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CARBONATE PETROLOGY OF ALGAL LIMESTONES (LOIS-CIGUERA FORMATION, UPPER CARBONIFEROUS, LEÓN, SPAIN)

BY

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ABSTRACT

The Lois-Ciguera Formation is a unit of alternating limestones and terrigenous sediments of Lower to Upper Moscovian age in the Cantabrian Mountains of northern Spain. The proportion of limestones is fairly high, 30 to 50% of the total thickness. In the eastern part of the Lois-Ciguera Synclinorium, the formation consists almost exclusively of limestones. One section (LSW) is selected to serve as a model for the depositional and diagenetic textures of the limestones of the entire formation. More than 80% of the limestones appear to be algal-bound. Description and subdivision of these algal boundstones was possible by a modification of the classification scheme of Dunham (1962). The algal boundstones are classified as algal-bound lime mudstones, algal-bound lime wackestones and algal-bound lime packstones.

Algal-bound lime wackestones and algal-bound lime packstones appear to be the most important. The first are thought to have been formed on the floor of a quiet lagoon by precipitation of algal micrite in the hairy masses of non-calcareous Algae (pseudostromata bioherms). Among the algal-bound lime packstones, three groups can be distinguished: (1) those formed by intergrowth of calcareous Algae (calcareous Alga bioherms), (2) those representing carbonate sand from littoral or lagoonal settings invaded and bound or agglutinated or entrapped by non-calcareous Algae, (3) those intermediate between groups (1) and (2). The bioherms of calcareous Algae are thought to have formed at a depth ranging between low tide level and ca. 12 m in an environment of variable turbulence.

Neomorphism of algal-bound micrite is distinct from neomorphism in mechanically deposited micrite because of the interaction of pore-filling calcite in the originally porous algal micrite sustained by an organic framework.

Several generations of pore-filling calcite can be distinguished. Complete filling of the pores with calcite may have occurred during an epidiagenetic interphase during syndiagenesis.

There are indications that dolomitization was syndiagenetic. Both the capillary action/evapo-transpiration theory and the theory of a refluxing hypersaline brine may provide explanations which fit the conditions of formation of the LSW dolomitic limestones (dolomite content of 5 volume percent or more). The low dolomite content of 5 volume percent or less of the LSW limestones is explained by neomorphism of the originally high-magnesium algal micrite during cementation.

Calcitized dolomite crystals and diagenetic silica are commonly observed together in the LSW limestones. It is shown that silicification is the cause of calcitization of the dolomite crystals. The origin of the diagenetic silica is ascribed to the ability of living algal mats to hold considerable concentrations of silica in solution in their interstitial waters. The silica is precipitated during early burial of the algal-bound sediment and goes into solution again during cementation of the limestones. Reprecipitation of the silica occurs after sharp-edged fracturing.

Several phenomena of carbonate solution are described. Void creating solution is confined to limestones supported by an algal framework. At present all original pores and voids in the LSW limestones are filled with calcite and the porosity is low.

The sequence of diagenetic changes has been analyzed and summarized separately for LSW limestones with an epidiagenetic interphase during syndiagenesis and those lacking an epidiagenetic interphase.

SAMENVATTING

De Lois-Ciguera-Formatie bestaat uit een afwisseling van kalkstenen en terrigene sedimenten van boven-karbonische (Moscovien) ouderdom. De kalkstenen maken ongeveer 30 tot 50% van de totale dikte uit. In het oostelijke deel van het Lois-Ciguera-synclinorium bestaat de formatie vrijwel geheel uit kalksteen. Sectie LSW in de Lois Synclinaal West dient als model voor de beschrijving van afzettingstexturen en diagenetische texturen van de kalkstenen van de gehele formatie. Meer dan 80% van de kalkstenen blijkt door algen gebonden. Onderverdeling van deze „boundstones" was mogelijk door een variatie op de kalksteenklassifikatie van Dunham (1962). In plaats van „boundstones" worden alggebonden „mudstones", „wackestones" en „packstones" onderscheiden.

Alggebonden „wackestones" en „packstones" komen het meest voor. De eerstgenoemde zijn gevormd op de bodem van rustige lagunes door precipitatie van micriet in de dradige massa's van algkolonies (pseudostromata biohermen). Binnen de alggebonden „packstones" worden drie groepen onderscheiden: (1) bouwsels van aaneengegroeide kalkalgen (kalkalg biohermen), (2) kalkzanden van kusten en lagunebodems gebonden of gevangen door algen en (3) een groep met kenmerken liggend tussen die van (1) en (2). De kalkalgbiohermen zijn gevormd op een diepte varierend van de laagwaterlijn tot ongeveer 12 m in water van wisselende turbulentie.

Alggebonden micriet is van nature fijn poreus en blijft dat ondanks de kompaktiedruk van het bovenliggende sediment. Kolonies van algdraden met geprecipiteerde micriet in de omhullende slijmmassa's vormen het dragende „geraamte" waardoor de

alggebonden micriet poreus blijft en nauwelijks beïnvloed wordt door kompaktie. Rekristallisatie van calciet of inversie van aragoniet wordt door deze primaire porositeit bevorderd en het blijkt dikwijls moeilijk een onderscheid te maken tussen poriën-vullende calciet en calciet tengevolge van rekristallisatie of inversie.

Het is mogelijk een aantal generaties van poriën-vullende calciet te onderscheiden. Cementatie en lithificatie van alggebonden kalksteen blijkt reeds vroeg voltooid te kunnen zijn, indien tijdens de syndiagenese een epidiagenetische tussenfase optreedt.

Er zijn aanwijzingen dat dolomitisatie plaats had tijdens de syndiagenese. Het dolomietgehalte van de dolomitische LSW kalkstenen (5—50 volumeprocent dolomiet) en de LSW dolomieten kan verklaard worden door verdamping en uitzweting via capillaire werking in aan zee grenzende poreuze kalksedimenten of door het zinken van een zware hypersaline brijn in het kalksediment op de bodem van een afgesloten lagune in een warm klimaat. Het lage dolomietgehalte van 5 volume procent of minder van de LSW kalken wordt verklaard door neomorphisme van de oorspronkelijk magnesium-rijke alg-micriet, gedurende de cementatie.

Gecalcitiseerde dolomiet en diagenetische kwarts worden algemeen in elkaars gezelschap waargenomen in de LSW kalkstenen. Aangetoond wordt dat silicifikatie de oorzaak is van de calcitisatie van dolomiet. De oorsprong van de diagenetische kwarts wordt toegeschreven aan de invloed van algkolonies op de pH van hun interstitiële water waardoor in dit laatste aanzienlijke concentraties van silicium-oxyde in oplossing gehouden kunnen worden. Silicium-oxyde kristalliseert syndiagenetisch wanneer het kalksediment zich enigszins onder de kontaktlijn van het sediment en het bovenliggende water bevindt. Tijdens latere cementatie van het kalksediment kan kwarts weer gedeeltelijk in oplossing gaan. Na barstvorming in de kalkstenen tengevolge van tektonische bewegingen en opheffingen en na vulling van deze barsten met calciet, kristalliseert het in oplossing zijnde silicium-oxyde op grote schaal, vervangt calciet en leidt tot calcitisatie van dolomiet.

Verschillende oplossingsverschijnselen in de LSW kalkstenen worden beschreven. Oplossing leidend tot holten en poriën, soms verbonden door barsten waardoor een samenhangend geheel van holle ruimten ontstond, bleef beperkt tot kalksteen met een dragend alg-geraamte.

De opeenvolging van diagenetische veranderingen is afzonderlijk geanalyseerd en samengevat voor kalkstenen met een epidiagenetische tussenfase tijdens de syndiagenese en voor kalken zonder zo'n tussenfase.

CONTENTS

Drawing of the text figures and the Appendix by Miss C. Roest.
Photography by Mr. W. C. Laurijssen.

CHAPTER I

INTRODUCTION

The Upper Carboniferous Lois-Ciguera Formation on the southern slope of the Cantabrian Mountains (province of León, northwestern Spain) was defined by Brouwer & van Ginkel (1964). Van Ginkel (1965) revised this definition and identified the western part of the former Lois-Ciguera Formation as the Lena Formation. He considered these rocks, outcropping in the valleys of the Porma and Huerna Rivers, to be the southeastern continuation of the "Cuenca Central de Asturias" rock sequence near Pola de Lena, La Vega and Bárzana, designated by Barrois (1882, p. 526) as "Assise de Lena". Today, despite the many confusing redefinitions and the creation of new Carboniferous formations, the Lois-Ciguera Formation still exists mainly because of its structurally isolated position and the resulting well-defined geographic location (Fig. 1).

The sequence of limestones, sandstones and silty shales, which has a fairly high percentage of limestone of ca. 30 to 50% of the total thickness, was folded into a synclinorium. To the southeast and east, the ratio of terrigenous sediment is drastically reduced and the entire sequence consists almost completely of limestones. This can be observed at the narrowly folded Peñas Pintas mountain ridge in the southeast and east and at the intricately folded and faulted Pico Yordas dome in the northeast. The Lois-Ciguera Synclinorium is bordered by faults related to major structural units: the Peña Cruz unit in the north (Sjerp, 1966), the Armada unit in the west and the Esla unit in the south (Rupke, 1964).

The Peñas Pintas ridge and the Pico Yordas dome, which form the southeastern, eastern and northeastern borders of the synclinorium, are in contact with the Curavacas Conglomerate (Kanis, 1955; Koopmans, 1961; van Veen, 1965; and others) and related sediments. Originally the sediments at the eastern border of the Lois-Ciguera Formation were unconformably overlain by these conglomerate-bearing sediments, but subsequent folding and faulting have obscured the sedimentary contacts. The contacts now visible are mainly fault contacts.

The Lois Syncline in the northwestern part of the synclinorium is divided into two parts by a transverse fault. In this paper, the western part will be called Lois Syncline West (LSW) and the eastern part, Lois Syncline East (LSE). Both parts of the Lois Syncline are separated by a fault from the basal Carboniferous limestone formation, the Caliza de Montaña Formation (Boschma and van Staalduinen, 1968, p. 225), which belongs to the nappes of the Peña Cruz unit. The statement by van Ginkel (1965, p. 188), based on data supplied by the present author, that the Lois-Ciguera Formation rests paraconformably on the Caliza de Montaña Formation (Escapa Formation, van Ginkel, 1965) is no longer regarded by the present author to be correct.

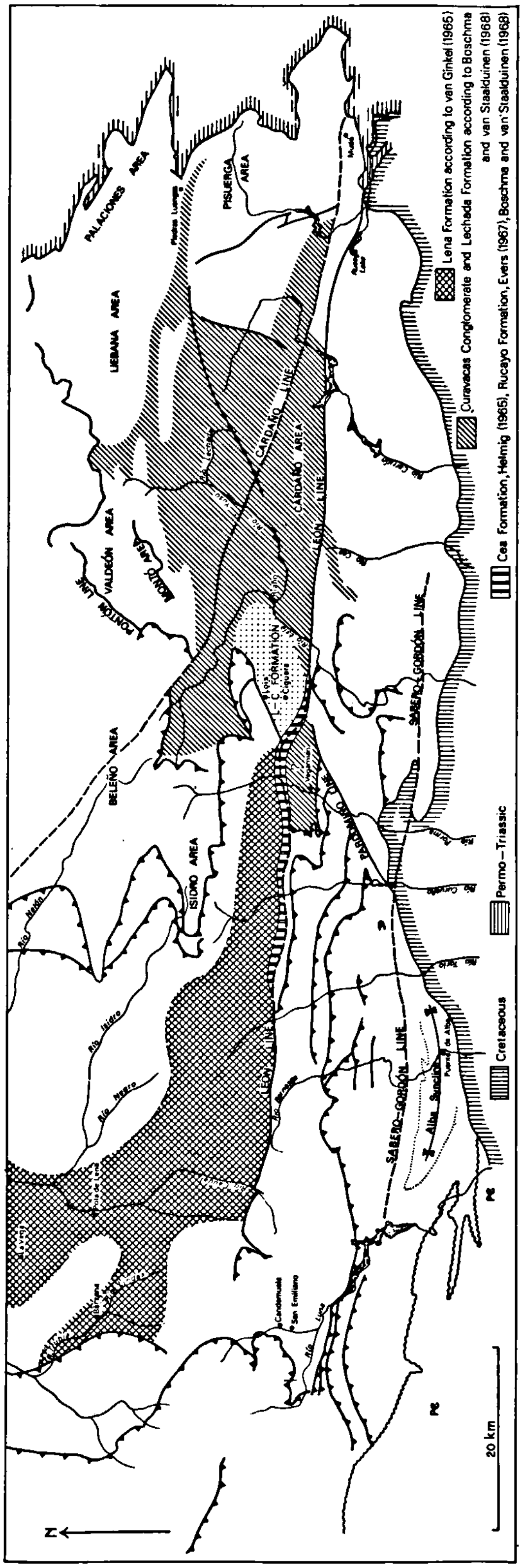

Fig. 1. Distribution of the Lois-Ciguera Formation and adjacent formations (modified after Boschma and van Staalduinen, 1968)

The fault, bordering the Lois-Ciguera Formation in the west and separating it form the Armada unit, is covered by conglomerates and related sediments, of Stephanian age (Cea Formation, Helmig, 1965; Rucayo Formation, Evers, 1967; Boschma and van Staalduinen, 1968). These conglomerate-bearing sediments unconformably overlie the sediments at the western border of the Lois-Ciguera Formation.

The age range of the Lois-Ciguera Formation, as determined with the aid of fusulinids (van Ginkel, 1965), is from Lower to Upper Moscovian.

Limestones form an important part of the Carboniferous sequence in the Cantabrian Mountains. The Lois-Ciguera Formation is only one of a number of Carboniferous formations in which limestones are abundant. Despite the rather varied character of the Carboniferous sequence as a whole, the limestones from the different formations are quite similar. Recently one of the members of the Leiden Geology Department was tempted to write the following:

"From what the present author has seen of these different limestone-bearing sequences and from what is known from published accounts (Racz, 1965, de Meijer, 1969, Winkler Prins, 1968, van Loon, this volume), it seems clear that most Carboniferous limestones in the Cantabrian Mountains can be described adequately in terms of a limited number of facies" (van de Graaff, 1970).

Van de Graaff (1970) described the Piedraslenguas Limestone, which is clearly exposed in a road section in the gorge about one kilometer south of the Puerto de Piedraslenguas along the road between Cervera de Pisuerga (Palencia) and Potes (Santander). In his opinion this limestone provides a facies model for most of the Carboniferous limestones in the Cantabrian Mountains. The top of the Piedraslenguas Limestone is in contact with shales containing a lens of quartzite conglomerate; the base is in contact with turbidites. The terrigenous sediments, intercalated between the limestones of the Lois-Ciguera Formation, differ from those in contact with the Piedraslenguas Limestone. The former consist of silty shales and sandstones, which occasionally show cross bedding, ripples and burrows. The fossil content of these terrigenous sediments is low but specific enough to indicate that they were formed in a marine environment, although the general presence of plant remains indicates that land was not far away. In the Ciguera Syncline and at the northern flank of the Ciguera Anticline a thin (30 cm) irregular coal bed has been observed on top of a limestone bed. Van Loon (pers. comm.), who kindly studied some of the sandstones in thin section, concluded that the sandstones are very immature. The angularity and lack of sphericity of the sand grains together with the poor sorting (abundant matrix) and the presence of small rock fragments suggest that there was little transport. The proximity of land therefore is also indicated by the microscopical properties of the sandstones. The occasional presence of cross bedding and ripples indicates a deposition above the wave base. The limestones of the Lois-Ciguera Formation are very similar to the Piedraslenguas Limestone and seem to be independant of the different environmental conditions suggested by the association with various terrigenous sediments.

The purpose of the present study is to give (1) an analysis of the depositional textures of the limestones of the Lois-Ciguera Formation, (2) an analysis of the diagenetic changes of these limestones, and then using these analyses (3) to interpret their depositional and diagenetic history.

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CHAPTER II

METHOD AND TECHNIQUES

SAMPLING TECHNIQUE

Thin section studies of limestone samples taken from various sections of the Lois-Ciguera Formation showed that the variations in depositional texture in one section are representative for all variations observed in the formation as a whole. One section therefore was selected as a model of the limestone depositional textures in the Lois-Ciguera Formation.

The northern flank of the Lois Syncline West (LSW) was chosen, because it offers the most complete sequence and it lies in the tectonically least deformed and least disturbed area of the synclinorium. Within each limestone in this section, samples were taken from every unit with a different lithologic aspect as seen in the field. Frequently these differences were so subtle that no effort was made to show them in the lithologic column, since eventual variations would be revealed by thin section analysis. Monotonous limestone units of considerable thickness were sampled every 4 m. During a previous thin section study, a monotonous massive limestone bed in the Lois Syncline East (LSE), 20 m thick, was sampled every 30 cm; it appeared that a sample distance of 4 m is sufficient to characterize the lithologic properties as well as the fossil content of the limestone bed. The fossil content data were also sufficient for a biostratigraphic zonation with the aid of calcareous Algae and fusulinids.

Near contacts with intercalated terrigenous sediments, samples were taken from both sides of the contact. In many cases, however, only samples from the limestone side of the contact could be taken since the terrigenous sediments were hidden bij strong brooms.

CLASSIFICATION SCHEME

The LSW samples were thin sectioned and subsequently classified according to Dunham (1962). At first sight the LSW limestones give the impression of being normal lime mudstones, lime wackestones and lime packstones. On closer examination however there are indications of binding by Algae, which will be discussed in chapter IV. Although according to Dunham, limestones showing these features should be classified under the single category of boundstones, this has not been done for the following reasons. More than 80% of the LSW samples appear to fall in the boundstone class. The aim of a classification scheme is to provide a basis for subdivision and description; this is lost if all the samples are grouped into one single class. Therefore the above-mentioned superficial differentiation into lime mudstones, lime wackestones, and lime packstones is used together with the category algal-bound [1]. In addition to the subdivision of the boundstones, this method is advantageous because it separates within the classification scheme the interpreted elements from the descriptive. If one does not agree with the indicated binding, which is based on interpretation, the algal-bound sub-heading can be omitted without loss of information on the depositional texture of the rock, based purely on descriptive elements.

[1] In the description of the LSW samples the abbreviation a.b. is used.

THIN SECTION ANALYSIS

Classification of the samples implies an analysis of the properties regarded as indicative of the depositional texture, such as grain-support/mud-support, allochems responsible for grain bulk and the indicated binding with its related characteristics. In addition to the depositional textures, the diagenetic textures were studied by analysis of cementation, neomorphism, replacement, solution and fracturing. All thin sections were treated with Alizarin Red-S for calcite identification (Friedman, 1959). The percentage of the rock constituents (e.g. mud, grains, minerals) were estimated by visual comparison with a set of percentage charts. A number of ultra-thin sections were prepared to study the properties of the micrite mosaic. Other ultra-thin sections were removed from the slide and dissolved in a weak solution of Na_2-EDTA to study the relationship between the texture and the insoluble residue, consisting of an organic algal frame and disseminated quartz crystals. These techniques and their results are discussed in detail in the sections dealing with neomorphic calcite and diagenetic silica.

CHAPTER III

TERMINOLOGY

All terms not defined below are used as listed in the glossary of Bissel and Chilingar (1967, p. 150) or they are defined separately in the sections where the relevant concepts are discussed.

Mud, grains, allochems

Application of Dunham's classification scheme implies the use of his terms mud and grains. To quote Dunham (1962, p. 113):

"The terms mud and grains are used variously by different authors. Usage here is based on particle size, grains being larger than 20 microns and mud being smaller than 20 microns. The distinction thus parallels the distinction between matrix and grains in sandstone (Pettijohn, 1957, p. 284)".

The present writer however agrees with Folk (1962, p. 63) that the term grain is not specific enough since it can also refer to an isolated single crystal. Therefore, unless otherwise required by the classification scheme, Folk's term allochem is preferred for all organized carbonate aggregates, whatever their size. The term grains, if used, refers then to allochems larger than 20 microns. Single crystals will always be indicated as crystals. Mud is useful as a general term to indicate material smaller than 20 microns regardless of composition. A more specific term, micrite, is used in this study to indicate consolidated or unconsolidated lime ooze or lime mud of either chemical or mechanical origin smaller than 20 microns. Micrite is lime mud or its indurated and possibly neomorphic equivalent (see also the section "diagenetic calcite").

Matrix

Matrix refers to the mud and grain material which filled the interstices of a grain-supported framework or a skeletal intergrowth framework.

Pseudostromata

This term was introduced by Wolf (1965a, p. 137) to designate the products of irregular spongiostromatic algal growth in situ. These products are irregular masses or patches of dense, grumous, cellular, spongy, tubular, pelletoid and granuloid algal micrite with a possible "foreign" admixture of detrital components that may make up a considerable proportion of the mass.

Pores, voids
All original voids, even if at present filled with cement or other material, are indicated as pores or voids. They originated by sedimentary allochem arrangement, by decay of organisms inside enveloping hard parts, by development of skeletal intergrowths or non-calcareous algal intergrowths in combination with the precipitation of calcium carbonate, by shrinkage or by fracturing.

According to their genesis the pores are designated as follows:
1. depositional inter-allochem pores or: inter-allochem pores,
2. depositional intra-allochem pores or: intra-allochem pores,
3. pores caused by non-calcareous algal growths with internal precipitation of calcium carbonate or: constructed voids,
4. pores caused by intergrowths of skeletal matter or: skeletal framework interstices,
5. pores created by selective dissolution of bioclasts or: fossil molds; since these pores are always filled with pore-filling calcite, they are called pore-fill fossil molds,
6. pores created by indiscriminate solution of micrite and allochems or: solution voids,
7. pores caused by desiccation and shrinkage or: desiccation or syneresis cracks,
8. fractures.

Internal sediment
The sediment that accumulated in the above-mentioned pores is called internal sediment. An exception is the sediment in inter-allochem pores and skeletal framework interstices, which is referred to as matrix.

Diagenesis
The terminology for diagenesis proposed by Fairbridge (1967, p. 32) is used in this paper. He identified three diagenetic stages:
1. syndiagenesis (the sedimentation phase),
2. anadiagenesis (the compaction-maturation phase),
3. epidiagenesis (the emergent pre-erosion phase).

Syndiagenesis is the early sedimentary condition which begins the very moment a sedimentary particle comes to rest on the basin floor. Two subphases of syndiagenesis are recognized: (a) initial phase, marked by oxidizing conditions, and (b) early burial phase, marked by reducing conditions.

Anadiagenesis is the deep burial stage during which sedimentary basins progressively subside and fill. Compaction is accompanied by expulsion of connate water which tends to rise to the surface. Some of the connate water is trapped as a result of compaction and cementation to the point of impermeability. Tectonism with the resulting diastrophic structures belongs to this phase.

Epidiagenesis is the emergent stage during which the sediment is exposed to subaerial conditions, and deep-working meteoric ground water modifies the connate solutions. During short periods of uplift or stability in the history of a subsiding basin, the sediments can be exposed to epidiagenesis shortly after deposition (epidiagenetic interphase), so that epidiagenesis does not always represent the last stage of diagenesis.

Diagenetic calcite
The terminology proposed by Folk (1965) for diagenetic calcite is used with some slight modifications. First, calcite which precipitated directly into a cavity is called pore-filling calcite in this paper. Second, since this study deals with algal-bound limestones, the distinction between microspar (recrystallized micrite of 4—30 microns) and normal micrite (1—4 microns) has not been made for the simple reason that Folk himself does not consider blue-green algal reefs as typical of normal micrites (Folk, 1965, p. 31). The definition of micrite in this paper therefore includes all calcium carbonate material smaller than 20 microns, a boundary similar to Dunham's definition of mud. Micrite in this sense thus includes microspar if we change Folk's arbitrarily chosen upper limit of 30 microns to 20 microns. Microspar grades into pseudospar, which implicates that in this paper pseudospar is defined as beginning at a crystal size of 20 microns.

Diagenetic dolomite
Limestones containing more than 5 volume % dolomite are indicated by their class name plus the term dolomitic according to the percentage scale of Schmidt (1965, p. 28):

volume percent of dolomite	classification
5—10%	slightly dolomitic
10—25%	fairly dolomitic
25—50%	highly dolomitic

Carbonate rocks containing over 50% dolomite are called dolostones. The same scale is used for dolostones, now with the adjective calcitic.

CHAPTER IV

DEPOSITIONAL TEXTURES

GRAPHIC PRESENTATION

The classification of the algal limestones of section LSW has been graphically illustrated in a depositional texture column, drawn next to the lithologic column (Appendix). Three parameters have been used for illustration (Fig. 2): (1) the allochems responsible for grain bulk [2], (2) grain-support/mud-support and (3) algal binding. The grains or allochems (parameter 1) are illustrated in a column separate from the depositional texture column. The latter is divided in half by an imaginary vertical line, representing the division between mud-support and grain-support. When a bar in fact ends at this line, as in the case of wackestone,

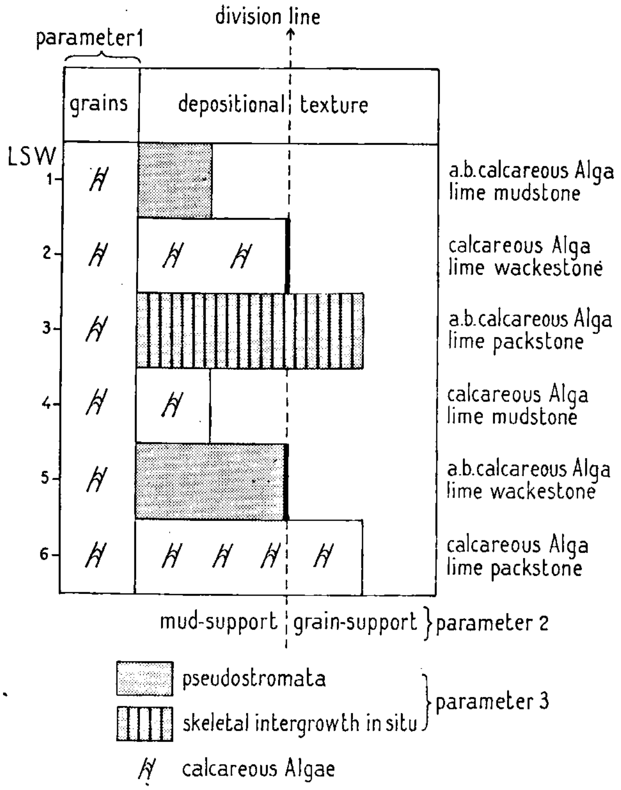

Fig. 2. Parameters used for illustration of the algal limestone classification

the line has been thickened. The total width of the column represents grain-support without mud. Three-quarters of the column indicates grain-support with mud (packstone); half the width means mud-support with more than 10% grains (wackestone). One quarter of the column means mud-support with less than 10% grains (mudstone). Bars of these widths have been constructed for each limestone sample; the thickness of each bar usually represents half the distance to the sample above plus half the distance to the sample below. The bar for a sample lacking signs of binding is filled with symbols of the allochems responsible for grain bulk. In cases of binding the bar has been filled with one of the two (or both) symbols of binding: the pseudostromata symbol and the skeletal intergrowth symbol. The allochems responsible for grain bulk then appear only in the grain column. In addition to the two major symbols of binding, additional properties are noted which accentuate the autochthonous and algal-bound character of the sample, such as local growth in situ, local intergrowth in situ, local algal mat lamination and constructed voids.

SUMMARY

Of the 174 limestone samples from section LSW, 25 belong to the mudstone class (ca. 14%), 100 to the wackestone class (ca. 56%) and 49 to the packstone class (ca. 28%). Grainstones were not found (Fig. 3). About 12% of the samples are not algal-bound. Algal influence however is evident for most of the samples. Generally this algal influence is found in the allochems, which are partly algal products such as algal pellets, algal grains and fragments of calcareous Algae. The major part of the allochems of mechanically deposited limestones are non-algal allochems which however show algal coating and/or algal corrosion in the form of degrading neomorphic aphanocrystalline calcite.

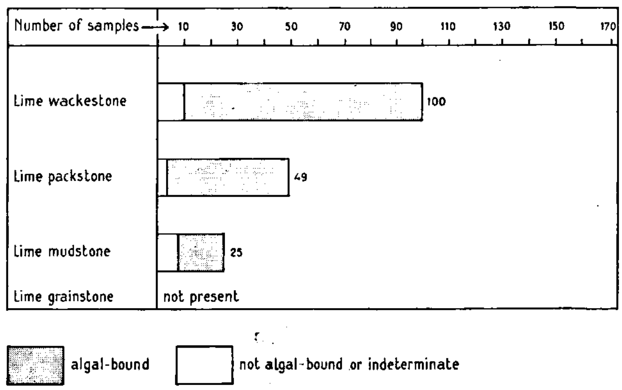

Fig. 3. Summary of the classification of the algal limestones of the LSW section

The algal-bound mudstones and wackestones are generally pseudostromatic with occasional local growths in situ or local intergrowths in situ of calcareous Algae

[2] Allochems responsible for grain bulk is a somewhat loosely defined concept which works well in practice. The percentage of allochems in an individual thin section, as visually estimated with the aid of a percentage chart, includes several kinds of allochems. Those responsible for grain bulk are those which count in estimating the over-all percentage, while the others, present in small amounts, make only a negligible contribution to the bulk of grains.

or other organisms. The algal-bound packstones consist entirely of intergrown calcareous Algae or they are mechanical deposits of allochems encrusted and bound by calcareous Algae or invaded and bound, agglutinated and bound or entrapped and bound by non-calcareous Algae. Transitions between these two major types, the algal-bound intergrowth packstones and the algal-bound non-intergrowth packstones, occur. For instance one can find local intergrowths in situ of calcareous Algae in the midst of mechanically deposited allochems – usually algal debris – invaded and bound, agglutinated and bound or entrapped and bound by non-calcareous Algae.

SIGNS OF BINDING

A number of features are discussed and illustrated which are considered indications for algal binding. The first two are the most frequent and most obvious signs of binding. The others, except for 6, are not conclusive enough on their own to classify a limestone as algal-bound. However in combination with one of the first two, they supply added evidence for this interpretation.

Pseudostromata, sign 1 (Pl. VII, Fig. 3; Pl. XII, Fig. 1; Pl. XVI, Figs. 1, 2, 5, 8)

Micrite with a dense, grumous, cellular, spongy, tubular, pelletoid or granuloid aspect suggests an original supporting non-calcareous algal framework which rotted away or was converted into clotty aphanocrystalline calcium carbonate, sometimes with conservation of the organic material (de Meijer, 1969). Molds of this organic framework have filled with pore-filling calcite and sometimes can be recognized as such.

Skeletal intergrowths frameworks, sign 2

In the LSW limestones, skeletal intergrowth frameworks were formed exclusively by skeletons of calcareous Algae. These intergrowing Algae may have been erect and branching or plate-like and encrusting each other or loose interstitial debris. This phenomenon of calcareous Algae encrusting and binding loose debris has been observed in a number of samples. The pressure from the overburden, which was supported by the skeletal framework, was transferred to the mechanically deposited material. The latter, as a result, shows signs of compaction such as embayed contacts between allochems and parallel solution stringers in the micritic parts.

In those places where encrusting forms grew over an irregular surface or where framework interstices developed as a result of close encrusting forms, it appears that the voids are frequently occupied by pseudostromatic masses which lack any sign of compaction. These voids were protected from being filled with mechanically deposited material (umbrella effect) and formed conveniently sheltered places for non-calcareous Algae to grow and precipitate micrite, resulting in a complete filling of the original voids with a pseudostromatic mass. The lack of compaction can be explained either by the support of the intergrowth framework, which would have kept these voids open even if they had not been filled with pseudostromata, or by the very nature of the algal-bound, rapidly consolidated mass of the pseudostromata. The latter does not show any sign of compaction even when there is evidence of enough pressure to break the coherence of the framework (fractures in the skeletons).

In three places in the LSW section, skeletal intergrowth frameworks have been found in a continuous sequence of samples indicating that the limestone was formed by a biohermal development of calcareous Algae. The other skeletal intergrowth frameworks are restricted to individual samples and are nothing more than expansions of the more frequent local intergrowths in situ of calcareous Algae.

In two cases the bioherms of intergrown calcareous Algae show lenslike terminations in the field (LSW 33—36 and LSW 43—45) in the immediate neighborhood of the location where the section was measured, but in this respect they do not differ essentially from the other limestones regarded as pseudostromatic algal bioherms (e.g. LSW 39—42).

Because no details are given in the depositional texture column as to the components and aspects of the skeletal intergrowth frameworks, a brief description follows below.

LSW 33/2. Intergrowth of *Archaeolithophyllum missouriensum* Johnson, 1956. Erect branching and encrusting plate-like forms are equally abundant. The matrix is predominantly pseudostromatic – pelletous with constructed voids – but in some places laminated by parallel solution stringers indicating compaction. Other calcareous Algae such as *Komia abundans* Korde, 1951, phylloid codiaceans and dasycladaceans are associated with the *Archaeolithophyllum* intergrowth. The same holds for bryozoans growing in situ and a sphinctozoan calcareous sponge (Pl. II, Fig. 2). Of all the above-mentioned organisms, the specimens of *Archaeolithophyllum* in particular are encrusted with algal tubes and Foraminifera which are embedded in a dark algal micrite coating.

LSW 34. Intergrowth of *Archaeolithophyllum missouriensum* Johnson, 1956, (Pl. II, Fig. 3). Packstone patches of closely packed fragments of this Alga are encrusted and bound at regular intervals by specimens of platy *Archaeolithophyllum*. The supporting framework is formed by several specimens of *Archaeolithophyllum,* which grew erect and connected the various encrusting forms. Compaction of the encrusted mechanically deposited patches is shown by the embayed contacts between allochems and the parallel solution stringers in the micrite. The packstone texture clearly developed from an original wackestone texture. Compaction is further illustrated by broken *Archaeolithophyllum* skeletons, especially those of the erect forms, and by crushed brachiopod valves. In protected places under encrusting *Archaeolithophyllum* or brachiopods in situ, pseudostromata developed which lack any sign of compaction.

LSW 35. Intergrowth of *Archaeolithophyllum missouriensum* Johnson, 1956. The Algae grew erect as well as encrusting. Dasycladacean Algae are associated with the *Archaeolithophyllum* intergrowth. The interstices of the framework are filled mainly with pseudostromata. Mechanically deposited micrite and fragments of Algae occur in places. Compaction of this material is indicated by parallel solution stringers in the micrite and a crushed bivalved brachiopod. The pseudostromata do not show any compaction: constructed voids in

the lower part of algal mat-like developments are well-preserved (Pl. II, Figs. 5, 6). The specimens of *Archaeolithophyllum* are encrusted by algal tubes and encrusting Foraminifera, embedded in a dark algal coating.
LSW 36. Intergrowth of erect *Archaeolithophyllum missouriensum* Johnson, 1956, and dasycladaceans. Associated with this intergrowth are bryozoans. The interstices of the framework are almost completely filled with pseudostromata, lacking any sign of compaction. In places the framework is interrupted by mechanically deposited micrite with fragments of *Archaeolithophyllum,* bryozoans and valves of pelecypods and brachiopods. The latter have been crushed as a result of the compaction. Compaction is furthermore revealed by embayed contacts between the allochems and parallel solution stringers in the micrite.
LSW 43. Intergrowth of *Archaeolithophyllum missouriensum* Johnson, 1956. A framework of erect forms was locally interrupted by mechanical depositions with *Archaeolithophyllum* fragments, which in turn were bound by encrusting *Archaeolithophyllum.* Dasycladacean Algae and bryozoans are associated with the intergrowth (Pl. III, Fig. 3). The mechanical depositions and the framework of erect forms show compaction, the first by embayed allochem contacts and parallel solution stringers in the micrite, the latter by fractures in the skeletons. In places protected by the intergrowth framework, pseudostromata have developed.
LSW 44. Intergrowth of *Archaeolithophyllum missouriensum* Johnson, 1956, (Pl. III, Fig. 4). Codiacean Algae are associated with the *Archaeolithophyllum* intergrowth. The intergrowth is made up of encrusting forms, which grew upon each other or bound mechanically deposited wackestone patches. These patches show compaction lamination by parallel solution stringers and scattered crushed valves. In voids formed by irregular growth of encrusting *Archaeolithophyllum* or by growth of the latter over a wavy substratum, pseudostromata developed which lack any sign of compaction (Pl. III, Fig. 5). Algal tubes and Foraminifera, which encrust the specimens of *Archaeolithophyllum,* show a preference for growth in these same protected places.
LSW 45. Strangely enough the bottom sample of the lens-like calcareous Alga bioherm (LSW 43—45) is an algal-bound wackestone without a skeletal intergrowth framework. Several local growths in situ of *Archaeolithophyllum missouriensum* Johnson, 1956, were observed, but on the whole this limestone is pseudostromatic with a pelletous, granuloid aspect and an admixture of algal fragments.

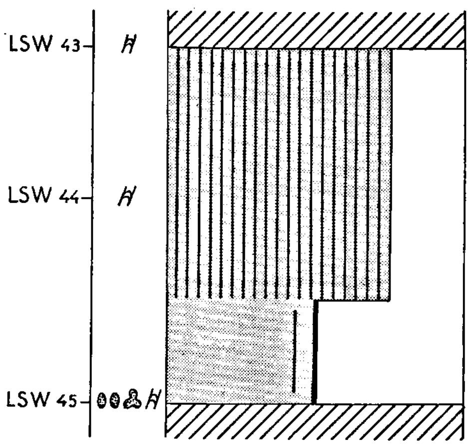

Fig. 4. Depositional texture column of the calcareous Alga bioherm LSW 43—45 (legend see appendix, scale 1 : 100)

LSW 86. Intergrowth of *Anthracoporella* sp. Framework interstices are filled with pseudostromata. Locally the intergrowth was interrupted by mechanically deposited material, which shows compaction by embayed contacts between the allochems and parallel solution stringers in the micrite. Fragments of *Anthracoporella* in the mechanically deposited material show oncolitic envelopes of pseudostromatic micrite and concentrically grown algal tubes.
LSW 92. Intergrowth framework of thickly branched *Anthracoporella* sp. The framework interstices are filled mainly with pseudostromata and an admixture of mechanically deposited material. Locally the supporting skeletal framework is interrupted by a fracture of an *Anthracoporella* branch. The pressure of the overburden was therefore transferred to the interstitial sediment, which consequently shows broken valves, embayed contacts and parallel solution stringers in the mechanically deposited components. However, the pressure had no effect on the pseudostromatic parts of the matrix.
LSW 141. Intergrowth of erect *Archaeolithophyllum* sp. The identification of these Algae is not fully reliable because they are poorly preserved. Aggrading neomorphism after previous micritization altered the Algae to algal molds with only vague relicts of hypothallus or perithallus cells. The interstices of the framework are completely filled with pseudostromatic matrix. Compaction phenomena were not observed.
LSW 148. Intergrowth of erect *Dvinella comata* Chvorova, 1949. These slender Algae grew together like stalks of corn (Pl. XV, Fig. 6). Since there are no sheltering effects the mechanically supplied sediment should have filled the interstices completely instead of producing floors. However, the interstices are incompletely filled, due to irregular growth of pelletous pseudostromata. The calcareous Alga *Ungdarella* sp. and fusulinids are associated with the *Dvinella* intergrowth.
LSW 149. The same as LSW 148.
LSW 150. A lime packstone of intraclasts problably derived from intergrowths similar to those of LSW 148 and LSW 149. The only difference between the supposed intergrowth and those of LSW 148 and LSW 149 is the presence of *Ungdarella* sp. in the same ratio as *Dvinella comata.* Because of the relatively small dimensions of the intraclasts, the intergrowth framework cannot be identified with sufficient certainty. Another possibility is that the intraclasts are derived from a packstone of *Dvinella* and *Ungdarella* debris, invaded and bound by Algae as in the case of recent crusty flakes (Monty, 1967).
LSW 170. Intergrowth of *Ungdarella* sp. and *Dvinella comata* Chvorova, 1949. The specimens of *Ungdarella* sp. are irregular branching forms, which grow erect like *Dvinella.* The interstices of the framework are incompletely filled with pseudostromata. Smaller Foraminifera and fusulinids are associated with the intergrown Algae. Locally the intergrowth framework was interrupted by mechanically deposited micrite with algal fragments in a packstone texture, showing exceedingly close packing.

Constructed voids, sign 3 (Pl. X, Fig. 5; Pl. XVIII, Figs. 6, 7)

Organic algal growths often form loose constructions which include natural voids. Syndiagenetic precipitation of calcium carbonate within these organic algal growths generally did not fill these originally empty spaces. The latter remained intact and were only modified by calcification of sparse organic material, always present in these voids, and by other syndiagenetic processes such as burrowing and periodic desiccation with resulting compaction. Voids, too large to be interstices, are sometimes found in micrite and may be constructed voids caused by algal binding. To be sure of such an identification one has to distinguish them from other voids larger than interstices, such as those resulting from solution. Solution voids are easily recognized if they originated by selective solution of bioclasts, because of the well-known outline of the latter. Indiscriminate solution voids are more difficult to distinguish from constructed voids unless there is conclusive evidence for the former, for instance the presence of partly dissolved fossils adjacent to the voids. Naturally the presence of pseudostromatic micrite surrounding a void reveals its origin just as the reverse is an indication of the pseudostromatic character of the surrounding micrite. The internal sediment floors are useful for identification of the original void now visible as a calcite patch, thereby forming a criterium to differentiate between pore-filling calcite and neomorphic calcite (pseudospar). In this respect also Bathurst's crystal morphology criteria are helpful although in many cases fallible (Folk, 1965, p. 44). The presence of a floor of internal sediment however does not reveal the original character of the void because it can also occur in other types of voids (see the section "internal sediment"). Therefore it cannot be used as a criterium for recognition of constructed voids.

Lamination contrary to gravity, sign 4 (Pl. V, Fig. 5; Pl. XIV, Fig. 4; Pl. XVIII, Figs. 6, 7)
This sign of binding was recognized by Dunham (1962, p. 117) and used to describe the special type of binding found in algal stromatolites (Pl. I, Figs. 1, 2; Pl. X, Figs. 1, 2, 3). Here it is used in a broader sense to include pseudostromatic binding. In this sense it refers to sedimentary or compaction lamination contrary to gravity, and encrusting growth contrary to gravity over micritic parts which lack stratification and compaction. It is thought to indicate the presence of a pseudostromatic algal colony rising above the sediment floor and buried later by sediment or encrusted by organisms. The mechanically deposited sediment will show stratification or compaction lamination contrary to gravity whereas the algal colony, by internal precipitation of calcium carbonate and consequent early lithification, resisted compaction and by the nature of its formation lacks stratification. Encrusting growth contrary to gravity over a micritic body indicates that the latter formed a hard substrate rising above the neighboring sediment floor. Here too the micritic body is thought to indicate early lithification of a pseudostromatic algal colony. The preceding is based on the assumption that mechanically deposited micrite will not form a hard substrate rising above the adjacent sediment floor. One can imagine however conditions under which mechanically deposited micrite might show similar phenomena. For instance temporary subaerial exposure might cause early lithification, and weathering might give the surface an initial karst relief. Renewed advance of the sea could be expected to produce lamination contrary to gravity by the draping of sediments or the encrusting growth of organisms over the rich relief. Therefore when this sign of binding is recognized, it is necessary to check whether the observed phenomena could not equally well be ascribed to the above-mentioned process.

Compaction/non-compaction, sign 5 (Pl. IX, Figs. 5, 6, 7, 8; Pl. XIII, Fig. 8; Pl. XIV, Figs. 2, 3; Pl. XVI, Figs. 1, 2, 5)
In the specific case of 4 it was noted that the identification of a micritic body as algal-bound can be supported by non-compaction in the micritic body versus compaction in the overlying mechanically deposited sediment, draped contrary to gravity. Also in general absence of compaction in a micritic body in contrast to compaction phenomena in the immediate surroundings is considered a possible indication of the pseudostromatic nature of this micritic body.

Algal mat lamination, sign 6 (Pl. XII, Fig. 2)
When algal mat lamination is observed as in domed algal stromatolites (see 4), the algal binding is perfectly clear and needs no further comment. Relatively flat, poorly laminated algal mats are less obvious, whereas their recognition is important for the identification of the algal-bound nature of the sediment. Logan, Rezak and Ginsburg (1964, p. 69) give the following significant criteria for diagnosis: (1) detrital texture, (2) structures which require a sediment-binding surface film, (3) minor domes, (4) bubbles, (5) undulation and micro-unconformities and (6) confluence of laminae with larger heads. In addition, the flat, laminated algal mat shown in plate 7 of Monty (1967) is also instructive; the lamination in the lower half of this mat has been considerably altered by various processes, such as burrow activities and calcification of the organic matrix which led to the formation of algal pellets.

Non-intergrowth packstones, sign 7
About the packstone texture Dunham (1962, p. 118) writes the following:

"Grain-support is generally a property of rocks deposited in agitated water and muddiness is generally a property of rocks deposited in quiet water. A rock exhibiting both properties is peculiar and it is well to have it isolated for further study. It may record simple compaction of a wackestone, as is suggested where interstices are completely filled with mud. It may record early or late infiltering of previously deposited mud-free sediment, or prolific production of grains in calm water, as is suggested where interstices are floored with mud. It may record mixing by burrowers or incomplete winnowing or partial leaching of mud as is suggested by patchily distributed mud".

In the modified classification scheme of Dunham, used in the present study, a packstone texture may also record binding by Algae. In the LSW limestones evidence for the explanations of the packstone texture, as suggested by Dunham, is generally lacking while evidence for algal binding is present. It includes: (1)

algal activity as shown by algal coating and micritization of the allochems, (2) a pseudostromatic micrite matrix and (3) the resemblance to recent crusty flakes and other algal mats, such as described by Monty (1967).

Crusty flakes are grain-supported by nature of their formation: sediment floors of skeletal sand are invaded by Algae, which bore the allochems and partly convert them into algal pellets or algal grains, grow around them and bind them together. The allochems are progressively embedded in an aphanocrystalline matrix, which precipitates in the organic material. Packstone textures with a patchily distributed pseudostromatic micrite matrix result. Even packstones with completely filled interstices may occur if the precipitation of micrite in the inter-allochem pores continues long enough. Distinction between packstones with completely filled interstices resulting from compaction of a wackestone and packstones with completely filled interstices formed as a crusty flake with abundant micrite precipitation can be made by reasoning as follows. If there has been compaction of a wackestone it must be seen in embayed contacts between mud-sized allochems, pressure stratification of micrite particles parallel to the bedding or sets of solution stringers parallel to the bedding. If these phenomena are lacking and if the interstitial micrite is pseudostromatic while the allochems consist of algal pellets, algal grains and bioclasts with algal coating and micritization, then it is very likely that we are dealing with a fossilized crusty flake. Recrystallization of recent crusty flakes is frequently found. Their interstitial aphanocrystalline micrite has been converted into a coarse mosaic (neomorphic micrite grading to pseudospar) and even the allochems are affected by neomorphism. Corresponding phenomena in the LSW packstones have been observed.

In non-laminated, agglutinating mats (Monty, 1967, p. 86 and 87) and entrapment mats (Monty, 1967, p. 85 and 93), grain-support is not a primary feature but may possibly be a result of the process. In non-laminated mats, finely grained and generally well-sorted particles agglutinate on the mucilaginous surface of the mat and are bound by further algal growth. If the allochem supply is so rich that the surface becomes densely covered but not enough for algal life to be destroyed, then subsequent fossilization could result in a packstone texture. The same holds for entrapment mats, which show loose irregular patterns of allochems between bundles of algal filaments but which, with a sufficient supply of allochems and conversion of the organic material into micrite during fossilization, might alter to packstones.

A review of the various non-intergrowth packstone textures of the LSW section, with the emphasis on whether or not there are indications for binding by Algae, is given below.

LSW 28. An a.b.[3] algal-coated ooid and echinoderm lime packstone (Pl. I, Fig. 6). Indications for algal binding are (1) algal coating and micritization of the allochems, (2) patchy distribution of the micrite matrix and (3) aggrading neomorphism of the micrite matrix and partly of the allochems, giving this packstone the aspect of a grainstone with a pseudosparitic matrix resembling a recent recrystallized crusty flake.

LSW 29. A highly calcitic a.b. Alga dolo-packstone (Pl. I, Fig. 7). Packstone patches with completely filled interstices, recording compaction of a wackestone, are encrusted and bound by plates of *Archaeolithophyllum* sp. In sheltered places beneath the algal plates pseudostromata developed.

LSW 37. A quartz grain, ooid and echinoderm packstone. Sand-sized quartz grains make up 30% of the volume. Often the sand-sized quartz grains form the nucleus of an ooid. The allochems show exceedingly close packing. The contacts of the carbonate allochems with each other or with the quartz grains are embayed. Where concentrations of ooids are present, compaction caused polygonal mosaics. The polygons did not originate by plastic deformation but by pressure solution. This is shown by the ooid lamination, which is concentric about the nucleus and is cut off by the polygonal outline. Locally the concentration of the sand-sized quartz grains is so large that it can be considered a calcareous sandstone. In the section "relation to underlying and overlying sandstones", an interpretation of the genesis of this packstone is given.

LSW 42. An a.b. quartz grain, ooid, algal grain and algal mold lime packstone. This limestone is similar to LSW 37 but differs in being algal-bound. Locally, embayed contacts are present but the overall picture indicates support by an algal framework. The bioclasts are heavily coated and micritized by Algae to such a degree that some have even been changed to algal grains. The micrite matrix of the completely filled interstices is pseudostromatic and often can hardly be distinguished from the algal grains (Pl. III, Fig. 2). Probably the genesis of this limestone is comparable to that of recent crusty flakes.

LSW 56. An a.b. highly calcitic, quartz grain and algal grain dolo-packstone (Pl. IV, Figs. 5, 6, 7, 8; Pl. V, Figs. 1, 2). Indication for algal binding is its resemblance to recent recrystallized crusty flakes, except that the patchily distributed micrite matrix has not only been recrystallized but also dolomitized. The allochems show algal coating, micritization, aggrading neomorphism and some partial dolomitization. The algal grains originated by algal coating and micritization of bioclasts. Sometimes pieces of the original bioclasts can still be recognized. The sand-sized quartz grains show all transitions from quartz grains without algal coating through quartz grains with algal coating to quartz grains as the nucleus of an ooid.

LSW 60. An a.b. highly calcitic, neomorphic fossil mold and spherulite dolo-packstone. This sample is more or less identical with LSW 56 but differs in the allochems responsible for grain bulk. Algal coating of the allochems is not as frequent, but heavy micritization can be observed especially in calcareous Algae and echinoderms.

LSW 64. An a.b. neomorphic fossil mold, algal grain and echinoderm lime packstone. Indication for algal binding is its resemblance to recent recrystallized crusty flakes. The allochems show algal coating and micritization. The patchily distributed micrite matrix is aggraded neomorphic. Aggrading neomorphism also affected the allochems, making the distinction between matrix and allochems less clear (Pl. V, Figs. 7, 8). The calcareous Algae are codiaceans with an algal coating, which occasionally show an oncolitic development.

LSW 71. An a.b. fairly dolomitic, neomorphic fossil mold, algal grain and echinoderm lime packstone. Indication for

[3] See note 1.

algal binding is its resemblance to recrystallized recent crusty flakes, except that the patchily distributed micrite matrix has not only been recrystallized but also fairly dolomitized. The allochems show micritization and algal coating. The algal grains were formed by heavy micritization of bioclasts, which sometimes can still be recognized, or by disintegration of pseudostromatic bodies.

LSW 72. An a.b. calcareous Alga lime packstone (Pl. VI, Figs. 5, 6, 7). This sample is an intermediate type between intergrowth and non-intergrowth packstone. Intergrowth of codiacean Algae, algal tubes and pseudostromata locally show an oncolitic development of algal tubes in a pseudostromatic algal coating with codeacean Algae as nuclei. In some places the non-intergrowth packstone indicates compaction of a mechanically deposited wackestone. Usually however there is a resemblance to recrystallized recent crusty flakes.

LSW 77. An a.b. calcareous Alga and algal grain lime packstone. Indication for algal binding is its resemblance to recrystallized recent crusty flakes. The allochems show algal coating and micritization. The patchily distributed micrite matrix is aggraded neomorphic and grades locally to pseudospar. The codiacean Alga, cf. *Eugonophyllum* sp., and the rhodophycean Alga (incertae sedis), *Archaeolithophyllum* sp., serve locally as nuclei for oncolites with an algal coating of alternating pseudostromatic micrite and algal tubes (Pl. VII, Figs. 5, 7). The algal grains originated by thick pseudostromatic coating and heavy micritization of bioclasts or by disintegration of pseudostromatic bodies.

LSW 82. An a.b. algal pellet lime packstone (Pl. VIII, Figs. 2, 3, 4, 5, 6). This type is an intermediate type between intergrowth and non-intergrowth packstone. The local intergrowths consist of calcareous Algae (molds of *Archaeolithophyllum* sp.) and fenestrate bryozoans, embedded in a relatively thick pseudostromatic algal coating; the non-intergrowth parts consist exclusively of well-sorted algal pellets, some revealing their origin by containing tiny fragments of bioclasts at the center. These algal pellet packstone parts are thought to indicate a formation comparable to recent non-laminated algal mats or entrapment algal mats. Because the allochems are so fine (100—200 microns) and well-sorted, one is inclined to compare them with recent non-laminated algal mats. However sparse relicts of externally calcified algal filaments with organic walls have been observed. These, although not present in bundles, suggest instead algal entrapment mats.

LSW 87. An a.b. algal mold and spherulite lime packstone. Binding is due to local encrusting growth of the Alga *Archaeolithophyllum* sp. over packstone patches consisting of algal fragments (molds of *Archaeolithophyllum* sp. and *Anthracoporella* sp.) and spherulites. In sheltered places pseudostromata developed. The encrusted and bound packstone parts indicate formation by compaction of a mechanically deposited wackestone and show embayed contacts between the allochems and parallel solution stringers in the micrite parts.

LSW 119. An a.b. algal mold and calcareous Alga lime packstone (Pl. XIII, Fig. 8). This limestone is not a typical packstone but a mixture of an a.b. pseudostromatic wackestone with algal molds of *Anthracoporella* sp. and an a.b. calcareous Alga packstone with algal plates (algal molds), locally forming an intergrowth framework and locally encrusting and binding mechanically deposited material with a wackestone texture or a packstone texture showing compaction of a wackestone. Since the mixture contains more a.b. packstone than a.b. wackestone, this sample has been illustrated in the texture column as an a.b. packstone with local skeletal intergrowths.

LSW 122. An a.b. algal mold, calcareous Alga and algal grain lime packstone (Pl. XIV, Fig. 1). Platy algal molds encrust and bind packstone patches composed of fragments of algal molds and algal grains and prostrate specimens of the calcareous Alga *Anthracoporella* sp. Within these packstone patches, which indicate compaction of a wackestone, there are some erect specimens in situ of the calcareous Alga *Archaeolithophyllum* sp. In sheltered places under the encrusting algal plates or the specimens of *Anthracoporella,* which lie flat, pseudostromata developed.

LSW 124. An a.b. algal mold, calcareous Alga and algal grain lime packstone. This is an intermediate type between intergrowth and non-intergrowth packstone. In between packstone patches resembling recrystallized recent crusty flakes are local specimens of *Archaeolithophyllum* in situ and intergrowths of *Archaeolithophyllum,* dasycladaceans and algal tubes, surrounded by pseudostromatic bodies.

LSW 129. An a.b. echinoderm, bryozoa, smaller Foraminifera, algal pellet and pore-fill fossil mold lime packstone. Algal binding in this packstone is suggested by complete filling of the interstices with pseudostromatic micrite, lack of any compaction, algal coating and micritization of the allochems and the occurrence of solution voids. The solution did not lead to leaching of the inter-allochem pores – as would be expected in a packstone which is not algal-bound – but indiscriminately attacked the pseudostromatic matrix and the allochems (Pl. XIV, Fig. 8).

LSW 131. An a.b. algal pellet, calcareous Alga and algal grain lime packstone. This is an intermediate type between intergrowth and non-intergrowth packstone. In situ calcareous Algae, algal-coated *Ungdarella* sp. and codiaceans, and in situ intergrowths of the calcareous Algae *Dvinella* sp., *Ungdarella* sp. and algal tubes, surrounded by pseudostromatic bodies, exist amidst depositions of algal pellets with a packstone texture. The same criteria for algal binding as mentioned in the description of LSW 129 can be applied to these pelletal packstone patches.

LSW 142. An a.b. calcareous Alga lime packstone. Binding is indicated by a patchily distributed, grumous, pelletous, pseudostromatic micrite matrix, which in places interrupts the packstone texture by the development of pseudostromata containing constructed voids.

LSW 150. An intraclast lime packstone (Pl. XV, Figs. 7, 8). The intraclasts grade from micrite size to 4 mm, and lie in exceedingly close packing while the interstices are completely filled with micrite. The angularity of the intraclasts, the bad sorting and the poor washing indicate that the source of this sediment must have been nearby. The nature and genesis of this source sediment has been discussed in the section "skeletal intergrowth" and will be discussed in further detail in the section "intraclasts".

LSW 153. An echinoderm, brachiopod, calcareous Alga and bryozoa lime packstone (Pl. XVI, Fig. 3). The allochems grade from micrite size to 4 or 5 mm. They show an arrangement of exceedingly close packing with embayed contacts. Algal influence is manifested by algal coating and micritization of the allochems and the presence of dark algal micrite in some inter-allochem pores. It was however not strong enough to cause algal binding.

LSW 156. An a.b. algal pellet, calcareous Alga, smaller Foraminifera and fusulinid lime packstone. Algal binding is suggested by its resemblance to recrystallized recent crusty flakes. Many allochems show algal coating and overgrowth by algal tubes and encrusting Foraminifera. Most allochems show micritization. The patchily distributed pseudostromatic micrite matrix is aggraded neomorphic, grading to pseudospar. The algal-bound nature of this matrix is demonstrated by the development of pseudostromatic patches, locally interrupting the packstone texture. One such a patch surrounds a pelecypod valve, algal-coated and encrusted by algal tubes. The encrusting tubes seem to have protected this valve because where they are missing, the microstructure of the valve has been totally destroyed by micritization (Pl. XVI, Fig. 8).

LSW 158. An a.b. algal pellet, algal grain, calcareous Alga and bryozoa lime packstone. Algal binding is indicated by algal coating and micritization of the allochems and the pseudostromatic pelletous character of the patchily distributed micrite matrix. Neomorphism and silicification have obliterated part of the evidence of the original depositional texture (Pl. XVII, Fig. 1).

LSW 162. An a.b. algal pellet, algal grain, neomorphic mold and calcareous Alga lime packstone. A packstone with interstices completely filled with a pseudostromatic matrix. Locally the latter has developed into pseudostromata, which interrupt the packstone texture. No sign of compaction has been observed. All allochems show algal coating and micritization. Some algal grains show relicts of fusulinids indicating that they originated by micritization and algal coating of these Foraminifera. The pseudostromatic matrix is neomorphic and grades to pseudospar. It is supposed that this packstone originated as a crusty flake with abundant precipitation of micrite in the interstices.

LSW 164. An a.b. algal pellet, algal grain, calcareous Algae and smaller Foraminifera lime packstone, more or less identical with LSW 156. Algal binding is suggested by its resemblance to recrystallized recent crusty flakes. The allochems all show algal coating and micritization. The patchily distributed pseudostromatic matrix is aggraded neomorphic, grading to pseudospar. The pseudostromatic nature of this matrix is illustrated by local development of pseudostromata, which interrupt the packstone texture. All stages from algal-coated bioclasts via bioclasts with heavy algal coating and micritization to algal grains with relicts of bioclasts have been observed (Pl. XVII, fig. 4).

LSW 165. An a.b. calcareous Alga lime packstone, almost identical to LSW 164, differing only in allochems which consist exclusively of fragments of the calcareous Algae *Ungdarella* sp. and *Dvinella* sp. In addition the algal coating of the allochems is not as heavy as in LSW 164 and where it did develop, it can hardly be distinguished from the pseudostromatic matrix.

LSW 168. An a.b. calcareous Alga, algal pellet, echinoderm, smaller Foraminifera and fusulinid lime packstone. Algal binding is suggested by its resemblance to recrystallized recent crusty flakes. The patchily distributed matrix is locally neomorphic and grades to pseudospar. Its pseudostromatic nature is indicated by the gradual transition to the algal coatings of the allochems (Pl. XVII, Fig. 5).

LSW 169. An a.b. calcareous Alga, echinoderm, bryozoa, algal grain and smaller Foraminifera lime packstone, identical to LSW 168 (Pl. XVII, Figs. 6, 7).

LSW 171. An a.b. echinoderm, fusulinid and smaller Foraminifera lime packstone, identical to LSW 168 and 169, except that calcareous Algae or products of Algae do not form a part of the allochems responsible for grain bulk.

LSW 176. An a.b. calcareous Alga, algal pellet, smaller Foraminifera and echinoderm lime packstone, identical to LSW 168, 169 and 171.

LSW 177. An a.b. calcareous Alga and echinoderm lime-packstone. The interstices are completely filled with neomorphic micrite, which grades to pseudospar. The allochems are generally also neomorphic. Locally algal coatings are noted which grade into the micrite matrix. This and the complete lack of compaction are considered indicative oi algal binding.

LSW 181. An a.b. echinoderm and bryozoa lime packstone (Pl. XVIII, Fig. 2). This packstone can best be compared to recrystallized recent crusty flakes. There is exceedingly close packing of algal-coated and heavily micritized allochems. Locally compaction phenomena are seen such as embayed contacts and crushed bioclasts. On the other hand the pseudostromatic matrix, which fills the inter-allochem pores completely, lacks any sign of compaction. It is neomorphic and grades to pseudospar. The close packing of the allochems can be explained by the presence of a bimodal grain size distribution: the echinoderms being the larger grains and the bryozoans the smaller.

LSW 182. An a.b. algal pellet, pore-fill fossil mold and neomorphic fossil mold lime packstone (Pl. XVIII, Fig. 3). The allochems are fairly well-sorted, showing a mean grain size of 90 microns. The micrite matrix is patchily distributed, neomorphic and grades to pseudospar. Signs of algal binding are the algal coatings around nearly every allochem and the resemblance of this packstone to recent non-laminated agglutinating algal mats as far as the good sorting and the corresponding grain size of the allochems are concerned. Non-laminated agglutinating algal mats however are only known from rocky substrates, whereas in this case the substrate is a sandstone. Therefore an origin similar to that of a crusty flake is more likely. The good sorting may have resulted from currents only strong enough to carry small allochems, together with some fine sand-sized quartz grains which are also present.

LSW 183. An echinoderm, fusulinid, calcareous Alga and bryozoa lime packstone. This packstone contains 7 volume percent sand-sized quartz grains and is rather clayey. The allochems are exceedingly close packed and show embayed contacts. Compaction of the micrite matrix is shown by sets of parallel solution stringers. All these features show that this packstone developed by compaction of a mechanically deposited wackestone. On the other hand there is also influence of Algae which is indicated by algal coating and micritization of some of the allochems.

LSW 187. An a.b. calcareous Alga, algal pellet and smaller Foraminifera lime packstone. This is an intermediate type between intergrowth and non-intergrowth packstone. The non-intergrowth packstone patches surround a local intergrowth in situ of the calcareous Algae *Ungdarella* sp. and *Dvinella* sp., enveloped by pseudostromata. Locally the non-intergrowth packstone indicates compaction of a mechanically deposited wackestone; this is shown by the completely mud-filled interstices with parallel solution stringers and by embayed contacts between the allochems. In most other places however it shows a resemblance to recrystallized recent crusty flakes. The unevenly distributed pseudostromatic matrix developed locally into a pelletous pseudostromatic patch, interrupting the packstone texture.

LSW 188. An a.b. calcareous Alga, smaller Foraminifera and algal pellet lime packstone identical with LSW 187. However, packstone patches suggesting mechanical deposition, as in LSW 187, have not been observed. Around the local intergrowth the pseudostromatic micrite matrix developed into real pseudostromata, which interrupt the packstone texture.

LSW 191. An a.b. calcareous Alga, algal grain and algal pellet lime packstone. Algal binding is suggested by its resemblance to recrystallized recent crusty flakes. Algal coating of the calcareous Algae together with overgrowths of algal tubes resulted in the formation of oncolites. Algal coating of the calcareous Algae and other bioclasts together with heavy micritization resulted in the formation of algal grains; all stages of development can be observed. The patchily distributed micrite matrix is neomorphic and grades to pseudospar, which can hardly be distinguished from the equally abundant pore-filling calcite.

In situ growths and local intergrowths in situ, sign 8
In situ growths and local intergrowths in situ of calcareous and non-calcareous Algae, and other organisms to a lesser degree, are numerous in the LSW limestones. In situ growths and intergrowths in situ indicate conditions which permit colonization of the bottom. This is the case when the substrate is stable, which implies that there is absence of shifting bottom sediments. Such conditions are fulfilled when the substrate is firm enough to withstand high current or wave velocities and the sediment supply is low, or when the environment is quiet with low current or wave velocities. In the latter case, both unconsolidated and consolidated sediments can function as stable substrates.

In the quiet environment the sediment surrounding in situ growths or local intergrowths in situ is supplied by the settling of clay-sized and silt-sized particles out of suspension, together with the in situ accumulation of skeletal fragments resulting from scavengers or corrosion. Under suitable conditions, this type of protected setting may also form an ideal environment for colonization by non-calcareous Algae, which can bind or agglutinate the mechanically deposited material.

In environments where the substrate is stable because of its firmness and resistance to current and wave action and where the supply of allochems is not large enough to immediately cover the substrate with a shifting bottom sediment, sediments will be built or collected only when intergrown calcareous skeletal frameworks are formed and/or the sparse sediment particles are trapped by freely waving non-calcareous Algae or other plants.

The occurrence of in situ growths or local intergrowths in situ therefore indicates one of these two types of environment. Although it does not determine conclusively whether or not the sediment is bound, it accentuates the autochthonous character of the sediment and helps to make other signs of binding more convincing.

A special type of local intergrowth is found in the oncolites. According to Johnson (1961), oncolites are Algae of the section Spongiostromata which grow on an object not attached to the bottom. These algal overgrowths show a lamination identical to the one found in stromatolites, but arranged concentrically around a nucleus. In this paper the definition of oncolites has been extended to include concentric intergrowths of both Porostromata and Spongiostromata around a nucleus. This is the only type of oncolite observed in the LSW limestones. They are similar to the forms called algal pisolites by Wolf (1965, p. 140 and Fig. 10). Wolf discusses algal pisolites together with the algal ooids, thus suggesting that the concentric lamination originated by overturning. This is also apparent from what he states about their origin (p. 140, op. cit.):

"It seems that the few pisolite occurrences found in the Nubrigyn limestone, were formed in shallow depressions within algal reefs and were only occasionally turned over".

From this it can be concluded that, despite the overturning, algal pisolites are considered almost autochthonous by Wolf. From the studies by Monty (1965) on recent oncolites, it appears that the concentric lamination is not necessarily caused by overturning. In this respect it is interesting to quote the following (Monty, 1965, p. 398):

"It would perhaps be better to say that they are unattached, soft or calcified nodules, built by an algal community, showing a radial or concentric centrifugal growth. Further studies will undoubtedly lead to distinguish structures growing naturally and simultaneously in all directions from structures where the laminated oncolitic pattern results from accidental overturning".

Examination of the LSW limestones has led to the same conclusion. Many skeletons, locally grown in situ or locally intergrown in situ, are surrounded by pseudostromatic bodies. Sometimes the latter have developed an oncolite-like intergrowth pattern of alternating laminae of pseudostromatic micrite and calcareous algal tubes. These oncolite-like overgrowths on in situ grown or intergrown skeletons differ from true oncolites only in that the concentric lamination is interrupted where the skeletons are attached to the bottom. It is clear that these oncolite-like overgrowths are not due to overturning of the overgrown skeletons. The conclusion therefore seems warranted that the oncolites found in the LSW section are not necessarily indicative of overturning and consequently of allochthony of the overgrown allochems. Those oncolites, which are associated with oncolite-like overgrowths on skeletons attached to the bottom, are nothing more than allochems with an unusually heavy algal coating, which originated from concentric centrifugal growth in situ of an algal community. Other oncolites, observed in crusty flake-like packstones, may under certain conditions [4] suggest overturning. Thus the two types suggested by Monty can be identified by differences in habitat of the associated allochems and the depositional texture of the limestone sample. If overturning is probable, the oncolite intergrowth is not regarded as an intergrowth in situ although the oncolites were probably transported only over small distances.

In the texture column, the organisms which have grown in situ or formed a local intergrowth in situ are not specified. A list of local in situ growths and local intergrowths in situ therefore follows below. This list also includes all oncolites whether formed in situ or by overturning.

LSW 29. Local intergrowths in situ of encrusting, platy calcareous Algae, *Archaeolithophyllum* sp. (Pl. I, Fig. 7).
LSW 32. Local intergrowth in situ of erect calcareous Algae, *Archaeolithophyllum* sp., surrounded by pseudostromata (Pl. I, Fig. 8).

[4] See discussion of oncolites in the list below.

LSW 39. Local growth in situ of a calcareous Alga, *Archaeolithophyllum* sp.
LSW 45. Local growth in situ of a calcareous Alga, *Archaeolithophyllum missouriensum* Johnson, 1956.
LSW 47. A brachiopod in situ.
LSW 48. Local growth in situ of a calcareous Alga (algal mold).
LSW 51. Local intergrowth in situ of calcareous Algae (algal molds).
LSW 52. Local growth in situ of a dome-shaped colony, 1 mm thick and 4 mm long, of prostrate calcareous algal tubes.
LSW 53. Local growth in situ of colonies, 5 mm thick and 15 mm long, of prostrate calcareous algal tubes.
LSW 63. Local intergrowth in situ of colonies of loosely arranged calcareous algal tubes, intimately associated with pseudostromata (Pl. V, Figs. 3, 4); in situ growths of laminated colonies, 15 mm long and ½ mm thick, of calcareous algal tubes associated with dark pseudostromatic micrite, growing contrary to gravity over pseudostromatic bodies (Pl. V, Fig. 5).
LSW 64. Oncolites with codiacean Algae as nuclei (Pl. V, Fig. 6). The association with sand-sized quartz grains suggests formation of the oncolites by overturning, caused by currents which also delivered the sand-sized quartz grains. Perhaps this is valid for the initial stage of the oncolites but the laminations which developed later are interrupted locally and show integration with the pseudostromatic matrix of the packstone. This suggests an autochthonous intergrowth with the invading and binding Algae, which caused the formation of this crusty flake.
LSW 69. Local growth in situ of calcareous Algae (algal molds); local internal and external overgrowth over an algal mold by calcareous algal tubes embedded in dark pseudostromatic micrite (Pl. VI, Fig. 4).
LSW 72. Local growth in situ of a calcareous Alga, *Archaeolithophyllum* sp., and local intergrowths in situ of codiacean Algae, surrounded by colonies of calcareous algal tubes, embedded in pseudostromata. Locally an oncolite-like overgrowth over a codiacean Alga in situ is noted. True oncolites around fragments of codiaceans are also present. Because of their association with oncolite-like overgrowths, these are interpreted as intergrowths in situ (Pl. VI, Fig. 7).
LSW 74. Local intergrowth in situ of calcareous Algae (algal molds) and fenestrate bryozoans, intimately associated with pseudostromata.
LSW 77. Oncolites around molds of rhodophycean Algae (incertae sedis), *Archaeolithophyllum* sp., and codiacean Algae, cf. *Eugonophyllum* sp. (Pl. VII, figs. 5, 7). This sample resembles a crusty flake, which means that the allochems may have been transported. Perhaps the inner layers of the oncolites were formed by overturning during this transport. The irregular lamination of the later stages in the oncolite development is locally interrupted and shows integration with the pseudostromatic matrix. This suggests an autochthonous intergrowth with the invading and binding Algae, which caused the formation of this crusty flake.
LSW 82. Local intergrowth in situ of calcareous Algae, *Archaeolithophyllum* sp., fenestrate bryozoans and pseudostromata. The aspect of this intergrowth is that of an oncolite without concentric lamination: bryozoans and *Archaeolithophyllum* sp. embedded in a thick pseudostromatic envelope (Pl. VIII, Figs. 2, 3, 4, 5).
LSW 85. Intimate, local intergrowth of loosely arranged calcareous algal tubes and pseudostromata with constructed voids, surrounding a brachiopod in situ and in situ codiacean Algae (Pl. IX, Figs. 1, 2, 3).
LSW 86. Some calcareous Algae, *Anthracoporella* sp., of the intergrowth framework show an oncolite-like overgrowth with calcareous algal tubes and pseudostromata.
LSW 87. Local growth in situ of a calcareous Alga, *Archaeolithophyllum* sp., surrounded by a pseudostromatic body.
LSW 89. Local growth in situ of a calcareous Alga (algal mold).
LSW 91. Local growths in situ of calcareous algal tubes, as overgrowths on pseudostromata.
LSW 94. An egg-like algal head in situ, consisting of several algal mat-like laminae and pseudostromatic patches with fossil molds (Pl. X, Fig. 1). The upper part and the sides of the intergrowth are enveloped by a dark pseudostromatic coating, containing bryozoans, ostracods, encrusting Foraminifera, calcareous algal tubes and an encrusting calcareous Alga, *Parachaetetes* sp.
LSW 101. Intimate local intergrowths in situ of colonies of calcareous algal tubes and pseudostromata with constructed voids (Pl. X, Fig. 8); local intergrowths in situ of calcareous Algae, *Komia abundans* Korde, 1951.
LSW 103. Local growth in situ of colonies of flat calcareous algal tubes, roofing constructed voids in pseudostromata.
LSW 106. Local growth in situ of calcareous Algae (molds of codiaceans).
LSW 108. Intimate local intergrowth in situ of colonies of calcareous algal tubes and pseudostromata with constructed voids. Some colonies of calcareous algal tubes have grown contrary to gravity over a pseudostromatic body.
LSW 115. Local intergrowth in situ of calcareous Algae, *Ungdarella* sp.; in situ growth of a colony, 1 mm thick and 4 mm long, of prostrate calcareous algal tubes, roofing a constructed void in a pseudostromatic body.
LSW 119. Local intergrowths in situ of platy encrusting calcareous Algae, *Archaeolithophyllum* sp., and colonies of calcareous algal tubes.
LSW 122. In situ growth of platy calcareous Algae (algal molds); in situ growth of both encrusting and erect calcareous Algae, *Archaeolithophyllum* sp., and calcareous Algae *Anthracoporella* sp., which lie flat (Pl. XIV, Figs. 1, 2).
LSW 123. Local growths in situ of calcareous Algae, molds of *Archaeolithophyllum* sp.
LSW 124. Local intergrowths in situ of calcareous Algae, molds of dasycladaceans and *Archaeolithophyllum* sp., surrounded by pseudostromata.
LSW 126. Local growth in situ, contrary to gravity, of calcareous algal tubes embedded in dark pseudostromatic micrite, encrusting a pseudostromatic body.
LSW 127. Dasycladacean Algae which lie flat, surrounded and invaded by pseudostromata in intimate association with calcareous algal tubes; in situ growths of a bryozoan colony and a colony, 2 mm thick and 5 mm long, of tightly packed, criss-cross calcareous algal tubes.
LSW 128. Local growth in situ of flat calcareous algal tubes, embedded in dark pseudostromatic micrite. This in situ growth has the appearance of a laminated algal mat, 1 mm thick and 8 mm long.
LSW 131. Local intergrowths in situ of calcareous Algae, *Dvinella* sp. and *Ungdarella* sp., and colonies of algal tubes, surrounded by pseudostromata; local growths in situ of erect calcareous Algae, *Ungdarella* sp., with pseudostromatic coating and codiaceans.
LSW 137. Local growths in situ of calcareous Algae, algal molds.
LSW 143. Intimate local intergrowth in situ of colonies of calcareous algal tubes and pseudostromata.
LSW 160. Local growths in situ of calcareous Algae.
LSW 172. Local intergrowth in situ of calcareous Algae,

Ungdarella sp., and calcareous algal tubes, surrounded by pseudostromata.
LSW 173. Local intergrowth in situ of calcareous Algae, *Ungdarella* sp.
LSW 174. Local intergrowths in situ of calcareous Algae, algal molds (Pl. XVII, Fig. 8).
LSW 180. In situ growth of a bryozoan colony (Pl. XVIII, Fig. 1).
LSW 184. Local growth in situ of calcareous Algae (algal molds) surrounded by pseudostromata.
LSW 185. Local growths in situ of calcareous Algae (algal molds), some of which can be identified as *Archaeolithophyllum* sp., surrounded by pseudostromata (Pl. XVIII, Figs. 6, 7).
LSW 187. Local intergrowth in situ of calcareous Algae, *Ungdarella* sp. and *Dvinella* sp., surrounded by pseudostromata.
LSW 188. Local intergrowth in situ of calcareous Algae, *Dvinella* sp.
LSW 191. Oncolites formed around fragments of dasycladacean Algae in a crusty flake-like packstone. Formation by accidental overturning is suggested by the clear-cut outline of the oncolites indicating a lack of integration with the matrix. The abraded, somewhat rounded habitat of the other allochems indicates that currents or waves were indeed active (Pl. XIX, Figs. 5, 6).

Relation to underlying and overlying sandstones, sign 9
The relationship between stability of the substrate and in situ growths and local intergrowths in situ is also important for the interpretation of the limestone/sandstone contact.

The limestone samples from the contact with an underlying sandstone generally show that at a given moment the sandstone formed a substrate stable enough to be colonized by Algae. In other words, the currents which initially delivered terrigenous sediment were no longer strong enough to supply sand-sized quartz particles [5]. Occasionally the currents were still able to carry small amounts of sand-sized quartz grains. Together with bioclasts and other allochems, these formed the grains of the lime grainstones. The latter were converted by algal binding to crusty flake-like lime packstones. As a result the substrate became stable and ready for further colonization.

The samples from the contact with an underlying sandstone, which contain an admixture of some quartz grains, are listed below. Since they are all non-intergrowth lime packstones, their textural features and their signs of binding were discussed under sign 6. Here only details of their quartz grain content are given.

LSW 42. Sand-sized quartz grains form a part of the allochems responsible for grain bulk. They form the nucleus of an ooid or have an algal coating.
LSW 56. Sand-sized quartz grains form a part of the allochems responsible for grain bulk. They show all transitions from nude quartz grains through quartz grains with an algal coating to quartz grains as the nucleus of an ooid.
LSW 60. Contains 1% sand-sized quartz grains.
LSW 64. Contains 3 to 4% sand-sized quartz grains.
LSW 71. Contains 1% sand-sized quartz grains.
LSW 182. Contains 5% sand-sized quartz grains.

The samples from the contact with an overlying sandstone suggest that the limestones formed substrates firm enough to resist current and wave activity. Mixture with and gradation to the overlying sandstones do not occur. This means that although the currents were strong enough to carry along sand-sized quartz particles, they had no effect on the substrate. The bottom obviously was not soupy, but instead solid enough to prevent mixing. Yet the limestones forming the substrate have in many cases a mudstone or wackestone texture, in other words they contained a sufficient amount of mud to have been soupy. Therefore something must have happened to these limestones to change them into solid substrates. The cause may be sought in early lithification by temporary subaerial exposure, or in consolidation by algal binding. If other indications for algal binding also exist in these limestones, the latter process most probably caused the consolidation of the substrate. Of course if there are also indications of a subaerial exposure, then both processes might have been at work. In any case the lack of mixture at the contact with an overlying sandstone will support the other indications that the limestone is algal-bound.

On the other hand we may reverse the reasoning and say that this phenomenon is a strong argument for the fact that in general algal binding causes substrates to be firm. As discussed under sign 7, under conditions of current and wave activity, such firm substrates can only be colonized if there is not a large supply of sediment since this would lead to a shifting bottom. Under such conditions, new sediment can only be built by skeletal intergrowth and/or entrapment by plants. The occurrence of limestones with skeletal intergrowth frameworks (a.b. skeletal intergrowth lime packstones) or limestones which might result from entrapment (certain a.b. non-intergrowth lime packstones) and which lie above other algal-bound limestones might be a reflection of these conditions. The lens-like biohermal development of LSW 43—45 (Fig. 4) is tentatively explained in the light of the foregoing. At some locality in an environment of currents carrying sand-sized quartz grains, the bottom was temporarily stable enough to be colonized by Algae, i.e. growth in situ of the calcareous Alga *Archaeolithophyllum* sp., surrounded by colonies of non-calcareous Algae (pseudostromata). Due to this algal growth the temporarily stable condition became fixed and a firm, probably somewhat elevated, platform provided the base for further limestone building; because of the current conditions, this could only be attained by intergrowth of calcareous algal skeletons.

Unfortunately, the contacts with the overlying sand-

[5] Continued strong current activity, without the supply of sand-sized quartz grains, is not likely because this would have led to shifting of the sandy bottom and thus to an unstable substrate. Moreover the generally immature character of the sandstones is also contra-indicative for lasting current activity. Strong wave activity cannot have been present for the same reason.

stones could not always be sampled precisely, due to vegetation and the irregular course of the contact-line. Moreover the overlying sandstones are frequently poorly exposed. Characteristic features of these sandstones, which might also explain the lack of mixing with the underlying limestone, could not be observed. Thus we are left with only five samples, in which the observed lack of mixing with the overlying sandstone is considered reliable enough to conclude that the limestones formed a solid substrate. These samples are:

LSW 21. Algal binding cannot be detected, due to intensive fracturing which obscures the picture. Indications of subaerial exposure have not been observed either, unless the dolomite content of this sample can be explained by the formation of a dolomitic crust (See the section "diagenetic dolomite"). Sample LSW 22, which lies 35 cm below LSW 21, is clearly algal-bound. One is therefore inclined to believe that the solid substrate character of LSW 21 is also due to algal binding.

LSW 33/2 and LSW 34. These samples come from the top of a bioherm, built up of intergrown calcareous Algae, *Archaeolithophyllum missouriensum* Johnson, 1956, which sufficiently explains the solid nature of the substrate.

LSW 62. Algal binding is indicated by pseudostromata with constructed voids, surrounded by solution stringers contrary to gravity. There are no indications of subaerial exposure.

LSW 126. Algal binding is indicated by pseudostromata with constructed voids, overgrown by calcareous algal tubes, contrary to gravity (Pl. XIV, Fig. 4). There are no indications of subaerial exposure.

Finally there are also samples that do show mixing with the overlying sandstones.

LSW 28. This sample represents the upper 10 cm of a limestone under an overlying 16 m thick sandstone. The latter is covered with vegetation and contains laterally limestone lenses. The contact-line sandstone/limestone is very irregular. Only 3% of the allochems of this sample are sand-sized quartz grains. Often these quartz grains form the nucleus of an ooid.

The texture of this a.b. non-intergrowth packstone has been discussed under sign 6. Indications of algal binding are found in its resemblance to recent recrystallized crusty flakes. Interpretation of this sample can best be made together with samples LSW 29 and 30, from 20 and 30 cm beneath the sandstone/limestone contact, respectively. LSW 30 shows pseudostromatic algal binding. LSW 29 shows local intergrowths of encrusting calcareous algal plates, *Archaeolithophyllum* sp., surrounded by mechanically deposited micrite with fragments of Algae and two or three ooids with a quartz grain nucleus, in a packstone texture indicating compaction of a wackestone (Pl. I, Fig. 7). The packstone parts are encrusted and bound by offshoots of the local *Archaeolithophyllum intergrowths.* A slowly increasing current velocity for the sequence of these samples is suggested. The first indication of increasing current velocity is the appearance of a few quartz grains as nuclei of ooids. Under these conditions limestone is built by encrusting and intergrowing Algae. The presence of large amounts of mechanically deposited lime mud, originally in a wackestone texture, is somewhat contradictory but the encrusting Algae may have trapped it and thus prevented it from winnowing.

Increased current velocity during deposition of LSW 28 delivered numerous bioclasts (echinoderms) and ooids and a smaller number of sand-sized quartz grains. The abundance of shifting allochems (ooids!) formed an obstacle for further growth of the calcareous Algae. During a temporary subaerial exposure invasion and binding by Algae finally stabilized the shifting substrate. The abundance of these binding non-calcareous Algae is proven by the algal coating and micritization of the echinoderms, the algal coating of even the ooids and the patchy precipitation of micrite in the inter-allochem pores. Temporary subaerial exposure is further indicated by the recrystallization of the micrite and parts of the allochems, which suggests a recrystallization as in recent crusty flakes due to rather frequent exposure to rain. The stabilization and consolidation by algal binding explains why at the contact with an overlying sandstone, the sand-sized quartz grains make up only 3% of the volume of a lime packstone.

LSW 37. A sample representative for the entire 2 m thick sandy limestone bed of this locality. Sand-sized quartz grains make up 30% of the volume. Locally they are present in such large concentrations that they form calcareous sandstone patches. This sample represents a zone of transition between quartz sandstone deposition and carbonate deposition. From the latter, fragmented skeletons of crinoids, calcareous Algae and gastropods have been transported to and deposited in this transitional zone. The only organisms able to colonize the shifting sands at the bottom seem to have been the non-calcareous Algae, that grew upon and around the allochems causing algal coating and micritization. Perhaps the formation of ooids around the sand-sized quartz grains was also induced by algal activity. The large supply of sand-sized quartz grains neatly filled the interstices between the generally larger bioclasts and ooids. Thus not much space was left for eventual algal invasion. In fact, the remaining small inter-allochem pores were filled by algal micrite, but consolidation by a coherent organic algal framework was not attained. Mixing of quartz sand and carbonate material went on, unhindered by consolidation of the substrate. Finally the supply of sand-sized quartz grains was so large that even the neighboring environment of carbonate deposition was eliminated and the limestones were buried under a quartz sandstone. The weight of this overburden caused compaction in the sandy limestone since the grain-support was not sustained by the support of an algal framework reinforced by precipitation of carbonate as in the case of the crusty flakes. A remarkable honeycomb mosaic of ooids resulted from pressure solution at their contacts (Pl. II, Fig. 7).

LSW 183. This is a clayey lime packstone which contains 7 volume percent sand-sized quartz grains. The environmental conditions are comparable to those of LSW 37 except that the currents in this case did not deliver much sand-sized quartz grains but silt and clay in quantities enough to stop most algal activities.

ALLOCHEMS

In his classification scheme, Folk (1959, 1962) distinguished four allochem types: intraclasts, ooids (Folk, oolites), pellets and fossils (bioclasts). In the description of the algal limestones of the Lois-Ciguera Formation, section LSW, the identification of two other allochem types, algal grains and algal pellets, appear to be useful. The algal grains and algal pellets are defined by Wolf (1965, p. 14), but some additional data are given below in the detailed description of the allochems.

The allochems responsible for grain bulk, indicated in the grain column of the appendix, are listed in

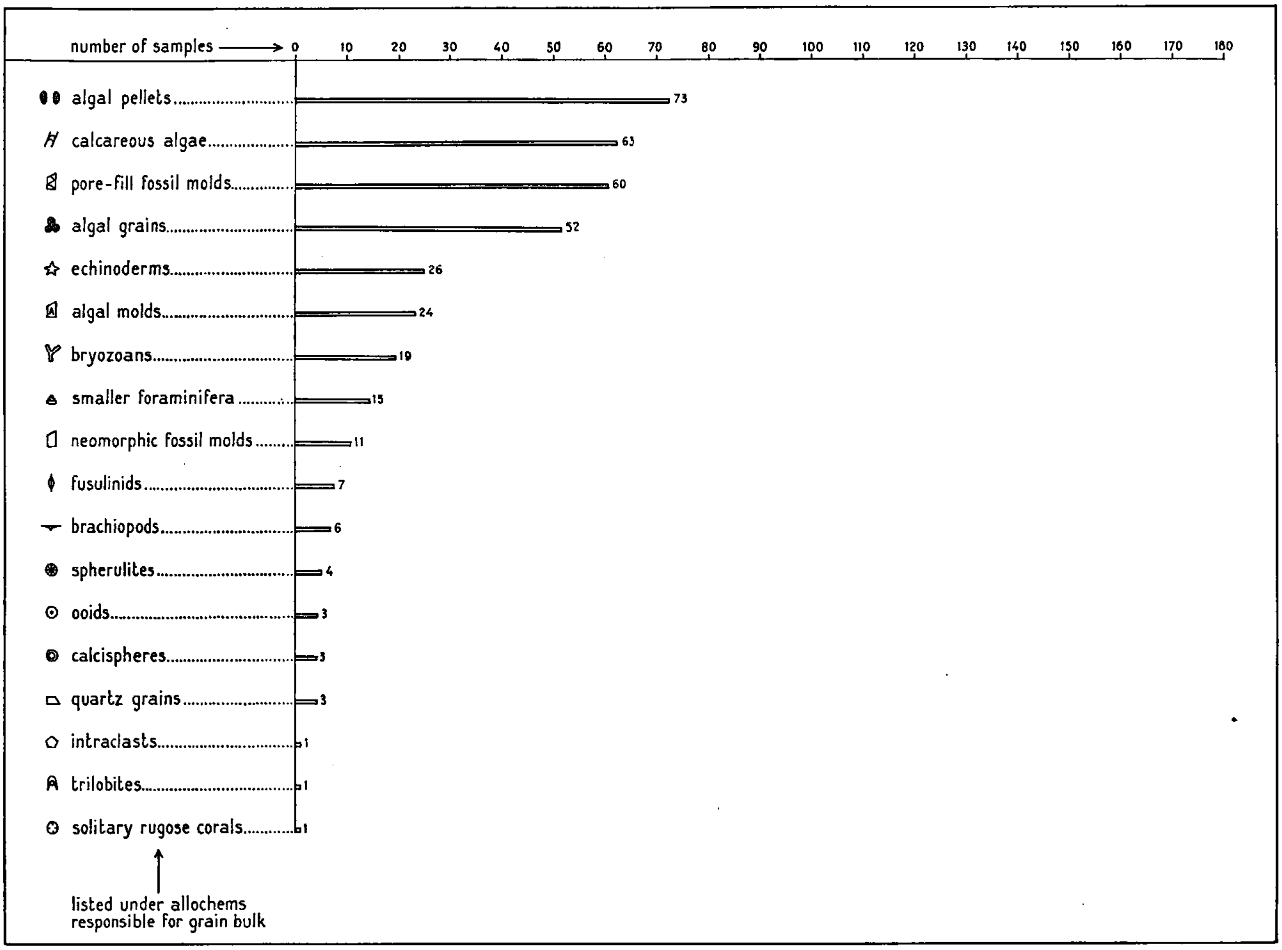

Fig. 5. The allochems responsible for grain bulk listed in order of their frequency

Fig. 5 in order of their frequency. Algal pellets, calcareous Algae, non-algal pore-fill fossil molds and algal grains are obviously the most important allochems. For Fig. 6 the number of samples containing at least one of these four allochems has been calculated. This illustrates their frequency in another way: thirty samples contain none at all, but all other samples include at least one or more of the four most important allochems.

The fact that three of the four most important allochems are algal products shows how influential the Algae were. If we calculate the number of samples containing at least one of the four algal products (Fig. 6, second line), their importance emerges still more clearly.

The four most important allochems can occur in the grain column in six combinations of two: algal pellets/algal grains, algal pellets/pore-fill fossil molds, algal pellets/calcareous Algae, algal grains/pore-fill fossil molds, algal grains/calcareous Algae, and pore-fill fossil molds/calcareous Algae. The frequency of these combinations is also given in Fig. 6. In the calculations, the algal molds have been added to the calcareous Algae, since they differ from the latter only in condition of preservation. Fig. 6 suggests that combinations of allochems with a genetic relationship – algal pellets/algal grains and calcareous Algae/algal pellets – (see description of allochems below) are more frequent than other combinations. If this higher frequency is indeed a measure of the genetic relationship between the partners of a combination, then one might also conclude from Fig. 6 that algal pellets are more closely related genetically to the calcareous Algae than algal grains. In Fig. 7 it is shown that the relationship between calcareous Algae, algal grains and algal pellets is one of abrasion, micritization and distintegration of the algal skeletons. Therefore the above-mentioned conclusion is probably incorrect and it is more likely that the difference in frequency is due to a difference in grain size. The grain size of algal grains (coarse calcarenite to calcirudite) is such that original structures are more easily recognized in abrasion and disintegration products than at the grain size of algal pellets. Therefore calcareous Algae-clasts of algal grain size have a greater chance of being identified and counted as calcareous Algae than those of algal pellet size. The same fact partly explains the higher frequency of algal pellets (Fig. 5) compared with algal grains.

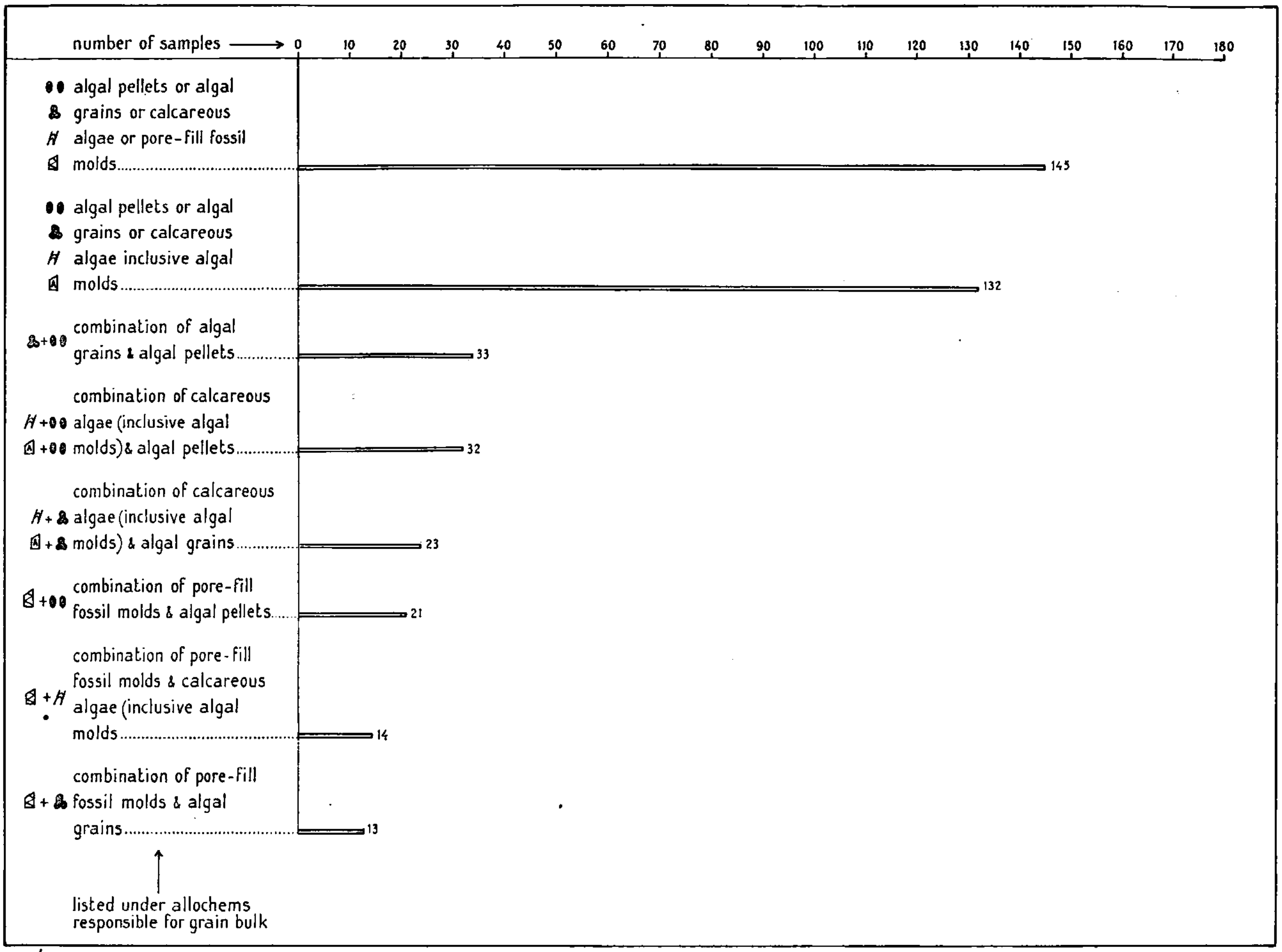

Fig. 6. Frequency of the four most important allochems

On the other hand the greater diversity in modes of formation and thus the greater probability of production of algal pellets (Fig. 7) will also influence these results.

Algal pellets

Wolf (1965, p. 141) describes algal pellets as:

"... angular to round detrital particles composed of biogenic algal calcilutite, which is mainly dense or grumous, and possibly some algal-bound fine debris (fig. 22, 23). Their diameter is up to 1,5–2 mm. Table III illustrates that algal pellets can be formed from any primary algal calcilutite growth directly or through an intermediate "algal grain" stage".

To this definition the following can be added. Algal pellets differ from the pellets defined by Folk (1959, 1962) in:

1. shape: the outline is neither as uniform nor as clearly defined and therefore is not necessarily spherical, elliptical or ovoid,
2. size: they display greater diversity in size varying from mud size to 2 mm,
3. composition: although usually lacking any internal structure, this need not necessarily be so since occasionally algal-bound fine debris is observed within the algal pellets (Pl. VIII, Fig. 1),
4. origin: Folk considers the pellets he defined as probably invertebrate fecal pellets, whereas algal pellets owe their existence to the activity of Algae. Variety in algal pellets reflects their diverse origins.

Wolf (1965, p. 137, table III) gives a summary of the various origins of algal pellets. The present writer agrees with this summary, although in his opinion Wolf's table is not quite complete. It shows algal pellets as products of abrasion, disintegration and algal corrosion (boring and micritization) of algal biogenic forms. Since the papers by Monty on recent algal mats from the Bahamas, we know that algal pellets can also be formed by direct precipitation. To quote Monty (1967, p. 73):

"cryptocrystalline particles ranging from a few tens of microns to one or two mm in diameter are frequently found in the mats. They result from in situ calcification of unicells or colonies of unicells, most of the time *Entophysalis deusta*. Calcified unicells appear as small spheres of dense, cryptocrystalline calcite".

Folk (1962, p. 65) in passing indicates the possible existence of pellets, other than fecal pellets:

"it is possible that some pellet-appearing objects may form by recrystallization processes, a sort of auto-agglutination of once homogeneous calcareous mud; of such nature may be the "grumuleuse" structure of Cayeux (1935, p. 271)".

Monty (1967, p. 74) gives an example of a recent formation of this structure [6]:

"Clotty structure of the carbonate is well known from fossil stromatolites and has originated the name "Spongiostromata". A similar clotty structure is well exposed in modern supratidal mats and results from various processes.
a – The erratic precipitation of fine-grained carbonate around and (or) in loose mucilaginous masses of unicells, diatoms or yet bacteria belonging to calcified as well as old hyaline [7] layers, originates flocs. Similarly bacteria fungi or yet parasitic *Schizothrix* may originate the precipitation of clots in the mucilaginous material enveloping coarser filaments of *Scytonema* or *Lyngbya*.
b – In the deeper layers of the mats, calcified filaments of *Scytonema* – composed of very fine-grained calcite – become extremely fragmented as a result of the collapse of the organic framework; this breakdown originates minute fragments of tubes forming as many denser clots in the somewhat coarser limy matrix of the calcified layers. Ageing and compaction of mats resulting from successive desiccations reduce the thickness of the individual laminae in the older parts of the structure. Generally the hyaline layers are converted to brownish organic streaks separating clotty calcareous layers where fragments of calcified tubes as well as small spheres and pellets can be found here and there. This is a well kown design in the fossil record".

We see that process (b) is one of disintegration, a

[6] The term structure has been used here, because both Folk and Monty use this term. However the present writer thinks that use of the term texture would be more correct.

[7] Non-calcified, organic layers – author's note.

FORMATION OF ALGAL GRAINS AND ALGAL PELLETS

unicellular algae —— 1 ——→ algal pellets
colonies of unicellular algae —— 1 ——→ algal grains —— 4 ——→ algal pellets
one or more allochems, bound and/or coated by filamentous and/or unicellular algae —— 1+2 ——→ algal grains —— 4 ——→ algal pellets
around or in loose mucilaginous masses of unicellular algae, diatoms or bacteria, belonging to calcified or old hyaline layers of algal mats, inclusive pseudostromata * —— 1 ——→ algal pellets, forming grumous texture
around mucilaginous masses of coarser filaments in algal mats —— 1 ——→ algal pellets, forming grumous texture
calcified filaments in algal mats —— 3 ——→ algal pellets, forming grumous texture
—— 1 ——→ stromatolites —— 4 ——→ algal grains —— 4 ——→ algal pellets
—— 1 ——→ algal mats, incl. pseudostr. —— 4 ——→ algal grains —— 4 ——→ algal pellets
—— 1 ——→ algal coatings —— 4 ——→ algal grains —— 4 ——→ algal pellets
—— 1 ——→ stem- and branch fragments of calcareous algae —— 2+4 ——→ algal grains —— 4 ——→ algal pellets
—— 1 ——→ oncolites —— 4 ——→ algal grains —— 4 ——→ algal pellets

1 algal precipitation of fine-grained calcium carbonate
2 boring and micritization
3 fragmentation in situ by shrinkage and compaction, caused by periodic desiccation
4 abrasion and disintegration

* pseudostromata lack clear layers, but the process of algal pellet formation is the same

Fig. 7. Formation of algal grains and algal pellets (modified after Wolf, 1965)

process also mentioned by Wolf. Another process mentioned by Wolf, algal corrosion, has also been found by Monty (1967, p. 83) to be active today as a producer of algal pellets:

"The skeletal grains within the lumps become completely unrecognizable because of algal boring and appear as cryptocrystalline pellets, easily mistaken for "pellets" resulting from calcification of gelatinous masses of unicells".

In conclusion we may state that algal pellets are the products of abrasion, disintegration, algal corrosion (micritization: see the section "neomorphic calcite") and algal carbonate precipitation. These several modes of formation, together with those of the algal grains, have been summarized and illustrated in Fig. 7, which is an extension of Wolf's table (1965).

Algal grains (Pl. XIV, Figs. 5, 6; Pl. XVII, Figs. 2, 3, 4)
Algal grains show only gradational differences with algal pellets. Generally they are larger than algal pellets (coarse calcarenite to calcirudite size), but they sometimes also overlap in size. The main difference with algal pellets is that there is more internal structure: grumous-pelletous pseudostromatic, occasionally with algal-bound, micritized debris and/or algal cells and filaments. They differ in origin from intraclasts and consequently contain algal structures which make such an interpretation possible. The latter depends on the personal experience of the investigator. Folk (1962, p. 63) for instance considers the "grapestone" aggregates of Illing (1954) intraclasts, whereas Monty (1967, p. 83), quoted below, points out that there is a close resemblance between these aggregates and his algal particles. He concludes that the first were probably also formed by algal binding and algal carbonate precipitation, rather than mere physical conditions such as sub-marine erosion, turbulence and sorting. Therefore it is possible that some of the allochems identified as algal grains in this paper would be called intraclasts by others. In the writer's opinion, however, there is ample evidence of algal structures and the reader is invited to check this in the relevant photographs of this thesis.

The discussion on the origin of algal pellets in general also applies for the formation of algal grains. Examples of recent algal grain formation by carbonate precipitation are again given by Monty (1967, p. 73):

"Calcified unicells appear as small spheres [8] of dense cryptocrystalline calcite whereas calcified colonies are larger particles [9] showing generally a large core of dead cells loaded with cryptocrystalline calcite, surrounded by a thin peripheral layer of living cells".

Later on the same page he continues:

"The eventual formation of subspherical to ovoid particles within mats must be kept in mind interpreting fossil stromatolites; it shows that all the grains found within fossil mats are not necessarily detrital entrapped material as was previously supposed".

On pages 82 and 83 Monty (1967) describes algal particles, called algal grains here:

"Algal particles are also variously differentiated. Some are platy or globulous lumps 100 microns to 1.5 cm in size composed of substratal sand grains and fragments of mangrovian shells bound by solid bundles of *Schizothrix.* They are furthermore coated by a dense brownish cover of unicells, or by a gelatinous envelope of *Schizothrix,* or yet by *Scytonema* which stretches parallel or twisted filaments around the lumps (in a way very reminiscent of coatings by *Girvanella* or *Osagia* in the fossil record). The skeletal grains within the lumps become completely unrecognizable because of algal boring and appear as cryptocrystalline pellets easily mistaken for "pellets" resulting from the calcification of gelatinous masses of unicells. Another type of globulous algal particles, up to 1 cm in size, comprises very loose growths of *Scytonema crustaceum* pervaded by *Schizothrix calcicola* with, here and there, a colony of *Entophysalis deusta*; some grains [10] are eventually bound and fine-grained carbonate is irregularly precipitated forming dense patches in the older portions and flocs in the newer often peripheral ones".

Finally Monty (1967, p. 83) makes some interesting remarks, previously referred to in the beginning of this section:

1–many of the algal particles and crusty flakes previously described would be interpreted in the fossil record as "algal fragments" (Phytoclasts, Monty, 1963), as intraclasts or yet as inorganic lumps (case of the crusty flakes, where *Schizothrix* does not calcify its filaments and is not preserved). In fact these particles are either young mats (crusty flakes, platy *Scytonema* mats) or particular globular colonies (algal lumps) . . .
2–Many of these algal particles are very reminiscent of lumps s.l. formerly described by Illing (1954) and Purdy (1963 a, b); for instance Purdy's organic aggregates (1963, a, Pls 3A, B, C, D) may be compared with the loose algal lumps (pl 14–1) whereas much of his marine grapestone structures is similar to the globose and platy algal lumps from flats of tidal ponds (pl 14–2, 3, 4). In fact Illing (1954) and Purdy (1963) have recognized the presence of algal material in their lumps and grapestones but Purdy interprets the organic material and part of the silty and clayey carbonate as detrital material that settles out of the water to accumulate between the grains. The informations too briefly reported in this paper indicate on the contrary that the organic material is not detrital but proceeds from the algal unicells and filaments that invade, bind and agglutinate the grains into a lump, whereas fine-grained carbonate is precipitated *in situ* for the most part. Furthermore, and provided the comparison of Purdy's and Illing's lumps, grapestones and limestone-flakes with the ones here reported is valid, the areas where these particles occur would not solely depend on plain physical conditions (turbulence, sorting etc.) but also and before all, on biological and ecological factors affecting algal growth".

[8] Algal pellets – author's note.
[9] Algal grains – author's note.

[10] "Foreign" admixture of detrital allochems – author's note.

Summarizing we may state, as in the case of the algal pellets, that algal grains are formed as products of abrasion, disintegration, algal corrosion and algal binding with carbonate precipitation; these processes have been schematically illustrated in Fig. 7.

Algal-coated allochems

Many allochems show algal coating and micritization to some degree, but are still easily identified. A more advanced stage of this process of algal coating and micritization results in complete loss of the skeletal microstructure, and consequently the bioclasts are identified as algal grains or as algal pellets. Generally the volume of the algal coating is small compared to the volume of the allochem but there are cases in which the algal coating has grown out of proportion. Such coatings are described as pseudostromatic algal coatings, or oncolites when some concentric lamination is present (see the section "in situ growths and local intergrowths in situ"). The algal coating generally consists of dark algal micrite with calcareous algal tubes or molds of algal tubes. Sometimes there are only calcareous algal tubes. Frequently an allochem with algal coating also shows an overgrowth of encrusting Foraminifera.

Monocrystalline overgrowths on skeletons, such as frequently noted on echinoderms (see the section "pore-filling calcite"), appear to be effectively impeded when algal coatings are present. Sometimes however when the algal coating is relatively thin, its effect is negligible and it is incorporated in the overgrowth. Occasionally the algal coating on a skeleton is locally interrupted; it is then possible that a monocrystalline overgrowth will develop there and fill a neighboring pore-space. In this way a thicker algal coating can also be included in a monocrystal (Pl. XVII, Figs. 5, 6, 7). The effects of these inclusions in macro-crystalline calcite will be discussed in the section "neomorphic calcite".

For the algal-coated allochems to be listed in the grain column of the appendix the criterium was that the majority of allochems in the sample should be algal-coated. In other words, algal-coated allochems are much more frequent than would appear from the grain column.

Calcareous Algae and algal molds

Rhodophyceans (incertae sedis), chlorophyceans (codiaceans, dasycladaceans) and cyanophyceans are all present in large quantities.

In the lower part of the section, there is an abundance of the rhodophycean (incertae sedis) *Ungdarella* sp. and the dasycladacean *Dvinella* sp.; in the middle part of the section, the rhodophycean (incertae sedis) *Komia abundans* Korde, 1951, is a credit to its name; and in the upper part, the rhodophycean (incertae sedis) *Archaeolithophyllum missouriensum* Johnson, 1956, the dasycladacean *Anthracoporella* sp. and codiaceans resembling *Eugonophyllum* sp., *Anchicodium* sp. and *Ivanovia* sp. are numerous. The cyanophyceans are thought to have contributed to the formation of pseudostromata, algal grains, algal pellets and algal coatings, which are all abundant throughout the entire section.

The conditions of preservation of the calcareous Algae vary. In the grain column, a distinction has been made between calcareous Algae and algal molds. This distinction is not sharp since the criterium is the general impression: a patch of calcite crystals with the outline of an Alga and/or sparse relicts of an algal structure is identified as an algal mold, whereas an Alga with neomorphic patches or partly dissolved patches, filled with calcite, is identified as a calcareous Alga.

Algal molds originate in several ways:

1. By dissolution of the algal skeleton and subsequent filling with calcite, so that only the outline of the Alga is preserved (Pl. III, Fig. 2). However the outer edge of an Alga frequently shows micritization. It appears that the micritized parts are less easily affected by dissolution. As a result the algal pore-fill mold is frequently rimmed with relicts of the algal structure. The latter, although heavily attacked by micritization, sometimes permits a more precise identification of the Alga. Codiaceans for instance are frequently preserved as pore-fill molds of this type.
2. By aggrading neomorphism of the algal skeleton. The neomorphic crystals enclose sparse relicts of the algal structure. This kind of preservation is frequently observed for the rhodophycean Alga (incertae sedis) *Archaeolithophyllum* sp.
3. By heavy micrization of the algal skeleton. A patch of dense algal micrite develops with the outline of a calcareous Alga and with very sparse relicts of the original algal structure. Yet the resemblance with the original Alga is too obvious to identify it as an algal grain, especially when there is evidence of in situ growth or intergrowth in situ (Pl. III, Fig. 2).
4. By a combination of heavy micritization and subsequent recrystallization of an algal skeleton. The result is a patch of neomorphic calcite (neomorphic micrite and pseudospar) with relicts of micrite and the outline of a calcareous Alga.

Although we see that algal molds can be divided into algal pore-fill molds (1) and algal neomorphic molds (2, 3, 4), this has not been done to avoid confusion of the symbols in the grain column.

Non-algal fossil molds

Patches of calcite crystals with outlines suggesting their original bioclastic nature are very frequent in the LSW limestones. In the determination of the depositional texture of a sample, i.e. whether a sample is grain-supported or mud-supported, the fossil molds are counted with the grains. In the fore-going section, the algal molds have already been discussed.

The remaining non-algal fossil molds can be split up into neomorphic molds and pore-fill molds. Pore-fill molds are pores created by selective dissolution of bioclasts, filled with calcite. Neomorphic molds are patches of neomorphic calcite with relicts of the microstructure of the original bioclasts. For pore-fill molds, only the outline might eventually reveal the nature of the original bioclast, whereas for neomorphic molds the relicts of the microstructure can also give additional information. The identification of crystalline patches as fossil molds is sometimes made easier by the presence of algal coatings or encrusting Foraminifera indicating the original bioclastic character of the patch of calcite crystals.

Echinoderms

Echinoderms occur as fragments varying in size from very fine calcilutite to fine calcirudite. They are especially common in the lower part of the section. In many samples they are associated with bryozoans, smaller Foraminifera and brachiopods. A more precise differentiation of the echinoderms into crinoids and echinoids is possible in many instances. The fragments of the crinoids are stem fragments. Among the echinoid remains, both spine fragments and plates with tubercles (Pl. XVIII, Figs. 4, 5) have been observed.

The specific microstructure of the echinoderms indicates many different conditions of preservation. The single crystal habit has almost always been preserved, even in cases of silicification or heavy micritization. In one sample, a mechanically deposited wackestone, the single crystal habit has changed into a two-crystal habit by compaction pressure and consequent microfracturing, which resulted in a slight deviation of orientation of the two parts of the seemingly unbroken fragment (Pl. XIII, Fig. 1). Another echinoderm fragment, when observed under parallel light, seems to be a normal unit without any sign of the conjunction of several plates. Under crossed nicols, however, it appears to consist of five single crystals (Pl. VIII, Fig. 8). There is no evidence of pressure so that the previously mentioned possibility of the conjunction of several plates might still be the explanation. The reticulate aspect, caused by the original porosity of the echinodermal skeleton, generally remains recognizable in spite of many changes. When the pores filled with calcite syntaxial with the skeletal monocrystal, they remained visible as relicts because of the impurities which originally lined these openings. Even when an echinoderm fragment developed into a calcite crystal with calcite cleavage the impure linings of the pores remained visible. When the pores filled with dark algal micrite, the resulting contrast is even greater than in the original state unless the contrast decreased due to micritization of the skeleton around the pores.

Bryozoans

Bryozoans are found as complete, unfragmented colonies and as fragments. Fenestellid forms are numerous. The bryozoan colonies in situ are frequently associated with Algae. However when fragments of bryozoans are present in quantities responsible for grain bulk, they are almost always associated with crinoid fragments (Pl. XVIII, Fig. 2).

Smaller Foraminifera

All non-fusilinid Foraminifera are included in this group. This division has been made because of the great stratigraphic value of the fusulinids and the general contrast in size between representatives of these two groups. In the LSW limestone, neither a cyclic alternation nor any kind of division into beds containing predominantly larger Foraminifera (fusulinids) and beds with predominantly smaller Foraminifera, as in the Moscovian of the Moscow Basin (Rauser Chernousova, 1953, in Pokorny, 1958), were found. In many samples the smaller and larger Foraminifera occur together and both groups are usually associated with Algae or algal products. There are no indications of specific associations for different depths.

The group of smaller Foraminifera has no particular systematic value. It comprises several taxonomic units such as the Ammodiscidae, Endothyridae, Textulariidae and Tetrataxidae.

Fusulinids

Usually only random sections through individual specimens of these Foraminifera are available. As a consequence identification is possible only down to the generic level. For a biostratigraphic zonation of the section however, this suffices if they are studied together with genera and species of the calcareous Algae.

Brachiopods

Both complete shells and single valves of brachiopods are present. Their size is generally small, on the order of five mm, perhaps because many of them are juvenile forms. Probably for the same reason the microstructure of the shell is not always clear. Both lamellar microstructures and punctate prismatic microstructures have been observed. In the thicker anterior part of the brachiopods with prismatic microstructures, a transition is sometimes visible between a thin outer zone of posteriorly inclined fibrous prisms and a thick inner zone of prisms oriented perpendicular to the shell surface. The transition is gradual.

For some brachiopods with a prismatic microstructure, a recrystallization to perpendicular orientation is suggested. Some intra-brachiopod pores are partly filled with a bladed overgrowth, composed of crystals perpendicular to the inner shell surface. In transverse sections through these brachiopods, where the prisms of the skeletal microstructure form a mosaic of rhombohedra, this pattern is repeated by the cleavage lines of the bladed crystals of the overgrowth; one is therefore tempted to assume that the crystal boundaries of the prisms, in perpendicular orientation in the overgrowth, continue into the shell (Pl. XII, Figs. 3, 4).

Spherulites

The bodies in the LSW samples designated as spherulites are brown to yellow spheres with a radial fibrous aspect. The spherulites vary in size from 50 to 250 microns. Their outline is perfectly circular, and if not, there is evidence of neomorphism, replacement or pressure solution.

The radial fibrous aspect is caused by extremely fine fibres, less than one micron thick. Examined under crossed nicols, the picture of extinction is comparable to that of very fine micrite. The extinction effect of one fibre is destroyed by the fibres below and the result is that no clear extinction of the spherulite can be observed. Yet some extinction is generally observed because of neomorphism, which is always present to some degree (Fig. 8). The neomorphism tends to start from the center of the sphere. Many spherulites with one crystal in the center have been observed. This crystal may grow radially towards the margin by replacement of the fibres until it finally occupies the entire sphere [11] (Pl. IX, Fig. 4). Intermediate stages

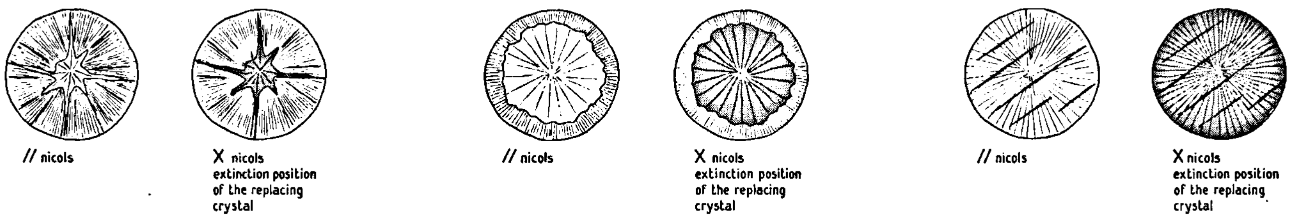

Fig. 8. Spherulites, different stages of neomorphism

have been observed in those spherulites which, under crossed nicols, show an extinction "cross" in one position only: the position of extinction of the central crystal. Another intermediate stage shows a concentric outer zone, which is not yet neomorphic and does not show extinction. The fact that neomorphism also may follow a concentric zone is probably due to the original presence of concentric zones. This is equally suggested by the occurrence of faint, dark concentric rings in some spherulites which are only slightly neomorphic. Neomorphism also follows totally different patterns. There are for instance neomorphic spherulites with two or three crystals or with a radially arranged aggregate of fibrous crystals, each fibre clearly showing extinction. In all instances however the delicate original fibres have been preserved as relicts. There is only one sample, LSW 84, containing spheres which closely resemble spherulites in outline and size, but where the original radial fibres have not been preserved. The crystals in these spheres are therefore [12] thought to be pore-filling and the spheres are represented in the grain column as pore-fill molds and not as spherulites (Pl. VIII, Fig. 7).

The nature of the spherulites is not clear, but can be defined more precisely. The spherulites differ from neomorphic ooids in (1) the absence of a detrital nucleus and (2) the radial fibrous appearance which for spherulites is delicate and gives the impression of being a primary feature whereas for the neomorphic ooid, it is coarser and indicates a secondary feature. The spherulites differ from authigenic aggregates of radially arranged fibrous crystals – the spherulitic neomorphic calcite type of Folk (1965) – by those features which clearly show their allochem nature: (1) their distinct circular outline, (2) the presence of an algal coating for some of them. In some samples, e.g. LSW 84 [13], 87 and 89, cylindrical sections occur with comparable diameter and the same fibrous appearance. Misík (1968) gives an example of a codiacean Alga from the Maastrichtian, *Microcodium elegans* Glück, 1912, which has a spherulitic appearance in cross section, but can be identified by the presence of longitudinal cylindrical sections. Perhaps the spherulites of the LSW section should also be classified as codiacean Algae. The only objection here is the fact that there are always more cross sections than longitudinal sections, whereas there are no indications of allochem alignment by currents.

Ooids

Ooids are found in the upper part of the LSW section. They are neomorphic spherulitic with relicts of concentric lamination. Quartz grains and bioclasts form the nuclei of the ooids. They are thought to have been formed by algal coating in combination with regular overturning. Their association with algal-coated allochems, which lack a regular concentric lamination, is indicative of such an origin. From the shape and the size of the allochems, it is clear that regular overturning was not as easy for these allochems as for the small and more or less spherical nuclei of the ooids.

Calcispheres

In almost all LSW samples a number of calcispheres are present, but only in three samples are they so abundant that they form a part of the allochems responsible for grain bulk. The calcispheres, varying from ca. 25 to 200 microns in size, generally have a relatively thick wall on the order of magnitude of 10 to 50 microns. Most walls are circular in outline and enclose a central part, which is usually filled with clear calcite.

The microstructure of the wall is either microgranular with a radial arrangement of dark rods, pores or canals, or dense and homogeneous micro-

[11] One case is known where the monocrystal of calcite has been syntaxially replaced by quartz.

[12] An arrangement according to the "Bathurst Law" is not always apparent, as there are also spheres with two or three big crystals or sometimes even with one big crystal. Total obliteration of the original fibres by neomorphism might also be possible, but why only in this sample? (see note 13).

[13] It is remarkable that in sample LSW 84, where the fibrous aspect in the spheres is lacking, it is present in some cylindrical, longitudinal sections.

granular[14] sometimes with an arrangement of two or more concentric layers of different opacity. According to Cayeux (1935, p. 90), who described calcispheres with both dense and porous walls, the perforation is an original feature and its preservation depends upon the mode of fossilization. In his opinion this indicates that the organization of the calcispheres is similar to that of the siphonaceous green Algae, and he concludes that the calcispheres are microscopically small, unicellular dasycladaceans. However the unit of organization of the siphonaceous green Algae is a multicellular vesicle or tube. This tube corresponds to the so-called central stem of the dasycladaceans. According to Bold (Alexopoulos and Bold, 1967) the tube, usually multinucleate, is interpreted by some as a multinucleate or coenocytic cell and by others as acellular. It is evident that an unicellular Alga cannot have a siphonaceous type of organization. Therefore the present writer believes that Cayeux saw the calcispheres as microscopically small, spherical coenocytic cells with the dasycladacean type of branching which, as a result of the mode of calcification and preservation of the branches, may have a porous appearance.

In the opinion of the present writer, the calcispheres may also have originated by the calcification of true unicellular Algae. Some special requirements however have to be met in order to achieve conversion into calcisphere-like particles. From the observations of Monty (1967) on recent algal mats from the Andros Island, we know that unicellular blue-green Algae upon calcification convert into dense micritic algal pellets. A similar process has been observed by the present author for blue-green unicells in a recent algal mat from Curaçao (Netherlands Antilles). Only empty unicells can convert into calcified spheres with a clear calcite filling. Empty unicells may have formed as a result of damage to the cell wall or, as in the case of unicellular green Algae, by liberation of zoospores or germination of a zygote. In fact, openings or interruptions in the walls of some calcispheres have been observed. In the case of derivation of the calcispheres from unicellular Algae, differences in the wall structure can be explained by original differences in the walls of the unicells. Among zygotes of the unicellular green Algae, for instance, forms are known with spiny walls. Similar forms, upon calcification and subsequent fossilization into calcispheres, might have been responsible for the porous appearance of the latter.

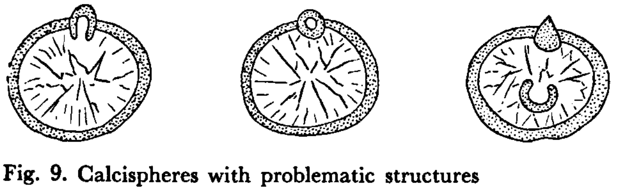

Fig. 9. Calcispheres with problematic structures

[14] Comparable to the microgranular microstructure of the porcellaneous walls of fusulinid and alveolinid Foraminifera.

Without arriving at a definite conclusion about the origin of the diverse kinds of spheres grouped under the general heading of calcispheres, it can be stated that an algal origin is possible for many of them. For the others, a different origin cannot be excluded since they deviate from the above in that their walls are interrupted by small problematic structures, as illustrated in Fig. 9.

Quartz grains

Of all LSW samples only ten contain sand-sized quartz grains; in only three samples do the sand-sized quartz grains form a part of the allochems responsible for grain bulk. The sand-sized quartz grains are sub-rounded to sub-angular. Most of them have an algal coating or form the nucleus of an ooid. The algal coating was not without effect and in many sand-sized quartz grains algal micrite projections towards the center have been observed.

The scarcity of sand-sized quartz grains contrasts directly with the abundance of silt-sized idiomorphic quartz crystals. Many of them possibly originated by authigenic growth around a clay-sized or silt-sized detrital quartz grain. More information about this subject is given in the section "silicification".

Intraclasts

There is only one sample containing allochems which can be called intraclasts. The intraclast-like allochems of all other samples have been interpreted as algal grains (see the section "algal grains"). Even the few intraclasts of the solitary sample, LSW 150 (Pl. XV, Figs. 7, 8), do not completely conform to the definition of Folk (1962, p. 64), because they are angular fragments of previously lithified rock. It can, however, be shown that they satisfy the main criteria for Folk's intraclasts since they are: 1. contemporary or penecontemporary with the sediment in which they are incorporated, and 2. derived from intrabasinal sediments.

In particular, (1) or the contemporaneity is proven by the fact that the genera and species of the calcareous Algae and fusulinids in the intraclasts are similar to those from the overlying and underlying samples, LSW 149 and LSW 151. The rock which is the source of the intraclasts is therefore approximately as old as the rock in which the intraclasts are incorporated.

Concerning (2) or the intrabasinal origin, the following can be stated: the source of the intraclasts is an algal-bound *Dvinella* and *Ungdarella* lime packstone with neomorphism of the allochems and the micrite matrix. The depositional and diagenetic textures of this lime packstone suggest a formation comparable to that of recent crusty flakes (Monty, 1967). Many algal-bound packstones with similar textures are present in the LSW section. This fact, together with the above-mentioned agreement in age, indicates an intrabasinal formation. On page 10 it was suggested that it is also possible that the packstone texture is comparable to that of the overlying LSW 149 and LSW 148 intergrowth packstones. In this case an intrabasinal formation would be obvious. However the intergrowth framework texture cannot be identified with certainty because of the relatively small dimensions of the intraclasts.

The lithified condition of the rock that produced the intraclasts is deduced from the angularity of the intraclasts and from the fact that the intraclasts are neomorphic whereas the surrounding micrite, in which they are embedded, is not. A crusty flake as well as an algal-bound intergrowth packstone as source rock readily explains this early lithification.

Trilobites and corals
Trilobites and corals are rare in the LSW limestones. Occasionally isolated fragments of trilobites and unfragmented specimens of solitary rugose corals were observed.

Gastropods, pelecypods, ostracods and sponges (Pl. I, Fig. 6; Pl. II, Fig. 2; Pl. IV, Figs. 5, 6; Pl. V, Figs. 1, 2; Pl. XVI, Figs. 7,8)
Although these organisms are present in many samples, they only occur in small quanties and never form a part of the allochems responsible for grain bulk. Both bivalved, unfragmented ostracods and isolated valves are present. The gastropods are generally seen as unfragmented specimens, whereas only valve fragments of the pelecypods have been preserved. The original microstructure of some of the skeletons of gastropods and pelecypods has been partly preserved (Pl. VII, Figs. 2, 4, 6, 8). In other completely neomorphic skeletons, the original microstructure has been totally obliterated, or preserved as a barely visible relict. Many of the gastropod skeletons have been preserved only as pore-fill molds (Pl. XIV, Fig. 7).

The sponges are usually represented by isolated polyaxial calcified or calcitic needles. Some of them show a monocrystal extinction and belong to the calcareous sponges. Most of the others show a mosaic of calcite crystals and are the replaced needles of siliceous sponges. In one slide, LSW 33/2, a longitudinal section through a sphinctozoan calcareous sponge is seen.

CHAPTER V

DIAGENETIC TEXTURES

INTERNAL SEDIMENT
Internal sediment falls under the heading deposition but it also falls under the heading diagenesis. Internal sediment has been observed in intra-allochem pores, constructed voids and solution voids.

The internal sediment in the intra-allochem pores generally differs from that of the constructed and solution voids. The first contains small bioclasts and other allochems, suggesting deposition contemporary with the surrounding sediment. The internal sediment of constructed and solution voids, generally a light gray pelletous micrite, is devoid of bioclasts. Where bioclasts containing internal sediment were selectively dissolved, it has been observed that the internal sediment was preserved instead of being washed into the newly formed empty molds (LSW 82, Pl. VIII, Fig. 6). This suggests a consolidation of the internal sediment before the selective dissolution of the allochem. This suggestion is supported by a solution void in the internal sediment of a pore-fill algal mold (LSW 133, Pl. XV, Fig. 1). The pore-filling calcite of the solution void forms a whole with the mosaic of the pore-filling calcite of the algal mold. Thus both voids were filled contemporaneously and it is likely that their origins were also contemporary. If the internal sediment had not consolidated, it would have been washed into the empty algal mold or it would have been washed away altogether, and solution voids could not possibly have developed within it.

Internal sediment in constructed voids generally shows a gradual transition to the surrounding sediment. The similarity in composition with the surrounding sediment and the gradual transition suggest that the internal sediment was derived from the immediate neighborhood and that it was probably formed at the same time as the constructed voids (Pl. III, Fig. 1). In one sample, LSW 85, however, it is clearly demonstrated that the deposition of the internal sediment was not contemporary or penecontemporary with the construction of the voids. After construction, the voids were first rimmed with a fibrous crust. Not until after this first phase of pore-filling was the internal sediment deposited (Pl. IX, Figs. 1, 2, 3).

The internal sediment which fills the solution voids clearly must have been formed later during syndiagenesis. It is similar in composition to the internal sediment of the constructed voids, but it differs in its relationship with the surrounding sediment in that it is more clearly confined and has a somewhat sharper contrast. In those samples with an interconnected pore network of constructed voids, solution voids and crumbly fractures (see the section "carbonate solution"), it is possible that the internal sediment in both the constructed voids and the solution voids is of the same generation, which means deposited after the formation of the solution voids. But it is also possible that the internal sediment in the solution voids is younger than that in the constructed voids and that the latter was preserved instead of being washed away by water circulating through the pore network. Previously it was shown that internal sediment in intra-allochem pores probably consolidated before the bioclasts dissolved;

a solution void in this type of internal sediment has even been observed. Therefore it is just as likely that the internal sediment in the constructed voids had already consolidated at the time that the solution voids were formed. Thus it need not necessarily have been washed away but may instead co-exist in the pore network with a younger generation of internal sediment in the solution voids.

The internal sediment in the intra-allochem pores of many samples is neomorphic and consists of neomorphic micrite and pseudospar (Pl. VII, Fig. 1; Pl. XII, Figs. 5, 6). The pore space above the intra-allochem internal sediment can be filled with crusts or syntaxial overgrowths on the skeleton of the enveloping bioclast. These crusts or overgrowths project into the internal sediment and replace the upper part of it. This process was facilitated by the fact that the internal sediment in intra-allochem pores is somewhat coarse due to the presence of small bioclasts and other allochems. The inter-allochem pores of the internal sediment therefore are easily filled with crystals, some of which are syntaxial with the crystals of the crusts or overgrowths. Consequently the crystals of crusts or overgrowths form a whole with some of the calcite crystals of the inter-allochem pores of the internal sediment; in addition to the small bioclasts and other allochems, the calcite crystals also include micrite, which is then changed into neomorphic micrite or pseudospar.

The internal sediment of intra-allochem pores, like the mechanically deposited micrite outside these pores, generally has been dolomitized selectively with respect to algal-bound micrite (Pl. XI, Figs. 3, 4, 5). In a few dolostones (LSW 102) it seems as if the internal sediment, in contrast to the surrounding sediment, was protected against dolomitization since it is either only slightly dolomitized or not at all.

The internal sediment in constructed voids and solution voids is often a neomorphic micrite like the sediments surrounding these voids. In solution voids the neomorphism of the internal sediment is generally more advanced and consequently the latter is often partly pseudosparitic. In dolomitic samples the internal sediment of solution voids shows more numerous clear large rhombs than the surrounding sediment.

MINERALOGY OF THE ORIGINAL CARBONATE SEDIMENT

The original composition of the LSW limestones was probably a mixture of high-magnesium calcite [15] and aragonite. The original presence of aragonite is deduced from aragonitic or partly aragonitic skeletons, such as codiacean Algae and molluscs. The aragonitic composition of these skeletons is determined by comparison with recent representatives of these groups, in accordance with the arguments of Bøggild (1930) and Lowenstam (1963) that the original mineralogy and chemistry of fossil skeletal carbonate is similar to that of recent skeletal carbonate (Schmidt, 1965, p. 136). The original aragonitic composition of these skeletons is furthermore suggested by their mode of preservation. The original aragonitic skeletal microstructures of the molluscs have generally been destroyed by neomorphism or dissolution; most of the codiacean Algae have been dissolved almost completely and are preserved as algal pore-fill molds. Among the non-skeletal allochems there are the ooids, which were probably aragonitic in analogy with recent marine carbonate ooids.

The original presence of high-magnesium calcite is suggested by:

1. the probable similarity in composition to recent algal-bound limestones,
2. the abundance of rhodophycean algal skeletons,
3. the dolomite content: in general up to 5 volume percent of the depositional carbonate and in 16% of the samples, 5 to 90 volume percent.

The compositions of recent algal-bound limestones are given by Monty (1967, p. 74 and Fig. 7; p. 79 and Fig. 9). The mineralogical composition of crusty flakes is quite heterogenous since they are formed from lagoonal sands, which are a mixture of aragonite (fragments of gastropods and *Halimeda*) and magnesium calcite (fragments of echinoderms, peneroplids, red Algae etc.) with about 14 mole percent $MgCO_3$. In recrystallized crusty flakes this complex mineralogy is drastically simplified into a high-magnesium calcite of about 9 mole percent $MgCO_3$. Furthermore Monty points out that most of the carbonate in algal mats has precipitated within the mat and is not detrital. The precipitated carbonate is a high-magnesium calcite ranging from 5 to 10 mole percent $MgCO_3$. The eventually agglutinated or entrapped detrital carbonate is derived for the most part from aragonitic or high-magnesium calcite skeletons so that the overall composition of recent algal mats is a mixture of high-magnesium calcite and aragonite.

Recent corallinacean red Algae consist of calcite with the maximum amount of magnesium carbonate known in any organism (Johnson, 1961, p. 13). By comparison the fossil calcareous red Algae (incertae sedis) of the LSW limestones are also assumed to be typical calcium-magnesium organisms consisting of high-magnesium calcite.

The dolomite content of the LSW limestones can be explained by various processes. One hypothesis, attractive because it explains the observed selective replacement of micrite precipitated by Algae, is based on the original presence of high-magnesium calcite (see the section "diagenetic dolomite"). High-magnesium calcite and aragonite which, as argued above, are thought to be the original minerals of the LSW limestones can be assumed to have been lost during diagenesis.

[15] According to Schmidt (1965, p. 136) low-magnesium calcite is calcite with less then 3 mole percent $MgCO_3$; calcite with a higher magnesium content is called high-magnesium calcite.

[16] Other terms describing this process are grain diminution (Bathurst, 1958, Orme and Brown, 1963), retrograde recrystallization (Schmidt, 1965), algal corrosion or corrasion (Wolf, 1965) and degrading neomorphism – inversion or recrystallization – (Folk, 1965).

NEOMORPHIC CALCITE

Degrading neomorphic aphanocrystalline calcite (Nd E_1 calcite)
This type of neomorphic calcite has been observed in allochems of every LSW sample. To describe the process involved, the verb micritize and the noun micritization are used in this paper [16]. These are suggestive of the kind of product one can expect. Bioclasts showing micritization have partially lost their specific microstructure because of the dark cloudy invasions of micrite, which is similar to the dark algal micrite in algal coatings. Micritization is thought to be caused by Algae (Wolf, 1965, fig. 9; Monty, 1967, p. 82), which are destructive, corroding agents with respect to the microstructure of the allochem, but constructive because they convert the original material into micrite. Any allochem with an algal coating has been micritized to some degree. However, micritization has been observed in allochems without any algal coating. Perhaps this micritization is the first stage in algal coating, but it could also indicate that other factors play a role in this process. One such factor might be the action of bacteria. In the numerous micritized or partially micritized allochems of the LSW section, the number of clearly visible algal borings (Pl. XIX, Fig. 5) is comparatively small, which perhaps means that bacteria are indeed active in the micritization process thereby destroying the boring channels of the Algae.

The effects of micritization on various other processes have been discussed previously in the section on allochems. Therefore only a short recapitulation is given below.

1. Algal pellets and algal grains can originate by complete micritization of bioclasts. Allochems in an advanced stage of the transition to algal grains have been observed frequently in the LSW section.
2. Micritized skeletal fragments appear to be less susceptible to dissolution. Consequently pore-fill molds are frequently lined with undissolved micritized remnants of the original skeletons.
3. Aggraded neomorphic molds of bioclasts frequently show inclusions of micrite in the aggrading neomorphic calcite crystals. This is regarded as an indication for micritization during a previous stage.

Neomorphic micrite
Some micrite in the LSW limestones originated by mechanical deposition (a), but most of it was precipitated by Algae (b). In the following discussion on the neomorphism of micrite, these two types of micrite will be treated separately.

Mechanically deposited micrite. – The criteria for recognition of neomorphism in this type are the same as those listed by Folk (1965, p. 37) for the recognition of microspar. These criteria are: (1) crystal size: 5 to 20 microns; the boundary between micrite (including neomorphic micrite) and pseudospar in this paper has been drawn at 20 microns (see p. 7), (2) uniformity in size, (3) overall crystal shape, generally equant, (4) impurities, trapped interstitially between the crystals. These four properties have been observed for most mechanically deposited micrites, although criterium (2), the uniformity in size, is not always obvious, due to the presence of allochems with a size of 10 to 20 microns. Neomorphism of mechanically deposited micrite is most clearly visible in micritic internal sediments of intra-allochem pores and solution voids.

Precipitated algal micrite (Pl. VI, Fig. 8). – As shown in the preceding section the original mineralogical composition of precipitated algal micrite was probably high-magnesium calcite. We can assume that this high-magnesium calcite was converted into a stable low-magnesium calcite and that this process was accompanied or followed by neomorphism of the original micrite into a coarser neomorphic micrite. The criteria for recognition of neomorphism in micrite precipitated by Algae are much the same as those mentioned previously for mechanically deposited micrite, but it should be kept in mind that there may be differences as a result of the exceptional nature of a micrite sustained by an organic framework. An important factor in this respect is the original porous nature of the precipitated algal micrite, which causes the interaction of pore-filling calcite and makes the distinction between neomorphic and pore-filling calcite crystals more difficult. Clearly neomorphic algal-bound micrites are those which grade from micrite to pseudospar or which show an arrangement of crystals, on the order of 5, 10 or 20 microns in size and outlined by organic black streaks in a fairly equigranular mosaic of polygons. This second type of micrites satisfy the four previously mentioned criteria of Folk. These four criteria form a combination which has proven to be a reliable indication for neomorphism in algal-bound micrites, since similar mosaics have been observed in recrystallized micrites of recent crusty flakes (Monty, 1967, pl. 11–2). Such clearly neomorphic algal-bound micrites, identifiable even at moderate magnifications (50x, 100x), have been observed in the micrite matrix of algal-bound packstones, resembling recent recrystallized crusty flakes, and in some pseudostromata. Pseudostromatic micrites, which appear as dense algal micrites under moderate magnifications, have been examined in ultra-thin sections under high magnifications (900x) with the phase-contrast microscope (Pl. XX, Fig. 6). These micrites show irregular, embayed and deeply interlocked crystals in a pattern resembling the amoeboid mosaic, distinguished by Fischer, Honjo and Garrison (1967, p. 17) in their electron micrographs of micritic limestones. The pattern also resembles the crystal mosaic of the electron micrograph of a micrite "caught in the act" of recrystallizing into a microspar (Folk, 1965, p. 33). Generally inclusions of clay-sized and fine silt-sized quartz crystals and inclusions of an organic framework can be discerned, together with relicts of former smaller crystal forms. The presence of insoluble inclusions has also been clearly demonstrated by dissolution of several ultra-thin sections (see the section "diagenetic silica"). The presence of relicts of former smaller crystals is indicative of neomorphism of the pseudostromatic micrite. As in the electron micrograph of Folk, several larger crystals are found in the mass of smaller ones. This may suggest porphyroid neomorphism (Folk, 1965, p. 22), but as pointed out previously, one should consider the exceptional nature of the original micrite which was sustained by an organic framework. It may be that larger pore-filling calcite crystals were present in addition to phenocrysts of neomorphic micrite.

Summarizing we can conclude that (1) algal-bound micrite of the LSW limestones is neomorphic in various stages of evolution, and (2) because of the Alga-supported nature of the pseudostromatic micrite, the evolution pattern for neomorphism may differ somewhat from that sketched by Folk (1965, p. 22) for mechanically deposited micrites, as a result of the interaction of pore-filling calcite. This different evolution pattern is fully discussed in the following section.

Pseudospar

This term has been introduced by Folk (1965) to cover the sparry calcite formed not by pore-filling but by neomorphism, which is inversion or recrystallization in the solid state in the presence of liquid films. Pseudospar is neomorphic calcite coarser than neomorphic micrite. It can be formed in several ways:
1. inversion or recrystallization of bioclasts (skeletons),
2. inversion or recrystallization of non-skeletal allochems,
3. inversion or recrystallization of carbonate mud.

The recognition of pseudospar formed in the first two ways is no problem since the original microstructure of the skeletons and the outlines and structures of the non-skeletal allochems remain preserved as relicts in the neomorphic mosaic. For example, pseudospar has been observed in many specimens of the rhodophycean (incertae sedis) Alga *Archaeolithophyllum* sp., in all neomorphic algal or other fossil molds, in most spherulites and in some gastropods and pelecypods. The majority of the skeletons of the gastropods however have dissolved completely and filled with sparry pore-filling calcite. In addition pseudospar has been observed in ooids, algal pellets and algal grains. All ooids in the LSW limestones show neomorphism into fibrous spherulitic pseudospar, while the original concentric lamination has been preserved as a relict. Algal pellets occasionally show neomorphism. The algal pellets of LSW 80, for instance, appear to consist of neomorphic fibrous spherulitic micrite which locally grades into fibrous spherulitic pseudospar (Pl. VIII, Fig. 1). For this reason, they resemble ooids, the more so because the origin of these algal pellets is comparable to that of the ooids. The algal pellets appear to have been formed by an algal coating around a small allochem nucleus. They differ from ooids because they lack relicts of an original concentric lamination. In algal grains, the results of neomorphism are seen more frequently than in algal pellets (Pl. XIV, Fig. 6). Both neomorphic micrite and pseudospar have been observed just as in pseudostromata, which are thought to be one of the sources of algal grains. Finally, the discussion on pseudospar in allochems should be concluded by mentioning an interesting type of pseudospar, which occurs in both skeletal and non-skeletal allochems. It is sometimes noted that allochems are locally pseudosparitic when they are transected by a fracture. This fracture did not cause offset or separation of the two transected parts but instead neomorphism in the form of pseudospar, which contains relicts of the outlines and eventual microstructures or structures of the allochems. The mechanism of this process will be discussed later on in this section and in the section "neomorphic calcite creating solution".

The third mode of pseudospar formation results in a sparry calcite which is very difficult to distinguish from pore-filling calcite. In algal limestones, it is even more difficult because pore-filling calcite, neomorphic micrite and pseudospar appear to be closely associated. Pseudospar formed by neomorphism of micrite is discussed below according to its occurrence in different depositional and diagenetic textures.

Pseudospar in algal-bound packstones comparable to recent crusty flakes. – As discussed in the previous section, neomorphic micrite in such packstones can easily be recognized by its gradation into pseudospar and/or the arrangement of crystals (larger than 5 microns) in a uniform equigranular mosaic. The gradation from neomorphic micrite is helpful in identifying pseudospar. On the other hand, there is also a gradation from pseudospar to pore-filling calcite. Between these two however it is not as easy to draw a boundary. Let us consider what happens. The patchily distributed micrite in the inter-allochem pores is sustained by an organic framework. As the pores fill, this micrite becomes impregnated with calcium carbonate-rich solutions and recrystallizes into neomorphic micrite and speudospar. Originally dense patches of micrite recrystallize into neomorphic micrite [17], but the loose porous patches become incorporated in the pore-filling calcite and recrystallize into pseudospar.

Pseudospar in calcite mosaics. – Calcite mosaics may contain scattered allochems or micrite patches which, to quote Folk (1965), "float in the spar like nuts in nut bread". The phenomenon of allochems which float in sparry calcite and are too widely spaced to be grain-supporting has long been used as a criterium for the neomorphic origin of these calcite mosaics (Bathurst, 1958, p. 26; Folk, 1959, p. 33–36; 1965, p. 40). In the algal limestones, similar phenomena are seen not only with allochems but also with micrite patches. The latter have been observed in samples where a pore network of constructed voids, solution voids and fractures has developed. Patches of micrite are isolated by the calcite patches of voids and fractures. This isolation of course is only suggested on the two-dimensional thin section and, in contrast to the floating allochems,

[17] Zones of gradation to pseudospar and pore-filling calcite are present only at the boundary with pore-filling calcite.

cannot serve as a criterium for neomorphism of the surrounding calcite. But as in the case of the crusty flakes, the "isolated" micrite patches, which were surrounded by pores, were probably impregnated by calcium carbonate-rich solutions and consequently recrystallized into neomorphic micrite and pseudospar. Generally one can see that the micrite has been "digested" to various degrees and it is often incorrect to describe the entire mass of the calcite of a pore network as pore-filling calcite, because the dark inclusions in some crystals indicate clearly that one is also dealing with pseudospar.

Pseudospar in pseudostromata (Pl. XVI, Figs. 1, 5, 6). – Sometimes pseudostromata are more clearly neomorphic than the surrounding mechanically deposited carbonate sediment, even if the overall composition is the same. This is explained by the greater resistance of pseudostromata to compaction, due to the support by an organic framework possibly in combination with early lithification. Pseudostromata therefore remain more porous, and as pore-filling and impregnation with calcium carbonate-rich solutions continues, a pseudostromatic body develops consisting of a hodge-podge of micrite, neomorphic micrite, pseudospar and pore-filling calcite.

Pseudospar in relation to fractures (Pl. XII, Fig. 8). – Some patches of pseudospar have been observed amidst relatively homogenous micrite. The crystals of this pseudospar are highly irregular in shape and size, have wiggly boundaries and are comparable to Folk's pseudospar from neomorphism of carbonate mud (Folk, 1965, p. 43). These pseudospar patches are connected with crumbly fractures, which also contain pseudospar. The crumbly fractures transect bioclasts but do not cause offset or separation of the transected parts; instead neomorphism occurs in the form of pseudospar containing the outlines and skeletal microstructures as relicts. This phenomenon was mentioned previously in the discussion of pseudospar in allochems. The mechanism has been described in so-called recrystallization veinlets by Misík (1968, p. 132). Misík found the recrystallization phenomena for sharp-edged fractures, whereas the present author observed these phenomena for both types of fractures. The crumbly fractures however are the only ones that deteriorate into patches of pseudospar. The following is quoted from Misík:

"It appears that the mentioned veinlets originated along submicroscopical cracks, transecting also the organic remains. Moisture in these submicroscopical cracks caused recrystallization of the surrounding micrite mass. As the extent of the recrystallization process was approximately the same, the result of this is a calcitic veinlet of almost equal thickness. A certain weakness of this explanation is the comparatively sharp contours of the veinlets".

The present writer agrees with Misík but should like to add the following about the weakness mentioned: a simple experiment [18] with a very finely crystalline to aphanocrystalline Devonian lime mudstone with stylolites, solution stringers and microscopically fine fractures showed that water penetrated only parallel to these "lines" in zones extending a few mm or a fraction of a mm to either side of the lines. The small crystal size and the slight porosity of the Devonian lime mudstone are thought to be responsible for the sharp parallel contours of the penetration zones. The crumbly fracture, even when microscopically small, is not as straight and sharp as the sharp-edged fracture, because it originates in rocks which are in an early phase of consolidation. The porosity around this type of crack is greater and more irregular, and consequently irregular zones, and locally even patches, of pseudospar can develop.

Another type of pseudospar, mentioned by Misík, occurs in fractures which contain dark enclosures in rows, parallel to the margins of the veinlet. This type has also been observed in the LSW limestones, but only in sharp-edged fractures. This phenomenon is explained by Misík by the existence of thin, dense, parallel fractures. Upon recrystallization, the micrite mass between them became assimilated and preserved as parallel smudges of pseudospar.

Summarizing we may conclude that the pseudospar related to fractures is also caused by the impregnation of more or less porous micrite by calcium carbonate-rich solutions. Moreover the formation of neomorphic calcite seems to be related to zones in which circulation of solutions is greater and easier [19]. The differentiation between neomorphic calcite and pore-filling calcite depends on the size of the pores. When the pores are small, the pore-filling calcite may grow in several pores in crystallographic unity and thereby replace the micrite mass in between these pores. In this way a pseudospar crystal is formed with relicts of former crystal forms and inherited inclusions of clay, quartz and organic material. In the next section it will be shown that pore-filling calcite crystals containing micrite and organic material can also grow in larger pores. The difference is that because the pores are larger, the pore-filling nature of the calcite crystals is more obvious.

PORE-FILLING CALCITE

The pores, defined in the section "terminology", generally are easy to recognize when they are relatively large and consequently the calcite which fills them is easily recognized as pore-filling calcite. As the size

[18] This sample was sawed so that two parallel faces were obtained. One of these faces was ground with 1-micron carborundum powder. The flat rock sample was then put into a dish with enough water so that all sides of the sample, except the ground upper surface, were in contact with the water. Twenty four hours later, the sharply confined penetration zones of water along the above-mentioned "lines" on the ground surface were visible.

[19] See the section "neomorphic calcite creating solution" where it is shown that as a result of percolation dissolution can also occur.

decreases, the recognition of the pores as well as the differentiation between pore-filling calcite and neomorphic calcite becomes more difficult. Several generations of pore-filling calcite can be distinguished.

Generation 1a (Pl. I, Fig. 4)
An initial fringing crust of fibrous crystals, oriented perpendicular to the pore walls. The color of this crust is yellow to brown. It is present in only six LSW samples: LSW 51, 52 (Pl. IV, Figs. 3, 4), 80, 85, 142 and 198. In the opinion of many investigators, such fibrous crusts were formed soon after deposition (Newell, 1955; Bathurst, 1959; Philcox, 1963; Lees, 1964; cited in Folk, 1965, p. 26). According to Wolf (1965, p. 218), fibrous crusts of calcite or aragonite are formed particularly in littoral, supra-littoral and splashwater environments. In the present paper accordingly, the fibrous crusts of pore-filling calcite generation 1a are assumed to be indicative of subaerial exposure soon after deposition.

Pore-filling calcite of generation 1a has been observed in inter-allochem pores and in constructed voids. In the LSW section, it was not found in solution voids. In one sample, LSW 190, the walls of the solution voids appear to be lined by a crust, which is not fibrous but has the appearance of algal micrite. Some fibrous crusts are neomorphic and the fibres have only been preserved as relicts in equant calcite crystals (Pl. XV, Figs. 4, 5). The algal micrite crust of sample LSW 190 is also neomorphic and grades via pseudospar into the pore-filling calcite of the solution voids. The mechanism of pore-filling calcium carbonate-rich solutions penetrating into the porous algal micrite seems to have been effective here (Pl. XIX, Figs. 1, 2, 3, 4).

Generation 1b
Generally most pores are completely filled with only this generation of pore-filling calcite. Generation 1b starts from the pore walls as a fine crystalline crust and continues as crystals which increase in size until the entire pore is filled. If the pore walls are formed by bioclasts, like for instance echinoderms, the initial crust is lacking and this generation starts with overgrowths (Pl. XVIII, Figs. 4, 5). If a fibrous crust (1a) is present in the pores, generation 1b starts by growing from the surface of this crust. There is an elapse in time between the formation of the fibrous crust (1a) and the formation of the next generation (1b) because the latter appears to transect the crust (Fig. 10; Pl. IV, Figs. 3, 4; Pl. IX, Figs. 2, 3).

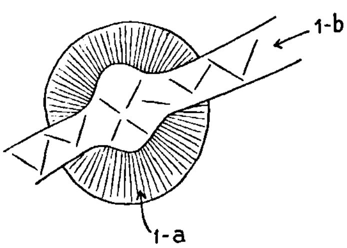

Fig. 10. A crumbly fracture filled with pore-filling calcite 1b transects the fibrous crust of pore-filling calcite 1a. The center of the pore is filled with pore-filling calcite 1b

The pores filled by generation 1b are: intra-allochem pores, inter-allochem pores, constructed voids, solution voids, desiccation or syneresis cracks and crumbly fractures. Although some of these pores did not originate at the same time, it appears that they have been filled by one and the same generation of pore-filling calcite. This is evident from the occurrence of pore networks or pores connected by crumbly fractures. The pore networks are filled with calcite mosaics, which must be integrated since there is no evidence that these mosaics transect one another. It is assumed that these integrated mosaics are of the same generation (Pl. XIV, Figs. 7, 8; Pl. XV, Figs. 1, 2, 3). This assumption might be fallible: the crystals of one mosaic might have grown syntaxial upon the crystals of another preexisting one. Therefore the identification of integrated mosaics should include a study of as many contacts as possible.

A sample not taken from the LSW section but from the southern flank of Lois Syncline West indicates that complete filling of the pores by calcite generation 1b can be achieved during an epidiagenetic interphase of syndiagenesis. Subaerial exposure soon after deposition is deduced from the presence of fibrous crusts of pore-filling calcite generation 1a in constructed voids and inter-allochem pores. A laminated mat, a true stromatolite, is present at the top of the sample and truncates pores and crumbly fractures, both of which are filled with pore-filling calcite generation 1b. Since most stromatolites are formed in supratidal and intertidal environments and since the same environment is indicated by the fibrous crusts, it is assumed that this stromatolite grew in an environment that was subaerially exposed at least periodically. Most probably therefore this sample can be considered a completely cemented beach rock, which formed the appropriate hard substrate for overgrowth by a stromatolite. This sample is highly significant because it shows that cementation by pore-filling calcite generation 1b could occur early during diagenesis (Pl. I, Figs. 1, 2).

Generations 2a, b, c, etc.
These later generations of diagenetic calcite fill the pores of sharp-edged fractures, which clearly transect the calcite mosaics of generations 1a and 1b. In many cases, the sharp-edged fractures show relative differences in age and consequently so do the generations of calcite filling them. This can be observed when there is (1) offset of one sharp-edged fracture by another (Fig. 11a), or (2) if there is no offset, by the presence of initial crusts of pore-filling calcite in the younger, which is built on top of the mosaic already present in the older (Fig. 11b).

Pore-filling calcite with micrite inclusions
This type of calcite has been observed in some pore-fill molds. It could also be called pseudospar, and therefore be considered the product of recrystallization.

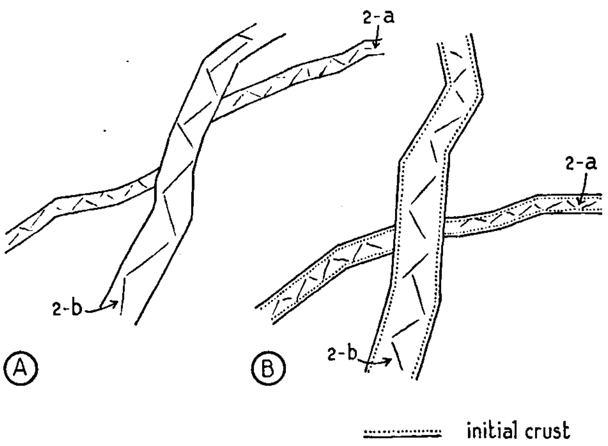

Fig. 11.

Consequently the molds would have been identified as neomorphic molds. The calcite mosaics in most of these molds, however, conform to the criteria of Bathurst (1958) for pore-filling calcite and show integration with the mosaics of those pore networks with which they are associated. As shown in the section "neomorphic calcite", the difference between pore-filling calcite and neomorphic calcite is in most cases only a question of grade. This is again evident from the following explanation of this phenomenon.

Micritized skeletal fragments appear to resist dissolution to some extent; this is the reason that many pore-fill molds are lined with micritized relicts of the original skeleton. Skeletons, which have reached a more advanced stage of micritization, may dissolve into a coherent porous algal micrite mass. Upon filling of the allochem solution void, this mass is included in and partly replaced by the pore-filling calcite. The remaining algal micrite is loose and porous and does not occupy much space. Consequently the pore-filling calcium carbonate-rich solutions are able to crystallize according to the so-called "Bathurst law". And if there is a connection with other pores, the resulting mosaics show integration clearly. On the other hand, completely micritized and subsequently dissolved skeletons may leave a relatively dense algal micrite "framework". When this is impregnated with pore-filling calcium carbonate-rich solutions, there is no room left for crystallization according to the "Bathurst law" and because of the quantity of included and replaced micrite, integration with mosaics of interconnected pores is not as clear. Therefore this calcite can be identified as neomorphic micrite and/or pseudospar without difficulty.

Inclusion of algal micrite in pore-filling calcite has been observed not only in pore-fill molds but also in intra-allochem pores and in overgrowths on skeletal fragments. Some bivalved brachiopod shells and unfragmented gastropod shells show a light internal algal coating, which becomes included during pore-filling. Similar algal coatings on fragments of echinoderms and brachiopods have been observed as inclusions in crystalline overgrowths on these skeletal fragments. Thick algal coatings, however, appear to impede the development of crystalline overgrowths.

REPLACEMENT CALCITE

Calcite replacing a mineral of different gross composition such as quartz has been observed only a few times. The sand-sized quartz grains, which occasionally occur in some limestones, usually show an algal coating. The corroded surface of the quartz grains beneath this algal coating show penetrating projections of algal micrite, replacing the quartz (Pl. V, Fig. 2).

Calcite replacing a mineral of slightly different composition such as dolomite has been observed in many cases. This phenomenon will be treated extensively in the next section.

DIAGENETIC DOLOMITE

About 16% of the samples of the LSW section show dolomitization of 5 to 90% of its volume. The dolomite originated diagenetically through replacement of calcium carbonate, although in two samples a partial pore-filling origin is possible (LSW 29, LSW 56). The dolomitization tends to obscure the depositional texture, but the distinction between mud-support and grain-support remains possible even in the case of dolostones. This is due to the fact that relatively speaking skeletal allochems resist dolomitization and therefore remain recognizable; in addition the former existence of calcite micrite can be deduced from the micrite inclusions in the dolomite crystals. In some dolostones indications of possible algal binding can no longer be recognized.

Calcitization of dolomite has been observed in all dolomitic limestones and dolostones. Therefore the dolomite percentages listed next to the textural column do not reflect the original degree of replacement by dolomite, which was higher especially in the dolomitic limestones.

Occurrence of dolomite

A few isolated dolomite crystals are found in almost all LSW samples, but the total amount of dolomite generally does not exceed 5 volume percent. Only 16% of the samples contains dolomite in quantities greater than 5 volume percent. These samples are confined to the upper half of the section, where the total thickness of terrigenous sediments greatly exceeds the total thickness of carbonate sediments. In the Lois-Ciguera Formation but outside the LSW section, clearly epidiagenetic dolomite has been observed in relation to faults, but in the LSW section itself the observed dolomite is syndiagenetic or anadiagenetic in origin and is not connected with the existence of faults.

The dolomite present in the dolomitic LSW limestones has an uneven distribution, suggesting a replacement origin. In fact dolomite has been observed which replaced (1) micrite (mechanically deposited micrite and algal-bound micrite) and pseudospar, (2) pore-filling calcite and (3) allochems. The replacement is selective in that order with the exception of algal grains and algal pellets, which were as selectively replaced as algal-bound micrite.

Dolomite replacing micrite and pseudospar

In the dolostones, replacement of micrite by dolomite can be deduced from the micrite inclusions in the dolomite crystals. In the dolomitic limestones very fine to fine crystalline anhedral, subhedral and euhedral dolomite crystals occur isolated or in clusters in the micrite groundmass. Their most frequent crystal size lies between 10 and 20 microns. Occasionally large crystals up to 200 microns are seen. Most crystals were originally euhedral or subhedral, but anhedral forms developed as a result of calcitization.

The two different types of micrite which can be distinguished in the LSW limestones, algal-bound micrite and mechanically deposited micrite, are both easily dolomitized. In some samples, LSW 29, 86, 91, 92, where these two types of micrite occur together, it has been observed that the mechanically deposited micrite has been dolomitized whereas the algal-bound shows little or no dolomitization. This might suggest that mechanically deposited micrite is relatively more susceptible to dolomitization than algal-bound micrite. This is perhaps related to the higher content of mud-sized phyllosilicates in the mechanically deposited micrite, a factor which is believed to influence dolomitization (Schmidt, 1965).

Although algal-bound micrite may be slightly less susceptible than mechanically deposited micrite, it has been observed that in general algal influence has a positive effect on dolomitization. This is indicated by the algal coatings, algal grains and algal pellets, which are generally dolomitized to the same degree as algal-bound micrite and which are selectively replaced with respect to pore-filling calcite and other allochems.

The micrite, in which dolomite crystals are found, is generally clearly neomorphic. This is regarded as an indication for a relationship between neomorphism and dolomitization of micrite. Another argument supporting this hypothesis is that in dolomitic limestones, pseudospar resulting from continued neomorphism of micrite or from impregnation of rather porous micrite with calcium carbonate-rich solutions is dolomitized to the same degree as the neomorphic micrite or even more. The difference is that the dolomite rhombs in pseudospar are larger and more translucent (Pl. IV, Figs. 1, 2).

Dolomite replacing pore-filling calcite

Pore-filling calcite partially replaced by dolomite is a rather common phenomenon in dolomitic limestones and dolostones. The degree of replacement depends on the degree of dolomitization of the sample, but a relationship with the occurrence of micrite inclusions in the pore-filling calcite has also been observed. This is seen clearly in intra-allochem pores in dolostones. Some of these pores are filled with micritic internal sediment and pore-filling calcite with inclusions of the internal algal micrite coating. The original micritic internal sediment has generally been dolomitized completely, whereas the pore-filling calcite above this internal sediment shows preferred dolomitization around the micrite inclusions. As discussed in the section "diagenetic calcite", pore-filling calcite with micrite inclusions has been observed in pore-fill molds, in overgrowths on skeletal fragments with light algal coatings and in intra-allochem pores with light internal algal coatings. In dolomitic limestones this type of pore-filling calcite has been selectively replaced with respect to pore-filling calcite lacking micrite inclusions.

The pore-filling calcite in crumbly fractures in dolomitic limestones or dolostones generally has been partly or completely replaced by dolomite. As discussed in the section "pseudospar", zones adjacent to crumbly fractures are impregnated by percolating carbonate-rich solutions. Most of the sparry calcite at the borders of crumbly fractures or, if the fracture is microscopically small, the sparry calcite of the entire crumbly fracture is in fact pseudospar. The selective replacement of pseudospar by dolomite probably explains why dolomite crystals are often as abundant in crumbly fractures as in transected dolomitized micrite; it also explains why in general there are more dolomite crystals along the borders of the crumbly fractures than in the center.

In the pore-filling calcite of sharp-edged fractures, dolomite crystals are only occasionally present. Generally sharp-edged fractures with their mosaics of pore-filling calcite cut through individual dolomite crystals or through clusters or mosaics of dolomite crystals in the transected dolomitic limestones or dolostones. Occasionally, transected anhedral dolomite crystals show euhedral dolomite overgrowths into the pore space of the sharp-edged fracture (Pl. XIII, Fig. 7).

Dolomite replacing bioclasts

Generally, skeletal allochems appear to be the least susceptible to dolomitization. Non-skeletal algal allochems such as algal grains and algal pellets are as readily dolomitized as algal-bound micrite but the non-skeletal ooids appear relatively to resist dolomitization like the skeletal allochems. Yet in the section on allochems, the formation of ooids was ascribed to algal coating and regular overturning. Their resistance to dolomitization in relation to algal grains and algal pellets might be ascribed to their relatively low porosity, one of the factors which also influences the susceptibility to dolomitization of skeletal allochems. The degree of dolomitization of bioclasts depends on a number of partly interdependant factors, which in order of importance are: (1) the presence of micritization and algal coating, (2) the original porosity of the skeleton, (3) the degree of dolomitization of the sample, (4) the presence of intra-allochem pores with dolomitized internal sediment and dolomitized pore-filling calcite. Possible influence of the original mineralogical composition on the degree of dolomitization was found only once, in sample LSW 32. The rhodophycean (incertae sedis) Alga *Archaeolithophyllum* sp., which is assumed to have consisted originally of high-magnesium calcite in analogy with the modern rhodophycean Algae, appears in this sample to be dolomitized to the same degree or even more than the surrounding algal-bound micrite. *Archaeolithophyllum* in other dolomitic samples does not seem to be more susceptible than other bioclasts but generally shows aggraded neomorphism; probably it lost its original composition before dolomitization. Bioclasts in many samples indicate that neomorphism took place before dolomitization. Gastropods and pelecypods for instance, composed originally of aragonite, always show an inversion to calcite before dolomitization. It cannot be concluded that these inverted skeletons are more resistant to dolomitization than skeletal material originally composed of low-magnesium calcite, as observed by Dixon (1907, in Chilingar, Bissell and Fairbridge, 1967, p. 296). Inverted gastropod skeletons in one sample, LSW 56, have been observed in all stages of dolomitization, ranging from skeletons with only nibbling dolomite crystals on their surface to skeletons which disappear completely in the mosaic of dolomite crystals (Pl. IV, Fig. 8). Originally low-magnesium calcite skeletons in the same sample show only dolomitization on the surface.

Generally the bioclasts are attacked by dolomitization from the outside inwards, a process facilitated by the four previously mentioned factors:

1. Algal coating and micritization increase the susceptibility of a bioclast to dolomitization (Pl. XI, Figs. 1, 2; Pl. XIII, Fig. 5). Algal coatings being as readily dolomitized as algal-bound micrite, the dolomitization starts at the coating and spreads out into the zones of micritization. Therefore allochems with algal coating and micritization appear to be selectively dolomitized with respect to allochems lacking these phenomena, both in dolomitic limestones and dolostones.
2. The original pores in skeletons are frequently filled with algal micrite, which is easily dolomitized. This phenomenon has been observed for echinoderms, which always appear to be dolomitized to a greater degree than other bioclasts. It is possible that the original high-magnesium content of the echinodermal skeletons was also influential, however dolomitization of echinoderms always seems to follow the original pore pattern.
3. The degree of dolomitization of the sample is influential because bioclasts in highly dolomitic limestones and especially dolostones are embedded in a groundmass of dolomite crystals, which nibble into the skeletons from all sides.
4. The presence of inter-allochem pores with dolomitized internal sediment and dolomitized pore-filling calcite is of influence because bioclasts, enveloping those pores are attacked from inside by nibbling dolomite crystals. Internal sediment, just like other mechanically deposited micrite, is selectively replaced with respect to algal-bound micrite. Bioclasts with dolomitized internal sediment are occasionally found in algal-bound micrite with only slight dolomitization. Due to the dolomitized internal sediment, local dolomitization of the bioclast may occur despite its presence in an environment with only minor dolomitization.

Dolomite cement

Dolomite cement is scarce and is identified with reservation in only two dolostone samples, LSW 29 and LSW 56. It is rather common for dolomite to prefer replacement of carbonate and to avoid pore spaces. This preference for growth by replacement of existing carbonate rather than the growth of new crystals in pre-existing void space has been interpreted by Murray (1960, 1964) as indicating that the dolomite grew by utilizing a local source of the carbonate ion. However, Schmidt (1965) found that pore-filling dolomite is a common feature in the dolostones of the Upper Jurassic Gigas Beds (northwestern Germany). Possibly it might depend upon when dolomitization took place. Syndiagenetic dolomite formed when pores were still open, is more likely to have been both replacing and pore-filling than anadiagenetic dolomite.

The two samples LSW 29 and LSW 56 both show dolomite in the pores of the walls of some Foraminifera. Usually these pores are filled with calcite, which is not readily replaced. All intra-allochem pores of LSW 29 are lined with a rim of dolomite crystals: the smaller have been "filled" completely with dolomite, whereas the larger are filled with pore-filling calcite in the center. The rims suggest an early replacement of the initial rims of pore-filling calcite, generation 1b, or a selective replacement, early or late, of rims of pore-filling calcite generation 1a. Relicts of fibrous crystals have not been observed, thus an early replacement of 1b rims seems most probable. In LSW 56 (Pl. IV, Figs. 6, 7) a void on top of the completely dolomitized internal sediment of a gastropod is lined with calcite cement with inclusions of an internal algal micrite coating. This calcite cement has been partially replaced by dolomite particularly around the micrite inclusions. Concentric to this partially replaced calcite rim is an inner rim of pure dolomite, interpreted as dolomite cement filling the void. The center of the void has again been filled with calcite. This phenomenon is thought to reflect the following course of events: (1) partial filling of the pore with calcite and nearly simultaneous replacement of internal sediment and micrite inclusions in the pore-filling calcite, (2) dolomitization, so intense that for a short time dolomite crystals grow into the pore space, (3) remaining pore space filling with calcite. Many smaller intra-allochem pore spaces of LSW 56 were dolomitized completely during phase 2; some pore-filling might also have taken place but this cannot be determined from the crystal figurations. If the same sequence of events is applicable to LSW 29, then in phase 2 the calcite rims of phase 1 would have been replaced and extended somewhat with pore-filling dolomite, a process which does not contradict the early replacement suggested by the dolomite rims on their own.

Time relationship

The dolomitization process of the LSW limestones can be located in time by the relationship of the dolomite crystals to sharp-edged fractures and crumbly fractures. The pore-filling calcite of the latter has usually been more or less dolomitized, depending on the degree of dolomitization of the sample, while in sharp-edged fractures a dolomite crystal has only occasionally been observed. Sharp-edged fractures cut through previously formed dolomite mosaics of dolostones or through isolated dolomite rhombohedra in dolomitic limestones (Pl. IV, Figs. 1, 2; Pl. X, Fig. 6; Pl. XII, Fig. 7). Therefore the main phase of dolomitization was active after crumbly fracturing and before sharp-edged fracturing. Dolomitization also took place after the formation of sharp-edged fractures but only on a small scale, as indicated by a few observations of dolomitized pore-fill calcite crystals in these fractures (Pl. IV, Fig. 2; Pl. XIII, Fig. 7). Because of their sharply defined borders, sharp-edged fractures are assumed to have originated in completely lithified rocks. Crumbly fractures, on the other hand, originated in poorly consolidated rocks. Dolomitization accordingly is thought to have been active during lithification, which is a process of pore-filling and subsequent neomorphism. In some samples, such as dolostones LSW 29 and LSW 56 (see above), the time of dolomitization can be determined rather precisely but for most other samples, it can only be deduced from more general considerations about the dolomitization process.

Hypotheses for the dolomitization process

The discussion below is based on the unifying model for dolomitization of Friedman and Sanders (1967, p. 334), who conclude that all dolostones whether syndiagenetic, anadiagenetic or epidiagenetic are the result of the action or reaction of hypersaline brines. The LSW dolomitic limestones and dolostones are considered in the light of this model and processes most likely to have been active are selected.

General dolomitization of 5 volume percent or less. – Inclusion of micrite in pore-filling calcite, which can also be seen as the "impregnation" with pore-filling calcite of micrite sustained by an organic framework, can result in the development of neomorphic micrite with dolomite rhombs (Pl. XIX, Figs. 7, 8; Pl. XX, Figs. 1, 2, 3, 7, 8). The development of these rhombs is explained by liberation of magnesium during recrystallization of originally high-magnesium algal micrite into stable low-magnesium neomorphic micrite. Local carbonate ions of the micrite are used by the dolomite rhombs for growth. No calculations have been made to determine whether the supposedly liberated magnesium is sufficient for the formation of the small dolomite rhombs observed. An additional magnesium supply perhaps comes from the solutions filling the pores. These solutions, originally having the composition of the supernatant sea water, supposedly become relatively richer in magnesium after sealing of the sediment because of the continued cementation of the pores with calcite. It has been observed that pore-filling calcite with micrite inclusions generally contains some minor dolomite rhombs and thus contributes to the content of those LSW limestones containing 5 volume percent dolomite or less. In cases of heavier dolomitization, these small rhombs will act as centers of attraction for magnesium and thus provide an explanation for the selective replacement of pore-filling calcite with micrite inclusions.

The same mechanism is thought to be active during neomorphism of algal-bound micrite. Originally high-magnesium calcite micrite recrystallizes into neomorphic micrite or pseudospar and the liberated magnesium causes the formation of local initial dolomite rhombs which will continue to grow because of the attraction of magnesium from magnesium-enriched interstitial water. This process of dolomitization of algal-bound micrites is limited in scale and is thought to account for the general dolomite content of 5 volume percent or less. The additional supply of magnesium from pore-filling solutions depends on the original composition of the sea water and the velocity of impregnation and cementation. If cementation of the algal-bound micrite is rapid, which is assumed to be the case, the porosity is reduced and the magnesium-enriched pore-filling solutions cannot easily reach the initial dolomite rhombs in the algal-bound micrite. Previously the selective replacement of mechanically deposited micrite with respect to algal-bound micrite was tentatively explained by the higher mud-size phyllosilicate content of the former. Another influence might be the faster cementation of the algal-bound micrite, resulting in its isolation from magnesium-rich pore-filling solutions. The latter consequently might remain in contact with the mechanically deposited, still unconsolidated micrite more easily and much longer, thus contributing to its selective dolomitization with respect to the algal-bound micrite.

The limit of 5 volume percent is set in analogy with the boundaries of Schmidt (1965, p. 139) between his lime facies (up to 5 volume percent) and partially dolomitized facies (5 to 95 volume percent). Of course this boundary is arbitrary and the present writer must admit that he is not able to calculate the degree of dolomitization resulting from the process postulated above. The conclusions here are based only on observations: the generally low content of dolomite in most LSW limestones and the phenomenon of the development of dolomite rhombs in association with neomorphism of micrite.

Dolomitization of more than 5 volume percent. – The dolomitization of more than 5 volume percent can be explained by a number of processes. The facts indicated by dolostones LSW 29 and LSW 56 together with the time relationship of dolomitization in general suggest that other LSW dolostones may also have been formed syndiagenetically. The action or reaction of hypersaline brines consequently must have taken place before burial of the sediments or during early burial. This means that (a) hypersaline brines were formed in the supernatant sea water and as a result of refluction reacted with the sediment or (b) the hypersalinity resulted from evaporation in sea marginal porous sediments.

Evidence for the hypersalinity of the supernatant sea water, for instance the occurrence of anhydrite beds or gypsum layers, has not been found in the sediments associated with the LSW limestones. Absence of gypsum in the model of Friedman and Sanders (1967, p. 336) is explained by bacterial decomposition below the wave-influence zone, but such a depth cannot be assumed for the algal LSW dolostones. In the Coorong Lagoon and associated lakes in southeastern South Australia, recent dolomite is formed by refluction of hypersaline brines reacting with previously formed carbonates. The salts, precipitated from the brines, are powdered by the summer heat and blown land-inward after the lakes reach their seasonal drying-up stage. By this process dolomitic sediments are preserved without evaporites. In the lagoon and lakes, calcium carbonate precipitation is promoted by photosynthesis of plant life which increases the Mg/Ca ratio of the brine. In analogy the LSW limestones may have been formed under influence of photosynthesis of algal plant life in bodies of saline water permanently or intermittently cut off from the sea, as in coastal lagoons and ponds or back reef shelves. Dolomitization analogous to that in the Coorong Lagoon and associated lakes may have been active, whereby precipitated salts from the hypersaline brines were repeatedly blown away.

The LSW dolostones could just as easily have been caused by capillary activity and evapo-transpiration of the sea water ground table in sea marginal porous sediments. A comparison with the recent dolomitic crust from western Andros Island, described by Shinn et al. (1965), is possible.

Shinn et al. (1965) think that the dolomitic crust is a product of replacement by dolomite. Direct precipitation of dolomite from the interstitial water is thought to occur only on a limited scale. Molluscs and Foraminifera in the crust are only slightly dolomitic and this dolomitization is generally associated with dolomite filling of algal borings. A similar conclusion can be drawn from the study of the LSW dolostones: calcite micrite inclusions in the dolomite crystals indicate the earlier existence of calcite micrite and thus the replacement origin of the dolomite; bioclasts are only partially dolomitized and dolomite filling of algal borings has been observed. Direct precipitation of dolomite on a limited scale is suggested by samples LSW 29 and LSW 56.

Vugs and pores in the dolomitic crust of Andros Island are lined with acicular calcium carbonate crystals. This pore-filling calcium carbonate is assumed by Shinn et al. (1965) to be the chief cause of both lithification and magnesium enrichment of the interstitial brine relative to calcium. The dolomitic crust from Andros Island contains algal mat laminations. The present author believes that precipitation of calcium carbonate in the algal masses, under influence of CO_2 extraction by photosynthesis of the Algae, may also influence the relative decrease in calcium with respect to magnesium. Pores in the LSW dolostones were also filled with calcite early in the diagenetic process. Later this early pore-filling calcite was partially or completely dolomitized. As in the Andros crust general algal influence together with the early precipitation of calcite in the pores may have caused magnesium enrichment of the interstitial brine, relative to calcium.

Salinity measurements in the interstitial waters of the dolomitic crust of Andros Island indicate that gypsum should precipitate. Gypsum, however, has not been found and it is thought to have disappeared in the humid climate. Similar humid conditions might be responsible for the absence of gypsum in the LSW dolostones. Indications for humidity in the LSW section are the presence of solution voids in subaerially exposed limestones and the occurrence of recrystallization in algal-bound crusty flake-like packstones.

The formation of a dolomitic crust requires subaerial exposure and results in the formation of a hard substrate. Evidence for the existence of the latter is found in dolostone samples LSW 21 and LSW 51. Both samples come from the contact with an overlying sandstone and do not show any mixing. In LSW 51, constructed voids and inter-allochems pores are lined with pore-filling calcite generation 1a, a feature thought to be indicative of subaerial exposure. All other LSW samples containing pore-filling calcite generation 1a and thus with an equal chance of subaerial exposure do not have a dolomite content of over 5 volume percent and did not form as a dolomitic crust. The fact that a dolomitic crust did not form could be explained in many ways. Suffice it to point out that the dolomitic crust of Andros Island has been found only on the west coast, whereas in the supratidal environment of the east coast Monty found that the algal mats contain only high-magnesium calcite because there the groundwater is fresh to slightly saline.

Two dolostone samples, LSW 56 and LSW 60, are thought to be comparable to recent crusty flakes. Recent crusty flakes from Andros Island are found on intertidal flats bordering creeks connected with the lagoon and flooded by waters with a salinity ranging from 32 to 36‰ or on flats of tidal ponds, flooded with waters sometimes very remotely connected with the lagoon but normally with a salinity higher than 25‰ (Monty, 1967, p. 77). Lower salinity values are introduced by heavy rains, whereas hypersaline conditions on the flats of tidal ponds may develop when seiches pile up waters which then rapidly evaporate. Furthermore in the absence of winds, cut off by the screen of Casuarina which covers the berm, ground temperatures over the flats of tidal ponds may rise considerably and reach 30 to 45°C. Rain causes recrystallization of crusty flakes (Monty, 1967, p. 79). The influence of hypersaline conditions and evapo-transpiration has not been described by Monty, but the present writer believes that samples LSW 56 and LSW 60 may have been dolomitized under such conditions.

Dolomitization by capillary activity and evapo-transpiration in sea marginal sediments is a mechanism not contradicted by the observations of the LSW dolomitic limestones and dolostones. The evapo-transpiration mechanism starts with normal salinity or even salinity somewhat below normal; consequently the dolomite content caused by this mechanism should theoretically be less than the 20 volume percent found by Shinn et al. (1965) as lowest dolomite content in the dolomitic crust of Andros Island. This means that to a large extent the range in dolomite content for the LSW dolomitic limestones and dolostones might be explained by this mechanism, provided the previous assumption of syndiagenetic dolomitization is generally valid.

Another possible cause of dolomitization is connate water from marine clays which may supply sufficient magnesium for small-scale dolomitization (Rudolf, 1959, in Schmidt, 1965). It has been observed that eight of the twenty seven dolomitic limestones or dolostones were found immediately above sandstone interbeds, which are generally rather silty or clayey. Moreover the dolomite distribution in the LSW section as a whole shows that dolomitization of more than 5 volume percent is confined to the upper half of the section, where the total thickness of terrigenous sediments greatly exceeds the total thickness of carbonate sediments. Dolomitization by percolation of connate waters from marine clays is anadiagenetic and offers an alternative explanation should the assumption of syndiagenetic dolomitization not be valid. But even in cases of syndiagenetic dolomitization, the process may have been prolonged during anadiagenesis by expulsion of connate waters from underlying sandstone beds.

REPLACEMENT OF DOLOMITE (Pl. X, Figs. 6, 7; Pl. XIII, Figs. 5, 6)

Calcitization of dolomite

Replacement of dolomite by either calcite or silicium oxide or both is a common feature in all samples of the LSW section. It will be demonstrated below that there is a causal connection between silicification and calcitization of dolomite and therefore these two phenomena will be treated together. Following Swett (1965) and Smitt and Swet (1969), the term dedolomitization will be avoided in this paper and calcitization of dolomite used instead. According to Evamy (1967) and de Groot (1967), calcitization of dolomite is caused by solutions with a high Ca/Mg ratio reacting with dolomite to form calcium carbonate. Experimental work by Yanat 'eva (1955) and de Groot (1967) indicates that calcitization of dolomite can only take place at or near the earth's surface, where pCO_2 and temperature are relatively low. Evamy (1967) therefore considers calcitization of dolomite to be a product of epidiagenesis. As all samples of the LSW section are outcrop samples, it would be logical to explain the observed calcitization of dolomite as a product of weathering. However porosity in the LSW samples is very low. Meteoric water penetrates only 1 to 2 mm into the LSW limestones, dolomitic limestones and dolostones. Deeper penetration takes place by way of fractures, stylolites and solution stringers. On both sides of these paths, the meteoric water again penetrates zones of only 1 to 2 mm. Calcitization of dolomite in the LSW samples should therefore be limited to these zones. It appears however that calcitization of dolomite is present in all parts of the thin sections and that calcitization around stylolites or solution stringers is not more advanced than elsewhere. Moreover dolomite crystals, transected by solution stringers but lacking calcitization (LSW 25), have been observed. Evidence of calcitization of dolomite caused by weathering is absent, whereas a connection with silicification, as will be shown below, is more convincing. Silicification is present in every limestone sample, to the same extent as small-scale dolomitization. The degree of silicification is difficult to express in a volume percentage because of its typical habitat. Euhedral quartz crystals are occasionally visible in thin section but generally the quartz, which replaces calcite crystals, allochems and dolomite rhombs and is present in the micrite matrix, is distributed as very fine particles in the host and the micrite matrix. Usually the host is only partially replaced by these fine quartz particles; when the host is a monocrystal, such as calcite crystals, dolomite rhombs and echinoderms, the replacing quartz particles are in optical continuity with the host crystal. Partially silicified echinoderms demonstrate this most clearly.

Thin sections, colored with Alizarin Red-S, are generally dissolved at their borders by the acid admixture of the coloring agent. In some thin sections dolomite crystals with ferric-oxide zones are seen, which are partially silicified and calcitized. At the dissolved borders, the calcite from the partially calcitized dolomite crystals has been leached out and the replacing quartz crystals left behind. The original outline of the rhombs and the brown iron zones are preserved. The residual quartz particles of a leached dolomite rhomb clearly show simultaneous extinction whereas this picture is obscured in the unleached rhombs by calcitization which regenerates the original mosaic of the micrite replaced by the dolomite (Evamy, 1967). The calcite particles formed by calcitization do not have the same optical orientation as the dolomite rhombs. Silicification therefore precedes calcitization because otherwise silicification of calcite particles with a different orientation would have produced quartz particles under a different orientation. Because of their relationship in time, and because of the general presence of diagenetic silica together with calcitized dolomite crystals, silicification is thought to be the cause of the calcitization of dolomite in the LSW samples. Silicification of calcite liberates Ca-ions. Solutions near silicified calcite crystals will consequently have a high Ca/Mg ratio. Reaction of these solutions with dolomite crystals results in calcitization. One condition which must be fulfilled for this hypothesis is that silicification must occur after dolomitization. This is clear from (1) the occurrence of silicified dolomite crystals and (2) the fact that silicification clearly affects the pore-filling calcite of sharp-edged fractures and thus evidently is later than sharp-edged fracturing whereas dolomitization is shown to occur between crumbly fracturing and sharp-edged fracturing.

Other indications supporting the hypothesis that silicification caused calcitization of dolomite were found in the lower part of the LSW section, in limestones with chert knolls parallel to the bedding plane. Samples LSW 156 and LSW 158, taken from this location, show more advanced silicification than other LSW samples. In completely silicified patches from these samples, enclosure of rhombohedra was observed; the rhombohedra appear to be completely calcitized dolomite crystals. In a sample from beyond the LSW section, taken from a chert knoll niveau of the Ciguera Syncline, a similar phenomenon has been observed. It is quite improbable that recent meteoric waters penetrated the chert knolls and caused calcitization. Silicification of the limestone containing dolomite rhombohedra resulted in chert knolls enclosing rhombohedra, which were calcitized because of the high Ca/Mg ratio of the local solutions (Pl. XXI, Fig. 14). These observations also suggest that calcite is replaced selectively by quartz with respect to dolomite. This observation is in accordance with the observations of Buurman and van der Plas (1971).

Fabrics and textures resulting from calcitization of dolomite

The calcite replacement mosaics of dolomite crystals, observed in the LSW section, cover all groups of fabrics and textures distinguished by Shearman et al. (1961), and by Evamy (1967). The following fabrics (1 and 2) and textures (3) have been observed: (1) composite calcite rhombohedra, (2) partially calcitized dolomite crystals, poikilitically enclosed in a mosaic of calcite crystals, (3) clotted or "grumeleuse" texture.

1. Composite calcite rhombohedra. Originally dolomite rhombohedra with micrite inclusions are now seen as rhombohedra relicts composed of equicrystalline mosaics of calcite. The replacement of the dolomite crystals by calcite is both centripetal and centrifugal and is usuallly not complete. As a result the most bizarre relict forms of dolomite have been observed. The resulting calcite mosaic is a regeneration of the originally dolomitized micrite.

2. Partially calcitized dolomite crystals, poikilitically enclosed in a mosaic of calcite crystals. The replacement of the dolomite crystals was probably both centripetal and centrifugal. They appear as externally corroded dolomite crystals with a calcite micrite core. This is thought to be related to the formation of the poikilitically enclosed dolomite crystals. Dolomite crystals poikilitically enclosed in calcite always form a part of a patch of micrite, which is enclosed in pore-filling calcite. They are thought to have originated from neomorphism of the enclosed micrite; continued growth was probably due to magnesium supply from magnesium-enriched pore-filling solutions. When the calcite is silicified, the enclosed dolomite crystals become calcitized partly by regeneration of the micrite core (centrifugal replacement) and partly by regeneration of the enveloping calcite crystals (centripetal replacement).

3. Clotted or "grumeleuse" texture (Evamy, 1967, p. 1209). This texture is caused by calcitization of zoned dolomite rhombohedra with cloudy centers (LSW 24, Pl. I, Fig. 3, LSW 25). The zonation is caused by an alternation of clear rims and rims stained by ferric-oxide. Upon calcitization, the clear rims changed into relatively coarse mosaics of calcite and the brown iron zones distintegrated and appear as clots in the crystals of the new mosaics. The cloudy center is left as one big brown clot or is split up into calcite crystals with clots. The matter is complicated by the fact that some of the crystals in the new mosaic are quartz crystals, inherited from previous silicification of the dolomite crystals, but the principle of the formation of a clotty texture is essentially the same.

As Evamy (1967) pointed out, a lime mudstone may be altered by dolomitization and subsequent calcitization to a clotted pseudo-micropelletoid lime grainstone or lime packstone; it could therefore be incorrectly identified as originally being a limestone with a clotty depositional texture. In the LSW section, slightly dolomitic limestones are present (LSW 48 and LSW 49) with the clearly depositional clotty texture of algal pellets and pelletous algal-bound micrite. The algal pellets have been selectively dolomitized. In numerous algal pellets, several small dolomite rhombs can be observed which often have dark outer borders and dark micrite inclusions. Complete or partial calcitization of the dolomite rhombohedra took place, resulting in coarser crystalline algal pellets. The dark appearance of the pellets is as a whole preserved – be it somewhat redistributed – as clots and ghosts of former dolomite rhombs within the pellets. Some algal pellets, now composed of calcite, show a vague rhombic outline indicating earlier dolomitization to one large dolomite rhomb with a cloudy center. The warning of Evamy to be cautious in the interpretation of clotty limestones is useful, but from the above it is clear that selective dolomitization of original clots or pellets may result in dolomite crystals with cloudy centers; after calcitization the original clotty or pelletous texture is regenerated.

Partial regeneration of the pre-dolomitization fabric, texture or skeletal microstructure

In the fore-going section, regeneration of pre-dolomitization fabrics and textures was mentioned. Composite calcite rhombohedra regenerate the originally dolomitized micrite; dolomite poikilitically enclosed in pore-filling calcite regenerates the originally enclosed micrite and part of the pore-filling calcite; originally clotty textures can also be regenerated by calcitization. The mechanism of the regeneration has been discussed in detail by Evamy (1967, p. 1207). Dolomite crystals originating in micrite contain micrite inclusions, which are more widely separated than the micrite particles in the original micrite since the widely spaced inclusions act as centers of growth for the new mosaic. In the dolomite crystals of the LSW samples, some partial silicification is usually seen. Upon calcitization of the dolomite crystal, the silicified parts remain unchanged. The resulting calcite mosaic thus generally contains some quartz, which adds to the effect of coarsening. The coarsening of the regenerated fabric, texture or skeletal microstructure is a fairly common feature in the LSW samples. Skeletons appear to be susceptible to silicification. Occasional dolomite rhombs within these skeletons consequently are readily calcitized. Regeneration of the skeletal microstructure is often seen, but some details are lost by coarsening.

Effect of calcitization of dolomite on dolomite content and texture

Calcitization had a marked effect on the dolomite content of the LSW samples. It is reasonable to assume that the original dolomite content was much higher than indicated by the percentages listed beside the depositional texture column. Calcitization however affected dolostones only slightly. This obviously is related to the relatively low content of undolomitized calcite, which upon silicification supplies the Ca-ions necessary for calcitization of the dolomite. The original dolomite content for some samples can be estimated reasonably due to the preservation of crystal zones and outlines in the form of ferric-oxide ghosts, although the clotty texture resulting from calcitization locally obscures the picture. For most other dolomitic samples, however, it can only be stated that the original dolomite content was higher; more exact information is not available. The effect on the texture of the calcitization of dolomite is likewise not known exactly. Much of the calcite micrite, indicated as neomorphic, might be the composite calcite mosaic of calcitized dolomite. This means that the diagenetic history, which in the case of neomorphism is a "simple" recrystallization or inversion to a coarser crystal mosaic, is much more complicated because the neomorphic micrite is then the result of dolomitization and subsequent calcitization, each process having its own complicated relationships with other diagenetic processes such as neomorphism and silicification, respectively (Pl. XVIII, Fig. 8).

DIAGENETIC SILICA

Since the relationship in time between silicification and dolomitization and the causal relationship between silicification and calcitization of dolomite have been discussed previously, this section will cover only the general appearance of diagenetic silica and the source and causes of silicification. Although silicification is a general phenomenon in the LSW samples, it is usually not apparent at first sight. This is due to the thickness of the slides and the relatively low ratio of fine replacement quartz particles with respect to non-replaced carbonate as well as the even distribution of the quartz particles. In thin sections of normal thickness, silicification is most obvious in skeletons and sparry calcite. In ultra-thin sections quartz also appears to be present in micrite. The nature of this quartz can best be studied in the dissolved borders of thin sections. It usually appears to consist of tiny elongated tube-like forms and tiny euhedral crystals. Silicification of skeletons often shows pseudomorphism of the replaced microstructural elements, such as prisms or fibres. Silicification of skeletons with a monocrystal microstructure is syntaxial with this microstructure. Pseudomorphic replacement by quartz has also been observed in calcite and dolomite crystals whenever the quartz particles are small and evenly distributed in the host (Pl. XX, Fig. 5). Along with a more advanced degree of silicification the evenly distributed quartz particles coalesce and form a mosaic of needle-like crystals (Pl. X, Fig. 4) or a patch of crystals without well-defined outer forms and with irregular or shadow extinction with optical and physical orientations independant of the host (Pl. XVII, Fig. 1). Samples of limestones, containing chert concentrations arranged parallel to the bedding, show spherulitic chalcedony and lutecite fabrics (Wilson, 1966) replacing skeletons, sparry calcite and micrite. Ghosts of replaced skeletons have not been found in these fabrics, only non-silicified skeletal remnants enclosed and surrounded by the silica concretions. The lack of radial or concentric inclusion ghosts in the silicified ooids of the State College siliceous oolite is explained by Wilson (1966) as micritization of the ooids prior to silicification, destroying their internal structure. The above-mentioned silica concretions in some of the LSW limestones, also lacking ghosts but enclosing non-silicified skeletal fragments, do not support Wilson's view since the skeletal remainders show perfectly preserved microstructures not destroyed by micritization. Therefore in the opinion of the present writer, the absence of ghosts of the replaced material is only an indication of the degree of silicification.

Source of the silica, a hypothesis

The silicification of the LSW limestones is a common phenomenon and in an advanced stage, it results in concretions parallel to the bedding. The silica is therefore thought to be of syndiagenetic origin, related to the formation of the algal limestones, and not an epidiagenetic product of weathering. Later diagenetic changes resulted in solution and reprecipitation, perhaps several times. The main phase of reprecipitation occurred, as shown, after sharp-edged fracturing. The presence of silica and the phenomena of silicification in the LSW limestones are explained by the ability of living algal mats to hold considerable concentrations of silica in solution in their interstitial waters. A tentative hypothesis, based on reports in literature and observations by the present author, is discussed below.

Photosynthesis removes carbon dioxide from water either as H_2CO_3 or as HCO_3-, thus increasing the pH. This shift in the bicarbonate-carbonate equilibrium causes precipitation of calcite in and around the algal mass, and if the water is highly saline dolomitization will be promoted. The pH can rise above 9, leading to the increased solubility of silica. The pH can be lowered to values of 7.0 to 6.5 by dying plant life, which causes liberation of CO_2. The death of algal plant life can be caused by evaporation of the body of water by subaerial exposure due to sea-level oscillations, or by burial. In both cases the silica held in solution will precipitate. Tubes and cells of the organic framework become partly or completely silicified. During subsequent cementation the porous micrite mass, precipitated around the organic framework, is impregnated by carbonate solutions and changes into neomorphic micrite with pore-filling calcite. The organic framework with its silicified and calcified parts is enclosed in the neomorphic micrite. During this process of calcite precipitation, the pH can again rise above 9 and part of the silica will again go into solution. After sharp-edged fracturing and subsequent filling with pore-filling calcite generations 2a, b, c, etc., the silica held in solution is precipitated. Sparry calcite and skeletons are selectively silicified. Remnants of the silicified parts of the organic framework, which were not dissolved during cementation phases 1 and 2, grow during silicification by accretion into authigenic euhedral quartz crystals of ca. 10 microns or into quartz aggregates. The process of dolomitization, which can occur together with cementation, stops during precipitation of silica and is locally even reversed because of the excess of Ca-ions liberated by silicification. Dolomite crystals grown in micrite containing silicified tiny tubes also appear to be partially, sometimes completely, silicified. The silicified tubes probably acted as centers of attraction for the silica and thus facilitated the silicification of dolomite. Normally dolomite is not as readily silicified as calcite. Supporting this hypothesis are:

1. observations of algal flocks from insoluble residues of the LSW algal limestones,
2. observations of dissolved ultra-thin sections of the LSW algal limestones,
3. observations of algal flocks from insoluble residues of a recent intertidal algal mat, and
4. reports in literature.

Evidence from dissolved samples and dissolved ultra-thin sections

A report on non-calcareous algal flocks from insoluble residues of the LSW algal limestones has been published earlier (de Meijer, 1969). Remarks concerning the present subject of silicification can be quoted from this report (p. 237):

"In all samples the Algae are found in a coherent granulate or vermiculate mass of earlier mentioned framework elements. Dispersed in this mass euhedral quartz and dolomite crystals are commonly found".

(p. 239):

"The framework seen in peels, colored thin sections and dissolved thin sections of algal boundstones consists of minute tube-like elements also encountered in the algal flocks. They form the coherent mass of the algal flocks and frequently stick to the filaments in such quantities as to cover them totally. Maybe they are comparable to the felts of *Schizotrix* overgrowing larger algal filaments as observed by Monty (1967, Plate 6–2 and 6–3)".

The above-mentioned paper only covers the presence of euhedral quartz crystals in the algal mass. Continued investigations on the algal flocks have shown that part of the tiny algal tubes, both in the framework and sticking to the larger algal filaments, are silicified and appear as tiny tube-like quartz crystals generally 5 microns long and 1 micron or less thick. In addition aggregates of quartz with inclusions of the tubular framework have been observed.

The algal flocks differ from sample to sample when the algal limestones are dissolved. In some samples small quantities of algal flocks appear locally on the sample surface; on the surfaces of other samples, they appear everywhere in large quantities. The question therefore arises: what is the relationship between algal limestone textures and their non-calcareous Algae content. To investigate this, ultra-thin sections were dissolved and studied. Ultra-thin slides from the LSW samples were prepared to eliminate three-dimensional effects in the residue after dissolution. The cement fixing the rock to the slide has to be removed since its presence blurs the picture of the residue after dissolution. The cement used in the preparation of slides in the laboratory of the Geological Institute of the Leiden University is a thermoplastic cement. Soaking the thermoplastic cement in 90% industrial alcohol for 24 hours gives good results. The thin section can easily be separated from the slide. To be sure no remnants of cement cling to the thin section, the solution is poured off and fresh alcohol is added. After one hour the isolated thin section is washed carefully first in alcohol, then in distilled water. Finally the thin section is dissolved in a very weak solving agent, a 2.5% solution of Na_2-EDTA. Escaping bubbles which might destroy the ultra-thin section are thus avoided. The dissolution can be carried out on a slide if the solvent is regularly replenished. After some 2 to 3 hours the ultra-thin section is completely dissolved, leaving a membraneous insoluble residue. The solvent has to be sucked away with a dropper and remnants of the solvent must be washed away carefully since on drying the solvent crystallizes. The chance is great that the residual membrane will be destroyed during these manipulations. This also holds for the subsequent adding of glycerine and covering with a cover glass.

It appears that after dissolution a membrane is left with the same characteristics as the groundmass of the non-calcareous algal flocks, i.e. a network of organic tube-like elements. Ultra-thin sections of mechanically deposited limestones from various localities and with different ages were prepared for comparison. Once again dissolution resulted in a membrane of organic matter and insoluble particles of other composition (quartz, iron, minerals etc.). The residual organic matter in these membranes however does not form a network of tiny tubes. It comes closer to resembling an assemblage of dead bacteria [20]. The only relationship

[20] This is only a comparison to indicate what these membranes look like. The present writer does not wish to state that this residual organic matter in fact originated from bacteria although the possibility is not excluded.

that could be detected between algal limestone textures and associated non-calcareous Algae is the common presence of an organic network of minute tubes. A relationship between the occurrence of larger non-calcareous algal filaments or algal cells and specific algal limestone textures could not be established. The coherence of the organic framework in the residual membrane is not always equally good; it is the greatest where larger non-calcareous algal filaments have also been preserved. This explains the restricted local appearance of non-calcareous algal flocks in some of the algal limestone samples.

In the organic frameworks of the residual membranes, as in the algal flocks, it has been observed that some of the tubes have been silicified and appear as tube-like tiny quartz crystals. Aggregates of quartz with inclusions of tubes and euhedral quartz crystals with inclusions of tubes have also been observed.

Evidence from a recent algal mat

A recent laminated algal mat was collected [21] from the lower intertidal zone of the northern shore of the Awa di Oostpunt Bay on the southeastern tip of Curaçao (Netherlands Antilles). When this mat was collected it was calcified to such a degree that it easily carried the weight of a person, although it felt rubbery. After drying it consolidated into a friable laminated calcareous rock. The insoluble residue of this rock contains abundant non-calcareous algal flocks, comparable to fossil algal flocks. The groundmass of the recent non-calcareous algal flocks is composed of felts of tiny filamentous *Schizothrix* sp., a cyanophycean Alga, and closely resembles the groundmass of fossil algal flocks. Another phenomenon, which is of great interest, is the fact that numerous filamentous and unicellular Algae clearly show silicification. The optical identification was affirmed by an X-ray diffraction diagram of the algal flocks, which showed lines typical of quartz although somewhat vague (Felius, pers. com.). Silicification of the groundmass of tiny *Schizothrix* filaments appears to be cloudy or patchy as a whole, but in the individual filaments the c-axis of quartz is always oriented parallel to the long direction of the filaments. The same orientation can be observed in the larger filaments, whereas, in the spherical unicells the c-axes of the quartz crystals are radially oriented.

The fossil non-calcareous algal flocks of the LSW algal limestones lack silicification of the larger algal filaments and unicells. Only *Schizothrix*-like tiny tubes appear to be locally silicified. On the other hand euhedral quartz crystals are frequently present in the fossil non-calcareous algal flocks, whereas in the recent non-calcareous algal flocks they are usually absent. If one assumes that the silicification of the LSW algal limestones was analogous to and as early as the silicification of the recent algal mat, then the quartz must have gone into solution again during diagenesis. On reprecipitation the quartz formed euhedral crystals, preferentially with silicified tiny algal tubes as nuclei.

Evidence from literature

The above-mentioned observation is not the only one of recent silica precipitation. The Coorong Lagoon and associated lakes of South Australia, already famous because of the reports on recent dolomite formation (Alderman and Skinner, 1957; Skinner, 1963), once more came into the news as a result of the discovery by Peterson and Von Der Borch (1965) of recent deposition of inorganic chert in this area. The following is quoted from their report (p. 1502):

> "The pH of lake water commonly rises to 10,2 during active photosynthesis by *Ruppia maritima* Linn.; the brine just as it approaches maximum concentration and either dries or sinks into the mud, has pH of about 8,2. Beneath the surface of the sediment there is a zone of rotting vegetation in which the pH of interstitial solutions is as low as 6,5. It is more or less at the boundary between these two pH realms that opaline silica is most obviously precipitating on the surfaces of the hardened plates".

Walker (1962) discussed the replacement relationship between carbonate and silica minerals from ancient rocks and he reported laboratory data from Correns (1950), Alexander et al. (1954), Krauskopf (1956, 1959), Okamoto et al. (1957) and Siever (1957) concerning relative solubilities of amorphous silica and $CaCO_3$ in water of varying pH. No experimental data are available concerning the relationship between pH and the solubility of quartz and other forms of crystalline silica which occur in chert. Walker, however, assumed that these minerals, except for a lower solubility, behave similarly to amorphous silica and stated:

> "These data suggest that chert-carbonate replacement reversals may take place where fluctuations of pH occur under conditions of high alkalinity (above pH9). In highly alkaline water even a slight increase in pH would favor solution of silica from chert and simultaneous precipitation of $CaCO_3$, whereas a decrease in pH would favor the reverse relationship – solution of carbonate and precipitation of silica".

Walker believed that natural waters of high pH might be more common than published records indicate. One of the natural waters of high pH he mentioned is the Coorong Lagoon. Baas Becking et al. (1960) plotted the pH/eH relationship for natural environments based on some 2000 measurements. High pH surface waters were found to be related to the photosynthesis of plant life. These authors state the following about the influence of Algae on their environment (p. 267 and p. 268):

> "respiration and photosynthesis are primarily active upon the carbon dioxide equilibrium. Photosynthesis will remove carbon dioxide, whether as H_2CO_3 or as HCO_3- from the solution, thus increasing the pH. In sea water and in fresh water, containing much calcium, photosynthesis will, by shift of the bicarbonate-carbonate equilibrium, often cause the precipitation of calcite (Baas Becking, 1934) or of dolomite (Alder-

[21] The sample was collected by Dr. C. G. van der Meer Mohr (Leiden) in the scope of his investigations on recent carbonate sedimentation in the Netherlands Antilles, a project supported by WOTRO.

mann and Skinner, 1957). The pH will rise to 9.2–9.4 after which the solution is buffered, and, inasmuch as the effect of photosynthesis is diurnal, it never lasts long enough to precipitate all the calcite or dolomite. However, if the alkaline earths are present in small quantities, as in certain fresh waters and alkaline evaporites, almost all the calcium and magnesium will disappear from the water, and at the end of the day we may get "flashes" of high pH values".

In reference to this data Dapples (1967, p. 327) made the following statement:

"Where an Algae matte is growing on carbonate sediments, periodically exposed to the atmosphere, interstitial waters attain high pH values; and in these waters concentrations of silica could be exceptionally large".

It seems quite probable that in the case of the LSW algal limestones and the recent algal mat of Curaçao, high pH waters were created by photosynthesis of the Algae and that consequently high concentrations of silica were held in solution, which precipitated when conditions of pH changed. The source of the silica may have been siliceous organisms and/or detrital quartz or other silicate minerals. As for the later diagenetic behavior of the silica, the following remarks by Baas Becking et al. (1960, p. 276) are of interest:

"The third manner of exceeding the normal surface limits is by burial of sea water in strongly reducing sediments. If the water becomes truly isolated to connate, removal of all its sulfate by reduction and all its calcium, magnesium, and carbonate or bicarbonate by precipitation can yield a water rich in sulfide with an extremely high pH. In Searles Lake California, the bottom salt brines reach pH 10,48, where the surface waters are around 8,5–9,0. The process goes even further in the case of the connate water from northern California, mentioned on page 263, with a pH of 11,6. We do not know what the ultimate limits of this process will be. Clearly they may be of great importance in the diagenetic transportation of silica, which has been shown by Krauskopf (1956) to increase its solubility tremendously above pH 9. The California water, by way of example, contains 4.000 p.p.m. silica as opposed to the general fresh water concentration of under 20 p.p.m.".

It is assumed that the quartz observed in the algal flocks of the recent algal mat will go into partial solution as the pH of the connate water increases. This would explain the lack of silicification of larger non-calcareous algal filaments and unicells in the algal flocks of the LSW algal limestones. Changing pH conditions after sharp-edged fracturing, probably connected with tectonism and uplift of the sediments, caused reprecipitation of the silica and therefore silicification of sparry calcite and skeletons and the formation of euhedral quartz crystals around remnants of silicified tiny algal tubes.

CARBONATE SOLUTION

Three categories of solution are distinguished: (1) void creating solution, (2) voidless solution, and (3) neomorphic calcite creating solution. The first two categories are defined according to Schmidt (1965). Void creating solution of carbonates leaves open voids, which in the LSW limestones are subsequently filled with pore-filling calcite. Voidless solution dissolves carbonate constituents; the resulting space is immediately occupied by the surrounding sediment. The third category is closely related to the first, but differs in that the space left by solution is not completely open but is occupied by undissolved remnants which, upon impregnation with calcium carbonate-rich solutions, change into neomorphic calcite.

Void creating solution

In general the void creating solution is related to crumbly fractures and pre-existing pores, such as constructed voids and inter-allochem pores, connected by these fractures. As a result of solution, allochems are dissolved and existing pores enlarged; pore networks are created. According to the degree of solution different pore networks can be distinguished: (1) pore networks of constructed voids and inter-allochem pores, connected by crumbly fractures; there is no evidence of extensive solution, (2) pore networks of constructed voids, inter-allochem pores and allochem solution pores, connected by crumbly fractures (Pl. I, Fig. 5); there is only selective solution of allochems, (3) pore networks of constructed voids, inter-allochem pores and allochem solution pores, some or all being enlarged by indiscriminate solution of both allochems and micrite (Pl. XI, Figs. 6, 7, 8; Pl. XIV, Figs. 7, 8).

Void creating selective allochem solution and void creating indiscriminate solution seem to have some relationship with algal-bound pseudostromatic limestones. Support by an organic framework, rapid consolidation, initially rather high porosity due to the presence of constructed voids, and spongy precipitation of calcite micrite in the organic mass probably facilitated the void creating solution. The similar relationship between selective allochem solution, presence of support and an originally high porosity of the limestone was observed by Schmidt (1965), who found that in the Jurassic Gigas Beds (northwestern Germany) the calcarenites with an originally high intergranular porosity are the only limestones in which significant selective and void creating solution of allochems took place.

The above-mentioned pore networks are all filled with the same generation of pore-filling calcite, generation 1b. The solution and subsequent filling with calcite preceded sharp-edged fracturing, which is indicated by the clearly transecting nature of the latter.

Neomorphic calcite creating solution

Some neomorphic calcite patches, resulting from this type of solution, resemble small scale karst pits and are clearly related to crumbly fractures. The form and size of the neomorphic calcite patches and the relatively clearly defined borders are suggestive of solution. In fact, if the same patches had filled with clear calcite, arranged according to the "Bathurst Law" for pore-filling calcite, they would have been identified as indiscriminate solution voids. The solution however was not enough to create open spaces, which subsequently could be filled with pore-filling mosaics of clear calcite, but instead leached the micrite sustained by an algal framework. The latter prevented much of the micrite from being washed away and a framework was left of undissolved remnants which, compared with the surrounding micrite, was highly porous. As soon as the percolating solutions became rich in calcium carbonate, impregnation of this highly porous framework resulted in the formation of pseudospar. That the solution was ineffective is probably due to the fact that many of the crumbly fractures related to this type of solution are microscopically small fractures, called recrystallization veinlets by Misík (1968), see the section "pseudospar". In the discussion on these recrystallization veinlets, the role of solution was not elaborated and will therefore be given more attention below.

LSW 43. Neomorphic karst pit-like calcite patches clearly related to solution. A recrystallization veinlet/solution channel runs through *Archaeolithophyllum,* which clearly shows dissolution in some places and recrystallization in others. Where dissolution occurred the channel has filled with pore-filling clear calcite. Adjacent to the latter, pseudosparitic areas can be observed with relicts of hypothallus and perithallus cells.

LSW 69. Neomorphic karst pit-like calcite patches (Pl. VI, Fig. 3) connect with recrystallization veinlets transecting allochems, which are usually pseudosparitic at the point of transection with relicts of the microstructure preserved in the pseudospar (Pl. VI, Fig. 2). However, there are some allochems without relicts and the calcite of the transecting veinlet is clear, suggesting pore-filling calcite. Probably this indicates local solution.

LSW 72. Neomorphic karst pit-like calcite patches with floating bioclasts debouch into desiccation cracks connected with constructed voids of a pseudostromatic body, enveloping *Archaeolithophyllum* sp. (Pl. VI, Fig. 6). The desiccation cracks are short and probably end in microscopically small fractures. Percolating waters running through the latter caused neomorphic calcite creating solution. Solution is evident from "eaten" allochems in the patch of neomorphic calcite; relicts were not preserved in the adjacent locally clear calcite. Voids in *Archaeolithophyllum* are equally indicative of solution.

Neomorphic calcite creating solution was mentioned previously in the section "pore-filling calcite". In this section the possibility has been discussed that some neomorphic molds may be pore-fill molds of heavy micritized allochems, which leave a coherent algal framework after dissolution. Neomorphic calcite creating solution has also been observed together with void creating indiscriminate solution. The latter leaves local leached patches of algal-bound micrite, which after subsequent impregnation with calcium carbonate-rich solutions changed to neomorphic micrite, pseudospar or pore-filling calcite with micrite inclusions (Pl. XIV, Fig. 8).

Voidless solution

Voidless solution in the LSW limestones is revealed by the following phenomena: (1) embayed contacts between allochems, (2) solution stringers in the micrite, (3) stylolites.

Embayed contacts between allochems. – In packstones where grain-support is not simultaneously sustained by an algal framework, i.e. the mechanically deposited packstones, the pressure of the overburden is transmitted from allochem to allochem and results in pressure solution at the contacts between the allochems (Pl. XVI, Fig. 4). Along with this process, the packing becomes denser and the planes of contact between the allochems more numerous. Sample LSW 37 (Pl.II, Fig. 7) provides an example of this process. Due to compaction, leading to pressure solution and exceedingly close packing, the ooids are arranged in a polygonal mosaic of pressure solution contacts.

Crumbly fractures transect the pressure solution contacts and indicate that compaction and pressure solution occurred before crumbly fracturing. In other samples however it has been observed that pressure solution along the allochem contacts continued and led to offset of the crumbly fractures. Another indication that compaction and the resulting pressure solution started early is the presence of crushed bivalved brachiopods and other organisms with large intra-allochem pores. These obviously were not filled with calcite before since the space, now occupied by the broken remnants, is much smaller than the original pore space (Pl. III, Figs. 6, 7, 8; Pl. XIII, Figs. 4, 8). This reduced pore space was filled later partly by the adjacent sediment and partly by pore-filling calcite of generation 1b. Reduction of the pore space after pore-filling is not probable as there are no indications of voidless solution in the pore-filling calcite.

In packstones resulting from compaction of mechanically deposited wackestones the allochems came into contact with each other after voidless solution of the micrite matrix. The voidless solution generally continued at the new allochem contacts.

Solution stringers in micrite. – Solution stringers are zones of concentration of insoluble residue, resulting from voidless solution in micrite. Solution stringers are generally parallel or subparallel to the bedding, although directions contrary to gravity may result from draping around allochems or other bodies resisting compaction, such as pseudostromata (see indications of binding 4 and 5, chapter IV). Like the embayed contacts, the solution stringers are the result of compaction and consequently are most numerous in mechanically deposited micrites (see indication of binding 4, chapter IV). The solution stringers preceded sharp-edged fractures since they are always clearly transected by the latter. Occasionally however, it has been observed that solution continued along some of the stringers resulting in offset of a sharp-edged fracture.

The solution stringers preceded pore-filling with calcite generation 1b since the compaction causing solution stringers in mechanically deposited lime mudstones and lime wackestones crushed fossils not yet filled internally with this calcite generation.

One sample, LSW 34 (Pl. II, Figs. 3, 4), contains a set of parallel solution stringers intermediate, in age and characteristics, between solution stringers and stylolites. They resemble stylolites because they affect both micrite and allochems equally, and because they do not follow the bedding plane. They resemble solution stringers because they are parallel to each other. These transitional solution stringers are perpendicular to the bedding plane and are found together with normal solution stringers parallel or subparallel to the bedding plane or draped around compaction-resistant bodies. The normal solution stringers are confined exclusively to mechanically deposited micrite and are never found in pseudostromata. The transitional solution stringers are regularly spaced and parallel to each other; they transect allochems, pseudostromata and mechanically deposited micrite. Locally they disturb the laminated appearance of the mechanically deposited micrite by dissection and offset of the normal solution stringers.

Stylolites. – Stylolites are sharply crenulated lines, along which allochems, micrite and sparry calcite are dissolved indiscriminately. Generally the stylolites are oriented at various angles with respect to the bedding plane in contrast to the solution stringers. Furthermore they differ from the solution stringers in age of formation, which is clearly late anadiagenetic and epidiagenetic since sharp-edged fractures are transected by stylolites and show offset. Occasionally voidless solution along solution stringers has continued, locally giving rise to stylolites.

FRACTURES

Three types of fractures are distinguished: (1) crumbly fractures (Pl. XVI, Fig. 7), (2) sharp-edged fractures, (3) desiccation or syneresis cracks.

Crumbly fractures and sharp-edged fractures

The terms crumbly fracture and sharp-edged fracture are borrowed from a paper by Dunham (1969, p. 141), although in this thesis the definition is slightly different. According to Dunham, crumbly fractures are similar to those produced when a friable beach rock is broken between the fingers; crumbly fractures break around strong allochems. Fractures with sharp-edged walls break through the allochems – the sharp-edged fractures of Dunham – indicating that the rock was cemented strongly enough to yield such fractures. The definition most suited for the LSW limestones must provide a reasonable basis for distinguishing between fractures, which are syndiagenetic to early anadiagenetic and form a part of pore networks (crumbly fractures), and fractures, which are late anadiagenetic and probably related to tectonism (sharp-edged fractures). In this definition crumbly fractures possess walls which generally are crumbly, but which occasionally may be rather sharply outlined. Their walls, when fitted together, do not match. This latter feature distinguishes them from sharp-edged fractures, whose sharp-edged walls always match when fitted together. Crumbly fractures originated after the start of the lithification of the limestone but before the completion of the cementation with pore-filling calcite generation 1b. Some difference in age therefore does exist among the various crumbly fractures. This is clear from the walls which vary from crumbly to rather sharply outlined. It is suggested that crumbly fractures with rather sharply outlined walls originated at a time when the rock was more strongly cemented [22]. In addition these younger crumbly fractures, instead of leaving the allochems intact and breaking around them, cause a microscopically small fracture which results in neomorphism of the allochem, generally in the form of pseudospar. Transection of allochems by fractures, however, depends not only on the degree of cementation of the limestone but also on the resistance of the allochems. Some early crumbly fractures have also been observed to break through allochems, causing a neomorphic zone in them. These fractures with different ages have been grouped together as crumbly fractures since it appears that all of them form integrated mosaics with calcite generation 1b, which fills the pores often connected by these fractures to form pore networks. Crumbly fractures have been observed to break through pore-filling calcite generation 1a, which means that they originated after this initial stage of cementation. Usually pore-filling calcite generation 1a is absent and initial cementation before crumbly fracturing is not always obvious, but is deduced from the simple fact that in uncemented soft sediment fracturing would not create an open space. From the fact that crumbly fractures connect allochem solution voids and indiscriminate solution voids, it is evident that crumbly fracturing was accompanied by physical or chemical removal of carbonate. The crumbly surface of the walls and occasionally their wide separation also suggest solution, although in many cases these phenomena could also be explained by the fact that most of the sparry calcite of the crumbly fractures is neomorphic, caused by impregnation of still porous limestone by calcium carbonate solutions (neomorphic calcite creating solution). The occurrence of pseudospar and neomorphic micrite along the walls indicates that the latter process was active, whereas widely separated crumbly fracture walls with distinct borders between the transected rock on one side and pore-filling calcite on the other indicate that solution and internal erosion were more effective. Generally, however, both processes were active simultaneously or nearly so.

Crumbly fractures are generally transected by sharp-edged fractures, which therefore must have formed later. The sharp-edged fractures originated after the rock was completely cemented by pore-filling calcite generation 1b. Their formation covers a considerable space in time as can be deduced from their age relationship, which indicates several generations of sharp-edged fractures (Pl. VI, Fig. 1). Sharp-edged fractures are probably related to tectonism since they are often seen in sets of parallel fractures.

[22] Crumbly fractures with different walls in one sample may also be indicative of different stages of cementation of the same rock at the same time.

Desiccation or syneresis cracks (Pl. II, Fig. 1; Pl. V, Figs. 3, 4)
This category is distinguished by means of comparison with recent desiccation phenomena. Desiccation or syneresis cracks generally possess rather sharp-edged, parallel walls and in this respect resemble sharp-edged fractures, but they differ from the latter because they are short. Another difference is that they do not occur in parallel sets. They generally rise vertically from the surface of those allochems which did not follow the shrinking of the surrounding sediment. Desiccation or syneresis cracks appear to be more or less synchronous with crumbly fractures since they too may connect constructed voids to form pore networks. In some samples desiccation or syneresis cracks and crumbly fractures appear to form part of the same pore network, filled with calcite generation 1b.

CHAPTER VI

CONCLUSIONS

DEPOSITIONAL TEXTURES

1. In the LSW section, algal-bound lime wackestones are by far the most important, followed by the algal-bound lime packstones. Lime grainstones were not found. Ca. 12% of the carbonate samples are either not algal-bound or indeterminate. The mudstones have the highest percentage of non algal-bound carbonates.
2. Three types of algal-bound lime packstones can be differentiated: (a) algal-bound intergrowth lime packstones, (b) algal-bound non-intergrowth lime packstones and (c) intermediate algal-bound lime packstones.
3. In three cases the algal-bound intergrowth lime packstones are found in sequences of samples and are therefore thought to be calcareous Algae bioherms. These sequences are: LSW 150 (?), 149, 148, LSW 45, 44, 43 and LSW 36 to 33/2. The latter two, situated in the uppermost part of the section, show lens-like terminations in the field at the location of the section and border on terrigenous sediment. Flank deposits were not observed. The first, situated in the lower part of the section can not be distinguished in the field from the surrounding limestone. LSW 36 to 33/2 and LSW 45, 44, 43 are made up of skeletal intergrowth frameworks of the rhodophycean (incertae sedis) Alga *Archaeolithophyllum missouriensum* Johnson, 1956. Dasycladacean and codiacean Algae and bryozoans are associated with the *Archaeolithophyllum* intergrowth. *Archaeolithophyllum* is encrusted by Foraminifera and calcareous algal tubes embedded in a dark algal micrite coating. Both erect, branched forms and encrusting plate-like forms of *Archaeolithophyllum* are seen. Pseudostromata developed in protected niches of the intergrowth framework or under encrusting forms of *Archaeolithophyllum*. LSW 150(?), 149, 148 is a "meadow" of intergrown dasycladaceans, *Dvinella comata* Chvorova, 1949. The rhodophycean (incertae sedis) Alga *Ungdarella* sp., fusulinids and pseudostromata are associated with the *Dvinella* intergrowth.
According to Johnson (1961), who summarized the data of Pia (1920), Taylor (1950) and Johnson, the dasycladaceans range in depth from about low tide level down to 10 or 12 meters. The most luxuriant growths of dasycladaceans are found just below tide level to depths of about 5 or 6 meters. The presence of dasycladaceans in the LSW bioherms therefore is probably indicative of a depth between low tide level and 12 meters. A rather quiet environment (lagoon floor) is suggested by the presence of codiaceans, bryozoans and plate-like forms of *Archaeolithophyllum* encrusting mechanically deposited wackstone masses, eventually compressed into packstones. The "meadow" of intergrown *Dvinella* specimens also suggests a quiet environment. On the other hand a more turbulent environment might be reflected by the erect, branched forms of *Archaeolithophyllum*, the occurrence of encrusting Foraminifera on these Algae and the occurrence of pseudostromata preferably in protected places. The latter however may also indicate that intergrowth frameworks and encrusting calcareous Algae effectively protected the non-calcareous Algae against intense sunlight. It has been argued that on firm substrates under turbulent conditions and a sparse supply of debris, sediment could only be built by skeletal intergrowth frameworks and/or entrapment by plants. The composition of the lens-like bioherm of LSW 45, 44, 43 is thought to reflect increasingly turbulent conditions. Summarizing, the LSW bioherms, as well as the other algal-bound intergrowth packstones, were probably built in an environment which varied from a quiet lagoon floor to the more turbulent conditions near shore.
4. The following algal-bound non-intergrowth packstones are interpreted as carbonate sands invaded and bound by Algae, like the recent crusty flakes (Monty, 1967): LSW 28, 42, 56, 60, 64, 71, 77, 156, 162, 164, 165, 168, 169, 171, 176, 181, 182 and 191. Recent crusty flakes are found in quiet intertidal settings.
The algal-bound non-intergrowth packstones LSW 129, 142, 158, 177 may be either entrapment or agglutination mats (non laminated) or crusty flakes; they were formed either on the lagoon floor or in quiet intertidal settings.
5. The intermediate type of algal-bound packstones is rather varied, LSW 29, 87, 119 and 122 are mechanically deposited wackestones, which are sometimes seen as

packstones as a result of compaction. These mechanical deposits are encrusted by platy forms of *Archaeolithophyllum* or other Algae. They indicate an environment quiet enough for mud to settle in large quantities. The encrusting platy specimens of *Archaeolithophyllum* also suggest restricted turbulence. The depth as determined by the associated dasycladaceans is between low tide level and ca. 12 m.

LSW 72, 82, 124, 131, 187 and 188 show local intergrowhts in situ of rhodophyceans (incertae sedis), codiaceans, dasycladaceans and bryozoans, associated with pseudostromata which occasionally form pseudostromatic or autochthonous oncolitic algal coatings around the organisms in situ. Around the intergrowths in situ skeletal and non-skeletal carbonate debris was deposited, which was entrapped, agglutinated or bound by non-calcareous Algae. A lagoon floor with restricted turbulence is indicated by these packstones.

6. The mechanically deposited non-intergrowth packstones LSW 37, 153 and 183 owe their lime-mud content to precipitation of micrite by Algae. However the algal binding was not sufficient to create a supporting framework. Possibly these samples represent channel deposits between or within algal banks.

The mechanically deposited non-intergrowth lime packstone LSW 150 contains intraclasts in exceedingly close packing, possibly a result of the gradation in size from micrite to 4 mm as well as compaction. LSW 150 may represent a deposit caused by an accidental storm. The source rock of the intraclasts may have been either a bioherm like LSW 148 and 149 or a crusty flake. Both source rocks were probably lithified during syndiagenesis. This explains the angularity of the intraclasts.

7. Algal-bound lime mudstones and wackestones mainly consist of pseudostromata. Local growths in situ and local intergrowths in situ, generally of calcareous Algae, are frequently included. Local algal mat laminations are less frequent. Intergrowths in situ and local growths in situ are indicative of stable substrates, permitting colonization of the bottom. Depending on the turbidity of the environment these stable substrates may have been soft or firm. A number of algal-bound limestones show lack of mixing at their contact with overlying sandstones. Thus they formed firm substrates which resisted mixing, a feature which might be applicable for all other algal-bound limestones. The stable substrate indicated by the local intergrowths in situ or local growths in situ can therefore be assumed to have been firm in most cases. The abundant pseudostromata, resulting from micrite precipitation in non-calcareous algal masses, indicate a stable substrate in a quiet environment. They can withstand turbulence if the supply of sediment particles is low. The local intergrowths in situ and local growths in situ consisting of rhodophycean (incertae sedis), codiacean, dasycladacean Algae and bryozoans in association with calcareous algal tubes and pseudostromata suggest a lagoonal environment. Lagoonal life could supply enough debris to cause a substrate of shifting skeletal sands under turbid circumstances. This would have been a threat to the colonies of non-calcareous Algae. Therefore the most probable environment for the algal-bound lime mudstones and wackestones is a quiet lagoon floor.

The pseudostromatic algal bioherms, indicated by the algal-bound lime mud and wackestones, continued growing while terrigenous sediments were deposited laterally (see LSW 42 to 39). Probably the pseudostromatic algal bioherms formed slightly elevated platforms and thus were protected from burial by the terrigenous sediments as long as the algal growth could keep up with the supply of sediment. Flank deposits of pseudostromatic algal bioherms were not found. LSW 37 (see conclusion 6) represents a transition between carbonate deposition and deposition of sandstone. When the accumulation of terrigenous sediments had reached the level of the pseudostromatic algal bioherm, the growth of algal colonies was threatened by the shifting sands. Algae could then only colonize the individual grains of the shifting sands (algal coating).

8. Colonization of quartz sand bottoms indicates quiet conditions. Limestones from immediately above the contact, 4 lime mudstones (1 not algal-bound), 9 lime wackestones (2 not algal-bound) and 13 lime packstones (1 not algal-bound) are, if algal-bound, indicative of quiet conditions which permitted colonization of the sandy substrate. A number of algal-bound packstones show by their admixture of sand-sized quartz grains that currents, strong enough to deliver small amounts of terrigenous sand-sized material, were still active during the first period of their formation. Non-calcareous Algae, probably cyanophyceans, were the first to colonize the sandy substrate. In a number of cases calcareous Algae are also found among these pioneers. In only two cases were skeletal intergrowth frameworks formed directly on a sandy substrate.

9. Three of the most important allochems in the limestones of the LSW section are algal products. It is remarkable that of the twenty limestones not algal-bound, 11 samples show that the allochems responsible for the grain bulk of the sample are all non-algal and that in the other 9 samples, non-algal allochems are as frequent as algal allochems.

10. Calcareous rhodophycean (incertae sedis) Algae are abundant throughhout the entire LSW section. The following sequence of species was noted

Archaeolithophyllum missouriensum Johnson, 1956
Komia abundans Korde, 1951
Ungdarella sp.

This sequence of rhodophyceans does not indicate varying depths since dasycladaceans and to a lesser degree codiaceans are always associated with them.

DIAGENETIC TEXTURES

1. Internal sediment in intra-allochem pores was deposited syndiagenetically, like most of the internal sediment in constructed voids. The latter was also deposited after the formation of a fibrous crust of pore-filling calcite generation 1a, thus probably some-

what later during syndiagenesis. Internal sediment in solution voids is either later than both internal sediments mentioned above or contemporary with the internal sediment in constructed voids if deposited after solution and creation of the pore network containing the constructed voids. It is also possible that the internal sediments of solution voids and constructed voids in one and the same pore network will differ in age. This occurs when the older internal sediment in constructed voids was not washed away by percolating solutions, but remained because of early consolidation.

2. The original depositional carbonate was probably a mixture of high-magnesium calcite and aragonite. The high-magnesium calcite was supplied predominantly by algal precipitation and to a lesser degree by high-magnesium skeletons. The aragonite was supplied by aragonitic skeletons. It can be assumed that the original mineralogy was lost during diagenesis and changed to a stable low-magnesium calcite.

3. Micritization of allochems is a general phenomenon in the LSW limestones. It was caused by syndiagenetic algal boring accompanied by bacterial processes.

4. Neomorphism in mechanically deposited micrites is common. It is most clearly visible in the mechanically deposited micritic internal sediment of intra-allochem pores and solution voids. Algal-bound micrites generally show neomorphism in various stages of evolution. In some crusty flake-like algal-bound lime packstones and in some pseudostromata, neomorphism is advanced. In dense pseudostromatic algal micrites, neomorphism is visible only in ultra-thin sections under high magnifications. It resembles the porphyroid stage of neomorphism, described by Folk (1965, p. 22). It has been argued, however, that the evolution pattern of algal-bound micrites is different from that sketched by Folk for the mechanically deposited micrites. Most probably it is not correct to speak of a porphyroid stage since the larger calcite crystals are not phenocrysts but crystals of pore-filling calcite, crystallized from calcium carbonate-rich solutions which impregnated small pores in the micrite, sustained and kept open by an organic framework. The products of this impregnation process are neomorphic micrite, pseudospar and pore-filling calcite with micrite inclusions.

5. Several generations of pore-filling calcite can be distinguished. Generation 1a consists of a fibrous crust, which lines inter-allochem pores and constructed voids. This generation is present only on a limited scale and is thought to be indicative of subaerial exposure, quite soon after deposition.

Generation 1b forms the pore-filling mosaics of inter-allochem pores, intra-allochem pores, constructed voids, solution voids, desiccation or syneresis cracks and crumbly fractures. This generation led to the complete lithification of the limestones and is syndiagenetic and anadiagenetic. A sample from beyond the LSW section, from the southern flank of the Lois Syncline West, indicates that this generation may have filled the pores completely during syndiagenesis. In this sample (Pl. I, Figs. 1, 2, 4), however, there is ample evidence of subaerial exposure, which is known to cause rapid and complete lithification (cf. completely cemented recent beach rocks). The angular, lithified intraclasts of LSW 150 also show that pore-filling with calcite generation 1b and simultaneous neomorphism of micrite and allochems took place during syndiagenesis of the source rock (Pl. XV, Figs. 7, 8).

Generations 2a, b, c, etc. fill the several generations of sharp-edged fractures.

6. Replacement of quartz by calcite was found in algal-coated quartz grains and is most probably a syndiagenetic process, related to an increase in the pH above 9 under influence of algal photosynthesis and algal carbonate precipitation (see conclusion 9).

7. Dolomitization in the LSW samples was synchronous with cementation by pore-filling calcite generation 1b. Dolomitization on a small scale continued locally during cementation with pore-filling calcite generations 2. Whereas cementation by calcite is pore-filling, dolomitization is preferably a replacement process. In only one sample has a clear indication of pore-filling dolomite been found. Mechanically deposited micrite (1), algal-bound micrite, pseudospar and pore-filling calcite generation 1b with micrite inclusions (2), pore-filling calcite generation 1b (3) and allochems (4) have been selectively replaced in this order. Algal grains and algal pellets, however, appear to be as easily replaced by dolomite as algal-bound micrite.

The generally low dolomite content of 5 volume percent or less for most LSW limestones is explained as a co-product of neomorphism of originally high-magnesium calcite formed by algal precipitation. The LSW dolomitic limestones and dolostones might be explained by capillarity and evapo-transpiration, caused during an epidiagenetic interphase during syndiagenesis, or by refluction of hypersaline brines reacting with the sediment. The first mechanism requires subaerial exposure which cannot always be demonstrated for the LSW dolomitic limestones or dolostones. The second mechanism requires a periodic complete evaporation of the supernatant waters, desiccation and powdering of the precipitated salts and elimination of the latter by wind transportation, because no salts indicating hypersaline supernatant brines have been observed in the sediments of the LSW section. The second mechanism therefore also requires temporary subaerial exposure and a process to explain the absence of the salts. In the environmental reconstruction, either sea marginal sediments with dolomitic crusts or evaporating saline to hypersaline coastal lagoons and ponds full of algal plant life and permanently or intermittently cut off from the sea are applicable. Explanation of the dolomitization by these two mechanisms is only valid if the assumption is justified that dolomitization is syndiagenetic. Indications for this assumption were found in some dolostones. In general, however, it could only be determined that dolomitization occurred after crumbly fracturing and before sharp-edged fracturing and that it is more or less synchronous with cementation by pore-filling calcite generation 1b. In subaerially exposed carbonates, complete filling of the pores may be confined to syndiagenesis (conclusion 5); thus if it could be demonstrated that the dolomitic limestones and dolostones had been subaerially exposed, then syndiagenetic dolomitization could be rather safely assumed and an important condition for the two postulated mechanisms would be fulfilled.

Should the assumption of syndiagenetic dolomitization not be valid, many of the dolomitic limestones might also be explained by dolomitization caused by rising magnesium-rich connate waters, originating by expulsion from underlying clayey and silty sandstone beds during anadiagenesis.

8. Calcitization of dolomite is a general phenomenon and was probably caused by previous silicification of the LSW carbonates. There are no indications that calcitization of dolomite was caused by weathering. Calcitization of dolomite is late anadiagenetic to early epidiagenetic, later than sharp-edged fracturing and silicification. The original dolomite content of the LSW samples was higher than indicated next to the depositional texture column, but it is not possible to say how much higher.

9. Silicification of the LSW carbonates is usually not apparent at first sight because of the fineness of the replacing quartz particles. For the same reason it is difficult to express the silicification numerically in a volume percentage. The silica is thought to be of syndiagenetic origin, related to the ability of living algal mats to hold considerable concentrations of silica in solution in their interstitial waters. The process in the LSW limestones is thought to be comparable to silica precipitation in a recent algal mat of Curaçao and the recent silica precipitation in the Coorong Lagoon area of southern Australia. Later diagenetic changes led to re-solution and reprecipitation of the silica, perhaps several times, but the main phase of reprecipitation took place after sharp-edged fracturing.

10. Void creating solution occurred after crumbly fracturing and before cementation by pore-filling calcite generation 1b. Void creating solution either selectively affected bioclasts or indiscriminately affected both bioclasts and micrite. Connection of pre-existing voids and solution voids by crumbly fractures created pore networks. Void creating solution selectively affected limestones supported by an organic framework. The organic framework together with early consolidation by algal micrite precipitation supported the voids created by solution and kept them open.

Voidless solution, seen as embayed contacts between allochems and solution stringers in micrite, started during the early burial phase of syndiagenesis and continued during anadiagenesis. In particular the mechanically deposited limestones and the mechanically deposited patches intercalated in algal-bound limestones suffered voidless solution, which is caused by compaction. Most voidless solution along embayed contacts between allochems and along solution stringers in micrite ceased before sharp-edged fracturing.

Voidless solution along stylolites is late anadiagenetic and epidiagenetic and younger than sharp-edged fracturing.

11. Fracturing took place as soon as the consolidation process had advanced far enough for the limestone to be able to support an open space. Since algal-bound limestones can maintain constructed voids even during their formation, this means that fractures may have originated syndiagenetically in these limestones. The first fractures were desiccation or syneresis cracks and crumbly fractures. They are older than the general cementation with pore-filling calcite generation 1b, but younger than the initial cementation by algal micrite precipitation and by the fibrous crusts of generation 1a. Among the crumbly fractures differences in age occur. As the cementation by pore-filling calcite generation 1b continued the borders of new crumbly fractures changed to less crumbly or even rather sharply outlined, but they remained non-parallel. After cementation was completed and the porosity of the limestones greatly reduced, fractures originated with sharply edged, parallel borders. Several generations of sharp-edged fractures followed; they are late anadiagenetic and probably related to tectonism.

DEPOSITIONAL AND DIAGENETIC HISTORY

The conclusions drawn from the analysis of the depositional and diagenetic textures of the LSW limestones contribute to an interpretation of the depositional and diagenetic history of the limestones of the Lois-Ciguera Formation as a whole. Data from beyond the LSW section mentioned in the Introduction (chapter I), but not discussed in this paper, are used together with these conclusions to reconstruct the depositional environment. The sequence of diagenetic changes inferred from the analysis of the diagenetic textures is summarized in Fig. 12 for limestones with an epidiagenetic interphase shortly after deposition and in Fig. 13 for limestones lacking evidence of such an interphase.

The limestones of the Lois-Ciguera Formation are thought to have formed on a flat shallow platform, which was transected by channels supplying terrigenous sediment and which was periodically covered completely by these sediments. The carbonate platform was temporarily exposed, locally forming islands. Occasionally the subaerial exposure lasted long enough for vegetation to develop. The supply of terrigenous sediments from the west only occasionally penetrated to the eastern border of the area. Lack of sorting and rounding in the sandstones indicate that the sand was not transported by longshore currents. The shallow platform therefore is thought to have been somewhat isolated from the open sea probably by the islands resulting fromt the temporary and local subaerial exposure of the carbonate platform. Algal binding in lime mudstone and lime wackestone environments did not create wave-resistant bioherms but algal banks (cf. van de Graaff, 1970 – biogenetic banks) rising only slightly above the surrounding sediment and preventing the advance of terrigenous sediments. As soon as the supply and/or the shifting of these surrounding sedi-

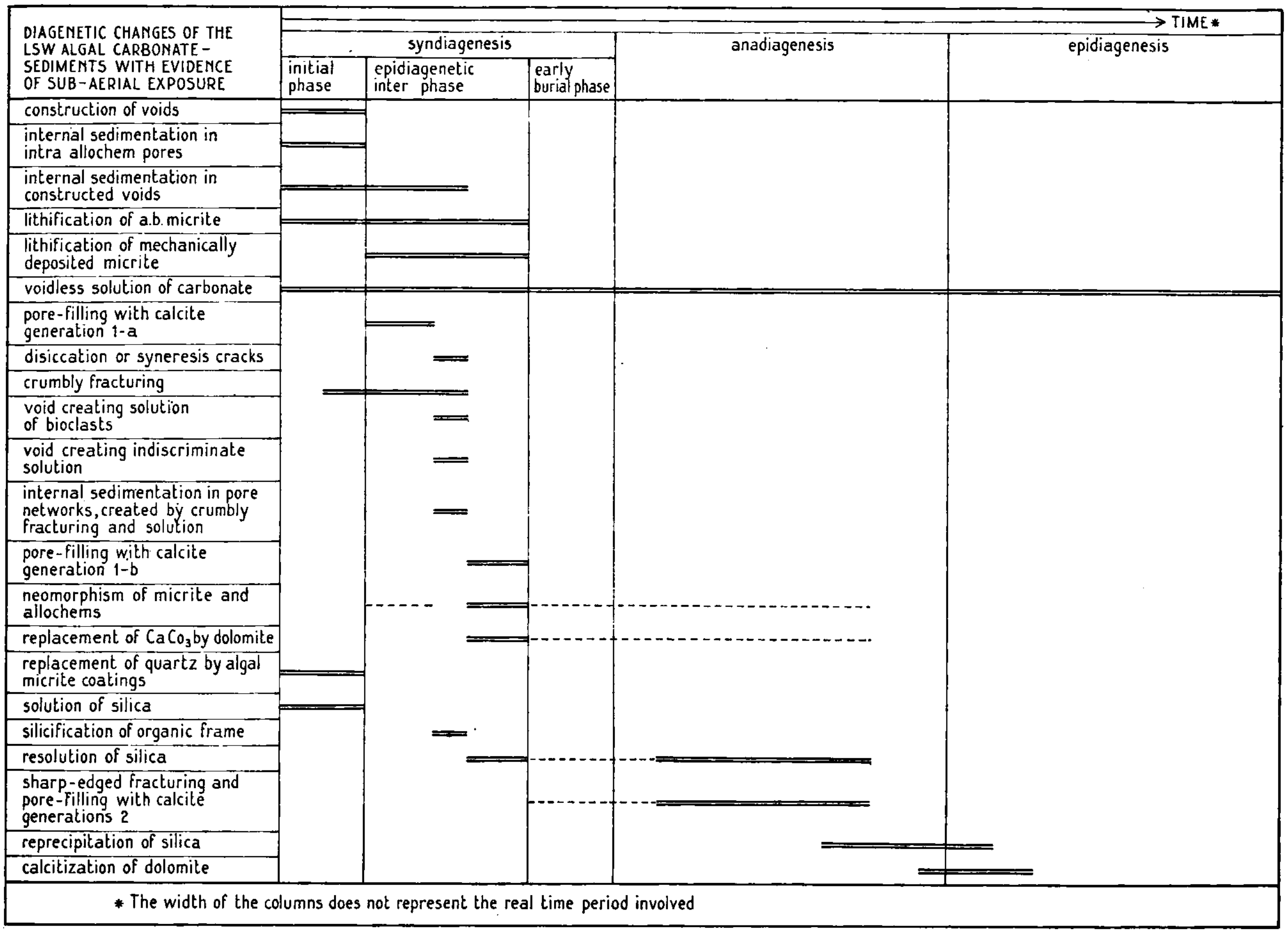

Fig. 12. Inferred time relationships of diagenetic changes in the LSW algal carbonate-sediments with evidence of subaerial exposure soon after deposition

ments ceased, they were colonized and the algal banks were extended laterally. On the other hand the formation of limestone was stopped by the abundant supply of terrigenous sediment. This mechanism was effective both vertically and horizontally. The presence of lenses of algal-bound limestone amidst terrigenous sediments indicates the capacity of algal communities to survive by creating their own stable substrate which probably rose slightly above the surrounding terrigenous sediments. Under turbulent conditions such a bioherm was built by intergrowing calcareous Algae. If algal growth could not keep up with the surrounding sediment supply, the community was killed and buried by terrigenous sediments.

Ponds and lagoons periodically cut off from the open sea or the sea on the shallow platform may have existed. Hypersalinity and reflux of the magnesium-enriched hypersaline brine, reacting with the carbonate sediment precipitated by Algae, may have resulted in and led to the formation of dolomite.

Temporary subaerial exposure of algal banks caused islands with beaches where carbonate sands were invaded and bound by Algae to form crusty flakes. The same islands provided porous sea-marginal sediments in which dolomite was formed by capillary action and evaporation. Around the islands, from low tide level down to ca. 12 m in the lagoon, calcareous Algae bioherms were formed.

The climate as indicated by the occurrence of dasycladaceans and codiaceans must have been tropical to warm temperate. Humidity is indicated by the recrystallization of crusty flake-like algal-bound packstones in analogy to the conditions of recrystallization of recent crusty flakes and the appearance of occasional vegetation on subaerially exposed islands.

Recent dasycladaceans and codiaceans are strictly marine whereas rhodophyceans have some tolerance for brackish water. Cyanophyceans have a very wide range of tolerance from hypersaline to fresh water. The salinity of the Lois-Ciguera sea will have been normal except in some isolated lagoons and ponds. The abundant supply of terrigenous sediments may have been accompanied by considerable refreshment of the water. When the area was completely covered by terrigenous sediments, as indicated by several thick, interbedded, widely distributed sandstone members in the Lois-

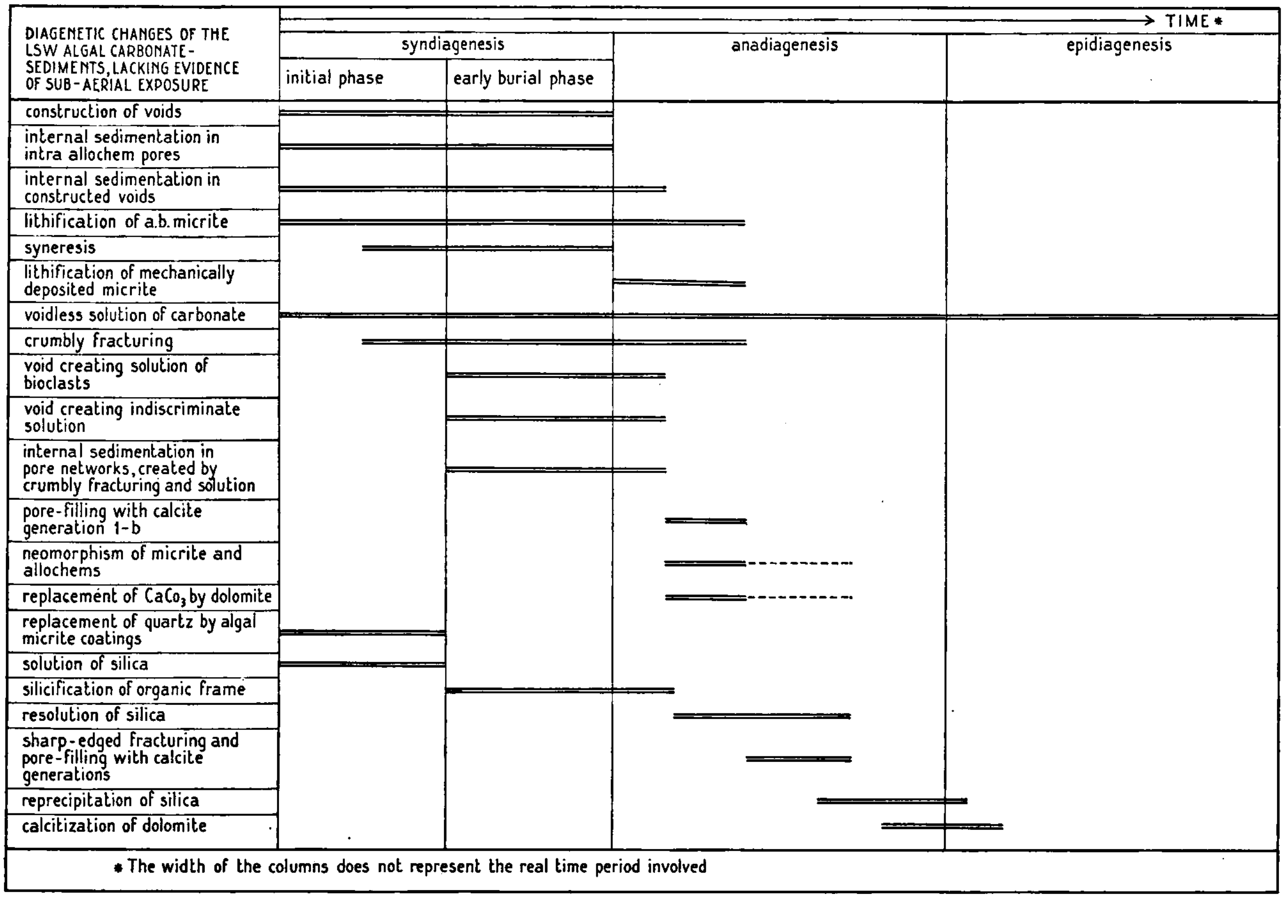

Fig. 13. Inferred time relationships of diagenetic changes in the LSW algal carbonate-sediments, lacking evidence of sub-aerial exposure soon after deposition

Ciguera Formation, the water may have been refreshed to such a degree that even during quiet periods (indicated by burrows) no significant colonization and consequent limestone building took place, since the number of species in these brackish environments was drastically reduced.

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