2cm.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Laminated calcareous mudstone with curled mud-flakes, mud cracks, ooid/intraclast layers, lenticular and wavey peloid laminae, and algal boundstone and lignitic marl near the Top.	LAMINATED CALCAREOUS MUDSTONE	UPPER INTERTIDAL TO SUPRATIDAL
Calcareous mudstone.	CALC. MUDSTONE	L. INTERTIDAL?
← Calcareous mudstone Crystalline limestones with dedolomitic textures; probably mostly calcareous mudstones originally. ← peloid grainstone; crystalline in places	CRYSTALLINE CARBONATE	PROBABLY INNER LAGOONAL (MODIFIED DURING DIAGENESIS)
Calcareous mudstone	CALC. MUDSTONE.	SUBTIDAL
Crystalline peloidal grainstone with a few foraminifera; peloids flattened; possibly dolomitised/dedolomitised.	OOLITIC GRAINSTONE	LAGOONAL
← Calcareous mudstone Crystalline limestones with dedolomitic textures; sometimes weathered to "calcaire cargneuliform". Probably deposited mainly as calcareous muds. Coarsely crystalline limestone beds passing laterally into finer crystalline rocks with ghost grainstone texture.	CRYSTALLINE CARBONATE	PROBABLY INNER LAGOONAL (MODIFIED DURING DIAGENESIS)
← Pseudomorphs after "axe-head" secondary anhydrite (no evidence of nodular anhydrite). Crystalline limestone Massive calcareous mudstones.	CALCAREOUS MUDSTONE	SUBTIDAL TO INTERTIDAL LAGOONAL; POSSIBLY ALSO SABKHAS.
← Laminated calcareous mudstone.	LAM. CALC. MUD.	U. INTERTIDAL
	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL.
Ooid-grainstone Peloid-grainstone	OOID-PELOID GRAINSTONE	SUBTIDAL OUTER LAGOONAL
Calcareous mudstone	CALCAREOUS MUDSTONE	
Massive and laminated crystalline limestones; dedolomitic texture.	CRYSTALLINE CARBONATE	
Peloid-ooid-grainstone (fine to medium sand grade).	PELOID-OOID GRAINSTONE	
← possible rhodolith ghosts ← peloid ghosts. Crystalline limestone with dedolomitic texture.	CRYSTALLINE CARBONATE	
Rhodolith-peloid-grapestone-grainstone (coated grapestones)	RHODOLITH GRAINSTONE	
ooid-grainstones; cross-bedded.	OOID GRAINSTONE	OOLITIC BARRIER
← grapestone grains	GRAPESTONE GSTN.	OUTER LAGOONAL
	OOID GRAINSTONE	OOLITIC BARRIER
Ooid-grapestone-grainstone passing laterally into crystalline limestone.	GRAPESTONE GRAINSTONE	OUTER LAGOONAL
← ooid-grapestone-grainstones	OOID GRAINSTONE.	OOLITIC BARRIER
	GRAPESTONE.	OUTER LAGOON
Massive and cross-bedded oolitic grainstones, sometimes with partial textures of dolomitisation and dedolomitisation.	OOID GRAPESTONE	OOLITIC BARRIER
← crystalline ooid-grapestone-grapestone.	GRAPESTONE	OUTER LAGOONAL
Crystalline limestone	MAINLY OOID GRAINSTONE	MOSTLY OOLITIC BARRIER
Crystalline grapestone-ooid-grapestone	GRAPESTONE	OUTER LAGOON
Ooid-grain stone with some grapestone grains and foraminifera; partial dolomitisation/dedolomitisation textures	OOID GRAINSTONE	BARRIER OR OUTER LAGOON
Crystalline limestones with ghost grainstone fabrics; dedolomitisation textures and corroded dolomite relicts.	CRYSTALLINE CARBONATE	OOLITIC BARRIER ?
Ooid-bioclast-grainstone; crystalline patches due to partial dolomitisation/dedolomitisation.	OOID GRAINSTONE	
Red, yellow or orange, coarsely crystalline limestones with dedolomitic textures and rhombic iron oxide ghost; sometime ghost grainstone fabric is preserved.	CRYSTALLINE CARBONATE	PROBABLY DEPOSITED AS OOLITIC GRAINSTONES AND LATER MODIFIED DURING DIAGENESIS.
Crystalline limestones with white calcareous geodes. Dedolomitic textures and rhombic iron oxide ghosts. Some silt-grade quartz grains.		
Dedolomitised bivalve-echinoid-peloid-quartz-packstone, with corroded dolomite relicts, passing laterally into dolomitic bioclastic-packstone. Rhodoliths abundant.	RHODOLITHIC PACKSTONE	OPEN MARINE NEARSHORE SHELF.
Dedolomitised bivalve-echinoid-peloid-quartz-foraminifera packstones with corroded dolomite relicts. Abundant fauna in lower parts.	BIOCLASTIC PACKSTONE.	
Shaley, dedolomitised quartz-echinoid-bivalve-foraminifera-packstone with dolomite relicts and pyrite; Gryphea abundant.		
Dolomitic quartz-echinoid-bivalve-packstones; partially dedol.		
Micaceous-quartz-dolomite-shale with ferruginous ooids at top.	Fe-OOID SHALE / MICACEOUS SHALE	OPEN MARINE OFFSHORE SHELF.

Enclosure 3

MARCILHAC SECTION



DESCRIPTION	LITHOFACIES	ENVIRONMENT OF DEPOSITION
Rhodolith-peloid-ooid-grainstone.	RHODOLITH GRAINSTONE	OUTER LAGOONAL
Wavey-bedded algal boundstones and peloid grainstones; calcitised layers of nodular anhydrite.	ALGAL BOUNDSTONE	UPPER INTERTIDAL AND SABKHA.
Poorly exposed marls.	MARL	SUPRATIDAL
Ostracod-peloid-wackestone.	OSTRACOD WACKESTONE	LACUSTRINE
Ooid-peloid-bioclast grainstone/packstone; some dolomitised/dedolomitised patches. Foraminifera.	OOLITIC GRAINSTONE	OUTER LAGOONAL
Finely crystalline ostracod-wackestone with microrhomb ghosts after dolomite; calcitised evaporite band. Angular parabreccia	OSTRACOD WACKESTONE	LACUSTRINE AND SABKHA
Peloid-packstone/mudstone; discoidal gypsum pseudomorphs		
Peloid-ooid-grapestone-bioclast-grainstone with fragments of calcareous algae. Evidence of dolomitisation dedolomitisation: calcitised rhombs in some grains, pseudo-breccias developed, and some unreplaced dolomite(?) relicts.	OOLITIC GRAINSTONE	OUTER LAGOONAL
Peloid-bioclast-packstone/wackestones and crystalline limestones with ghost fabrics and dedolomitisation textures. Also extensive replacement by secondary anhydrite (now calcitised).	CALCAREOUS MUDSTONE AND CRYSTALLINE CARBONATE	INNER LAGOONAL
Finely crystalline limestone with dedolomitic texture; probably originally a calcareous mudstone.		
ooid-peloid-bioclast-grapestone-grainstone	OOLITIC GRAINSTONE	OUTER LAGOONAL ?
← calcitised evaporite band - parabreccia. Crystalline limestones with ghost grainstone fabrics and dedolomitic textures; some dolomite relicts.	CRYSTALLINE CARBONATE	
Chalky ostracod-wackestone with intraclasts at the top.	OSTRACOD WACKE.	SUPRATIDAL AND LACUSTRINE
Rooted lignitic-marls, intraclast bands and peloid-packstone.	MAINLY MARL	
Ooid-peloid-grapestone-grainstone with *Burmirhynchia* sp.	OOLITIC GRAINSTONE	OUTER LAGOONAL
Laminated marl	MARL	SUPRATIDAL
Interbedded marls, algal-boundstones, intraclast-grainstones and ostracod-wackestones; three layers of calcitised evaporites	MARL, ALGAL BOUNDSTONE, & OST. WACKESTONE	SUPRATIDAL, SABKHA, U. INTERTIDAL AND LACUSTRINE.
Chalky ostracod-charophyte-wackestones with thin marl horizons; some secondary chert and pseudomorphs after secondary anhydrite. *Neritina bidens*, and stems and oogonia of charophytes.	OSTRACOD WACKESTONE	LACUSTRINE (WITH THIN TERRESTRIAL SOILS)
Laminated calcareous mudstones and marls	MARL,	SUPRATIDAL
Marls, algal-boundstones, intraclast bands, ostracod-wackestones and ooid-grapestone-grainstone; calcitised evaporite band. *Viviparus* sp. and *Neritina bidens*	ALGAL BOUNDSTONE, LAM. CALC. MUD., OST. WACK. OOLITIC GRAINST.	UPPER INTERTIDAL, LACUSTRINE AND SABKHA
Ooid-grainstone, intraclastic at the base	OOLITIC GRAINSTONE	OUTER LAGOONAL
Marl, algal-boundstone, calcareous-mudstone and intraclast-grainstone; bands of calcitised evaporites.	MARL AND ALGAL BOUNDSTONE	UPPER INTERTIDAL AND SABKHA
Laminated calcareous mudstone, thin marl and algal boundstone with intraclast band; calcitised evaporites.	LAMINATED CALC. MUDSTONE	UPPER INTERTIDAL TO SUPRATIDAL
Massive calcareous mudstones with bands of calcitised evaporites.	CALC. MUDSTONE	L. INTERTIDAL?
Laminated calcareous mudstone	LAM. CALC. MUD.	U. INTERTIDAL
	CALCAREOUS MUDSTONE.	SUBTIDAL INNER LAGOONAL TO LOWER INTERTIDAL; SOME UPPER INTERTIDAL; SUPERIMPOSED SABKHA CONDITIONS
Dolomite-mudstone with ghost lenticular bedding.	CRYSTALLINE CARBONATE	
Massive and cross-laminated calcareous mudstones; some laminated calcareous mudstones and algal boundstones; calcitised evaporite band.	MAINLY CALCAREOUS MUDSTONE	
Laminated calcareous mudstone with calcitised nodular anhydrite, discoidal gypsum and celestite; marl at the base.	LAMINATED CALCAREOUS MUDSTONE.	U. INTERTIDAL AND SABKHA
Calcareous mudstones.	CALC. MUD.	L. INTERTIDAL?
Laminated calcareous mudstone with ?*Pronoella raristriata*	LAM. CALC. MUD.	U. INTERTIDAL
	CALCAREOUS MUDSTONE	L. INTERTIDAL?
Marl.	MARL, ALGAL BOUNDSTONE AND LAMINATED CALCAREOUS MUDSTONE	SUPRATIDAL AND UPPER INTERTIDAL.
Interbedded marls, laminated calcareous mudstones with *Pronoella raristriata*, and algal boundstones; some oyster-intraclast bands.		
Massive calcareous mudstone.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Centimetre bedded algal boundstone with birdseyes and "heads".	ALGAL BOUNDSTONE	UPPER INTERTIDAL
Marls and ostracod-wackestone with gas-bubble birdseyes; *N. bidens*	OST. WACKE.	LACUSTRINE
Massive calcareous mudstone	CALCAREOUS MUDSTONE	SUBTIDAL TO L. INTERTIDAL
← Calcareous mudstone. Laminated calcareous mudstones with a marl horizon.	LAMINATED CALCAREOUS MUDSTONE	UPPER INTERTIDAL TO SUPRATIDAL
← Laminated calcareous mudstone. Massive and cross-laminated calcareous mudstones.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
	LAM. CALC. MUD.	U. INTERTIDAL
Laminated calcareous mudstone with ?*Pronoella raristriata*.	CALCAREOUS MUDSTONE	SUBTIDAL TO L. INTERTIDAL
← Marl	MARL	SUPRATIDAL
		L. INTERTIDAL
	CALCAREOUS MUDSTONE	SUBTIDAL
Laminated calcareous mudstone and marl.	LAM. CALC. MUD.	U. INT. TO SUPRA.
	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL

Enclosure 4

LARNAGOL SECTION

DESCRIPTION	LITHOFACIES	ENVIRONMENT OF DEPOSITION
Rhodolith-peloid-grainstone.	RHODOLITHIC GRAINSTONE	SUBTIDAL OUTER LAGOONAL.
Wavey bedded algal boundstones and peloidal grainstone/packstones; calcitised layer of entrolithic anhydrite.	ALGAL BOUNDSTONE	UPPER INTERTIDAL TO SABKHA
Marl	MARL	SUPRATIDAL
Poorly exposed wackestones and packstones	PROBABLY OSTRACOD WACKESTONE	LACUSTRINE ?
← Calcitised evaporite band.		SABKHA
Ostracod wackestones with gypsum pseudomorphs; partially dolomitised and dedolomitised.	OSTRACOD WACKESTONE	LACUSTRINE
Ooid-peloid-bioclast-grapestone-rhodolith-grainstone.	OOLITIC GRAINSTONE	OUTER LAGOONAL
Bivalve-ostracod-wackestones with *Neritina* sp; partially dolomitised/dedolomitised: ghost rhombs.	OSTRACOD WACKESTONE	LACUSTRINE
Peloid-ooid-bioclast-packstone/grainstone; orthobreccia.	OOLITIC GRAINSTONE	SUBTIDAL OUTER LAGOONAL
Ooid-grapestone-grainstone.		
Peloid-grainstone/packstone; calcitised evaporite band.	CALCAREOUS MUDSTONE MAINLY.	SUBTIDAL INNER LAGOONAL, INTERTIDAL AND SABKHA.
Rhodolith-bioclast-(?)wackestone; calcareous algae, bivalve and echinoid debris.		
Calcareous mudstones and algal boundstones with calcitised evaporitic band		
Angular parabreccia: evaporite band?	CRYSTALLINE CARBONATE	OUTER LAGOONAL ?
Crystalline limestones with dedolomitic textures and ghost grainstone fabrics; probably peloid-ooid-bioclast-grainstone		
← Finely crystalline limestone with dedolomitic texture; probably originally calcareous mudstone		INNER LAGOONAL ?
		OUTER LAGOONAL ?
Finely crystalline limestone with ghost rhombs?; angular parabreccia - evaporites?		INNER LAGOONAL AND SABKHA ?
Ooid-peloid-grapestone-grainstone.	OOLITIC GRAINSTONE	OUTER LAGOONAL
Ostracod-wackestone with *Viviparus* sp; algal boundstone.	OSTRACOD WACKESTONE	LACUSTRINE
Ooid-peloid-bioclast-grapestone-grainstone with algal boundstone at the base.	OOLITIC GRAINSTONE	OUTER LAGOONAL.
Ostracod wackestones with charophyte oogonia and stems; calcitised evaporite band.	MAINLY OSTRACOD WACKESTONES	LACUSTRINE
← Algal boundstone with calcitised evaporite band.		UPPER INTERTIDAL
		LACUSTRINE
Crystalline calcareous mudstone.	CALCAREOUS MUDSTONE	INNER LAGOONAL ?
Ooid-bioclast-grapestone-grainstone	OOLITIC GRAINSTONE	OUTER LAGOONAL
Algal boundstone with intraclast bands.	ALGAL BOUNDSTONE	UPPER INTERTIDAL
Laminated calcareous mudstone	LAMINATED CALC. MUDSTN.	
Algal boundstone with calcitised evaporite band	ALGAL BOUNDSTN.	
Calcareous mudstone	CALC. MUDSTONE	LOWER INTERTIDAL
Wavey-bd algal boundstone with calcitised evaporites.	ALGAL BOUNDSTONE	UPPER INTERTIDAL
Oolitic-intraclast-grainstone.	OOLITIC GRAINSTONE	OUTER LAGOONAL ?
Massive calcareous mudstones interbedded with algal boundstones; layers of calcitised evaporites.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
	ALGAL BOUNDSTN.	UPPER INTERTIDAL
	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
	ALGAL BOUNDSTN.	UPPER INTERTIDAL
	CALCAREOUS MUD.	LOWER INTERTIDAL
	ALGAL BOUNDSTN.	UPPER INTERTIDAL
	CALCAREOUS MUDSTN	LOWER INTERTIDAL
	ALGAL BOUNDSTONE	UPPER INTERTIDAL
	CALCAREOUS MUDSTN	LOWER INTERTIDAL
Laminated calcareous mudstone and algal boundstone.	LAMINATED CALCAREOUS MUDSTONE	UPPER INTERTIDAL
Massive calcareous mudstones with peloid horizons.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Marly laminated intraclast-oyster-packstone with algal boundstone at the base.	LAMINATED CALC. MUD.?	SUPRATIDAL OR UPPER INTERTIDAL
Peloid-ooid-bioclast-grainstone, becoming laminated towards the top	OOLITIC GRAINSTONE	SUBTIDAL OUTER LAGOONAL
Massive calcareous mudstone.	CALCAREOUS MUDSTONE.	SUBTIDAL ? INNER LAGOON
Laminated bioclast-intraclast-packstone.	LAM. CALC. MUD. ?	U. INTERTIDAL?
Massive calcareous mudstones.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
← Laminated calcareous mudstone	LAMINATED CALC. MUD.	UPPER INTERTIDAL
	CALCAREOUS MUDSTN	LOWER INTERTIDAL
Laminated calcareous mudstone	LAMINATED CALC. MUDSTONE	UPPER INTERTIDAL
Massive calcareous mudstones and bioclastic wackestones.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
← Algal boundstone	ALGAL BOUNDSTONE	UPPER INTERTIDAL
	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
← Algal boundstone with intraclasts	ALGAL BOUNDSTONE	UPPER INTERTIDAL
	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Ooid-bioclast-grapestone-grainstone	OOLITIC GRAINSTONE	OUTER LAGOONAL
Chalky wackestone.	OSTRACOD WACKESTONE?	LACUSTRINE ?
Laminated calcareous mudstone with ostracods; algal boundstone/oncolitic packstone with oysters, at the base	MAINLY LAMINATED CALC. MUDSTN.	UPPER INTERTIDAL
Massive, bioturbated, and cross-laminated calcareous mudstones, with intraclast-peloid-bioclast horizons.	CALCAREOUS MUDSTONE	SUBTIDAL INNER LAGOONAL TO LOWER INTERTIDAL
Lenticular and wavey laminated calcareous mudstone/peloidal siltstone.	LAM. CALC. MUDSTN.	UPPER INTERTIDAL
Massive and cross-laminated calcareous mudstones and bioclastic wackestones. ← Laminated calcareous mudstone. Fossiliferous horizon: *Entolium* sp., Lucinidae, etc.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Laminated calcareous mudstones with peloid laminae; sometimes burrowed; thin marl at the top.	LAMINATED CALCAREOUS MUDSTONE.	UPPER INTERTIDAL AND SUPRATIDAL.
Massive calcareous mudstone	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Laminated calcareous mudstone	LAMINATED CALC. MUDSTN.	UPPER INTERTIDAL
Massive, bioturbated and cross-laminated calcareous mudstones and bioclastic wackestones; intraclast-peloid-bioclast layers.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Laminated calcareous mudstone with peloid laminae; bioclast-intraclast-grainstone at the base and marl at the top.	LAMINATED CALC. MUDSTONE	UPPER INTERTIDAL TO SUPRATIDAL
Massive and cross-laminated calcareous mudstones with intraclast-bioclast layers.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Laminated calcareous mudstone; intraclasts at the base.	LAM. CALC. MUDSTN.	UPPER INTERTIDAL
Massive calcareous mudstone passing upwards from grainstone below.	CALCAREOUS MUDSTONE	LOWER INTERTIDAL / SUBTIDAL INNER LAGOON
Ooid-peloid-bioclast-grapestone-grainstone; mudstone layers lower part and intraclasts at the base.	OOLITIC GRAINSTONE	SUBTIDAL OUTER LAGOONAL
Ostracod wackestone with gas-bubble birdseyes.	OSTRACOD WACKESTONE	LACUSTRINE
Cross-laminated and burrowed peloidal siltstones and bioclastic wackestones; intraclastic at the base.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Ooid-bioclast-grapestone-grainstone.	OOLITIC GRAINSTONE	OUTER LAGOONAL.
Massive and bioturbated calcareous mudstones, with bioclast-intraclast and bioclast-peloid-ooid-grapestone horizons. ← Laminated calcareous mudstone.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Laminated calcareous mudstone with peloid laminae and celestite pseudomorphs	LAM. CALC. MUDSTN.	UPPER INTERTIDAL
Crystalline calcareous mudstone; probably dedolomitic.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Red and yellow crystalline limestones weathered to "calcaire cargneuliform"; dedolomitic texture.	CRYSTALLINE CARBONATE	PROBABLY INNER LAGOONAL
Laminated algal boundstone with crinkles and over folds.	LAM. ALGAL BOUNDSTONE	UPPER INTERTIDAL
Lignitic marls with root horizons and chalky ostracod wackestones with gas-bubble birdseyes. ← karst	MARL AND OSTRACOD WACKSTN.	SUPRATIDAL / LACUSTRINE / SUPRATIDAL
Planar cross-bedded peloid-ooid-bioclast grainstone; with shaley horizon.	OOLITIC GRAINSTONE	SUBTIDAL OUTER LAGOONAL
← laminated horizon. Red and yellow weathering crystalline limestones; sometimes "calcaire cargneuliform"; probably dedolomitised.	CRYSTALLINE CARBONATE.	PROBABLY DEPOSITED IN A LAGOONAL ENVIRONMENT AND MODIFIED DURING DIAGENESIS.

Enclosure 5

SECTION AT G.R.064259 NEAR CAJARC

DESCRIPTION	LITHOFACIES	ENVIRONMENT OF DEPOSITION
Crystalline limestone	CRYSTALLINE CARBONATE	LAGOONAL ?
Ooid-grapestone-bioclast-grainstone; intraclastic at the base.	OOLITIC GRAINSTONE	OUTER LAGOONAL
Wavey bedded algal boundstone with 'heads'	ALGAL BOUNDSTONE	U. INTERTIDAL
Poorly exposed; probably ostracod-wackestone.	OSTRACOD WACKESTONE	LACUSTRINE
Massive algal boundstone with a layer of calcitised nodular anhydrite	ALGAL BOUNDSTONE	U. INTERTIDAL & SABKHA
Poorly exposed; probably ostracod-wackestone.	OSTRACOD WACKESTONE	LACUSTRINE
Laminated calcareous mudstones and wavey-bedded algal boundstones; calcitised layers of nodular anhydrite and pseudomorphs after secondary anhydrite.	ALGAL BOUNDSTONE AND LAMINATED CALCAREOUS MUDSTONE	UPPER INTERTIDAL AND SABKHA.
← ooid-intraclast-grainstone ?	OOLITIC GRAINSTONE	OUTER LAGOONAL
		U. INTERTIDAL
← Algal boundstone ooid-intraclast-grainstone Algal boundstone with calcitised evaporites ← Algal boundstone Massive calcareous mudstones with calcitised secondary anhydrite; one bored horizon.	CALCAREOUS MUDSTONE, ALGAL BOUNDSTONE AND OOLITIC GRAINSTONE.	SUBTIDAL LAGOONAL, INTERTIDAL AND SABKHA.
Lenticular and flat laminated calcareous mudstones and peloidal grainstones; intraclasts and bioclasts at base	LAMINATED CALCAREOUS MUDSTONE	UPPER INTERTIDAL
Massive calcareous mudstone	CALCAREOUS MUDSTONE	SUB TIDAL TO L. INTERTIDAL LAGOONAL
Marl and laminated calcareous mudstone	MARL AND LAMINATED CALC. MUD.	SUPRATIDAL & U. INTERTIDAL
← Algal boundstone Massive calcareous mudstone	CALCAREOUS MUDSTONE	L. INTERTIDAL AND SUBTIDAL
? ostracod-wackestone; chalky	OSTRACOD WACKESTONE	LACUSTRINE
Oolitic grainstone with rippled mud layers	OOLITIC GRAINSTONE	OUTER LAGOONAL
Laminated calcareous mudstone. Laminated bio-intra-wackestone. Ostracods and *P. raristriata*	LAMINATED CALCAREOUS MUDSTONE	UPPER INTERTIDAL OR LACUSTRINE ?
Massive calcareous mudstone	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Laminated calcareous mudstone	LAM. CALC. MUD.	U. INTERTIDAL
Massive calcareous mudstone	CALC. MUDSTONE	L. INTERTIDAL
Laminated calcareous mudstone	LAMINATED CALCAREOUS MUDSTONE	UPPER INTERTIDAL.
← Algal boundstone Massive calcareous mudstones. ← Marl	CALCAREOUS MUDSTONE	MAINLY SUBTIDAL INNER LAGOONAL TO LOWER INTERTIDAL
Ooid-bioclast-intraclast-grapestone-grainstone.	OOLITIC GRAINSTONE	OUTER LAGOONAL
Chalky wackestone; *P. calculus*, *N. bidens*, ostracods, charophyte stems & oogonia.	OSTRACOD WACKESTONE	LACUSTRINE
Laminated, mud-cracked calcareous mudstone; *P. raristriata*	LAM. CALC. MUD.	UPPER INTERTIDAL.
Wavey bedded algal boundstone passing laterally into oncolitic packstone	ALGAL BOUNDSTONE	
Massive or cross laminated calcareous mudstones with some intraclastic/bioclastic layers; some bored or burrowed horizons. ← Laminated calcareous mudstone Laminated calcareous mudstone peloidal grainstone ← Laminated calcareous mudstone ← cemented oyster band.	MAINLY CALCAREOUS MUDSTONE.	SUBTIDAL INNER LAGOONAL, LOWER INTERTIDAL AND SOME UPPER INTERTIDAL
Laminated calcareous mudstone with organic laminated intraclastic algal boundstone at the top.	LAMINATED CALCAREOUS MUDSTONE	UPPER INTERTIDAL.
Massive calcareous mudstone with thin laminated horizon and intraclast band.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Laminated calcareous mudstone with a thin marl above.	MARL LAMINATED CALCAREOUS MUDSTONE	SUPRATIDAL UPPER INTERTIDAL
Massive calcareous mudstone.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Massive calcareous mudstone passing upwards into laminated calcareous mudstone, and then a thin marl.	MARL; LAM. CALC. MUD., AND CALC. MUDSTONE.	LOWER INTERTIDAL TO SUPRATIDAL
Marl and laminated calcareous mudstone.	LAM. CALC. MUD.	U. INTERTIDAL TO SUPRATIDAL.
Massive and cross-laminated calcareous mudstones with a thin marl horizon and an intraclast peloid band.	CALCAREOUS MUDSTONE	SUBTIDAL INNER LAGOON, TO LOWER INTERTIDAL.
Oolitic wackestone, burrowed in places, with marl at top		
Wavey and lenticular laminated calcareous mudstone / peloid grainstone	LAM. CALC. MUD.	U. INTERTIDAL.
Ooid-peloid-intraclast-grainstone.	OOLITIC GRAINSTONE	OUTER LAGOONAL.
Laminated calcareous mudstone with marl above	LAM. CALC. MUD.	U. INTERTIDAL
Massive and cross-laminated calcareous mudstones	CALC. MUDSTONE	SUB TO L. INTERTIDAL
Laminated calcareous mudstone with intraclasts at base	LAM. CALC. MUD.	U. INTERTIDAL
	CALC. MUDSTONE	SUBTIDAL TO L. INTERTIDAL
Laminated calcareous mudstone	LAM. CALC. MUD.	U. INTERTIDAL
intraclast-bioclast-peloid wackestone Peloid wackestone and grainstones with intraclasts Calcareous Mudstone	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Laminated calcareous mudstone, algal boundstone and thin marl.	LAM. CALC. MUD	SUPRATIDAL AND U. INTERTIDAL
← Algal boundstone Massive and cross-laminated calcareous mudstone; some peloid bands, and flat laminated horizon.	CALCAREOUS MUDSTONE	SUBTIDAL INNER LAGOONAL TO LOWER INTERTIDAL
Crystalline limestone, with dedolomitisation textures; probably originally calcareous mudstone.	CRYSTALLINE CARBONATE.	LAGOONAL?
Massive calcareous mudstone, with lenticular or wavey-bedded peloid layers.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL.
Rooted lignitic marl with *Equisetum*.	MARL	SUPRATIDAL
Ostracod wackestone with intraclasts karst	OSTRACOD-WACK.	LACUSTRINE
Rooted lignitic marl and ostracod-charophyte-wackestone with *P. calculus*, *N. bidens*, *Equisetum* karst	MARL & OST. W.	SUPRATIDAL AND LACUSTRINE
Cross-bedded peloid-ooid grainstone; some dolomitisation/dedolomitisation.	OOLITIC GRAINSTONE	OUTER LAGOONAL
← Marl Coarse and finely crystalline limestones, sometimes weathered to calcaire cargneuliform. Textures indicating dolomitisation/dedolomitisation; rhombic ghost corroded dolomite relicts, and ghost sedimentary fabrics.	CRYSTALLINE CARBONATE.	DIAGENETICALLY ALTERED LAGOONAL DEPOSITS?
← peloid ghosts ← Marl ← peloid and bioclast ghosts		DIAGENETICALLY ALTERED OUTER LAGOONAL DEPOSITS ?
← rhodolith ghosts ooid (?) ghosts (rhombic iron-oxide ghosts)		DIAGENETICALLY ALTERED OOLITIC BARRIER COMPLEX ?

Enclosure 6

LA PLOGNE SECTION

DESCRIPTION	LITHOFACIES	ENVIRONMENT OF DEPOSTION
Rhodolith-ooid-peloid-grainstone	RHODOLITHIC GRAINSTONE	SUBTIDAL OUTER LAGOONAL.
Wavey-bedded algal boundstones and peloidal grainstone with one layer of calcitised nodular anhydrite.	ALGAL BOUNDSTONE	UPPER INTERTIDAL AND SABKHA
Marl with layers of calcitised laminated gypsum; ostracods, charophytes and *Planorbis* sp.	MARL	SUPRATIDAL & SABKHA
Peloid-grainstone/mudstone.	CALC. MUDSTONE.	L. INTERTIDAL?
Mostly unexposed, but probably ostracod wackestone.	OSTRACOD WACKESTONE	LACUSTRINE
Peloid-bioclast-grainstone with ostracods and extensive replacement by secondary anhydrite (now calcitised).	OOLITIC GRAINSTONE	OUTER LAGOONAL ?
Calcareous mudstone with angular parabreccia-evaporites?	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Bioclastic wackestone with ostracods and echinoid debris.	OSTRACOD WACKESTONE ?	LACUSTRINE ?
Calcareous mudstone; angular parabreccia-evaporite band?	CALCAREOUS MUDSTONE	SUBTIDAL LAGOON LOWER INTERTIDAL AND SABKHA ?
Peloid-grainstones/packstones and mudstones; angular parabreccias - evaporite bands?	OOLITIC GRAINSTONE	MAINLY OUTER LAGOONAL ?
Calcitised layer of nodular anhydrite and discoidal gypsum. Crystalline limestones with dedolomitic textures; rhombic ghosts after dolomite.	CRYSTALLINE CARBONATE	MAINLY INNER LAGOONAL ?
Crystalline limestone with dedolomitic textures and ghost grainstone fabric.		OUTER LAGOONAL ?
Finely crystalline limestone with dedolomitic texture; probably deposited as calcareous mud; evaporite band.		INNER LAGOONAL ?
Crystalline limestone with a ghost grainstone fabric.		OUTER LAGOON ?
Finely crystalline limestone with dedolomitic texture; probably originally a calcareous mudstone.		INNER LAGOONAL ?
Crystalline limestone with dedolomitic texture and ghost grainstone fabric; angular parabreccia near base - evaporites?		OUTER LAGOONAL ?
Ostracod-wackestone; charophyte stems & oogonia; *Viviparus* sp. (brecciated laterally)	OSTRACOD WACKESTONE	LACUSTRINE.
Ooid-peloid-bioclast-grapestone-grainstone.	OOLITIC GRAINSTONE	OUTER LAGOONAL.
Ostracod wackestone with pseudomorphs after seondary anhydrite	OSTRACOD WACKESTONE	MAINLY LACUSTRINE
Recrystallised calcareous mudstone (dedolomite?) with layer of calcitised evaporites.	CRYSTALLINE CARBONATE	← SABKHA
Ostracod wackestone with *P. calculus* and charophyte oogonia and stems. Discoidal gypsum pseudomorphs in the upper part.	OSTRACOD WACKESTONE	
Marl	MARL	TERRESTRIAL
Chalky ostracod wackestone with gas-bubble birdseyes. *V. bulbiformis*, *N. bidens*, *P. calculus*, charophyte oogonia, smooth shelled ostracods and bivalve fragments.	OSTRACOD WACKESTONE	LACUSTRINE
ooid-grapestone-grainstone with bioclasts	OOLITIC GSTN.	OUTER LAGOON ?
algal boundstone	ALGAL BOUNDSTN.	UPPER INTERTIDAL
Ostracod wackestone	OSTRACOD WACKESTONE	LACUSTRINE
Ooid-grapestone-grainstone; multiple phase oolitic coating.	OOLITIC GRAINSTN.	OUTER LAGOONAL
Peloid-packstones and calcareous mudstones (fine dedolomitic texture); thin algal boundstone; layer of calcitised evaporites.	CALCAREOUS MUDSTONE	SUBTIDAL TO INTERTIDAL AND SABKHA.
Wavey-bedded algal boundstone with thick intraclast grainstone underneath.	ALGAL BOUNDSTONE	UPPER INTERTIDAL
Peloid-ooid-bioclast-grapestone-grainstone; ooids only superficially coated.	OOLITIC GRAINSTONE	OUTER LAGOONAL
Massive and cross-laminated calcareous mudstones passing up into peloid-bioclast-wackestones.	CALCAREOUS MUDSTONE	SUBTIDAL INNER LAGOONAL TO LOWER INTERTIDAL.
Wavey-bd algal boundstone and laminated calcareous mudstone; crinkles.	ALGAL BOUNSTN.	U. INTERTIDAL
Massive and cross-laminated calcareous mudstone or dolomitic mudstone; microrhombic dolomite.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Unexposed.	?	?
Laminated calcareous mudstone / Laminated calcareous mudstone / Laminated calcareous mudstone; Massive calcareous mudstones.	MAINLY CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL. / UPPER INTERTIDAL / LOWER INTERTIDAL / UPPER INTERTIDAL / LOWER INTERTIDAL ER / UPPER INTERTIDAL
Wavey-bedded calcareous mudstones and peloid-grainstones		SUBTIDAL TO LOWER INTERTIDAL
Laminated calcareous mudstone / Laminated calcareous mudstone; Massive calcareous mudstones.		UPPER INTERTIDAL / SUBTIDAL TO LOWER INTERTIDAL / UPPER INTERTIDAL / SUBTIDAL TO LOWER INTERTIDAL
Laminated calcareous mudstone with oysters, followed by a thin marl layer.	MARL AND LAMINATED CALCAREOUS MUDSTN.	SUPRATIDAL TO UPPER INTERTIDAL
Massive calcareous mudstone and bioturbated peloid-bioclast-intraclast-grapestone-wackestone.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Laminated calcareous mudstone with intraclast layer at base and thin marl at top.	LAMINATED CALCAREOUS MUDSTONE	UPPER INTERTIDAL
Intraclast-ooid-bioclast-grainstone passing up into peloid-ooid-grapestone-grainstone; peloids superficially coated; some mud layers.	OOLTIC GRAINSTONE	SUBTIDAL OUTER LAGOONAL.
Ostracod-charophyte-wackestone with birdseyes. *V. bulbiformis*, *N. bidens* charophyte stems	OSTRACOD WACKESTONE	LACUSTRINE
Lignitic marl with roots	MARL	SUPRATIDAL
Dolomitised laminated mudstone with peloid laminae; silt grade dolomite rhombs; wavey bedded algal boundstone with intraclasts at base.	CRYSTALLINE CARBONATE	UPPER INTERTIDAL
Massive calcareous mudstone	CALCAREOUS MUDSTN.	LOWER INTERTIDAL
Organic laminated dolomitic mudstone; peloid/ostracod laminae; marl at Top	CRYST. CARBONATE.	U. INTERTIDAL & SUPRA
Lenticular or wavey-bd calcareous mudstone and peloid grainstone	CALCAREOUS MUDSTN.	LOWER INTERTIDAL
Laminated intraclast-bioclast-grainstone; organic laminae; marl with roots at top	LAM. CALC. MUDSTN.	UPPER INT. & SUPRA.
Recrystallised peloid siltstone; microrhombic ghosts; ripple cross-lamination; bioclast-intraclast horizon.	CALCAREOUS MUDSTONE	SUBTIDAL AND LOWER INTERTIDAL.
Organic laminated microdolomite rock with peloid-ostracod laminae and thin marl at top.	MARL AND LAM. CALC. MUDSTN.	U. INTERTIDAL & SUPRATIDAL
← *Ornithella* cf. *bathonica* Finely recrystallised massive calcareous mudstones and cross laminated peloidal siltstones; lenticular or wavey-bd in places; intraclast-bioclast layers above bored horizons; microrhombic ghosts; dolomitised and dedolomitised?	CALCAREOUS MUDSTONE	LOWER INTERTIDAL / SUBTIDAL INNER LAGOONAL
Laminated calareous mudstone and lignitic marl.	MARL & LAM. CALC. MUDSTN.	U. INTERTIDAL & SUPRATIDAL
Cross-laminated peloidal siltstone and bioclastic wackestone (see figure 72)	CALCAREOUS MUDSTONE	LOWER INTERTIDAL SUBTIDAL.

Enclosure 7

ESPAGNAC-BRENGUES SECTION

DESCRIPTION	LITHOFACIES	ENVIRONMENT OF DEPOSITION
Rhodolith-peloid-grainstone.	RHODOLITHIC GRAINSTONE	OUTER LAGOONAL
Algal boundstones and peloid-packstone/grainstones; calcitised entrolithic band of anhydrite.	ALGAL BOUNDSTONE	UPPER INTERTIDAL
Marls	MARL	SUPRATIDAL
Unexposed.	?	?
Ooid-grainstone	OOLITIC GRAINSTONE	OUTER LAGOONAL
peloid packstone/wackestones and a layer of calcitised evaporite.	CALCAREOUS MUDSTONE	INNER LAGOONAL INC. SABKHA
Ostracod wackestone	OSTRACOD WACKESTONES	LACUSTRINE
Calcareous mudstone with Neritina sp.		
ooid-bioclast-peloid-grainstone.	OOLITIC GRAINSTONE	OUTER LAGOONAL SUBTIDAL
Peloid-packstone/grainstone; possibly oolitic.		
Crystalline limestone with dedolomitic texture and ghost grainstone fabric	CRYSTALLINE CARBONATE	
Crystalline limestones with dedolomitic textures. Angular parabreccias: calcitised evaporite layers		INNER LAGOONAL ?
Peloid-bioclast-packstone.	CALCAREOUS MUDSTONE	
Oolitic grainstone	OOLITIC GRAINSTONE	OUTER LAGOONAL
Crystalline limestone with dedolomitic textures with ghost grainstone fabric	CRYSTALLINE CARBONATE	
Algal boundstone and calcareous mudstone with calcitised evaporites.	CALC. MUDSTONE	SABKHA TO LOWER INTERTIDAL
ooid-bioclast-grapestone-grainstone.	OOLITIC GRAINSTONE	OUTER LAGOONAL
Algal boundstone with calcitised layer of evaporites	ALGAL BOUNDSTONE	SABKHA AND U. INTERTIDAL
Massive calcareous mudstone	OSTRACOD ? WACKESTONE	LACUSTRINE ?
Marl and algal boundstone with calcitised evaporites; nodular anhydrite and celestite.	MARL AND ALGAL BOUNDSTONE	SABKHA AND UPPER INTERTIDAL
Chalky ostracod wackestones.	OSTRACOD WACKESTONE	LACUSTRINE
	ALGAL BOUNDSTN.	U. INTERTIDAL?
	OSTRACOD WACKESTONE	LACUSTRINE.
Marls, algal boundstones, massive and laminated calcareous mudstones, and bioclastic-intraclastic layers.	MARL, ALGAL BOUNDSTONE, LAMINATED AND MASSIVE CALC. MUDSTN.	SUPRATIDAL U. INTERTIDAL AND L. INTERTIDAL
Algal boundstone with intraclast layers	ALGAL BOUNSTN	U. INTERTIDAL
Calcareous mudstone	CALC. MUDSTN.	L. INTERTIDAL
Algal boundstone with intraclast layers	ALGAL BOUNDSTN.	U. INTERTIDAL
Ooid-bioclast-intraclast-grainstone	OOLITIC GRAINSTN	OUTER LAGOONAL
Massive calcareous mudstones, algal boundstones and laminated calcareous mudstones.	ALGAL BOUNDSTONE	UPPER INTERTIDAL
	CALCAREOUS MUDSTONE	SUBTIDAL TO L. INTERTIDAL
	ALGAL BOUNDSTONE	U. INTERTIDAL
	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
	ALGAL BOUNDSTN.	U. INTERTIDAL
	CALC. MUDSTONE	L. INTERTIDAL
	ALGAL. BOUNDSTN.	U. INTERTIDAL
Crystalline limestones: probably dedolomitised	CRYSTALLINE CARBONATE.	INNER LAGOONAL ?
Massive calcareous mudstones with thin layers of algal boundstone and laminated calcareous mudstone.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
	ALGAL BOUNDSTN.	U. INTERTIDAL
	CALCAREOUS MUDSTONE	SUBTIDAL TO L. INTERTIDAL
Laminated calcareous mudstones	LAMINATED CALC. MUDSTN.	UPPER INTERTIDAL
Massive calcareous mudstone	CALCAREOUS MUDSTONE	SUBTIDAL TO L. INTERTIDAL
Calcareous mudstone passing up into laminated calcareous mudstone and algal boundstone; intraclastic bands.	ALGAL BOUNDSTN.	U. INTERTIDAL
	LAM. CALC. MUD.	
	CALC. MUDSTONE.	L. INTERTIDAL
Laminated calcareous mudstones and algal boundstones with peloid-intraclast-bioclast layers; marl at the top.	MARL	SUPRATIDAL
	LAMINATED CALC. MUDSTONE	UPPER INTERTIDAL
	ALGAL BOUNDSTN.	
	LAMINATED CALCAREOUS MUDSTONE	
Chalky, mottled calcareous mudstone with peloids.	OSTRACOD WACKESTONE?	LACUSTRINE ?
Ooid-peloid-intraclast-grainstones and algal boundstones.	ALGAL BOUNDSTN.	U. INTERTIDAL
	OOLITIC GRAINSTN	OUTER LAGOONAL
	ALGAL BOUNDSTN.	U. INTERTIDAL
	OOLITIC GRAINSTN.	OUTER LAGOONAL
Chalky ostracod wackestone with Neritina bidens; lignitic marl with roots at the top.	MARL	SUPRATIDAL
	OSTRACOD WACKESTONE	LACUSTRINE
Massive and laminated calcareous mudstones, with some bioclastic wackestone layers. (←Marl)	CALC. MUDSTONE	L. INTERTIDAL ?
	LAM. CALC. MUD.	U. INTERTIDAL
	CALCAREOUS MUDSTONE	SUBTIDAL TO L. INTERTIDAL
	LAMINATED CALC. MUDSTONE	U. INTERTIDAL
	CALCAREOUS MUDSTONE	SUBTIDAL TO L. INTERTIDAL
	LAM. CALC. MUD.	U. INTERTIDAL.
	CALCAREOUS MUDSTONE	SUBTIDAL TO L. INTERTIDAL
	MARL	SUPRATIDAL
	CALCAREOUS MUDSTONE	SUBTIDAL TO L. INTERTIDAL
	LAM. CALC. MUD.	U. INTERTIDAL
	CALC. MUDSTONE	L. INTERTIDAL
	LAM. CALC. MUD.	U. INTERTIDAL.
	CALCAREOUS MUDSTONE	SUBTIDAL TO L. INTERTIDAL
	LAM. CALC. MUD	U. INTERTIDAL
	CALCAREOUS MUDSTONE	SUBTIDAL TO L. INTERTIDAL
	ALGAL BOUNDSTN.	U. INTERTIDAL
	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
	LAM. CALC. MUD	U. INTERTIDAL
	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Laminated calcareous mudstone	LAMINATED CALC. MUDSTONE	UPPER INTERTIDAL
Massive calcareous mudstone with intraclastic band.	CALCAREOUS MUDSTONE	SUBTIDAL TO L. INTERTIDAL
Laminated calcareous mudstone	LAMINATED CALC. MUDSTN.	UPPER INTERTIDAL
Massive calcareous mudstone	CALCAREOUS MUDSTONE	SUBTIDAL TO L. INTERTIDAL.
Laminated calcareous mudstone and thin algal boundstone.	LAMINATED CALCAREOUS MUDSTONE	UPPER INTERTIDAL
Massive, bioturbated and cross-laminated calcareous mudstone	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Laminated calcareous mudstone	LAM. CALC. MUD.	U. INTERTIDAL.
Massive calcareous mudstone	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Laminated calcareous mudstone	LAM. CALC. MUD.	UPPER INTERTIDAL
Massive calcareous mudstone	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Laminated calcareous mudstone	LAM. CALC. MUD.	UPPER INTERTIDAL
Massive calcareous mudstone	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Laminated calcareous mudstone	LAM. CALC. MUD.	UPPER INTERTIDAL
Massive calcareous mudstone	CALCAREOUS MUDSTONE	LOWER INTERTIDAL
Unexposed.	?	?
Massive calcareous mudstone	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Laminated calcareous mudstone	LAM. CALC. MUD.	U. INTERTIDAL
Massive calcareous mudstone	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Unexposed.	?	?
Massive and cross-laminated calcareous mudstones.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Unexposed; exact thickness not known.	?	?
Massive calcareous mudstone.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Marl	MARL	SUPRATIDAL
Algal boundstone	ALGAL BOUNDSTN.	U. INTERTIDAL
Massive calcareous mudstone	CALCAREOUS MUDSTONE	SUBTIDAL TO L. INTERTIDAL
Marl	MARL	SUPRATIDAL
Peloid grainstone passing upwards into ooid-peloid-grainstone	OOLITIC GRAINSTONE	SUBTIDAL OUTER LAGOONAL
Marl	MARL	SUPRATIDAL
Chalky birdseye-mudstones; nodular and disturbed near the top. (←Marl)	BIRDSEYE MUDSTN.	LACUSTRINE
	MARL	SUPRATIDAL
	BIRDSEYE MUDSTONE	LACUSTRINE
Massive calcareous mudstones. pseudomorphs after secondary anhydrite; no evidence of calcitised nodular anhydrite.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL; ← POSSIBLE SABKHA ?

Enclosure 8

CORN SECTION

Description	Lithofacies	Environment of deposition
Massive calcareous mudstones.	Calcareous mudstone	Subtidal to lower intertidal
Laminated calcareous mudstone	Lam. calc. mud.	U. intertidal
		Subtidal to lower intertidal
Unexposed	?	
Laminated calcareous mudstone	Mainly calcareous mudstone	U. intertidal
Massive and cross-laminated calcareous mudstones.		L. intertidal
Laminated calcareous mudstone		U. intertidal
		Subtidal to lower intertidal
Unexposed	? Calcareous mudstone	
Laminated calcareous mudstone	Lam. calc. mud.	U. intertidal
Massive calcareous mudstones. geopetal structures in ostracods.	Calcareous mudstone	Subtidal to lower intertidal
Crystalline limestones, sometimes weathered to "calcaire cargneuliform".	Crystalline carbonate	Probably deposited originally as lagoonal calcareous muds, and later modified by dolomitisation and dedolomitisation
Peloid-ooid-grapestone-foraminifera-grainstone with large fragments of calcareous algae which resemble intraclasts.	Oolitic grainstone	Outer lagoonal
Massive and laminated finely crystalline limestones.	Crystalline carbonate	Probably deposited originally as lagoonal calcareous muds, and later modified by dolomitisation and dedolomitisation
Peloid grainstone with ripple cross-laminations.	Calcareous mudstone	Lower intertidal and subtidal inner lagoonal; sometimes supratidal
Massive calcareous mudstones.		
Peloid grainstone Root horizon (Equisetum?)		
Rhodolith-peloid-grainstone.	Rhodolithic grainstone	Subtidal outer lagoonal grainstone environment alternating with subtidal lagoonal mud environment. Occasional influxes of oolitic sediment from adjacent barrier complex.
Massive calcareous mudstone.	Calcareous mudstone	
Rhodolith-ooid-grainstone	Rhod. grainstn.	
Ooid-bioclast-wackestone	Calcareous mudstone	
Peloid-rhodolith-grainstone; a few ooids and calcareous algae fragments present.	Rhodolithic grainstone	
Massive calcareous mudstone.	Calc. mudstone	
Ooid-grainstone	Ooid grainstn.	
Massive calcareous mudstone	Calcareous mudstone	
Peloid-ooid-rhodolith-grainstone	Rhod. grainstn.	
Massive calcareous mudstone	Calcareous mudstone	
Peloid-rhodolith-grainstone	Rhodolithic grainstone	
Calcareous mudstone	Calc. mudstone	
Peloid-rhodolith-grapestone-ooid-grainstone	Rhodolithic grainstone	
Crystalline limestone with dedolomitic texture.	Crystalline limestone	Probably deposited in an oolitic barrier complex and later modified.
Ooid-peloid-bioclast-grainstone	Ooid-peloid grainstone	
Crystalline limestones with dedolomitic textures	Crystalline carbonate	
Ooid-grainstone	Ooid grainstn.	
	Crystalline carbonate	
Ooid-grainstone	Ooid grainstone	
Crystalline limestone	Crystalline carbonate	
Cross-bedded ooid-grainstones.	Ooid grainstone	Oolitic barrier complex
Crystalline limestone	Cryst. carb.	
Ooid-grainstone	Ooid grainstone.	
Crystalline limestone	Cryst. carb.	
Ooid-grainstone.	Ooid grainstone	
Crystalline limestones with dedolomitic textures.	Crystalline carbonate	
Ooid grainstone	Ooid grainstn.	
	Crystalline carbonate.	
Ooid grainstone	Ooid grainstn.	
	Crystalline carbonate	
Ooid-rhodolith-grapestone-grainstone	Rhodolithic grainstone	Open marine?
Ooid-grainstone	Ooid grainstn.	Probably deposited in an oolitic barrier complex and later modified
Crystalline limestones with ooid ghosts and dedolomitic textures.	Crystalline carbonate	
Bioclast-ooid-grainstone	Ooid-peloid grainstone	Oolitic barrier deposits with open marine influxes
Ooid-rhodolith-grapestone-grainstone	Rhodolithic grainstone	
Ooid-peloid-bioclast-grainstone	Ooid-peloid grainstone	
Crystalline limestone with peloid ghosts and dedolomitic texture.	Crystalline carbonate	Transitional from open marine into barrier complex
Rhodolith-bioclast-peloid-packstone with shaley parting near the base.	Rhodolithic packstone	Open marine nearshore shelf
Bioclastic packstones with shaley partings. Moderately fossiliferous.	Bioclastic packstone	

Enclosure 9

MONTBRUN SECTION

DESCRIPTION	LITHOFACIES	ENVIROMENT OF DEPOSITION
Rhodolith-ooid-peloid-bioclast-grapestone-grainstone	RHODOLITHIC GRAINSTONE	SUBTIDAL OUTER LAGOONAL
Algal boundstones and intraclast-peloid-grainstone / packstones	ALGAL BOUNDSTONE	UPPER INTERTIDAL
Marl and intraclastic-peloid-packstones (blackened intraclasts)	MARL	SUPRATIDAL
Mainly calcareous mudstones with algal boundstones; Brecciated.	OSTRACOD WACKESTONE ?	LACUSTRINE ?
peloid-packstones/grainstones and calcareous mudstones with calcitised layers of evaporites.	OOLITIC GRAINSTONE ?	OUTER LAGOONAL ?
Peloid-bioclast-packstone, with ostracods and *Neritina* sp. Bivalve fragments and calcareous algae.	OSTRACOD WACKESTONE	LACUSTRINE ?
Crystalline calcareous mudstone with Rhynchonellids. Dedolomitised: ghost microrhombs.	CALCAREOUS MUDSTONE	INNER LAGOONAL ?
Brecciated crystalline limestone with dedolomitic texture and ghost grainstone fabric ← Partially recrystallised ooid-grainstone.	CRYSTALLINE CARBONATE	OUTER LAGOONAL ?
Finely crystalline limestone; probably originally calc. mud.		INNER LAGOONAL ?
Ooid-bioclast-grapestone-grainstone	OOLITIC GRAINSTN.	OUTER LAGOONAL
Calcareous mudstone.	CALCAREOUS MUDSTONE	INNER LAGOONAL ?
Crystalline limestone with dedolomitic texture and ghost grainstone fabric.	CRYSTALLINE CARBONATE	OUTER LAGOONAL ?
Crystalline calcareous mudstone		INNER LAGOONAL ?
Crystalline limestone with dedolomitictexture and ghost grainstone fabric		OUTER LAGOONAL ?
Crystalline limestone with calcitised layer of evaporites		INNER LAGOONAL ?
Crystalline limestone with ghost grainstone fabric		OUTER LAGOONAL ?
Ostracod-charophyte-wackestone with gypsum pseudomorphs.	OSTRACOD WACKESTONE	LACUSTRINE.
Ooid-peloid-bioclast-grapestone-grainstone with intraclasts at the base.	OOLITIC GRAINSTONE	OUTER LAGOONAL
Ostracod wackestones with a layer of calcitised nodular anhydrite and celestite.	OSTRACOD WACKESTONE	LACUSTRINE AND SABKHA
Algal boundstone with "heads"	ALGAL BOUNDSTN.	UPPER INTERTIDAL
Ooid-peloid-intraclast-gramstones.	OOLITIC GRAINSTN.	U. INTERTIDAL ?
Massive calcareous mudstone with peloids at top.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Ooid-grainstone passing up into ooid-peloid-intraclast-bioclast wackestone/packstone/grainstone; algal boundstone at top with calcitised evaporite layer.	OOLITIC GRAINSTONE	MAINLY OUTER LAGOONAL
← Algal boundstone and laminated calcareous mudstone with *P. raristriata* Massive calcareous mudstones. Geopetally infilled ostracods?	MAINLY CALCAREOUS MUDSTONE	UPPER INTERTIDAL SUBTIDAL TO LOWER INTERTIDAL
Unexposed	?	?
Calcareous mudstone with a thin horizon of laminated calcareous mudstone and peloid-packstone.	MAINLY CALCAREOUS MUDSTONE	SUBTIDAL TO UPPER INTERTIDAL.
Laminated calcareous mudstone with bioclastic band	LAMINATED CALC. MUDSTN.	U. INTERTIDAL
Massive calcareous mudstones, bioclastic wackestones and laminated calcareous mudstones	CALCAREOUS MUDSTONE LAMINATED CALC. MUD. CALCAREOUS MUDSTONE LAMINATED CALC. MUD CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL UPPER INTERTIDAL SUBTIDAL TO LOWER INTERTIDAL UPPER INTERTIDAL SUBTIDAL TO LOWER INTERTIDAL
Flat organic laminated calcareous mudstone with marl at the top and *P. raristriata*	LAMINATED CALC. MUDSTONE	UPPER INTERTIDAL AND SUPRATIDAL
Ooid-intraclast-grainstone, passing up into packstones and wackestones; cerithid gastropods.	OOLITIC GRAINSTONE	OUTER LAGOONAL
Laminated calcareous mudstone	LAM. CALC. MUDSTN.	UPPER INTERTIDAL.
Ostracod-wackestone	OSTRACOD WACKESTONE	LACUSTRINE
Laminated calcareous mudstone with a marl horizon and an intraclast layer at the base.	MAINLY LAMINATED CALC. MUDSTONE.	UPPER INTERTIDAL SUPRATIDAL UPPER INTERTIDAL
Bioclast-peloid-wackestone.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Laminated calcareous mudstone	LAM. CALC. MUD.	UPPER INTERTIDAL.
Massive calcareous mudstones & peloid-packstones with thin marl and laminated calcareous mudstones	CALCAREOUS MUDSTONE LAM. CALC. MUD. CALC. MUDSTN. MARL CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL U. INTERTIDAL L. INTERTIDAL ? SUPRATIDAL. SUBTIDAL TO LOWER INTERTIDAL.
Organic laminated calcareous mudstone with bioclastic layer.	ORGANIC LAM. LIMESTONE	UPPER INTERTIDAL
Massive calcareous mudstone with bioclast-intraclast horizon.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Laminated calcareous mudstone	LAM. CALC. MUDSTONE.	UPPER INTERTIDAL
Massive and cross-laminated calcareous mudstones and intraclast-bioclast-wackestones, with thin laminated calcareous mudstone horizon.	CALCAREOUS MUDSTONE LAM. CALC. MUDSTN. CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL U. INTERTIDAL SUBTIDAL TO LOWER INTERTIDAL
Laminated calcareous mudstone	LAMINATED CALCAREOUS MUDSTONE	UPPER INTERTIDAL
Massive calcareous mudstones	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Laminated calcareous mudstone	LAMINATED CALCAREOUS MUDSTONE	UPPER INTERTIDAL
Massive calcareous mudstones and peloid-bioclast wackestones.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTER.
Laminated calcareous mudstone	LAM. CALC. MUDSTN.	U. INTERTIDAL
Massive and cross-laminated calcareous mudstones, wavey-bd peloid-grainstone/mudstones and bioclast wackestones.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Laminated calcareous mudstones and marls; Some lenticular or wavey peloid laminae.	LAMINATED CALCAREOUS MUDSTONE MARL LAMINATED CALCAREOUS MUDSTONE MARL LAMINATED CALC. MUDSTN.	UPPER INTERTIDAL SUPRATIDAL UPPER INTERTIDAL SUPRATIDAL UPPER INTERTIDAL
Massive calcareous mudstones with thin horizons of laminated calcareous mudstone and peloid-packstone; also some bioclast bands.	MAINLY CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Ooid-intraclast-grainstone	OOLITIC GNSTN.	OUTER LAGOONAL
Chalky peloid packstone/wackestone with birdseyes	OSTRACOD WKSTN.	LACUSTRINE?
Laminated calcareous mudstone	LAMINATED CALC. MUDSTONE	UPPER INTERTIDAL
Massive calcareous mudstone	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Laminated calcareous mudstone and marl	LAM. CALC. MUD.	U. INTERTIDAL TO SUPRATIDAL
Wavey-bedded peloid-grainstone / calcareous mudstone	CALC. MUDSTONE	L. INTERTIDAL
Laminated calcareous mudstone and lignitic marl with roots	LAM. CALC. MUDSTN.	SUPRA TO U. INTER.
Wavey and lenticular bedded calcareous mudstone/peloidal grainstone	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Laminated calcareous mudstone with lignitic marl at the top.	MAINLY LAM. CALC. MUDSTONE	SUPRATIDAL AND U. INTERTIDAL
Massive calcareous mudstone	CALCAREOUS MUDSTONE.	SUBTIDAL TO LOWER INTERTIDAL
Laminated calcareous mudstone, lignitic marl and intraclast-oyster horizon	MAINLY LAMINATED CALC. MUDSTONE.	U. INTERTIDAL SUPRATIDAL U. INTERTIDAL
Lenticular and wavey-bedded peloid grainstone/calcareous mudstones and bioclast-wackestones	CALCAREOUS MUDSTONE	SUBTIDAL TO L. INTERTIDAL
Laminated calcareous mudstone	LAMINATED CALC. MUDSTONE.	UPPER INTERTIDAL
Lignitic marl with roots	MARL	SUPRATIDAL.
Lenticular and wavey-bedded calcareous mudstone/peloid grainstone; some bioclast-wackestones.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Algal boundstone with "heads"	ALGAL BOUNDSTN.	U. INTERTIDAL
Lignitic marl	MARL	SUPRATIDAL
Laminated calcareous mudstones with wavey and lenticular peloid laminae and "cut and fill" structures — channels? ← Lignitic marl	LAMINATED CALC. MUDSTN. MARL	UPPER INTERTIDAL SUPRATIDAL
Birdseye mudstone with *Neritina* sp and *Viviparus* sp; roots at base	OSTRACOD WACKESTONE	LACUSTRINE.
Laminated calcareous mudstone and rooted lignitic marl.	MARL.	SUPRATIDAL
Peloid-ooid-bioclast-grainstone/packstone	OOLITIC GNSTN.	OUTER LAGOONAL
Lignitic marl with roots and ostracod-wackestone: *Neritina* and *Viviparus*	OSTRACOD WKSTN.	LACUSTRINE.
Laminated calcareous mudstone	LAM. CALC. MUD.	U. INTERTIDAL
Massive calcareous mudstones and bioclastic wackestones with lignitic marl and plant debris.	CALCAREOUS MUDSTONE	L. INTERTIDAL? SUPRATIDAL SUBTIDAL TO L. INTERTIDAL?
Peloid-intraclast-ooid-grainstone/packstone/wackestone, laminated at top; lenticular and wavey-bedded	CALCAREOUS MUDSTONE ?	SUBTIDAL INNER LAGOON ?
Peloid-wackestone.		
Birdseye mudstone with lignitic marl and roots at the top.	BIRDSEYE MUDSTONE	LACUSTRINE
Massive and laminated calcareous mudstones.	CALCAREOUS MUDSTONE	U. INTERTIDAL TO L. INTERTIDAL
Ooid-intraclast-grainstone	OOLITIC GRAINSTONE	OUTER LAGOONAL

Enclosure 10

LARROQUE–TORAIC SECTION

DESCRIPTION	LITHOFACIES	ENVIRONMENT OF DEPOSITION
Fissile laminated calcareous mudstone.	LAMINATED CALCAREOUS MUDSTONE.	UPPER INTERTIDAL
Massive calcareous mudstone.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Laminated calcareous mudstone.	LAM. CALC. MUD.	U. INTERTIDAL
Massive calcareous mudstones.	CALCAREOUS MUDSTONE	SUBTIDAL TO LOWER INTERTIDAL
Poorly exposed crystalline limestones, mostly weathered to "calcaire cargneuliform". (Probably dedolomitic) ← ghost grainstone fabric.	CRYSTALLINE CARBONATE	PROBABLY DEPOSITED AS CALCAREOUS MUDSTONES IN A COASTAL LAGOON COMPLEX, AND LATER MODIFIED BY DOLOMITISATION AND DEDOLOMITISATION
← ghost grainstone fabric. ← ghost rhodoliths ?		OUTER LAGOONAL ?
Ooid-grainstone.	OOID GRAINSTONE	OOLITIC SHOAL OR BARRIER.
Peloid-grainstone; ooids picking out ripple troughs.	OOID-PELOID GRAINSTONE	OUTER LAGOONAL
Ooid-peloid-grapestone-grainstone.		
Peloid-grainstone; ooids picking out ripple and dune troughs.		
Grapestone-peloid-foraminifera-packstone/wackestone.	RHODOLITHIC GRAINSTONE	
Ooid-peloid-grapestone-grainstone.		
Ooid-grainstone.	OOID GRAINSTONE	
Rhodolith-peloid-grapestone-grainstone.	RHODOLITH GSTN.	
Red, yellow and orange crystalline limestones with dedolomitic textures and ghost grainstone fabrics; weathered in places to produce "calcaire cargneuliform".	CRYSTALLINE CARBONATE	PROBABLY DEPOSITED AS A COASTAL OOLITIC BARRIER COMPLEX, AND LATER MODIFIED BY DOLOMITISATION AND DEDOLOMITISATION
Rhodolith-peloid-foraminifera-bivalve-quartz-packstone.	RHODOLITHIC PACKSTONE	OPEN MARINE NEARSHORE SHELF.
Bivalve-echinoid-foraminifera-gastropod-packstone; bioturbated and dedolomitised.	BIOCLASTIC PACKSTONE	
Shaley echinoid-bivalve-foraminifera-quartz-packstone; dedolomitised		
Bivalve-foraminifera-quartz-shale; dedolomitised with dolomite relicts.		
Dolomite-quartz-shale with Fe-ooids and foraminifera	FE-OOLITIC SHALE	OPEN MARINE OFFSHORE SHELF.
← Two thin bands of dolomite-bivalve-wackestone/packstone. Mica-quartz-dolomite-shale *Grammoceras* sp.	MICACEOUS SHALE.	