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T. J. A. Reijers (*).—DIAGENESIS IN THE REEFAL FACIES OF THE MIDDLE TO UPPER DEVONIAN PORTILLA LIMESTONE FORMATION OF NW SPAIN.

Recent stratigraphical, sedimentological and paleontological studies have added to our knowledge of the Portilla Limestone Formation in the Middle to Upper Devonian of the Cantabrian Mountains in NW Spain (ADRICHEM BOOGAERT 1967, SLEUMER 1969, REIJERS 1969, 1972, 1973, 1974, STRUVE and MOHANTI 1970, MOHANTI 1972). Fig. 1 summarises the main characteristics and the mutual relationships of the depositional facies. For a detailed description reference is made to an earlier publication (REIJERS 1972). It is now felt that a more precise definition is needed of the diagenetic facies.

The author believes that in many instances diagenetic processes, like depositional ones, are diagnostically selective with respect to the physiographic zone in which they act (Fig. 2). Especially early diagenetic processes show a preference to certain diagenetic and depositional environments which are defined by mechanical, physical and chemical properties of the agents. In contrast to depositional environments the criteria needed to differentiate diagenetic environments are only just beginning to establish.

In this contribution an attempt is made to describe diagenetic processes and to relate these, on a time base, to diagenetic environments. It will be shown that certain diagenetic facies (defined as assemblies of diagenetic fabrics which enable us to reconstruct diagenetic processes and environments) characterise certain diagenetic environments. These facies may even characterise physiographic zones if they are result of early diagenetic processes. In order to fulfill the scope of this study, diagenetic fabrics are described, illustrated, analysed and mutually compared. Finally, six lithofacies of the Portilla Limestone Formation are individually described as the final overprint of depositional and diagenetic processes acting on the same sediment.

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SEDIMENTARY ENVIRONMENTS IN PORTILLA LIMESTONE FORMATION					
FACIES SYMBOLS / PROPERTIES	B	C (D) C	E	F	G
PHYSIOGRAPHIC ZONE	PROTECTED PLATFORM	ORGANIC BARRIER	OPEN	SHALLOW	PLATFORM
FIELD OBSERVATIONS: DEPOSITIONAL TEXTURE (DUNHAM)	Mdst., Wkst. & (Pkst)	Pkst. & Bdst.	Gst., (Pkst.)	Pkst., Wkst., (Gst.), (Bdst)	Pkst., Wkst.
GRAINTYPES	bioclasts, intraclasts, pellets, pelletoids	bioclasts, intraclasts, (ooids)	encrinal/encrinite biocl. intraclasts, ooids, pel.	encrinal/encrinite biocl. ooids, pellets	bioclasts, ooids, pellets pseudooids.
INTERGRANULAR MAT. MUD/CEM. RATIO	mud/((cement)) 9/1	(mud)/cement 4/6	((mud))/cement 1/9	mud/cement 4/6	mud/(cement) 7/3
COLOUR rock colour chart, G.S.A. '63	N4,5-5Y8/1-5Y8/2	N3,7-5R 4/2, 4/6, 5/2 & N8,9 alternating 10YR8/6	N4,5 & 5Y6/1, 8/1	5GY 7/2-5YR 4/1	N3,2-5YR 3/2
SEDIMENTARY STRUCTURES	med. bedded, wavy, irreg., pseudo-nodules, slumps, wedges, X-beds, grading	med.-thick bedded, irreg. wavy, slumps, oriented biocl. pinching out, biostromal to biohermal	med. bedded, reg., X-beds, gullies	thin-med. bedded, irreg. X-beds, gullies, slumps	med. bedded, reg. (lam), X-beds, gullies, grading, trapping
ADMIXTURES/INTERBEDS TER. MAT.	marly beds alternating with Pkst, Wkst	minor amounts of siliciclastics admixed	(rnd. Qtz. grains)		silt-size siliciclastic admixed & interbedded
MISCELLANEOUS	chertification of bioclasts & chert nodules, aut. Qtz, birds eyes, algal coating, dol. rhomb. cryst., dedol.	bitumenous mat., pyr., dol. rhomb. crystals, biocl. chertified, dedol., auth. Qtz., pres. sol., erosion		authigenous quarts crystals, dol. rhomb. crystals	algal borings, vugs with sed. floors, rnd. detr. Qtz. grains, ferrugenous mat.
164 POINT COUNTED SAMPLES: OSTRACODA	1.7	1.5—1.0—1.5	2.5	1.5	2.5
CALCISPHERIDA	1.7	1.0—1.0		1.5	
FAECAL PELLETS	21.6	9.0—1.0—9.0	13.0	8.0	8.0
MOLLUSCA	1.7	1.0—1.0			
CORALS: TABULATA BRANCHING	1.4	30.0-40.0?-20.0	4.0	1.5	1.0
CORALS: TABULATA PLATY		?—10.0?—5.0			
CORALS: RUGOSA SOLITARY	4.0				5.0
CORALS: RUGOSA COMPOUND		?—20.0?—10.0			
BRYOZOA BRANCHING	4.5	4.0—1.5—4.0	8.0	8.0	8.0
BRYOZOA ENCRUSTING			3.0		
STROMATOPOROIDEA		5.0—5.0			
CRINOIDEA	21.6	15.0—10.0—15.0	39.0	46.5	39.5
BRACHIOPODA	3.5	1.5—1.5—1.5		3.0	
UNIDENTIFIED	38.3	29.0—10.0—27.0	30.0	30.0	36.0
GRAIN/MICRITE RATIO	1.85	3.38 15.8 3.88	3.83	7.30	6.35
based on point counts of 124 thin sections	20	4 / 40	20	25	15

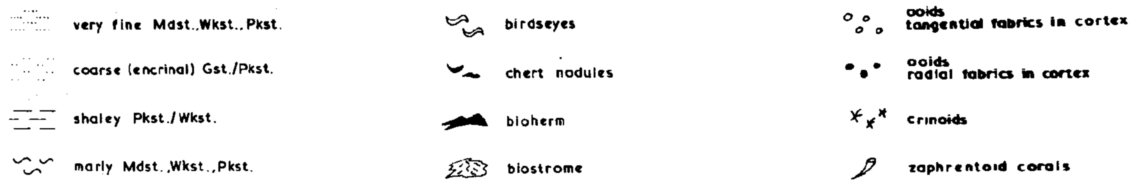


Fig. 1.— Sedimentary environments and their properties for the Portilla Limestone Formation (compare also REIJERS, 1972).

DIAGENESIS; SUBDIVISION AND CHARACTERISTIC PROCESSES

The field of diagenesis impinges on the fields of sedimentation, weathering and metamorphism. The depositional, weathering, and metamorphism interfaces form the three boundaries of diagenesis (Fig. 3). Strict definition of these boundaries is less important than clear recognition of individual substages. Therefore, these substages will now be discussed in terms of characteristic processes and their products.

The field of diagenesis includes syndepositional, precementation, cementation and postcementation substages. The syndepositional and precementation substages can be regarded as comprising the syngenetic stage, which roughly corresponds with NAGTEGAAL'S (1967) «interval of early and advanced diagenesis», and with FAIRBRIDGE'S (1967) «interval of syndiagenesis». The syngenetic stage is predated by a predepositional stage in which physico-chemical conditions are those of erosion and transport.

—In the SYNDEPOSITIONAL SUBSTAGE do the physico-chemical conditions of the physiographic zone (e. g. water temperature, Eh, pH) define the diagenetic envi-

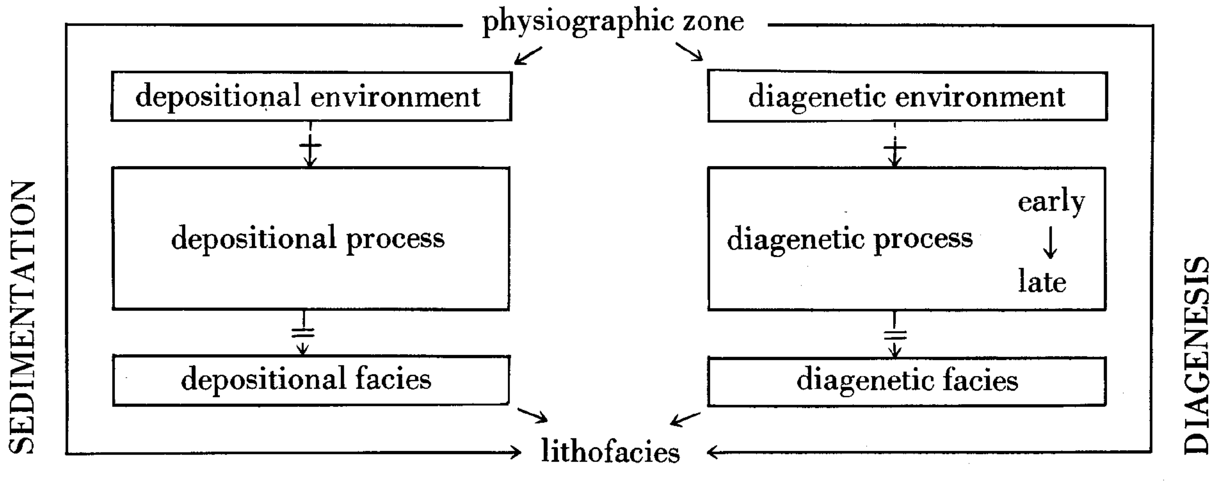


Fig. 2.— Terminology used in present paper.

ronments. They also directly control the diagenetic processes. Three processes characterise this substage in the Portilla Limestone Formation: silicification of corals and stromatoporoids, authigenesis of ferruginous material and bioturbation. The last one will not be discussed in detail.

(i) Silicification of corals and stromatoporoids.— Great quantities of chert are present in depositional facies C and D and smaller quantities in depositional facies B and F (Fig. 1). In certain intervals moderate to severe silicification of entire or fragmented corals and stromatoporoids occur (Fig. 4). The following questions are posed. Is this silicification an early or a late diagenetic process? Where does the silica come from? Why is silicification mainly confined to reef tract and back reef environment? Why are corals and stromatoporoids preferentially silicified?

The restriction of chert to certain depositional facies only, and to well defined horizons herein, is regarded as an indication for transportation of silica into the basin of deposition during sedimentation. Most of the silica was trapped behind the reef tract, explaining the areal preference of chert for depositional facies B, C and D. Only a small amount spilled into the fore-reef environment where it settled on the moderately energetic platform margin during periods of complete submergence of the reefs (cf. Reijers, 1974). The transportation and settling of silica was mainly governed by hydrodynamic and physico-chemical factors.

Erosional zones in bioherms continue in a lateral sense into chert-layers in back reef deposits (cf. Fig. 1, and Reijers 1972, 1974). This additional evidence supports the hypothesis that silica was brought into the basin during sedimentation because it suggests that transport of silica towards the open sea was prevented during emergence of bioherms, and silica was forced to settle behind, and in, the reefs. Silicification is therefore regarded as a syndepositional process.

The author has no direct knowledge and knows of no description of either desert environments or of volcanic activity in the Middle-Upper Devonian in NW Spain. Therefore he regards it unlikely that silica in the Portilla Limestone Formation was derived from desert dust or from volcanic glasses. The complete absence in silica and

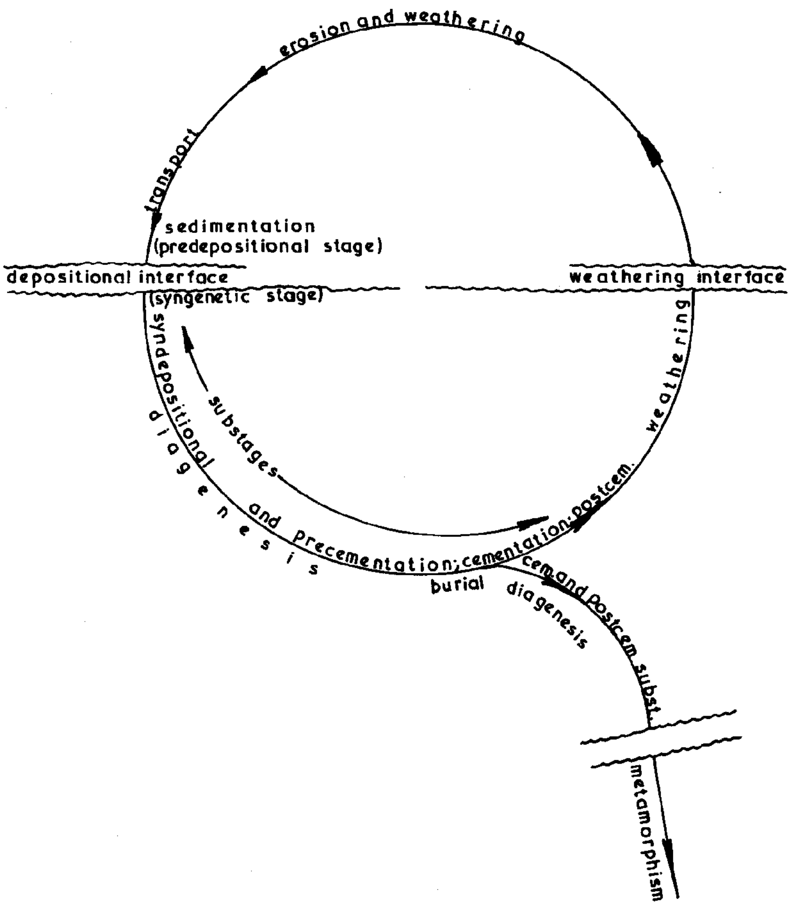


Fig. 3.—Lithogenetic cycle picturing the relations between sedimentation, diagenesis and metamorphism. Diagenesis is subdivided into stages and substages.

in carbonates of traces of organisms with siliceous skeletons such as radiolaria, diatoms or sponge spiculae rules out an organic origin. The most likely source of the silica is therefore a deeply weathered hinterland (cf. ADRICHEM BOOGAERT 1967, and REIJERS 1972, 1974). Presumably the silica was transported as a gel (cf. ERHART 1956, 1963). Support for this assumption is found in the clotty and irregular appearance of the chert, and in the extremely fine, unoriented crystalline substructure of silica under the polarising microscope. In the process of stabilising silica gels and transforming them into chert, coagulation is the next step.

Coagulation, according to KRAUSKOPF (1959) is triggered by a low pH-value. Microenvironments in which pH-values are low, were apparently abundantly present in the back-reef and reef tract where decaying organic material reduces the pH-value. Such microenvironments are encountered in small cavities like latilaminae and holes in coenostea of stromatoporoids (cf. SLEUMER 1969, p. 24) and in corallites of ramose and platy tabulate corals (Fig. 4). Because corals and stromatoporoids are present in abundance in the Portilla Limestone Formation, there was plenty of scope for the coagulation of silica gels.

Numerous intraformational discontinuities in depositional facies C and D and some in depositional facies B (REIJERS 1974) indicate periods of emergence. During these periods silica could dehydrate under evaporitic conditions, as suggested by the presence of length-slow chalcedony (cf. FOLK and PITTMAN, 1971).

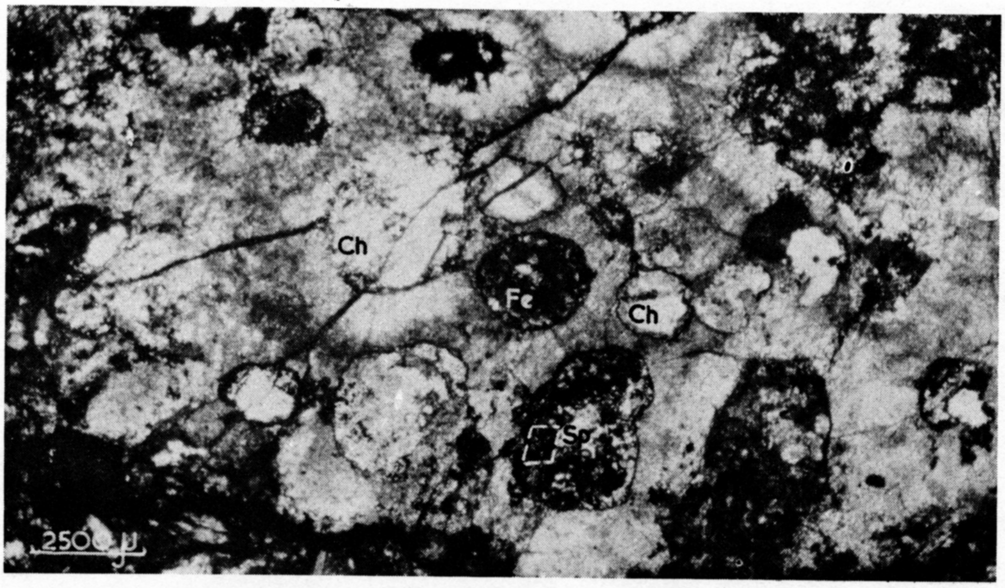


Fig. 4.—Positive photomicrograph. Sample stained with a mixture of alizarin red S and $K_3Fe(CN)_6$. Lithofacies B. Packstone. Compound rugose corals are surrounded and partly filled by micrite and ferruginous (Fe) microbioclastic silt. Chert (Ch) is preferentially present in septa, tabulae and dissepiments of corals. Silicification apparently started from the inside of the corallites and progressed gradually towards the outside. Fracturing occurred much later since fractures cross both, bioclastic fragments and chert patches. The following sequence of diagenetic events has been established. (i) *Predepositional and precementation substages:* Accumulation of bioclastic material. Decaying of organic tissues, resulting in pH-lowered surroundings in which silica gels stabilised. (ii) *Cementation substage:* Local precipitation of some sparitic cement. (iii) *Postcementation substage:* Local formation of some rhombohedral dolomite crystals. Fracturing. Some recrystallisation.

(ii) Authigenesis of ferruginous material.—Crystalline and colloform clotted aggregates of goethite, haematite and undefined amorphous ferruginous material are present in decreasing quantities from depositional facies B to G (Figures 5 a, b and 6 a, b). The questions posed here are: Where did the required iron come from? Why is it preferentially present in the back-reef area and reef tract and diminished in importance towards the margin of the basin? When was it formed?

Reasoning along similar lines as in the section about chert, it is considered likely that the hinterland which acted as a source area of silica, also supplied the iron. This is supported by the decrease in quantity of ferruginous matter towards the open marine environments.

The colloform and clotted character of the purely ferruginous aggregates could suggest a phase of mobile gel-like ferric hydroxide (cf. REIJERS 1972, p. 192 and Plate XV, and present paper Fig. 5 a, b). Such a mobile phase of gel-like ferric hydroxide was presumably followed by a dehydration phase during the same periods of emergence as discussed in the foregoing section. In this phase the gel was stabilised. Haematite crystallises in microenvironments with a low pH-value or, under influence of Mg^{2+} and Ca^{2+} ions in microenvironments with a neutral pH-value (cf. SCHELLMAN 1959).

A comparison of formation of the silica and the ferruginous material shows that the prerequisites, including the supply of raw material from a hinterland transportation and distribution of the gel, and the dehydration phase are similar. It seems therefore likely that goethite, haematite and amorphous ferruginous material were more

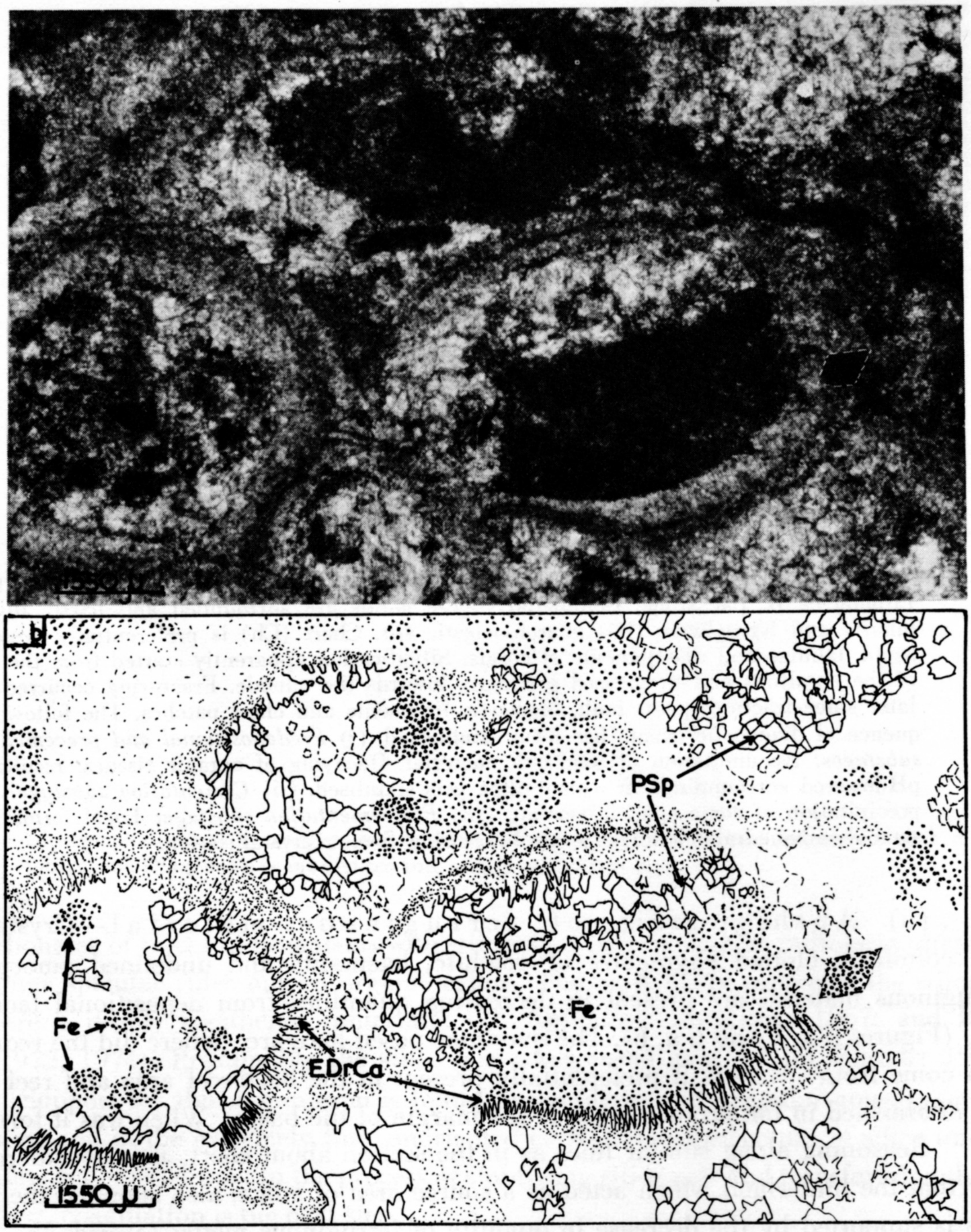


Fig. 5 a, b.—Positive photomicrograph and tracing of the same. Sample stained with a mixture of alizarin red S and $K_3Fe(CN)_6$. Lithofacies B. Packstone/Boundstone. Aulopore corals are indicated in the tracing in fine dense stippling. The interstitial material (fine wide stippling) is predominantly disintegrated bioclastic material and micrite. Locally, large quantities of amorphous, clotty, ferruginous material and of hydrous or non-hydrous iron oxyde (e. g. goethite, haematite) (Fe) are present. Sometimes pseudosparitic (PSp) calcite cement without iron in the crystal lattices (cf. Fig. 6 a, b) overlays this ferruginous material. A slightly darker, acicular/fibrous even drusy calcite (EDrCa) without iron in the crystal lattices is moderately to strongly recrystallised (fine dense stippling). This drusy calcite lines pores in the corals and underlies the internal sediment which, together with large quantities of ferruginous material (Fe), was introduced in the system during weathering. Such internal sediments are comparable to vadose silt (DUNHAM, 1969, a, b). Dolomitisation occured slightly later and resulted locally in haematite-coated rhombohedral dolomite crystals (Do). The following sequence of diagenetic events has been deduced. (i) *First syngenetic stage.* The corals are lined by fibrous/acicular even aragonite druses (now calcite) in a phreatic intertidal diagenetic environment. This is followed by (ii) *short periods of emergence and weathering*, and this by (iii) *Early second syngenetic stage:* Introduction in pores of stabilised ferruginous material and «vadose» silt. (iv) *Late second syngenetic stage:* Formation of pseudosparite. (v) *Postcementation substage:* Formation of dolomite crystals.

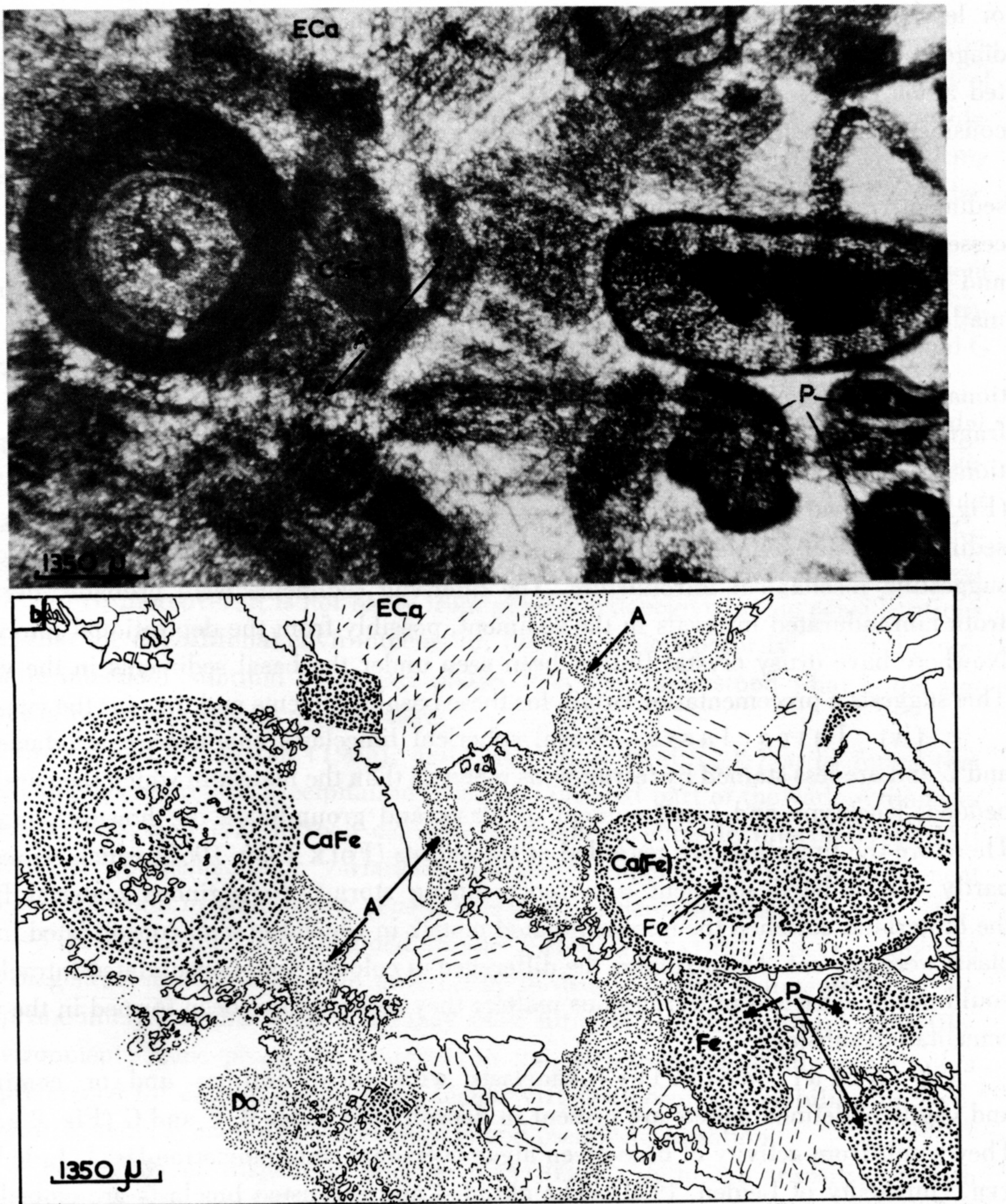


Fig. 6 a, b.—Positive photomicrograph and tracing of the same. Sample stained with a mixture of alizarin red S and $K_3Fe(CN)_6$. Lithofacies F. Grainstone. Crinoidal particles are characterised by a fenestral pore pattern in which ferruginous matter (Fe) is included. Some crinoids are coated by a thin layer of this ferruginous material and further by dark ferroan calcite (CaFe). The ooids are of the superficial type (one or two coating layers). Nuclei are moderately to strongly attacked by recrystallisation and by grain diminution and consist of low-ferroan calcite Ca(Fe). Well defined, irregularly shaped, subrounded to rounded pellets (P) have virtually no internal structures. The groundmass consists of a blocky mosaic of non ferroan calcite (ECa). On several places the results of abundant algal borings, encrustations and corrosion are visible and algal filaments are present in a mucilageous matrix (A) (cf. Chilingar et al., 1967 a, Plate XV-XVI). The following sequence of diagenetic events has been deduced. (i) *Predepositional substage:* Stabilisation of ferruginous material. Algal activity results in borings and encrustations. (ii) *Precementation substage:* Pigmentation with ferruginous material of bioclasts. Formation of micritic coatings in which ferruginous material is present. (iii) *Cementation substage:* Precipitation of blocky mosaic calcite crystals. (iv) *Postcementation substage:* Recrystallisation affects the whole rock moderately. An exception must be made, however, for places where algal borings, encrustations or algal filaments are present in a mucilageous matrix.

or less simultaneously formed with chert, namely in the predepositional substage of diagenesis. The ferruginous material was not necessarily formed in place, since limited amounts of ferruginous matter are present in lithofacies F and G which are not considered as emergent depositional facies at any time.

—The diagenetic processes which affect the semi-consolidated toplayers of sediments may be grouped into the PRECEMENTATION SUBSTAGE. They include the processes discussed below and in addition impregnation of ferruginous material in bioclasts and coatings, and mechanical transport and secondary introduction of ferruginous matter in certain bioclasts (Figs. 5 a, b and 6 a, b).

(iii) Vugs with or without basal sediments.—Depositional facies B is characterised by vugs with sedimentary floors of micrite, very finely fragmented bioclastic matter or haematite pellets. Similar vugs are present in depositional facies C, E, F and G (Fig. 7 a-e). Grains which remain in the «roofs» of vugs (Fig. 7 d, e) and did not fall down, suggest that vugs were formed in slightly indurated sediments. Basal sediments in the vugs show fining upwards sequences (Fig. 7 d, e) suggesting mechanical introduction. The inter-vug sediments were probably derived from non-indurated intervals in the sediment, possibly from the depositional interface. Nowhere have drusy crystal linings been seen under the basal sediments in the vugs. This suggests a precementation origin for these basal sediments and thus for the vugs.

(iv) Intraclasts.—Worn, spherical limeclasts characterise lithofacies B and C and are less stained by ferruginous material than the matrix in which they are embedded. Rocktype and fossil content of clasts and groundmass do, however, match. Therefore the limeclasts are regarded as intraclasts (FOLK 1959, 1962) which represent partly consolidated sediment torn loose during storms. Ferruginous material from the hinterland enriched the unconsolidated matrix in which the semi-consolidated intraclasts were present. This explains the difference in colour. Semi-consolidated intraclasts could not be enriched in ferruginous matter; they seem to have been formed in the precementation substage.

(v) Algal activity.—Bioclasts with worn outlines and/or coatings, and vague undefined pellets are present in depositional facies B, F and G (Fig. 8 a, b). They result from activity of blue-green algae (personal communication Dr. J. J. de MEYER, University of Leiden, 1971). The abraded and encrusted bioclasts are embedded in coarse blocky equant cement. Because the abrasion is only visible in previously formed bioclastic grains, the algal activity is dated as acting before the cementation substage.

—The CEMENTATION SUBSTAGE starts with the first precipitation of cement. This substage is considered to be terminated when sealing cement precludes further contact with the sedimentary environment.

(vi) Drusy cement.—Crystals with natural terminations and equant shapes form drusy cements in depositional facies B, E, F and G (Figs. 5 a, b and 9 a, b). Studies of recent carbonate environments (LAND et al., 1967; JAMES, 1972) have shown that such crystals, lining pores and accentuating their shapes, are present in diagenetic environments which occasionally suffered influence of meteoric water. By analogy these cements, present in unweathered samples of the Portilla Limestone Formation, may be regarded as characteristic for phreatic intertidal diagenetic environments. This fits reasonably well with the concept of the depositional environment of lithofacies B. Depositional facies E, F and G also have such drusy cements. It is considered unlikely however, that these facies came under influence of meteoric water during or after deposition, owing to their essentially subtidal nature. Therefore, it is not understood what the drusy remnants in these depositional facies represent.

(vii) B l o c k y c e m e n t.—Remnants of drusy cement rims may still be present while blocky calcite mosaics are precipitated. The blocky mosaics may partly or entirely fill the remaining intra/inter granular pores in depositional facies C, D, F, and G (Figs. 6 a, b; 7 a-e; 8 a, b and 9 a, b).

LAND et al. (1967) relate blocky mosaic textures to phreatic intertidal/subtidal diagenetic environments. In the studied sediments phreatic intertidal/subtidal diagenetic environments are thought to have prevailed temporary in depositional facies C and D. This is supported by additional evidence, e.g. erosion zones and remnants of solution-replacement processes. Such additional evidence is not present in depositional facies F and G; moreover, it is not likely from general palaeogeographic considerations (Fig. 1) that the depositional environments for these facies temporarily passed through a phreatic intertidal/subtidal diagenetic phase. It is not understood what is the significance of the blocky calcite mosaics here.

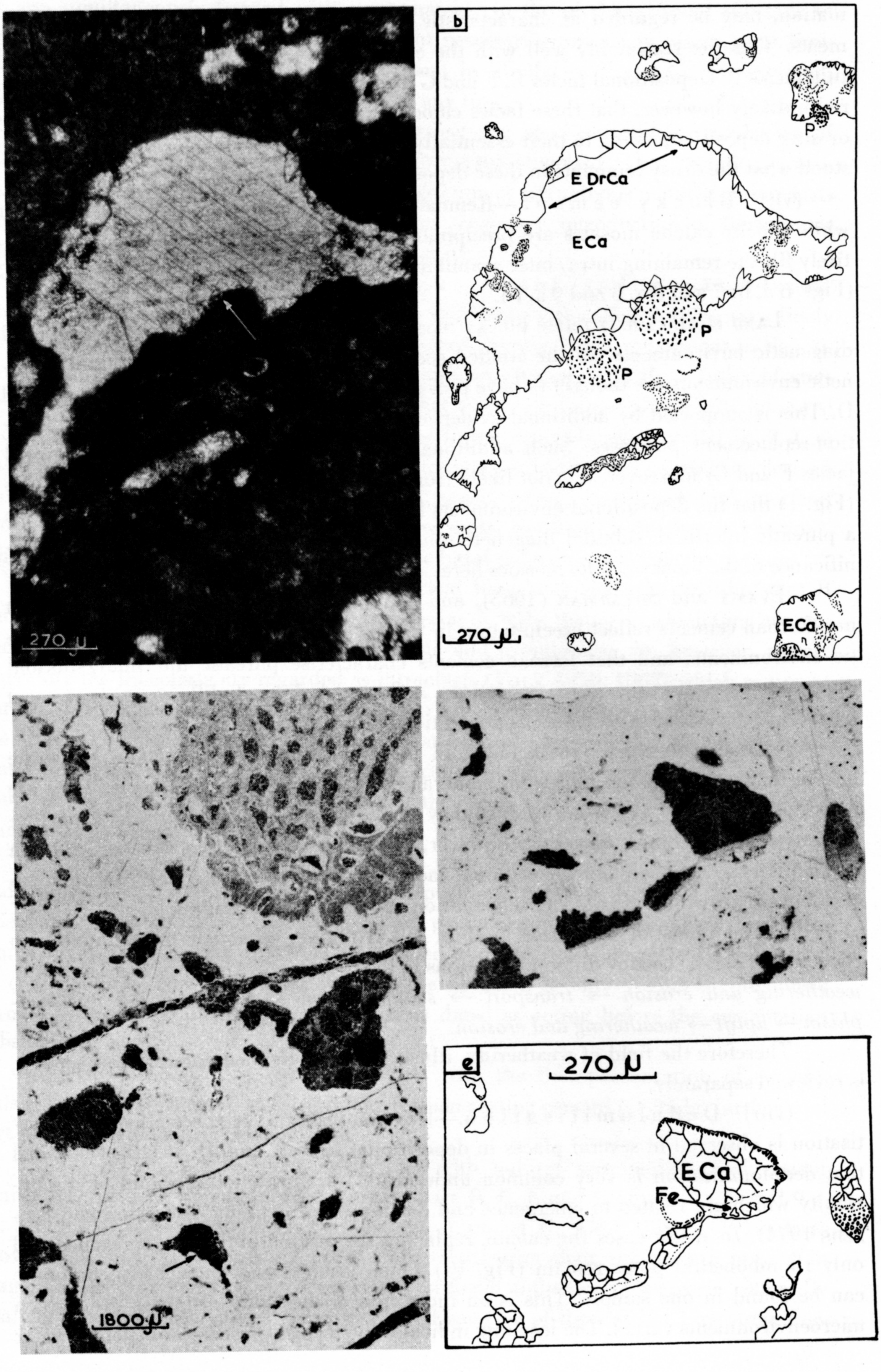
EVAMY and SHEARMAN (1965), and CHILLINGAR et al. (1967 a, b) found that non-ferroan cements reflect precipitation in the oxygenated part of the vadose diagenetic environments, and that ferroan cements characterise phreatic intertidal/subtidal diagenetic environments. Such variations and morphological differences in cement fabrics are important in establishing generations in the cementation substage.

—Processes which are included in the POSTCEMENTATION SUBSTAGE operate late in diagenesis and act mostly in moderately to deeply buried sediments. They are not of prime interest in this study since they show little relationship with the depositional environment. Some processes, however, in the postcementation substage show a slight preference for certain depositional facies, viz: neomorphism, stabilisation, syntaxial grain growth, syntaxial rim cementation and pseudosparitisation.

—The fields of diagenesis and of WEATHERING, although transitional with each other (Fig. 3) occupy different positions in the cycle:
weathering and erosion → transport → sedimentation → diagenesis → metamorphism → uplift → weathering and erosion.

Therefore the field of weathering, illustrated with the dedolomitisation process, is reviewed separately.

(viii) D e d o l o m i t i s a t i o n.—Dedolomitisation in the sense of recalcitisation is observed in several places in depositional facies C and D. It has been noted that dedolomitisation is very common underneath intraformational planes of discontinuity which are related to emergence and erosion (see foregoing discussion and REIJERS 1974). In a few cases the calcite, replacing the original dolomite, is leached and only rhombohedral pores remain (Fig. 10). Often leached and unleached dedolomite can be found in one sample. This is an indication of the small distances over which microenvironments varied. The leaching indicates the former presence of meteoric water



270 μ
b
E DrCa
ECa
P
P
P
ECa
270 μ
1800 μ
e
270 μ
ECa
Fe

which was slightly acidic and oxygenated, possibly due to adsorption of CO_2 and O_2 from the air. Acidity must have been increased locally, possibly due to organic acids from vegetation. This enabled metoric water locally to dissolve the calcitised dolomite.

Results, Discussion and Conclusions

In order to compare sequences of diagenetic processes which characterise lithofacies, a diagram is presented in which lithofacies are plotted against lithogenesis (Fig. 11). The lithofacies are grouped into certain physiographic zones which occupy a more or less fixed position in the sedimentary basin (Fig. 1). Based on pore characteristics, the supratidal/intertidal physiographic zones are subdivided into vadose and phreatic subzones. Lithogenesis includes sedimentation, diagenesis, metamorphism and weathering (Figures 3 and 11). The vertical axis is interpreted as an axis of time or alternatively, as an axis of relative depth of burial upto the second upper boundary of marine/terrestrial diagenetic environment (weathering interface).

The horizontal numbered lines in the diagram show the range of occurrence of diagenetic fabrics in the spectrum of lithofacies. The thickness of the line indicates the significance of the process in that particular lithofacies as compared with other lithofacies. The vertical position of these lines indicates in which stage of lithogenesis the represented process operated.

Such representation of stages in lithogenesis against a spectrum of lithofacies has advantages. Sedimentary, diagenetic, metamorphic and weathering processes can be plotted, for which the relative times of operation have been reconstructed by analysis of depositional textures or of diagenetic, metamorphic or weathering fabrics. Subsequently lithofacies can be described either in terms of sedimentary textures or, alternatively, in terms of diagenetic, metamorphic or weathering fabrics. Such a description of diagenetic facies, and an analysis of the environmental implications illustrated with the appropriate microphotographs, is given below for the six lithofacies of the Portilla Limestone Formation.

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Fig. 7 a, e.—Two negative photomicrographs (7 a, d) and one positive (7 a). Tracings (7 b from 7 a, and 7 e from 7 d). Negative photomicrographs made with green monochromatic filter. Samples partly stained with a mixture of alizarin red S and $K_3Fe(CN)_6$. Lithofacies B. Wackestone. Fragments of stromatoporoids, tabulate corals, ostracods, calcispheres and pellets, poorly defined aggregates of mud with a diameter of approximately 200 μ (coarse stippling). «float» in a predominantly pellotoidal groundmass. Vugs in the groundmass range from 100 μ to 500 μ. Their outlines are relatively smooth. Occasionally they are geopetally filled. Bubble-like, clotty haematite (Fe), often clustered in aggregates and pellets, and unidentified silt-sized bioclastic fragments are among the basal sediments. Sediments with fining upwards structures fill part of the vugs. the remaining voids are filled with ferruginous equidimensional blocky mosaics of calcite (ECa). Grains in the «roofs» (e. g. an ostracod in Fig. 7 d) suggest some induration before the vug was formed. Some vugs have linings of even drusy or isopachous (Land et al, 1967) cement (EDrCa). The remaining voids are filled with (ECa). Some dusty areas (fine stippling) have suffered recrystallisation. At least two generations of late diagenetic fractures, filled with late diagenetic blocky mosaic cement are recognisable. The following sequence of diagenetic events has been deduced. (i) *Syndepositional substage:* Ferruginous material stabilised and partly clotted into pellets. (ii) *Precementation substage:* After slight induration of the sediment, voids were formed (e. g. gas bubbles, desiccation), these voids are partly filled with sediments. (iii) *Cementation substage:* Even drusy cement (EDrCa) and/or equidimensional blocky mosaic calcite (ECa) with iron in the crystal lattices was formed. (iv) *Postcementation substage:* Fracturing and late diagenetic cement formation.

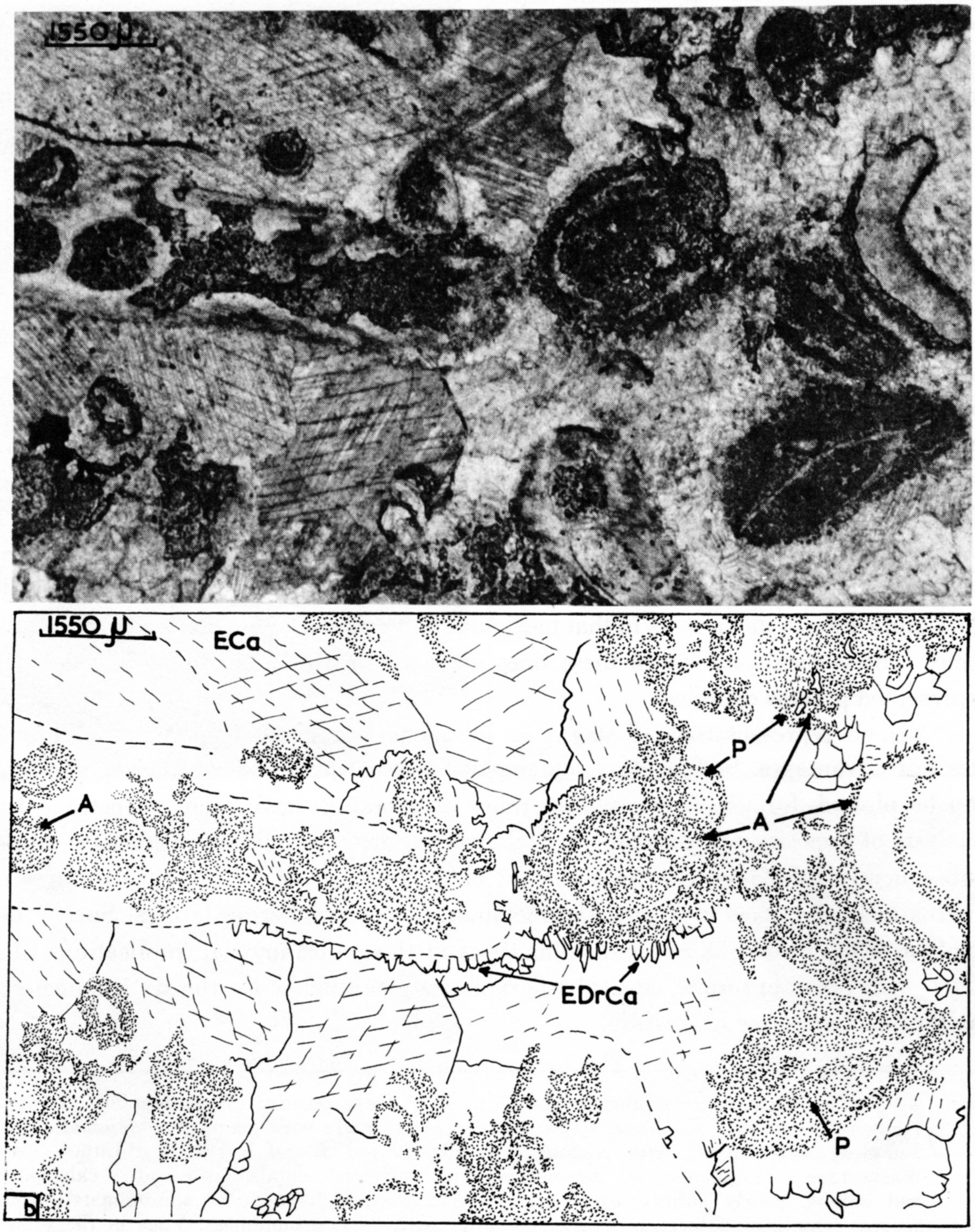

Fig. 8 a, b.—Positive photomicrograph and tracing of the same. Sample not stained. Lithofacies G. Packstone/Grainstone. Brachiopods, bryozoans, crinoids and ostracods are recognisable. Blue-green algae encrusted many grains and bored some (boring poorly visible on photomicrograph), occasionally producing areas with a mucilageous matrix. Ovoid to clot-like homogeneous microcrystalline grains with a moderately sharp outline (fine stippling), are best described as algal pellets (P). Occasionally in these pellets remains of the original bioclasts are recognised. Interstitial material is coarse equant blocky calcite (ECa) with straight intercrystalline boundaries. Some grains are coated with blade-like even drusy calcite rims (EDrCa); in others, the contacts with the equant blocky calcitic groundmass is very irregular. This is especially the case in places where mucilageous algal material was secreted, affecting the precipitation of subsequent (ECa) crystals. The following sequence of diagenetic events has been deduced. (i) *Precementation substage:* Depositional of bioclastic material. Algal corrosion and formation of algal pellets. (ii) *Cementation substage:* Precipitation of rims of blade-like even drusy calcite cements around some grains. Formation of such rims is followed by precipitation of coarse equant blocky calcite (ECa).

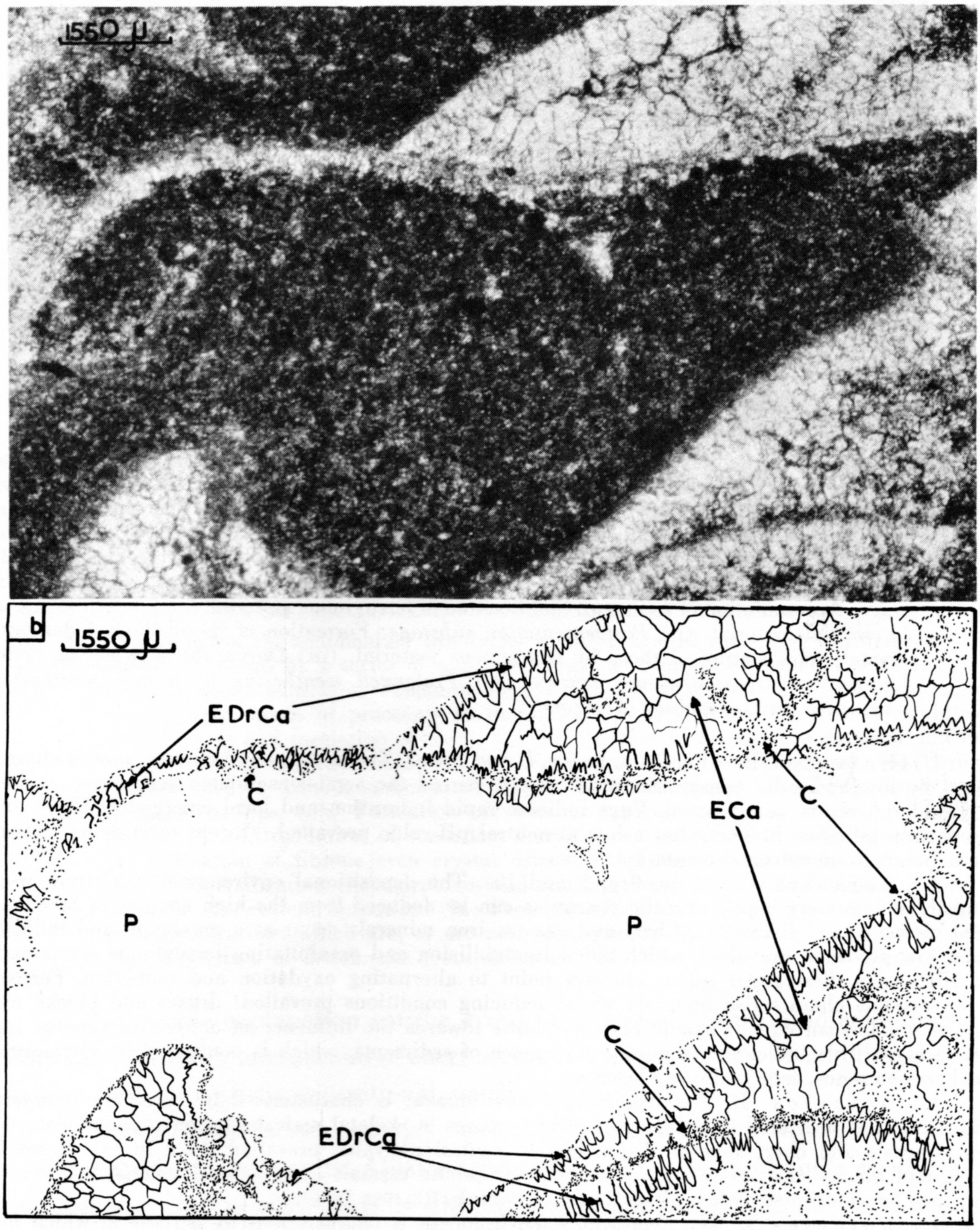

Fig. 9 a, b.—Positive photomicrograph and tracing of the same. Sample stained with a mixture of alizarin red S and $K_3Fe(CN)_6$. Lithofacies C. Packstone/Boundstone. Recrystallised corals are indicated with fine stippling. The groundmass is partly micrite, partly pelletoidal (P), partly cement. Less than 5 % dolomite crystals is present. The fibrous acicular even drusy calcite lining of the coral (EDrCa) and the blocky equidimensional, locally slightly granular cement (ECa) are characteristic. They fill some primary intergranular spaces. Other such spaces are completely filled with pelletoidal, haematite-bearing micrite. Since no iron has been found in the lattices of cement crystals, precipitation presumably occurred in reducing diagenetic environments. The acicular even druse points to cementation in phreatic intertidal/supratidal diagenetic environments. The following sequence of diagenetic events has been deduced. (i) *Syndepositional substage:* Stabilisation of ferruginous material. (ii) *Precementation substage:* Formation of pellets and filling-up of some intergranular spaces in the coral boundstone. (iii) *Cementation substage*: Precipitation of even drusy calcite and subsequently of blocky mosaic calcite in the remaining spaces of the coral boundstone. (iv) *Postcementation substage*: Formation of some rhombohedral dolomite crystals.

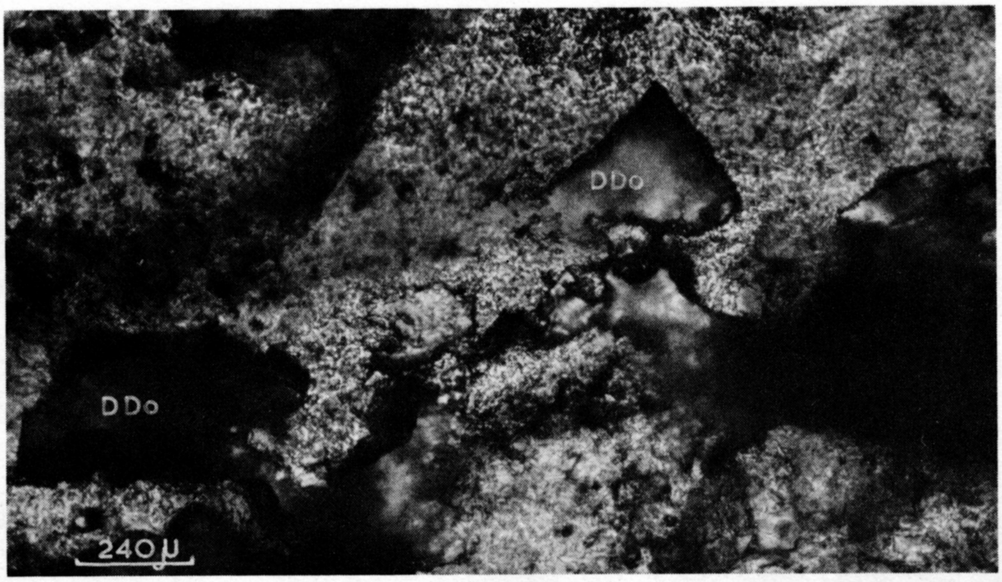

Fig. 10.—Positive photomicrograph. Sample stained with a mixture of alizarin red S and $K_3Fe(CN)_6$. Lithofacies C. Packstone/Boundstone. The microsparitic groundmass shown contains mouldic porosity. The moulds clearly show the outlines of leached rhombohedral dedolomitised crystals. Unleached dedolomite is still present elsewhere in the same sample. Occasionally dark rims occur in the groundmass around the former dolomite crystals. The following sequence of diagenetic events has been deduced. (i) *Syngenetic stage:* Accumulation of sediment. Stabilisation of ferruginous material. Microsparitisation of interstitial material. (ii) *Postcementation substage:* Formation of rhombohedral dolomite crystals and coating of these by ferruginous material. (iii) During the *weathering*, dedolomitisation (recalcitisation) occurs. (iv) *Prolonged weathering or a new weathering phase* gives rise to leaching of dolomite.

Lithofacies B. (Figs. 4 a, b; 5 a, b and 7 a-e). The depositional environment is characterised by low hydraulic energy. Storms however, stirred the semi-consolidated sediments occasionally and limeclasts were formed. Vugs indicate rapid induration and local emergence. Chert and various iron minerals indicate that a low to neutral pH-value prevailed. Fibrous even drusy ferroan calcite points to submarine cementation.

Lithofacies C. (Figs. 9 a, b and 10). The depositional environment is characterised by spells of relatively high hydraulic energy as can be deduced from the high amount of breccious reefal elements and limeclasts. Chert and various iron minerals occur at a maximum and indicate that a low pH-value prevailed, which aided in stabilising and precipitating ferruginous compounds and silica gels. Red/green colour changes point to alternating oxydation and reduction. Ferroan calcite crystals characterise intervals where reducing conditions prevailed; druses and blocky mosaics of non-ferroan equant calcite crystals points towards the influence of acidic, oxygenated meteoric waters. This indicates temporary emergence of sediments, which is confirmed by intraformational erosion zones, dedolomite and leaching.

Lithofacies D. The depositional environment is characterised by local low energetic conditions as is indicated by infilling of primary pores in skeletal material by ferruginous material. Iron minerals and chert suggest that a low to neutral pH-value prevailed. Like in lithofacies C, druses and blocky mosaics of non-ferroan equant calcite crystals suggest local emergence. This is confirmed by widespread dedolomitisation and leaching (Reijers 1974).

Lithofacies E. The depositional environment is characterised by periods in which moderately high hydraulic energy prevailed as is indicated by the presence of concentric ooids. Ferruginous pigment in crinoidal pores however, was not washed out. Formation of haematite and goethite indicates that pH-values remained low. Vugs with geopetal fillings indicate rapid induration was less common than in lithofacies B. Submarine cementation, however, is suggested by the presence of even drusy ferroan calcite crystals. Syntaxial grain growth destroys much of the earlier diagenetic fabrics.

Lithofacies F. (Fig. 6 a, b). The depositional environment is characterised by weak agitation as is indicated by the presence of characteristic radial ooids (Rusnak 1960). Authigenesis of iron minerals and of chert diminishes in importance, suggesting a neutral pH-value and a reduced rate of sediment accumulation. Vugs without geopetal structures point to a rapid induration of the toplayer. Algal coatings suggest a relatively shallow environment.

Lithofacies G. (Fig. 8 a, b). The depositional environment is characterised by a moderate to low hydraulic energy. Algal coatings suggest deposition within the photic zone. The presence of vugs with sedimentary floors points to slow induration of the top layers of the sediment. On the other hand, non-ferroan fibrous even drusy calcite crystals point to local submarine cementatation. Syntaxial grain growth and rim cementation destroyed many diagenetic fabrics.

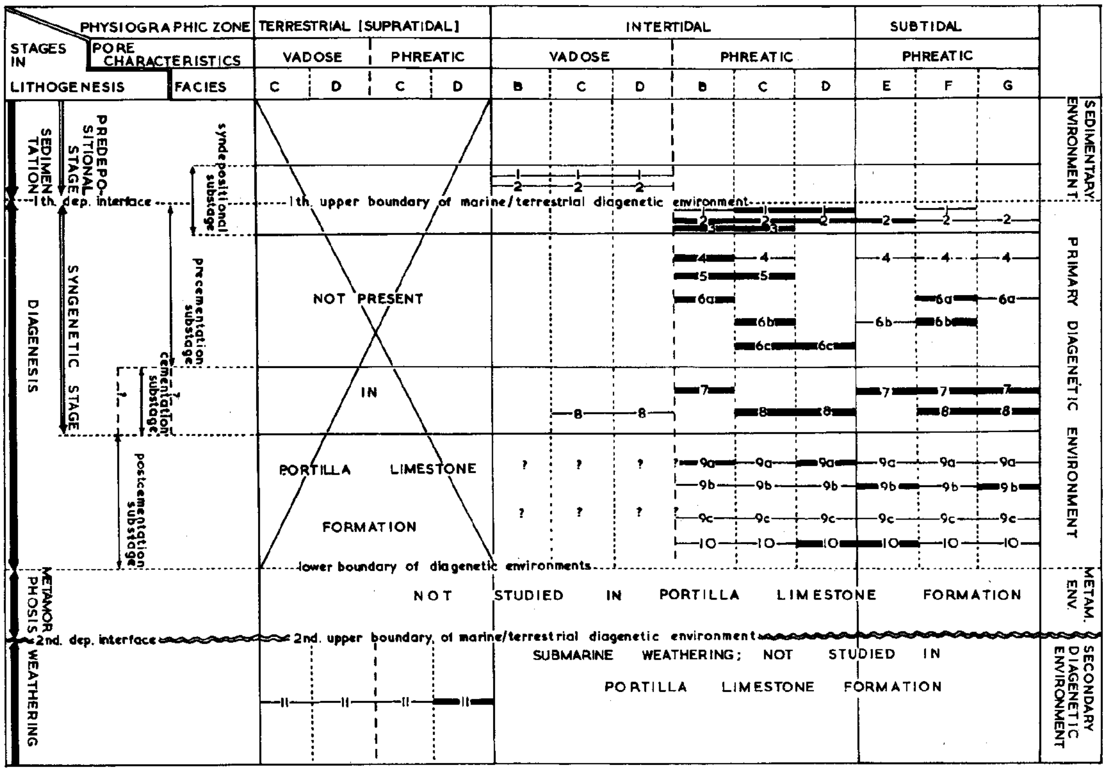

Fig. 11.—The spread of the sedimentary lithofacies is shown against the stages in lithogenesis. Each facies is defined by a series of numbered diagenetic processes which were active in certain diagenetic substages. Thickness variation in the numbered horizontal lines expresses relative importance of processes in the lithofacies. The processes are: (1) stabilisation of silica gels and formation of chert. (2) Stabilisation of ferruginous material and formation of authigenous iron minerals. (3) Formation of burrow structures. (4) Formation of vugs with or without sedimentary floors. (5) Formation of limeclasts. (6a) Formation of algal coatings. (6b) Formation of ooids and pigmentation of grains by ferruginous matter. (6c) Introduction of secondary ferruginous material in primary bioclastic pores. (7) Formation of fibrous even crystal druses. (8) Formation of blocky cement mosaics. (9a) Recrystallisation (neomorphism and stabilisation). (9b) Syntaxial grain growth and syntaxial rim cement formation. (9c) Pseudosparitisation. (10) Formation of fractures and pressure solutions which are, or are not, subsequently filled with late diagenetic cement. (11) Formation of dedolomite (recalcitisation) which is, or is not, subsequently leached.

No simple explanation can be given for the relationship lithofacies-diagenesis. Formation of iron minerals and of chert occurs in various lithofacies and the controlling factors seem to be partly depositional, partly diagenetic.

Depositional factors, notably hydraulic energy, control impregnations of crinoidal material by haematite. Algal activity and the formation of voids and intraclasts are also restricted to environments with narrowly defined depositional conditions. Formation of ferroan or non-ferroan calcite cement crystals with certain shapes, dedolomitisation and leaching, however, are controlled by certain physico-chemical conditions in the diagenetic environment.

Generalising it can be said that diagenetic processes in the early substages are largely controlled by depositional conditions, while those in the later substages are for an important part controlled by physico-chemical conditions of the diagenetic enviroments.

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