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THE STRATIGRAPHY OF THE CAMBRIAN LANCARA FORMATION BETWEEN THE LUNA RIVER AND THE ESLA RIVER IN THE CANTABRIAN MOUNTAINS, SPAIN

BY

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ABSTRACT

The Lancara Formation is a unit of carbonate sediments of Lower to Middle Cambrian age in the Cantabrian Mountains of northern Spain. The formation is divisible into a Dolomite Member, a Limestone Member and a Griotte Member. The Dolomite Member and the Limestone Member consist mainly of very shallow marine carbonate sediments, devoid of any fossils. Algal structures like stromatolites and oncolites are the only traces of Cambrian life found in them. It is likely that the Dolomite Member represents a sebkha-facies since it is mainly composed of finely to medium crystalline dolomites with intraformational breccias and 'birdseye' structures. The limestones are predominantly intrasparudites with stromatolites and oncolites. Locally the limestones have been subaerially exposed in Cambrian times. The Limestone Member is overlain by the Griotte Member. Locally the contact is disconformable. The Griotte Member is composed of red, argillaceous, nodular limestones and shales. These are very fossiliferous and contain glauconite-like pellets (muscovite-1M). The red color of the sediment is due to dispersed hematite. The nodular structure can have been caused by pressure solution, burrowing or brecciation. The formation as a whole represents a transgressive marine sequence. It starts with sebkha-like deposits and changes upward via algal limestones (algal reef?) into open marine biosparudites and biomicrudites and shales. The subaerial exposure and disconformable contact might indicate a local uplift and local regression of the sea prior to the deposition of the Griotte Member.
A brief survey on trace elements (Cu, Co, Ni, Sr) was carried out with an atomic absorption spectrophotometer. In the 'sebkha' dolomites Cu values showed peaks where the dolomites contain argillaceous matter. Co and Ni were predominantly concentrated in the algal limestones and the Griotte Member. Sr values were high in the algal limestones and in a shale bed underlying the stromatolite bed. The dolomites had generally a low Sr. content. The amount of Sr in the Griotte Member was also lower than in the algal limestones.

CONTENTS

CHAPTER I

INTRODUCTION

General. — Since the early fifties the Geological Institute of the University of Leiden has been working in the Cantabrian Mountains. This work included a mapping project under the supervision of Prof. Dr L. U. de Sitter and a paleontological and stratigraphical survey under the supervision of Prof. Dr A. Brouwer. The present study forms part of a stratigraphical survey of the Paleozoic sediments in the Cantabrian Mountains. The study started in the summer of 1965 when a brief survey was made of the carbonate rocks of the Lancara Formation. The study was extended on a wider scale in the summers of 1966 and 1967. The fieldwork was mainly carried out from two basecamps, namely a western one on the shore of the Pantano de Luna and an eastern basecamp in the valley of the Esla River near the hamlet of Valdoré. Much use was made of the 'Provisional geological map of the southern slope of the Cantabrian Mountains, 1 : 100.000 (de Sitter, 1962) and the 'Cea-Esla-Porma sheet' of the 'Geological map of the southern Cantabrian Mountains', 1 : 50.000 (Rupke, 1965).

Acknowledgements. — The author is much indebted to Prof. J. Harlan Johnson and Dr Cl. L. V. Monty for determining his fossil material and for their helpful comments.
He also likes to thank the Spanish people with whom he came into contact in the Cantabrian Mountains. Their hospitality and help made his visits to their country not only fruitful but also very pleasant indeed.

A GENERAL OUTLINE OF THE GEOLOGY

The northern part of the Iberian peninsula is formed by a long cordillera which is composed of rocks various in age, origin and composition. In the very northwestern part of Spain, near El Ferrol and La Coruña, igneous and metamorphic rocks predominate amidst sediments of Cryptozoic to Silurian ages (fig. 1). From just about west of Ribadeo to west of Aviles sedimentary strata of Cambrian to Ordovician ages start to dominate over the metamorphic rocks. East of the city of Aviles Devonian and Carboniferous sediments form the most important deposits. East of Unquera Mesozoic sediments cover the Paleozoic strata. The general strike around La Coruña and El Ferrol is north-south. More inland the strike changes into a more southeastern direction. North of the city of León the strike has become east-west, and east of Cervera de Pisuerga the Paleozoic disappears under a cover of Mesozoic strata. Paleozoic strata reappear east of Burgos to form the Sierra de la Demanda. Further to the south-east is another island of Paleozoic sediments near Catalayud. Lotze & Sdzuy (1961) suggested that we have to do with a trough which stretched out from the Gulf of Biscay to the Mediterranean (fig. 1). Our main area of interest lies north of León (fig. 2) and is bordered by the Luna River in the west and the Esla River in the east. In this part of the cordillera the most striking feature is the occurrence of two E-W trending longitudinal units. The northern unit has been called the Asturides (de Sitter, 1959). In the Asturides one finds mainly pre-Devonian strata and Carboniferous sediments of Westfalian age. The scant Devonian sediments present are sandstones of Upper Devonian age belonging to the Ermita Formation. The southern unit has been named the Leonides. The Paleozoic strata of the Leonides can be divided into four units.

D. Carboniferous sediments of Westfalian — Stephanian age deposited into small basins and unconformably overlying the older Carboniferous deposits.
C. Carboniferous sediments of pre-Westfalian age, Tournaisian — Namurian, mainly sandstones, shales and some limestones.
B. Devonian strata of the Bernesga Group, mainly limestones, shales and sandstones with an important unconformity of Upper Devonian age near the top of the group.
A. Pre-Devonian strata of the Luna Group. These are mainly sandstones and shales with the exception of the limestones and dolomites of the Lancara Formation.

Precambrian strata are present as slightly metamorphic shales and sandstones which form the Mora Formation.
The Asturides and the Leonides are separated by an imaginary line, the León Line, which can be considered as a hinge line between the two units. Another important feature is the Pardomino High. It lies in the eastern part of the studied area and cuts obliquely through the Leonides. It separates the area of the Esla River from the area between the Porma River and the Luna River.
Folding of the sediments took place in Carboniferous times and thrust-sheets were formed both in the Leonides and the Asturides. In the Leonides we find east-west striking thrustsheets which, from north to south have been called by de Sitter (1962):

Forcada thrustsheet,
Bodon thrustsheet,
Gayo thrustsheet,
Correcilla thrustsheet,
Rozo thrustsheet and
Bregon thrustsheet.

Except for the Bodon thrustsheet these overthrusts have in common that their base is always formed by the Lancara Formation. The Bodon thrustsheet cuts deeper into the Paleozoic strata and her base is formed by the Herreria Formation, a unit of Cambrian sandstones directly on top of the Precambrian.

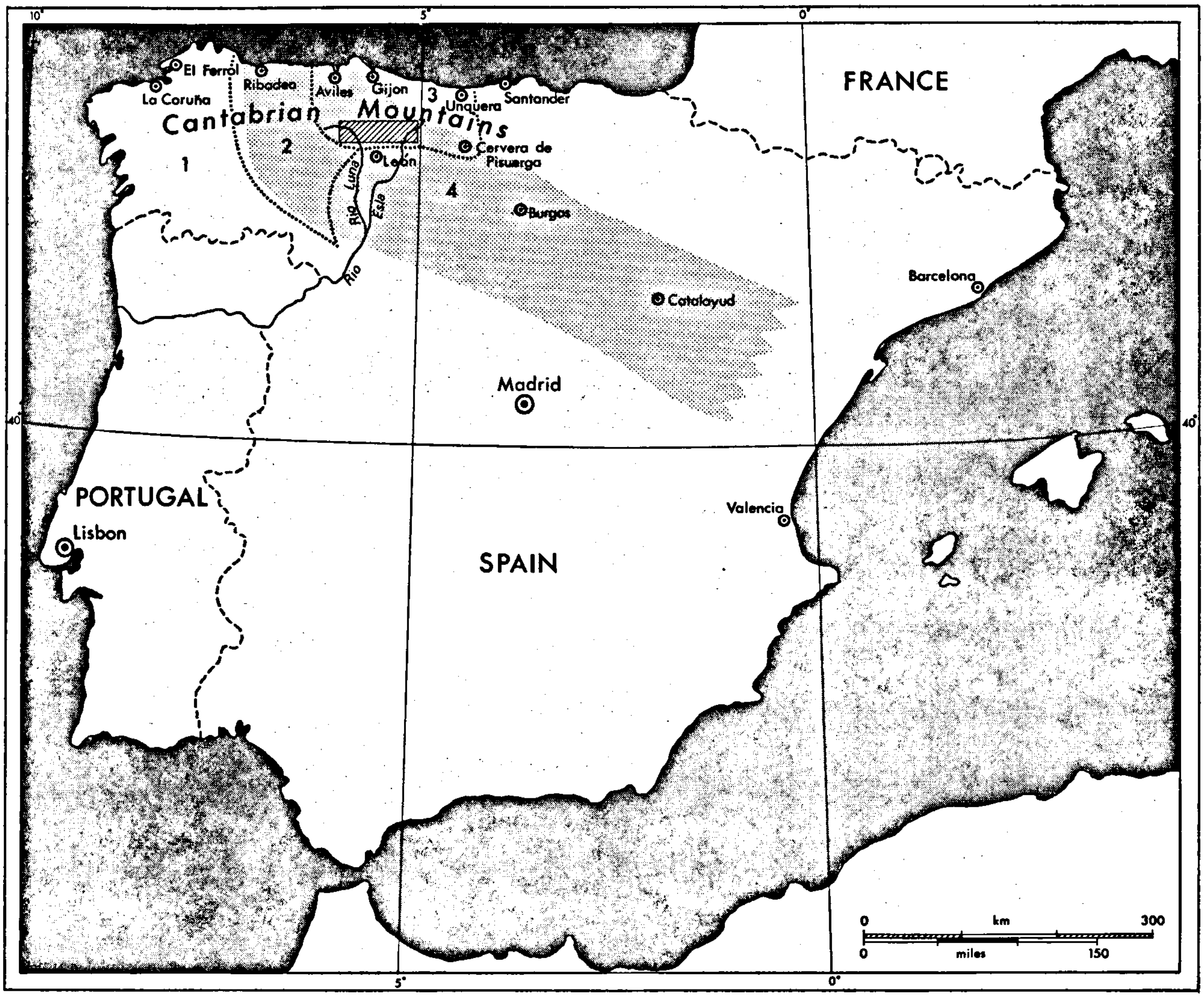


Fig. 1. Index map of Spain. Dotted area is the Paleozoic geosyncline postulated by Lotze & Szduy (1961). Area 1 consists mainly of igneous and metamorphic rocks amidst sediments of Cryptozoic to Silurian age. In area 2 are mainly Cambrian — Ordovician strata. Area 3 has mainly Devonian and Carboniferous strata. Area 4 has predominantly Mesozoic strata. Hatched rectangular is the area of study.

Previous work on Cambrian strata

Cambrian sediments have been described from the Cantabrian Mountains ever since the nineteenth century. It was Casiano de Prado (1860) who reported the presence of pre-Devonian sediments from this area for the first time. He described two bands of calcareous sediments between the Esla River and the Curueño River from which limestones he had collected Cambrian fossils. After Prado several other Spanish geologists worked on these Cambrian strata. Hernandez Sampelayo showed these strata on a geological map part of which map was later also published by Lotze & Sdzuy (1961). Comte (1937, 1959) is certainly to be named as the founder of the present stratigraphical concepts in the Cantabrian Mountains. His 1959 paper is still an extremely useful monograph on the stratigraphy and the paleontology of the Paleozoic of the Cantabrian Mountains. His lithostratigraphical units have been accepted by several later authors and will generally be followed in this thesis too. Lotze & Sdzuy published paleontological and stratigraphical data on the Cambrian of the Iberian peninsula. Oele (1964) discussed the sedimentological aspects, among others of the Lancara Formation, of the Lower Paleozoic deposits in the Esla River region and the surroundings of the Curueño River. Rupke (1965), Sjerp (1966), Evers (1967), van Staalduinen (1969, in press) and van den Bosch (1969, in press) briefly discussed the stratigraphy of the Cambrian in their thesis areas. Their main objective was the mapping of the area on a 1 : 50.000 scale, which they carried out in detail. Van der Meer Mohr & Schreuder (1967) published a

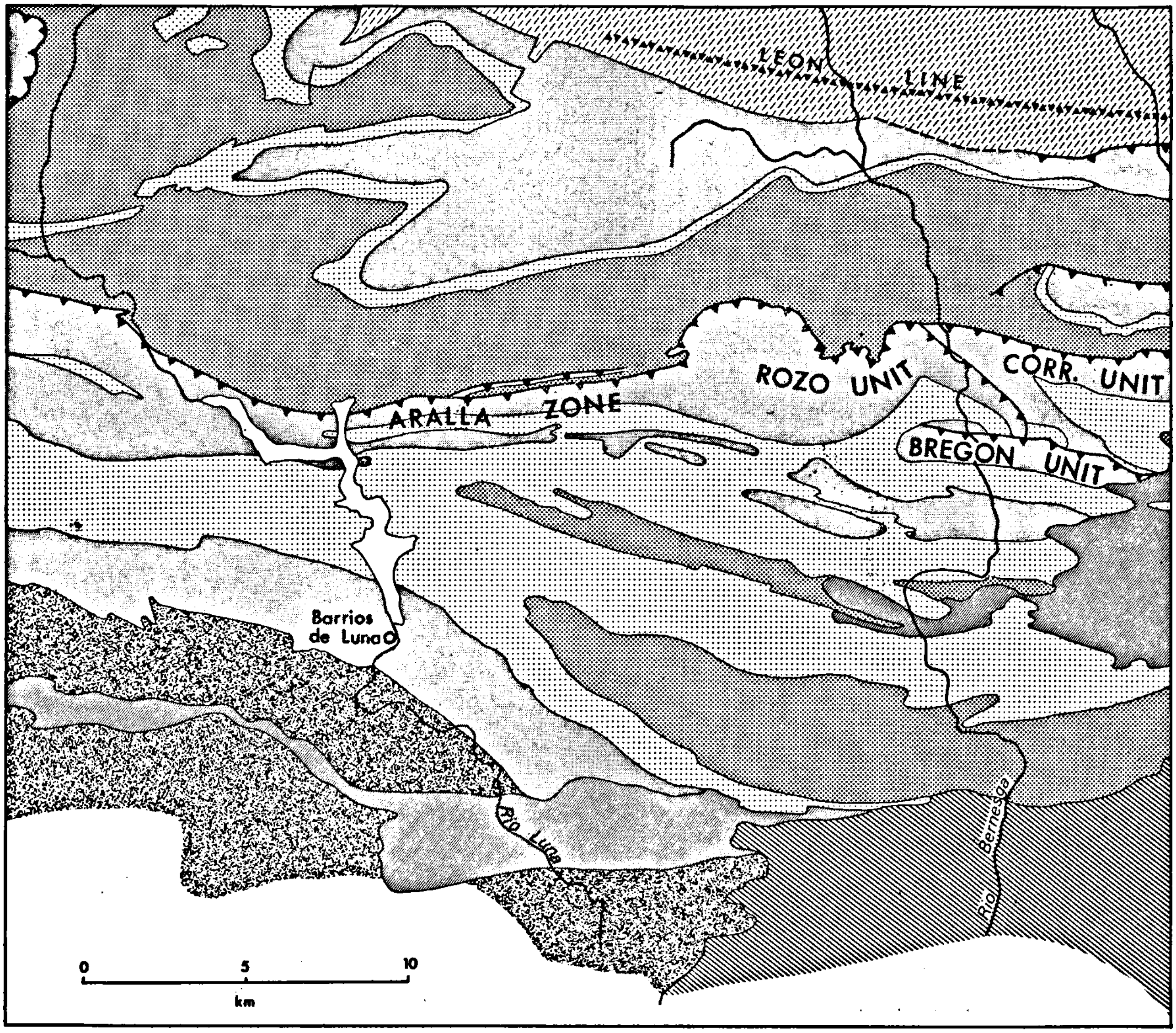
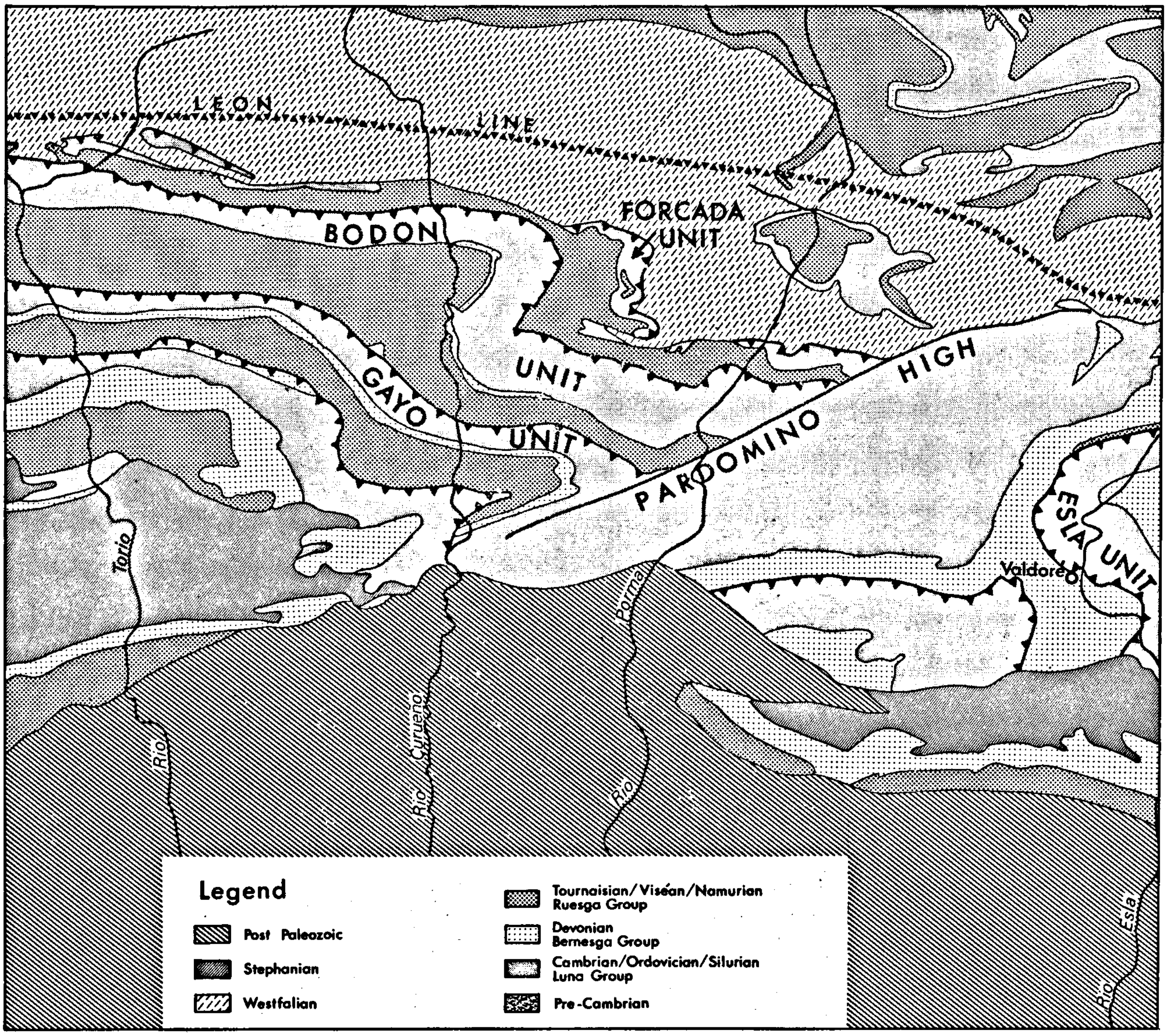


Fig. 2. Generalized geological map of the southern Cantabrian Mountains

preliminary paper on the Lancara Formation around the Sierra de la Filera in which they drew a comparison between the depositional environment of Recent carbonates and the environment in which the carbonates of the Lancara Formation have been deposited.

TECHNIQUES OF MEASUREMENT OF THE SECTIONS AND SAMPLE STUDY

All sections measured for this thesis are outcrop sections which are mainly located along the roads and riverbeds which cross the area in a N-S direction. The geographical location of the sections is given in figure 3. Most sections were measured with the aid of a 20 m tape and a Brunton compass. When due to the local circumstances detailed sampling and measuring could be done, the true thickness of the beds was measured with the aid of a 1,5 m long staff. Along rather monotonous sections samples were collected at approximately 2,5 m intervals along the stretched out tape. When necessary shorter intervals were taken. The individual samples were put into plastic bags which were labelled 'en place'. In the camp the bags were put into sturdier paper bags on which we wrote the locality of the section and the date of measuring. The samples were studied in the field with the aid of a handlens and a bottle of hydrochloric acid (10 % v.v.). Gross lithological features were noted in the fieldbook. In the laboratory a microscopical examination of the samples was carried out with a binocular microscope and a polarizing microscope. The samples (about a thousand) were cut, polished and examined under the binocular microscope. In addition chips were taken from each sample and dissolved in hydrochloric acid in order to get an idea



between the Luna River and the Esla River. Modified after de Sitter, 1962.

of the residu. Volumetric percentages were estimated with percentage-charts and the color of the specimen was compared with the Munsell rock color chart (distributed by The Geological Society of America). Thin sections were made of about 250 samples. All specimen of section LSD, which is the best section, were thin sectioned. Staining was done with a mixture of Alizarine Red-S and $K_3Fe(CN)_6$ Friedman, 1959). The specimen of LSD were checked in the geochemical laboratory of the Institute for copper, nickle, cobalt and strontium with the aid of an atomic absorption spectrophotometer, Perkin-Elmer 303. Parts of LSD were analysed, with the same instrument, for its magnesium and calcium contents in order to get an idea of the connection between the strontium content and the amounts of magnesium and calcium present in the sediments.

CARBONATE TERMINOLOGY

Since Grabau, at the beginning of this century, came out with a classification system for carbonate rocks many others have approached this problem, principally along two ways (for a comprehensive treatise on this subject see: Ham, 1962). A genetic classification was favored at first while in a later period a more descriptive way of classifying the sediments came 'en vogue'. The latter became more favored when it was realized that there are many different ways in which a particular sediment, with certain characteristics, could have been formed. A very important step in the classification of carbonate rocks was taken when the grains, the matrix and the cement were taken as the three cornerstones for a classification system (Folk, 1959; Monty, 1963 and others). In Folk's classification system, which is generally followed in this thesis, four types of grains (called 'allochems' by Folk) were suggested: intraclasts (i.e. clasts of carbonate sediment formed by disruption inside the basin of deposition), oölites, bioclasts (fragments of biogenic material), and pellets (ovoid, structureless, masses of microcrystalline calcite).

Wolf (1963 and following years) drew attention to the fact that the intrabasinal character of the intraclasts can not always be established with certainty. He presented a modification of Folk's scheme and introduced the term extraclast (equivalent to Folk's lithiclast) for extra-basinal fragments of carbonate sediment. When the origin of the clasts is unknown, Wolf suggested to use the term limeclast, under which term therefore both the intraclasts and the extraclasts can be brought. Monty (1963) suggested a splitting up of the term bioclasts into phytoclasts (floral fragments) and zooclasts (faunal fragments). The matrix of a carbonate sediment is an extremely fine carbonate mud (lime mud). Folk introduced the term micrite (microcrystalline calcite) and called the clear, calcite cement between the grains sparry calcite cement (calcite crystals larger than 20 mu filling the interstices between the grains and vugs in the lime mud). The origin of the lime mud is a much debated subject. There are those who adhere to a purely chemical mode of formation (precipitation from a solution, Cloud, 1962) and there are geologists who feel more for the idea that a significant part of the lime mud is detrital in origin (Lowenstamm, 1955; Ginsburg, 1957; Stockman et al., 1967). The relative turbulence (the 'energy') in an environment was believed to be reflected in the presence or absence of intergranular lime mud. Sediments, deposited in a very quiet environment are considered to contain lime mud between the particles or be even entirely composed of lime mud (Folk's micrite; Dunham's mudstone, Dunham, 1962). Under more turbulent circumstances the mud can be washed out of the sediment and only the grains would be left to be later on cemented by sparry calcite. Dunham (1962) came out with a classification system which was based on the absence or presence of the mud and the textural aspects of 'grain-supported' sediments (i.e. sediments in which the grains are in contact with each other) versus 'mud-supported' sediment (grains separated from each other by a substantial amount of lime mud). The essentiality of both, Folk's and Dunham's, classification systems as well as of other modern systems in the importance of mud and the presence or absence of mud is considered to be indicative for the turbulence of the environment. Imbrie & Purdy (1962) made a study of Bahamian sediments west of Andros Island and put their data in a computer. Their maps are generally in harmony with the maps, of the same area, based on Folk's classification system.

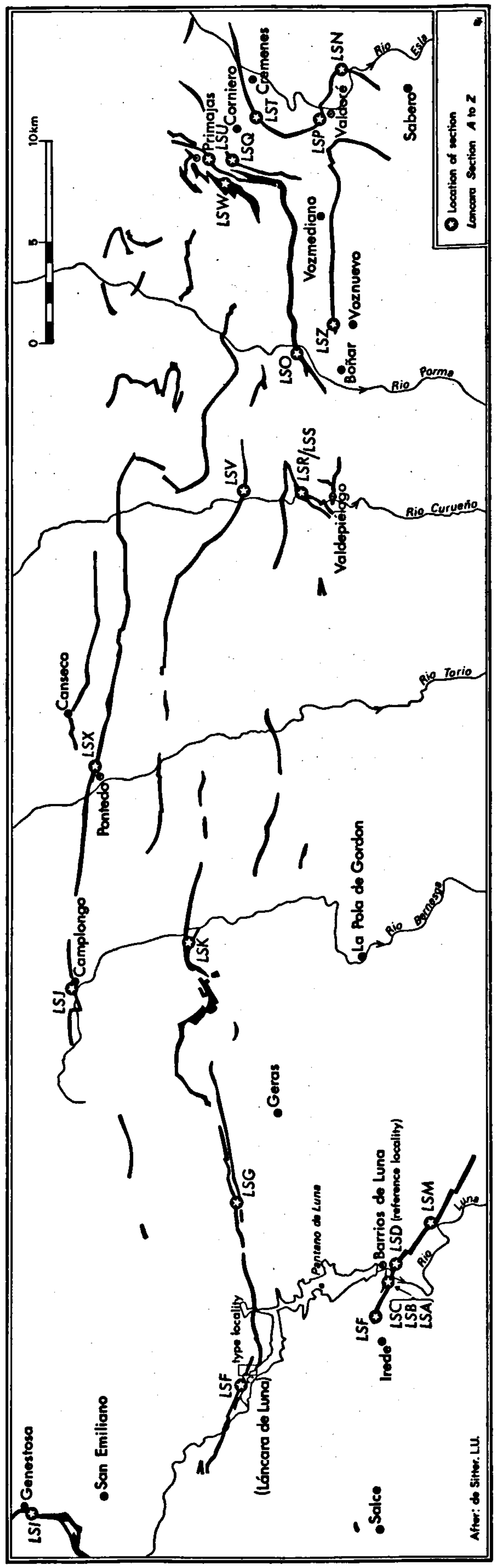


Fig. 3. Location map showing the outcrop pattern of the Lancara Formation, the location of the sections, the type locality and the reference locality.

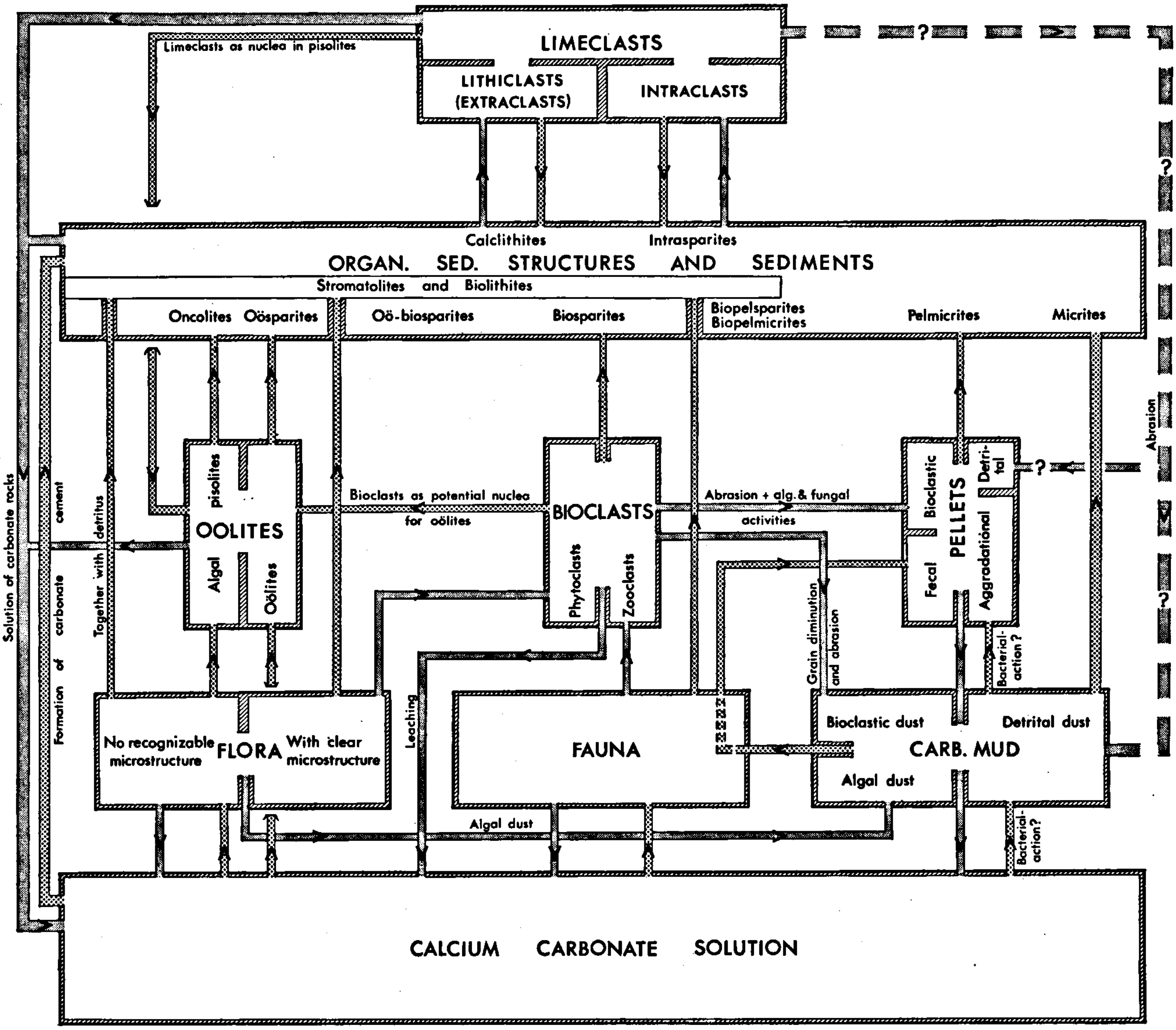


Fig. 4. Diagram showing some of the aggrading and degrading processes which can lead to the formation or destruction of calcium carbonate particles and sediments. Heavy dots represent aggrading processes and small dots represent degrading processes.

Monty (1965) pointed out, however, that one could also find very coarse carbonate particles without any interparticle mud in exceptionally quiet environments. Apparently the dimensions of the area over which a study is made and the degree of accuracy wanted can play a rôle by the choice of a classification system. In figure 4 the author has tried to present the cycle of calcium carbonate (be it aragonite or calcite) in a marine environment. The diagram is intended to give a rough idea of the complicated relationships that exist between the different graintypes, the importance of fauna and flora, chemical precipitation and solution etc. In this diagram it is assumed that there are two gross processes. Aggrading processes such as the forming of a shell or an oölite as well as the forming of the sediment (cementation included) and degrading processes which are the exact reverse. There are many more processes than shown in this diagram; some of those processes are so complicated and dependent of a multitude of conditions that, if they were shown, the whole scheme would become illegible. Secondary processes like dolomitization and recrystallization have also been left out of the picture as well as the addition of siliciclastic material to the sediment.

CHAPTER II

DEFINITION OF THE LITHOSTRATIGRAPHIC UNITS IN THE LANCARA FORMATION

INTRODUCTION

As written earlier it was Casiano de Prado who reported the first Cambrian strata from the Cantabrian Mountains. His study was centered around the Esla-Porma region but he also reported findings from more western localities. Prado's interest in the Cambrian sediments was focussed on the red, argillaceous, nodular limestones (the 'griottes' of later workers). These limestones yielded a rich fauna of trilobites, brachiopods and cystoids. Prado did not use the term Lancara Formation, but called the two bands of fossilliferous limestones the 'bande de Sabero' and the 'bande de Boñar (Prado, 1860, p. 518—519). Comte introduced in 1937 the term 'calcaires de Lancara' when he described sections in the Esla River region. The red nodular limestones were called 'griottes rouges' by him. In his publication from 1959 Comte mentioned the important occurrence of glauconite and pointed out that this mineral is found in his 'calcaires cristallins'. The following quotation is from Comte (1959, p. 71—72).

'On y distingue à première vue une formation inférieure en partie dolomitique de teinte grise ou jaunâtre assez claire et une formation supérieure, plus mince, d'un rouge vif absolument caractéristique. Tout cet ensemble est disposé en bancs réguliers. La formation inférieure est constituée en majeure partie par des calcaires dolomitiques compacts gris ou jaunâtres à patine claire, et se termine par des calcaires cristallins associés à des calcaires très fins. Le niveau où débutent les calcaires cristallins varie d'une région à l'autre; ces derniers sont par place assez chargés de glauconie, ils montrent aussi de rares traces d'organismes. Au microscope, les calcaires et calcaires dolomitiques des assises inférieures présentent une texture très fine de calcite ou de dolomies avec exceptionnellement des traces d'éléments étrangèrs: grains de quartz très petits, paillettes de mica et traînées d'oxyde de fer. Les calcaires cristallins sont formés d'une mosaïque assez régulière de rhomboèdres de calcite de quelques millimètres d'arrête, de la glauconie en petits grains est toujours présente et quelquefois assez abondante, elle est souvent accompagnée de très fins granules de pyrite; on y rencontre encore, de façon exceptionelle, de petits grains de quartz, des lamelles de muscovite détritique et lorsque la pyrite est décomposée des concentrations d'oxyde de fer. Certaines préparations montrent des cristaux de calcite de taille variable accompagnés de fragments d'organismes, de Trilobites surtout. Il est évident que la caractère cristallin de ces calcaires ne peut être attribué à des actions métamorphiques.
La formation supérieure est constituée par un calcaire marneux, souvent noduleux, d'un rouge intense tirant sur le violet. Il est moins compact, mais d'une couleur beaucoup plus crue que la griotte typique du Dévonien des Pyrénées.
Examiné en lame mince, ce griotte cambrien se montre formé de petits cristaux de calcite (accompagnée d'un peu de dolomie et sans doute de trace de sidérose), de fragments calcaires de Brachiopodes, de Cystides et de Trilobites noyés dans une masse de calcite pulvérulente, d'éléments phylliteux et d'hématite. On y trouve assez souvent des grains de glauconie, vers la base surtout. De quartz et de la muscovite ainsi que de petits cristaux de zircon s'y rencontrent de façon exceptionelle...'

Lotze & Sdzuy used a different nomenclature for their stratigraphic units than Comte. They pointed out that, in some areas, a tripartite could be made in the Lancara Formation and mentioned the occurrence of algal structures in the Lancara Formation. From fossils collected both from the strata directly underlying the Lancara Formation as well as from the 'griotte' they concluded that the age of the Lancara Formation must be from Lower Cambrian to Middle Cambrian (see fig. 5). In this thesis a general use is made of their age determinations but not of their lithostratigraphical terminology. Figure 5 gives a summary of the different viewpoints up to 1967.
Because of the data that have come available from this Lancara study is seems necessary to reconsider the whole nomenclature for the Lancara Formation (fig. 6). For that purpose use has been made of the Code of Stratigraphic Nomenclature by the American Commission on Stratigraphic Nomenclature (A.A.P.G. Bull., v. 45, no. 5 (May 1961), p. 645—660).

THE SELECTION OF NAME

(See articles 10, 11 and 12 of the Code), Prado's terminology is obsolete and his description of the regional distribution of Lancara outcrops has been overtaken by recent mapping. Priority should be given to the name Lancara Formation since it is by far the most widely used name in literature and has priority of date over the terminology used by Lotze & Sdzuy (1961). The geographic name should be the name of a natural or artificial feature at or near which the rock-stratigraphic unit is typically developed (Art. 10, remark a). A name that suggests some well known locality, region or political division should not, in general, be applied to a unit typically developed in another less well known locality of the same name (Art. 10, remark k). The terms León Kalke and León Dolomite etc. are poorly chosen. Although the particular part of the Cantabrian Mountains lies in the Provincia de León it is better to write about the Lancara Formation since this unit outcrops near Láncara de Luna. Moreover the outcrop near Láncara de Luna is a well known locality of Cambrian fossils in the Lancara Formation (Prado, 1860; Comte, 1959).

THE TYPE AREA

The type locality of the Lancara Formation is a number of outcrops, along the road from La Magdelena to San Emiliano, above the ruins of the village church of Láncara de Luna (fig. 3). The longitude of these

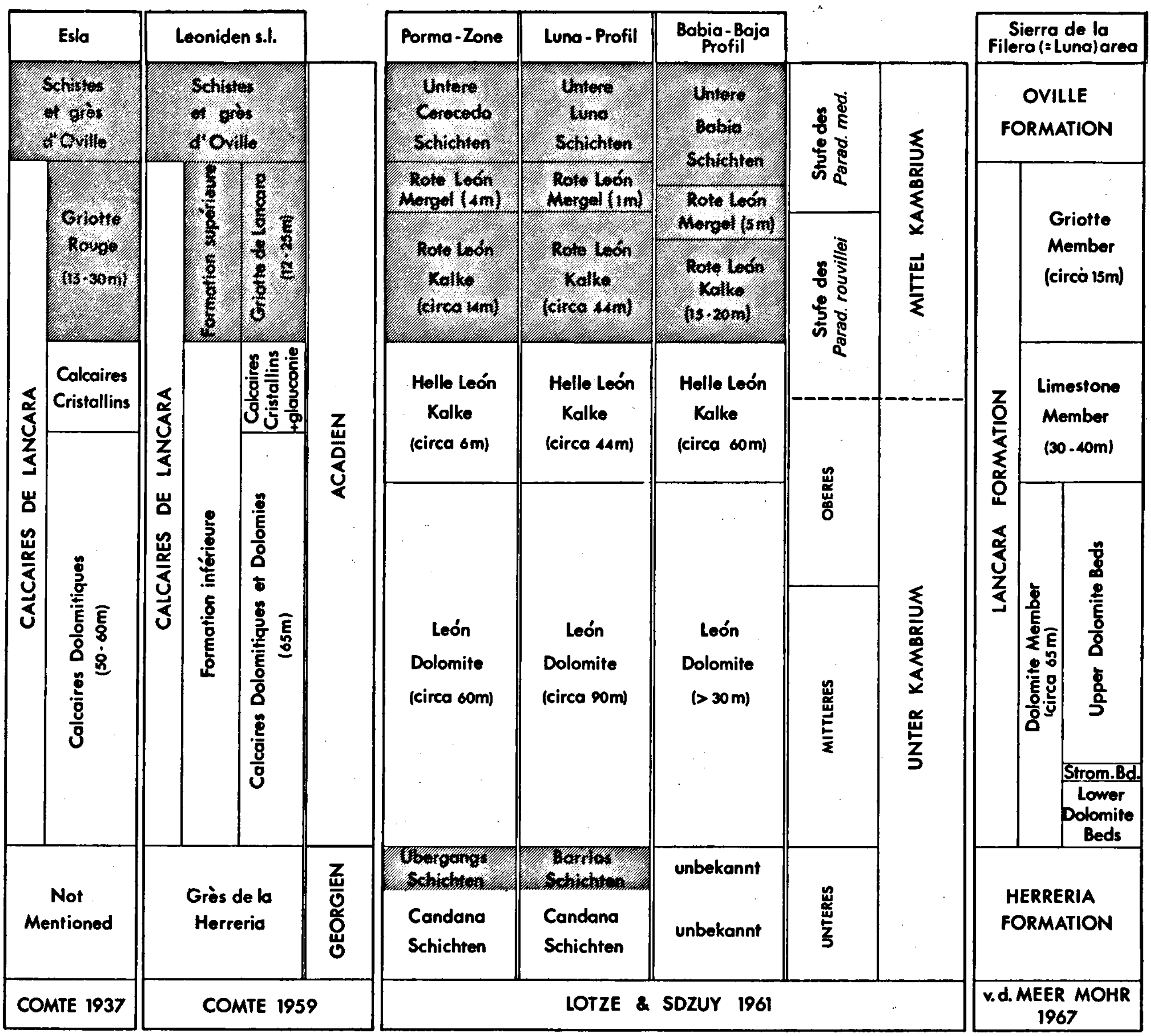


Fig. 5. Correlation chart showing the lithostratigraphic and biostratigraphic units of the Lancara Formation as used by Comte (1937, 1959), Lotze & Sdzuy (1961) (by permission of the Akademie der Wissenschaften und der Literatur) and van der Meer Mohr & Schreuder (1967). Fossils useful for the age-determination of the strata came from the shaded intervals.

Lancara outcrops is 2°14′ 15″ W of Madrid and its latitude is 42°54′30″. The locality is in a poorly chosen spot since the strata have been altered very much by orogenesis and dolomitization. The section is probably incomplete at the base of the formation. Thrustfaulting has also caused a repetition of the section. It would therefore be better to supplement the type section with a reference section (Art. 13, remarks a and i). For that purpose section LSD (fig. 3) was chosen as a reference section. Its longitude is 2°10′30″ W of Madrid and its latitude is 42°50′32,5″. It is located along the road from La Magdalena to San Emiliano above the village of Barrios de Luna. From the two outcrops of Lancara strata on the eastside of the road it is the most northern outcrop.

THE HERRERIA FORMATION

The sediments underlying the Lancara Formation are the siliciclastic deposits of the Herreria Formation. They form a sequence of about 600 m thickness (according to Rupke, 1965) and are mainly composed of sandstones, conglomerates and silty shales. The bulk of the beds consists of medium-grained quartzites (Oele, 1964). Lenses of oölitic dolomite can occasionally be found in it too. Evers (1967) mentioned the occurrence of stromatolites in the Herreria Formation

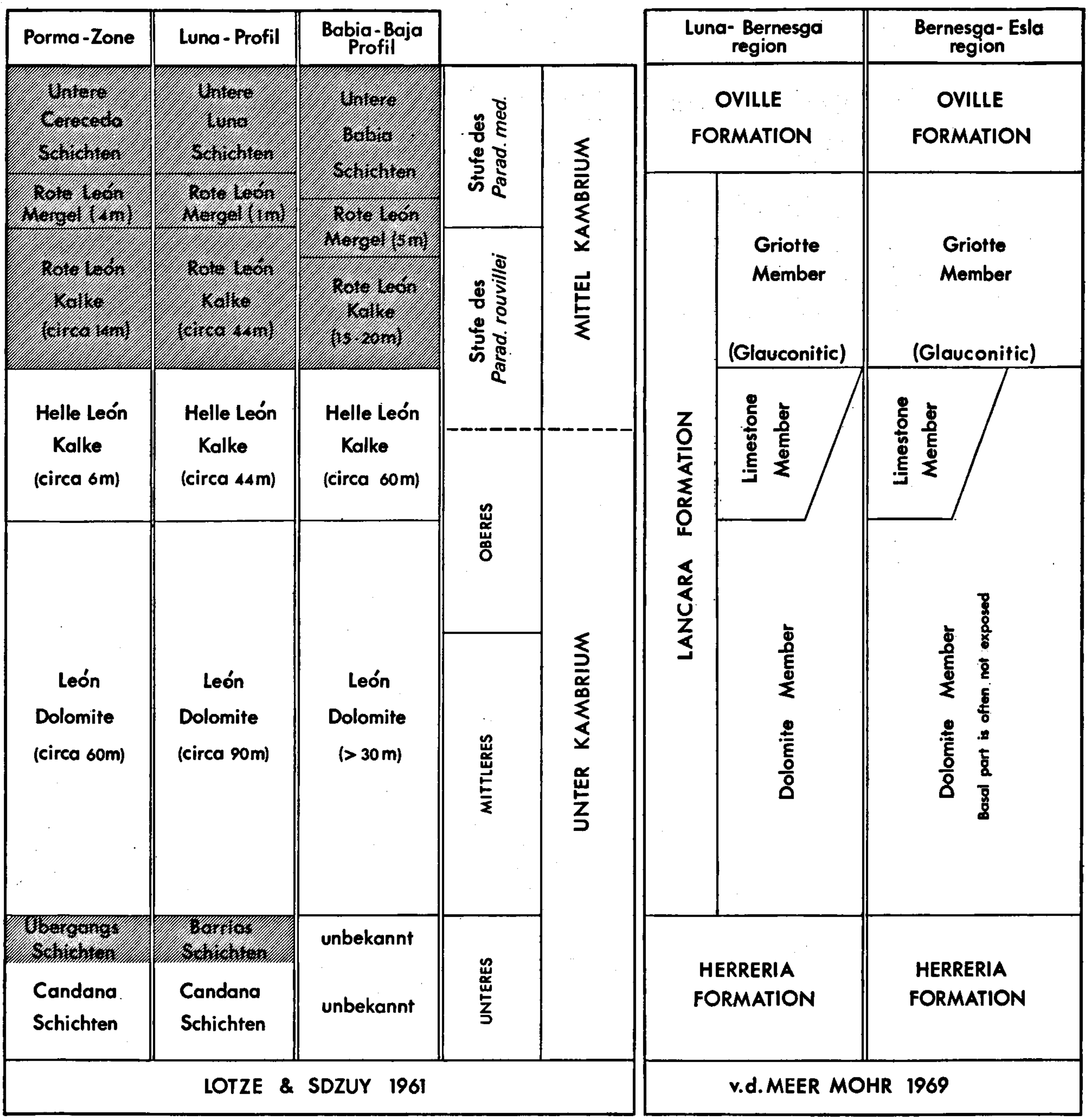


Fig. 6. Correlation chart showing lithostratigraphic units of the Lancara Formation as proposed in this thesis versus the lithostratigraphic and the biostratigraphic subdivisions by Lotze & Sdzuy (1961) (by permission of the Akademie der Wissenschaften und der Literatur). Fossils useful for the age-determination of the strata came from the shaded intervals.

between Cerecedo and Valdepiélago and north of Villanuevo de Pontedo. This would support Oele's idea that the Herreria sediments have been deposited in a shallow marine environment. Near the top of the Herreria Formation shales predominate over the quartzites. From these shales Lotze & Sdzuy collected Lower Cambrian fossils. Van der Meer Mohr & Okulitch (1967) mentioned the occurrence of *Scyphomedusa* (fig. 7) but this is probably wrong. Seilacher (pers. commun.) pointed out that he had determined these fossils as *Astropolithon* Dawson (Seilacher *in:* Lotze & Sdzuy, 1961, p. 76). The contact with the overlying deposits of the Lancara Formation is sharp and conformable.

THE LANCARA FORMATION

This is a sequence of Cambrian (Acadian) dolomites, limestones and red shales (fig. 6). It is in its reference section 183 m thick. The base of the Lancara Formation was taken at the occurrence of, usually oölitic, dolomite beds overlying (not intercalating with) the Herreria Formation. The top of the formation was taken at the top of a sequence of red (10 R 5/4), calcareous shales and nodular argillaceous, limestones underlying the brown (10 YR 6/2) shales and glauconitic sandstones of the Oville Formation.

In its reference section, near Barrios de Luna, the Lancara Formation can be subdivided into three members. From base to top these are the Dolomite Member, the Limestone Member and the Griotte Member.

The Dolomite Member

Its base is the base of the Lancara Formation. The top of the Dolomite Member was taken either: at the first occurrence of the thick banded, dolomitic (less than 50% dolomite) algal limestones of the Limestone Member or, at the first occurrence of the basal, glauconitic, beds of the Griotte Member.

The Limestone Member

This is a unit of algal limestones overlying the Dolomite Member and underlying the nodular, glauconitic, biosparudite-biomicrudite beds of the Griotte Member. The Limestone Member is rather restricted in its regional occurrence and is found mainly in the surroundings of Barrios de Luna and along th eEsla River.

The Griotte Member

This is a unit of red (10 R 5/4), bioclastic argillaceous, nodular, limestones and calcareous shales containing glauconitic pellets. The Griotte Member is either overlying the Limestone Member or the Dolomite Member. The top of the Griotte Member coincides with the top of the Lancara Formation.

In the area between the Luna River and the Bernesga River the Dolomite Member can be subdivided into different beds. Since it is difficult to recognize in the field the boundaries between the beds (thin sections are necessary) it would not be practical to establish formally any smaller rock-stratigraphic units than the members. The same goes for the basal part of the Griotte Member. This is a nodular biosparudite-biomicrudite and it grades vertically into the 'griotte'. A distinct boundary between the two does not exist. In this thesis the boundary was drawn where the siliciclastic content of the sample became over 15 percent (v.v.). No attempt was made to establish new biostratigraphic units. Figure 6 shows the biostratigraphic subdivision by Lotze & Sdzuy next to the lithostratigraphic column proposed in this thesis. Lotze's 'Helle León Kalke' from the Luna-Profil and the Babia-Baja-Normalprofil correspond with the Limestone Member. The Helle León Kalke of circa 6 m thickness in the Porma-zone are somewhat puzzling. They are most probably equivalent to the biosparudite beds since Lotze & Sdzuy (Tab. 7, 1961) reported fragments of brachiopods and cystoids from them. They should have been included in the Rote León Kalke.

THE OVILLE FORMATION

The shales, siltstones and sandstones of the Oville Formation overly the Lancara strata. Oele (1964) drew his boundary between the two formations at the lowermost sandstone bed in the Oville sequence. Locally this might be a useful criterium but it fails where this lowermost sandstone bed is underlain by a substancial amount of brown shales. It also fails in areas, such as north of San Emiliano, where sandstone beds are intercalated between the red, nodular, limestones. Since this color-change from reddish-brown to ochreous-brown is much easier distinguishable in the field (even in poorly exposed terrain) the color-change has been used as a criterium to draw the Lancara — Oville boundary.

The Oville Formation is approximately 180 m thick in the Esla region (Oele, 1964) and according to Evers (1967) its thicknesses can vary between 250 m and 200 m in the area between the Bernesga River and the Pardomino High. The series contain sandstones, siltstones and shales. Sjerp (1966) reported oölitic limestones from the Oville Formation. These were also reported, by field parties, from the surroundings of the Esla River. Glauconitic pellets and calcareous cement are very common in the Oville sediments. Oele (1964) found also loadcasts and slumpballs in the Oville Formation. His conclusions are that these marine sediments have been deposited in a series of deltas (Oele, 1964, p. 76).

CHAPTER III

DESCRIPTION OF THE STRATA

The area of study for this thesis has been divided into:

the Luna — Bernesga region,
the Bernesga — Pardomino High region,
the Esla region.

THE LUNA — BERNESGA REGION

This is by far the most important area since the best sections of the Lancara Formation in the Cantabrian Mountains are exposed in this area (Appendix I & II). Starting from the base of the formation the Lancara can be divided into a Dolomite Member, a Limestone Member and a Griotte Member.

The Dolomite Member

Several informal rock-stratigraphic units can be distinguished in this member.

The basal oölitic dolomite beds. — These are up to 15 m thick and well exposed near Barrios de Luna. They were not found in section LSF, whether this is due to poor exposure of the strata or to non-deposition could not be found out. In the northern part of the Luna — Bernesga region the base of the Lancara Formation has been cut out by faulting with the result that the oölite beds, if deposited there, were not found. Interbedded with the oölite strata are beds of finely crystalline dolomite and now and then some chert lenses. The top of the oölite beds has been taken at the base of an overlying shale bed. The oölites have a diameter of 1—1,5 mm and their centres are either formed by subhedral quartz or dolomite rhombs. Some well rounded fossil fragments were observed between the oölites (fig. 8). The spheres have sometimes been silicified in which case the concentric layers have been fairly well preserved. The concentric structure has practically vanished where the oölites have been dolomitized. The dolomitized part of an oölite lies outside the silicified part. The cement around the spheres is sometimes made of subhedral dolomite crystals which form a rim around the allochems suggesting the replacement of the original calcite cement rim by dolomite. Distorted oölites, as described by Cayeux (1936) and Carozzi (1961) were only found in LSD (fig. 9). According to Carozzi they are the result of distortion of the oölites prior to cementation.

The stromatolite marker bed. — A 2—3 m thick, grey colored, stromatolitic dolomite — dolomitic limestone forms in the Barrios de Luna area a useful marker bed. In other parts of the region this unit is absent. The stromatolites are made up of a combination of *Collenia* and *Cryptozoon* structures (SH-C and LLH-S structures of Logan et al., 1964). The stromatolites (fig. 10) are generally 10—50 cm high. Seen through a petrographic microscope they consist of tightly interlocking calcite anhedras of 5—10 μ and strings and clusters of dolomite rhombs, circa 40 μ in size. The dolomite strings follow the dome shaped pattern of the stromatolites (fig. 10), apparently the flow of the dolomitizing solutions was affected by the stratification of these algal structures. The dolomite clusters are scattered at random through the rock. Between and inside the stromatolites as well as in the strata immediately above and below the marker bed are pinkish white nodules of sparry, ferroan, calcite, 2—15 mm in diameter (fig. 10). These nodules occur in greatest abundance in lenses of stromatolite breccias which are interbedded between the algal structures. In thin section the calcite of the nodules turns out to be coarsely crystalline and shows straight intercrystalline boundaries. The crystals in the rim of the nodules are often subhedral (fig. 11). There is no gradational change in crystal size between the crystals in the nodules and the surrounding microspar of the stromatolites. The crystal size sometimes increases to the centre of a nodule and sometimes one particular crystal can extend from wall to wall, occupying the whole nodule. Colored with a mixture of Alizarine Red-S and $K_3Fe(CN)_6$ the calcite turned out to be a ferroan calcite, occasionally zonar built. Geopetal structures were never observed in the nodules. Closely packed dolomite rhombs consistently form a lining around the nodule and the inner part of this lining is mostly irregular. The dolomite rhombs can form peninsulas in the coarse calcite crystals or can be poikilitically enclosed in the calcite (figs. 11, 12 & 13).

The finely crystalline dolomites. — These deposits form a sequence of light-grey to medium-grey dolomites with a greyish-orange (10 YR 7/4) weathering color. It is an interval practically devoid of any fossils and the only traces of life are the occasional sedimentary structures formed by algae as well as indeterminable tubes (1/20th of a mm in diameter) which might be remnants of algae. In thin section we see a mass of subhedral dolomite crystals ranging from very fine to fine in size. They contain only traces of siliciclastic material and quite often very fine authigenetic quartz (about 1—2 percent). Only above and below the stromatolite marker bed do we find coarser grained dolomites. These are dolomitized calcarenites but the original nature of the allochems cannot be established. Some bioclasts and oölites? can be recognized. In the northern part of the Luna — Bernesga region, along the León-line, most of the Lancara Formation is formed by the finely crystalline dolomites. In section LSJ the unit almost extends up to the Griotte Member. Traces of possible pseudomorphs of dolomite after gypsum(?) were found in the Aralla zone (figs. 16 & 17) in section LSG. Small scale cross-bedding (v. d.

Meer Mohr & Schreuder, 1967, Pl. II A & IIIA), varve-like laminations (fig. 18) and intraformational breccias (fig. 19) can be found throughout the interval and are the only phenomena that break the monotony of this sequence. Dolomitic shales are intercalated between the dolomites and could locally be used as marker beds.

The pelletal dolomite beds. — In the Barrios de Luna area these beds form an unit of approximately 10—15 m thickness. They have the same color as the finely crystalline dolomites and can be traced into the Aralla zone and in the section LSE, near Lancara de Luna. From there onward correlations become pure guesswork. In sections LSA and LSB the pelletal dolomites have been correlated with an interval that contains abundant stromatolites and algal fragments which is comparitive with the sediments of the Limestone Member, except that it is dolomitized. The intervals in LSA and LSB, however, are underlain by finely crystaliline dolomites and overlain by coarsely crystalline dolomites. Hence they are in the same stratigraphic position as the pelletal dolomites in, for instance, LSC. The pelletal dolomites of LSC and LSD are therefore considered to change in facies towards LSE and LSA. Westward from Barrios de Luna there may also have been a facies change, since the pelletal dolomites seem to thicken in the direction of LSF. Thin sections show a completely dolomitized pelmicrite and pelsparite with frequent algal banding and an increase in the amount of dolomitized limeclasts towards the top of the section.
Micro-cavities are frequently found in this interval. Near Barrios de Luna they occur in the upper part of the interval and in the Aralla zone throughout the unit. Under high magnification the pellets are light brown ghoststructures in a very fine xenotopic dolomite. The dolomitic cement between the pellets shows fine subhedral dolomite crystals. Besides the pellets and the dolomitized limeclasts another, rather problematic, type of allochem occurs in LSD, sample 35 (fig. 20). These are dolomitized clasts of 1/5—2 mm in size which are made up of anhedral dolomite crystals set in a network of limonitic? material and clots of very fine to aphanocrystalline dolomite. The outlines of the clasts vaguely resemble crystals. No decisive evidence could be found, however, of any pseudomorphism. The clasts are surrounded by a rim of drusy dolomite. In the micro-cavities dolomite occurs as subhedral crystals along the walls of the cavities and as well developed rhombs in the centre. These micro-cavities, which show sedimentary floors, could have been formed by leaching of the original sediment. Traces of porosity occur in the centres of the cavities between the rhombs. Coloring gave a weak blue stain to parts of the drusy mosaic and a slightly darker blue stain to parts of the algal mats. The stain in the mats was concentrated in tubes. This might have been caused by traces of iron originally precipitated in the organic tissue of the algae.

The coarsely crystalline dolomites. — These are light-grey, moderately brown (5 YR 4/4) weathering sediments. In the field their weathering color contrasts with the lighter brown of the underlying dolomites. Sedimentary structures are rare in this interval, most primary structures, except for cross-bedding, have been obscured by the dolomitization. The dolomites are well developed in the southwestern part of the area and are still recognizable in the Aralla zone. Around Genestosa (LSI) they have vanished and in LSJ and LSK, near Villamanin, they cannot be recognized either. In thin section a patchy distribution of medium sized crystals between coarser grained dolomite can be observed. Oele (1964, fig. 17) noticed this too in the dolomites which he described from the Esla region. We have to do here with small cavities, like there can be found in 'birdseye limestones', but the original texture of the sediment has been partly obscured by dolomitization. The coarsely crystalline dolomites have both intercrystalline porosity as well as vuggy porosity (Archie's types I—III A and I C—D; Archie, 1952). These dolomites contain a fair amount of authigenetic quartz (figs. 21 & 22).

The Limestone Member

This part of the Lancara Formation is characterized by the abundant occurrence of algal structures and karst-like phenomena. It too is best exposed in the Barrios de Luna area. Eastward from Barrios de Luna it changes facies and becomes completely dolomitized in LSM. To the north, around Genestosa and Lancara de Luna (LSE), as well as in the Aralla zone. it has diminished in thickness and has been dolomitized completely. It was not found around Camplongo nor was it developed to any significance in section LSK, near Villamanin. The base of the Limestone Member has been taken at the first occurrence of limestone above the coarsely crystalline dolomites. In the dolomitized sections the base of the equivalent lithosome has been taken at the first occurrence of algal structures such as oncolites or algal mats. The top of the Limestone Member and its dolomitized equivalents, has been taken at the base of the overlying glauconitic biosparudite. The contact is, throughout the area, sharp and characterized by a very distinctive stylolite (fig. 23). In LSD a pale red (10 R 6/2) weathering zone was found in the upper part of the Limestone Member. The zone is locally dolomitized. This dolomitization might be due to the weathering or possibly to a minor tectonic disturbance(?) (fig. 25 f?). The red coloration has penetrated into the algal limestones. The stromatolites shown in fig. 24 owe their terra-rossa-like color to this weathering. The top of the limestone is, in this part of the mountains, disconformably overlain by the biosparudites (fig. 25) (the term 'disconformably' has been used here in the sense mentioned by Dunbar & Rodgers, 1957, p .117, fig. 57). Nowhere could any evidence be found to support Lotze's remark: 'Die Hellen León-Kalke, die nach unten mit den Dolomiten, nach oben mit den Roten Kalke durch Uebergang verbunden sind . . .' (Lotze & Sdzuy, p. 362 (80)). The contact was also overlooked by this author when he made, in 1965, a preliminary survey in the Barrios de Luna area (van der Meer Mohr & Schreuder, 1967). Around Barrios de Luna the Limestone Member is about 40 m thick and made up of massive, slightly dolomitic, algal limestones with a grey weathering color. The lihology is very complex in composition.

The main lithology is an intrasparudite — algal biolithite and scattered through the interval are lenses and veins of banded, fibrous, calcite (reef-tufa) which are old cavities filled up by cement. Figures 24, 26, 27, 28, 46 and 47 give an impression of the main rocktype. In general there are four important types of allochems in the Limestone Member:

Type A — bioclastic material represented by echinodermal? fragments and algal 'sticks'.

Type B — dolomitized fragments of stromatolites and algal encrusted limeclasts.

Type C — limeclasts of an undeterminable origin, mainly composed of microcrystalline calcite. Volumetrically they form the most important group.

Type D — pelletal material and superficial oölites.

There is very little siliciclastic material present in these sediments. Quartz is the most important accessory constituent. It is present as authigenetic quartz in the algal limestones (fig. 29) and as very fine, angular, detrital, quartz in the floors of cavities as well as in the cement. In the thin sections it is evident that the authigenetic quartz was formed earlier than the cavities in the limestones since the quartz crystals can be found in the sedimentary floor at the cavity's bottom. Corraded, angular quartz fragments occur as inclusions in the cement. It is mainly concentrated in a zone of bladed calcite crystals directly overlying the sedimentary infilling. In this bladed calcite (equivalent to Wolf's brown fibrous sparite, Wolf, 1965d) the quartz forms together with very small (0,5—1 μ reddish brown hematite grains a dusty, stratified, band. The cement which binds all detritus together is mainly a recrystallized sparry calcite cement. In the limestones which are made up of allochems of type B the grains are interconnected through layers and strings of fine equant calcite and dolomite. Detrital quartz and small carbonate detritus have been trapped in these layers.

Discussion of the allochems. — Type A. — From the bioclastic material present, the most interesting are the algal 'sticks' (figs. 30 & 31). These are made up of bundles of strands, 300 μ long and 15—20 μ in diameter. Each strand is divided into cells (fig. 31) and most sticks are surrounded by a halo of aphanocrystalline to very finely crystalline dolomite. This is due to the decomposition of the original organic structure. Wolf (1965b) described such processes from algal reefs in Australia and Timor. He introduced the term 'grain-diminution' for a process by which the original organic structure becomes obscured, or totally destroyed, and has changed into a very finely crystalline mass of calcium carbonate. No detailed paleontological investigations were made as to what particular algae these sticks came from. J. H. Johnson (pers. commun.) examined thin sections of these sticks and, although he agreed to their algal origin, did not go beyond that statement. The sticks resemble somewhat the *Rivularia* described by Monty (1967) but that is all that can be said up to now. Other possible bioclastic material are rounded, light colored objects (fig. 32). This might be echinodermal material but recrystallization has so far advanced that it cannot be determined with certainty. Trilobite fragments are rare in these limestones.

Type B. — These allochems are very complex items showing a great variety of forms and composition. From dolomitized pelsparites to perfectly formed oncolites are present (figs. 33, 34, 35 & 36). Regardless of their diversity in shape and composition they generally have the following common characteristics.

1. A dolomitized core with pellets, bioclasts, fragments of stromatolites etc. Many of the pellets have probably been algal fragments, now completely altered. The cement between the particles in the core can be either dolomite or calcite. Where the two types of cement occur together the dolomite generally lines the original pore and the calcite is in the centre. It cannot be stated with certainty, however, that the dolomite formed prior to the calcite since we have also observed dolomite scattered throughout the calcite.

2. A laminated part of both calcite layers and dolomite layers (figs. 33 & 35). In these laminations the dolomite follows the original pattern of the organo-sedimentary structures. Monty, who studied the formation of recent algal structures in the Bahamas, came to the conclusion that the algal laminations on Andros Island are caused by an intricate growth pattern of different algae (i.e. *Schizothrix calcicola, Scytonema* and others). These algae can form 'calcified layers', laminae considerably enriched in calcium carbonate, and 'hyaline layers' which are built of algal material. The algae which formed the Cambrian structures can seldom be recognized in thin section (fig. 37). The consistent occurrence of dolomite, parallel to the stromatolitic structures, strongly suggests, however, a relationship, be it directly or indirectly, between the algae and the dolomite. It could be that the hyaline layers formed during dry periods and were more susceptible to dolomitization. In a dry period evaporation could have created, on a very small scale, a magnesium rich brine which was able to dolomitize the local aragonite. The calcified layers did not dolomitize but recrystallized into sparry calcite which implies that in studying old stromatolite fragments caution must be observed in the interpretation of intrafragmental sparry calcite. It does not necessarily have to be drusy cement.

3. A non-laminated, spongy crust surrounding and connecting the allochems (figs. 35 & 38). These crusts are made up of small carbonate fragments and angular quartz grains, bound together by light brown dolomite and sparry calcite. The outside of the crust is formed by a dark brown coat of either biochemical or algal precipitate. These crusts are being interpreted as carbonate detritus washed into primary vugs, or on

chips exposed at the sediment surface, and bound together either by a chemical precipitate or by algal processes. The outer dark coat might be similar to the algal circumcrusts from Wolf (1965c) and Bathurst's micrite envelop (Bathurst, 1966). In connection to these crusts it should be mentioned that Lucia (1968) has described 'lacy carbonate crusts' from recent deposits in Bonaire. 'The texture of the lacy crusts is quite complicated. The crusts are composed of a complex arrangement of fine sand size pellets, lime mud, gastropods ... and drusy aragonite, all encrusted by fine grained, slightly laminar calcite and aragonite' (Lucia, 1968, p. 852—853, figs. 16 & 17). These carbonate crusts from Bonaire have been formed in a supratidal environment (Lucia, ibid.).

Dolomitization has altered parts of the non-laminated crusts in the Lancara Formation and two types of dolomite crystals occur. The first is very fine anhedral dolomite, light brown in thin section (fig. 38). The other is a fine euhedral dolomite and the rhombs are intermingled with fine anhedral calcite (fig. 38). From thin sections it is evident that the dolomite rhombs and the calcite can:

a. replace the brown anhedral dolomite and parts of the allochems (figs. 39 & 40);

b. fill up small interfragmental space (fig. 39): together with brown anhedral dolomite;

c. occur in bands lining larger interfragmental space (fig. 41);

d. be overlain by bladed calcite relatively rich in hematite inclusions; the contact with the bladed calcite is sharp (figs. 38 & 42).

From a and b it is concluded that there is a close relationship between the brown, non-laminated crusts and the idiotopic dolomite with the sparry calcite. From c and d it is deduced that the original material from which it was formed was deposited as either a matrix or a vug-lining prior to the deposition of the bladed calcite.

One explanation could be that the dolomitization of the allochems and the non-laminated crusts took place before the deposition of the bladed calcite. Following the dolomitization a subaerial exposure of the sediments could have caused partial dedolomitization (Shearman et al., 1961; Goldberg, 1967) which resulted in dolomite rhombs and the sparry calcite. In a subaerial environment the bladed calcite could also have been deposited (either as aragonite or fibrous calcite, see Wolf, 1965d, p. 218). Another possibility would be that following the dolomitization of the allochems by a magnesium enriched brine, an unstable high-magnesium cement might have been deposited. This cement could have changed later into low-magnesium calcite and dolomite. According to various scientists working on recent marine carbonates (e.g. Stehli & Hower, 1961; Sanders & Friedman, 1967) high-magnesium calcite, aragonite and low-magnesium calcite can be formed in nearshore marine sediments. Only low-magnesium calcite is stable. High-magnesium calcite seems to be the most unstable form. It can also be that, after a penecontemporary dolomitization, there was a drop of the Mg/Ca ratio in a subaerial environment until calcite filled up the vugs completely. Figure 43 gives a summary of the relationship between the allochems (the 'foundation'), the crusts and the sparry calcite cement (bladed and equant).

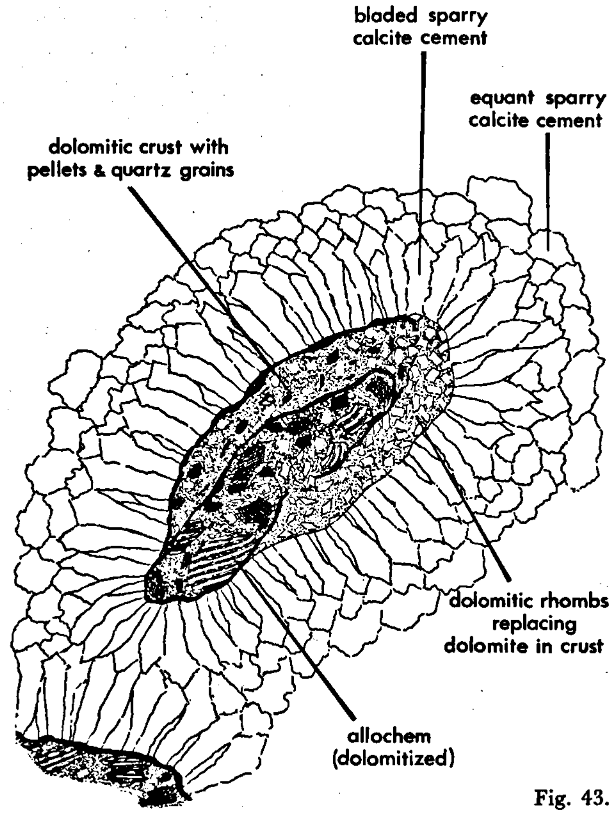


Fig. 43.

Type C. — A large amount of the allochems in the limestones is being formed by limeclasts of a grey microcrystalline calcite of undeterminable origin. occasionally the limeclasts (intraclasts?) are formed by ovoid pellets, lumped together to form a pelsparitic limeclast. Their most striking characteristics are the partial dolomitization and the occurrence of authigenetic quartz in circa 10% of the allochems. Another feature is their deformation due to orogenetic forces (fig. 44). Voll (1960) has described a similar deformation of fossils in different bioclastic limestones. The dolomitization occurs mainly at the rim of the allochems forming a coating of dolomite rhombs on the limeclasts. The sparry cement in the original voids between the allochems abuds against the dolomite. The long axis of the limeclasts and of the pellets in the clasts is not parallel to the bedding plane but almost vertical to it. This is the result of the orogenetic forces which folded the strata. Since it is evident from thin section that the sparry cement has also been deformed in a similar fashion it is concluded that the cement was formed before the orogeny. In a few thin sections calcite pseudomorphs after dolomite(?) were observed.

Type D. — The pellets are mainly ellipsoidal grains of microcrystalline calcite and are found in greatest abundance in section LSF. Wolf (1965c, Table II) has drawn attention to the fact that pellets can be formed out of calcareous algal sediment by extreme abrasion. This could very well be the case with the pellets in the Lancara Formation too since, except for the dolomitization of the Lancara sediments, the algal limestones of the Lancara have aspects similar to the limestones of the Nubrigyn reef complex. Hence it could be expected that many Lancara pellets are algal detritus. The superficial oölites are a very minor group of allochems and are mainly found together with the echinoderm? fragments. They do not form any significant stratum of their own in the Luna area.

Cavities and cavity-fillings. — An important aspect of the Limestone Member and its dolomitized equivalent is the presence of numerous calcite filled cavities. Examples can be found along the road from Barrios de Luna to Mallo, in section LSC, and in section LSF (figs. 24, 26, 45, 46, 47, 50 & 51) and are also present in the more northern sections LSE and LSI where the calcite has been replaced by dolomite. In the algal dolomites which occur in LSA and LSE they were found too. The cavities in the Limestone Member can be divided into two categories.

A. Lenses and veins filled up with layers of bladed calcite, some of these lenses can be more than 30 cm long (figs. 24, 44 & 45).

B. Highly irregular formed cavities filled with calcite. These cavities are much smaller in size than those of category A (fig. 48, and van der Meer Mohr & Schreuder, 1967, Pl. III B). They are comparable to the 'birdseye' cavities described by Wolf (1965 d).

In a way the intrafragmental and interfragmental sparry calcite cement discussed above could also be considered as a cavity-filling cement. Since the formation of these smallest voids is perhaps more a function of the piling up of fragments than of corrosion they were discussed together with the allochems.

The cavities of the Lancara Formation have three outstanding characteristics.

1. the light grey weathering layers (about ½ cm thick) of fibrous calcite which invariably form the outer part of the lens or vein (figs. 45 & 46). This calcite is equivalent to Wolf's brown fibrous orthosparite.

2. a very light grey (even white) weathering central part which is also fibrous and layered (figs. 45, 46 & 47).

3. the very centre of the cavity can be filled up by white, equant, coarsely crystalline calcite.

The sedimentary floors are in the field hard to detect. This is due to their weathering color (identical to the surrounding sediment) and their texture and composition which are also nearly equal to the wallrock of the cavity. A rather important specimen of these cavities was collected from section LSF (figs. 49, 50 & 51). This specimen contains two different infillings in a cavity. The oldest infill consists of sediment which is identical to the material of the hostrock. Overlying this infilling (Sed. floor 1) are a layer of bladed calcite and a brown sedimentary cone, shaped like the sandcone in an hour-glass. The cone is composed of layers of echinodermal debris, dolomite rhombs and quartz grains. The echinodermal debris is zonar in colored section showing both calcite and ferroan calcite layers. This is a feature often found in such debris (Evamy et al., 1965; Oldershaw & Scoffin, 1967). There are also dark green glauconitic pellets in the cone (fig. 50). This is all topped by bladed calcite with very fine hematite and very fine quartz inclusions. It is interpreted as a syndepositional cavity formed when the surrounding sediment was subaerial exposed. It became partially filled up by carbonate sediment (Sed. floor 1) of about the same age. The composition of the sedimentary cone proves the following. 1. That there must have been local solution of limestones in which authigenetic quartz had previously been formed. The quartz did not dissolve and was washed into the cave. 2. That the cave must have remained open through part of the time in which, elsewhere in the area, sediments of the Griotte Member were being deposited. The echinodermal debris and the dark green glauconite-like mineral (by X-ray analyses determined as muscovite-IM) are proof of this. Nowhere did we find this dark green material, by all field geologists called glauconite (Comte, 1959, Oele, 1964), in the algal sediment. It is strictly characteristic for the Griotte Member sediments and particularly for its basal part.

The cavities of type B (fig. 48) are very irregularly formed patches of sparry calcite. Bladed sparry calcite has filled up cavities which have no internal sediment. Their origin is an unsolved question. Birdseye limestone, as described by Ham (1952) and many other geologists (e.g. Wolf, 1965d; Dooge, 1966; Shinn, 1968) has smaller, ovoid, blebs of calcite. Yet the whole aspect of Lancara Limestone seems so similar that this author calls them birdseye-like cavities. Birdseye limestones are generally supposed to occur in supratidal-intertidal environments (Shinn, 1968). Wolf (1965d) also assumes a possible intertidal (Wolf's sublittoral setting) for birdseye limestones.

The Griotte Member

The nodular argillaceous, limestones and shales of this unit are almost through the whole unit present. In the field their dark reddish brown color (10 R 3/4—5 R 3/4) is the most striking feature. The only places where they are missing are west of Barrios de Luna and in the vicinity of Mora de Luna, east of section LSM. In that part of the region there are only some reddish brown shales present. The Griotte Member is at its base in sharp contact with the underlying algal limestones and dolomites. The upper boundary is more arbitrary. The Griotte Member has the following characteristics.

1. Its fauna which has yielded many useful trilobites, brachiopods and echinoïds). This fauna has been described extensively by various authors (Prado, 1860;

Comte, 1937; Lotze & Sdzuy, 1961). In this thesis no attempts have been made to contribute any new paleontological data.
2. The basal part of the Griotte Member is a very recrystallized biosparudite-biomicrudite which grades vertically into the nodular argillaceous limestones.
3. The occurrence of glauconite pellets, particularly in the basal part.
4. The nodular texture of the limestones (figs. 53 & 54).
5. The reddish brown color.

The biosparudite-biomicrudite beds are a few meters thick, well stratified and have a slightly nodular appearance. The beds have a very pale orange to greyish orange pink (10 YR 8/2—10 R 8/2) color and a light grey to greyish orange (N 7—10 YR 8/2) weathering color. They contain 1—3% glauconitic pellets. The nodular texture of the limestones has been caused by numerous parallel stylolites containing reddish brown hematitic material. The nodular appearance of the strata continues upward in the section into the argillaceous biomicrudites and calcareous shales (the 'griotte'-sensu stricto). The reddish brown color of the sediment is due to hematitic matter. In thin section it can be seen as 1—1½ μ sized grains mostly surrounding the calcite crystals and lining the cells inside the echinoïd fragments (fig. 55). A similar phenomena can be observed in iron-rich limestone deposits elsewhere. Hatch & Rastall (1965, fig. 68) give an example of a Lower Carboniferous bryozoa bed in Gloucester. In those beds the hematite is introduced into the sediment before or at the time of deposition. The canals of the echinoïds are obscured at an early stage by secondary (syntaxial) calcite, hence the iron-bearing solutions must have been introduced in an early stage.

THE BERNESGA-PARDOMINO HIGH REGION

In this area most of the measured Lancara sections are located along thrustfaults which invariably occur at the base of the formation (Appendix III). This makes it impossible to get an accurate idea of the original thickness of the formation. The thickness varies from 89 m in the south to 46 m in the north (LSX). These figures are close to Evers' (1967) estimates of 90 m and 35 m. Caution is advisable about the northern section, since there is much covered terrain at its base and the very contact of the Lancara Formation with the Herreria Formation is actually not exposed. The upward and lateral shift in lithology from the Luna River to the Porma River can only be established for the uppermost part of the pre-griotte sediments. On top of that comes the difficulty that the dolomitization can go right up into the Griotte Member (e.g. LSX). Generally speaking there are two distinct units in this part of the Mountains; a Dolomite Member and a Griotte Member whose base was taken again at the first occurrence of glauconitic pellets.

The Dolomite Member

None of the units into which the Dolomite Member of the Luna — Bernesga region was subdivided can be correlated into this central part of the area of study. In the largest part of this region we have to do with fine to medium crystalline dolomite showing relict structures of pellets, limeclasts, 'birdseye' structures and intraformational breccias. The southern part of the Bernesga-Pardomino High region shows some oölitic dolomites in the middle part of the Dolomite Member (LSO). Organo-sedimentary structures occur in the form of algal mats and as oncolites but these are not so abundant as in the Luna area. Towards the León-line the Lancara Formation becomes again more monotonous and the section near Pontedo is in its basal part as monotonous as the Camplongo section (LSJ). The strata are finely laminated dolomites with faint indications of possible pseudomorphs after gypsum. Distinct karst-phenomena were not found in the Dolomite Member of this region.

The Griotte Member

Its deposits are generally identical to those in the Luna-Bernesga region. One outstanding phenomenon is the occurrence of cavities in the griotte of LSX. The Griotte Member in this section has not got such a pronounced nodular appearance like elsewhere but is slightly more banded. It has been dolomitized and contains cavities filled up by red sediment and white, slightly ferroan dolomite (fig. 56). These cavities look identical to some of the *Stromatactis* described by British geologists from the Carboniferous in England (e.g. Bathurst, 1959a; Schwarzacher, 1961; Orme & Brown, 1963).

THE ESLA REGION

Bordered in the west by the pre-Lancara sediments of the Herreria Formation and overlain in the east by Carboniferous strata the Esla region forms rather a separate area (Appendix III). It is often divided into an autochtonous part and an overthrusted unit, the Esla 'nappe' (Rupke, 1965). The sections LSZ, LSN, LSP and LST are located in the Esla 'nappe'. The general lithology of the Lancara Formation both in the autochtone area and the Esla 'nappe' is fairly identical to the western region. It can be divided into a lower part of mainly dolomites and some algal limestones overlain by a Griotte Member with glauconitic pellets in its lower strata. In the following discussion we shall not discuss the autochtone area separately from the nappe since there are no fundamental lithological differences between them (i.e. not in the Lancara Formation).

The Dolomite Member

It is nearly everywhere present except in a section on the right bank of the Esla River upstream from Valdoré. Along the river the Lancara Formation consists of dolomitic limestones overlain by the griotte.

Oele (1964, fig. 16 and p. 43) mentioned the occurrence of a breccia consisting of angular limestone fragments set in a quartz-rich calcareous matrix. He interpreted this sediment as a shoal breccia. A breccia was found exposed near Valdoré (fig. 57). The rock is actually a tectonic breccia, of Carboniferous age, formed when Lancara strata were pushed over the Upper Devonian sediments of the Esla autochtone. A sample collected from the place where the 'shoal breccia' was found in 1962 (van Adrichem Boogaert, pers. commun.), contains a distinct Devonian coral next to very angular quartzite and limestone fragments (including griotte fragments).

The components of the breccia were derived from beds which have been overthrusted and crushed up. The limestones in the Valdoré section contain quite a lot of 'algal sticks' (figs. 58 & 59). These are interbedded with intraclasts (formed by the same sticks) and layers of oölites. Thin (5 cm thick) lenses of a waxy green, calcareous shale are intercalated between the limestones. Algal structures like oncolites were noticed in these limestones in an outcrop along the road on the left side of the river. West of the Esla River section LSP was measured. At the base of this section we found again a tectonic breccia. The Lancara limestones were dolomitized in this section as well as in LST. In a section near Verdiago we found the niveau with the algal sticks and below it a calcareous sandstone. The Verdiago section yielded also an interesting sample (LSN 17) containing *Hedstroemia* sp. (fig. 60), a green algae, generally believed to have a range from the Ordovicium to the Lower Carboniferous (Johnson, 1961).

The Griotte Member

This unit shows in general the same lithology as in the western part of the mountains. The biosparudite beds can locally contain sandstones or oölites. A sandstone bed, at the base of this member, is exposed in the Lancara outcrop along the Riaño-Cistierna road 1½ km northeast of Cremenes. It is a cross-bedded 'glauconitic' sandstone. The red, nodular, limestones of the Griotte Member in LSN show features which might point at the forming of cavities by leaching(?) (fig. 61).

CHAPTER IV

THE CONDITIONS OF DEPOSITION OF THE LANCARA SEDIMENTS

The only way to form an idea of the conditions of deposition of ancient sediments is by comparing them with analogous sediments in recent environments. The first point that should be considered is the position of a particular formation between its underlying and overlying strata. The sediments of the Lancara Formation are sandwiched between two thick sequences of siliciclastic material, the Herreria Formation and the Oville Formation. The contacts between the Lancara carbonates and its adjoining strata are conformable. The sediments have all been deposited under shallow marine conditions. Yet there must have been a reason for the abrupt change from sandstones and shales to mainly carbonate sediments in the Lower Cambrian.

One opinion in geology is that such a break in the supply of siliciclastic material has been caused by the peneplanation of the adjoining landmass. Shaw (1964) pointed out that the peneplanation is a relative conception. He gave examples of the relative peneplanation of the Cambrian surface in North America which surface still shows topographic differences of a few hundred feet. Apparently topography alone is no decisive factor. Siliciclastic material has to be transported to its area of deposition and this can be done either by rivers or by ocean currents. When both are negligible, or when the marine currents present do not carry a load of siliciclastic material, sandstones or shales will not be formed. The only sediments to be formed under such conditions are carbonate sediments or evaporites. Supposing that this happened in a shallow sea with hardly any relief of the sea bottom, a blanket of carbonate sediments (and/or evaporites) can be expected to be laid down over a considerable area. Once conditions in the hinterland change the supply of siliciclastic material picks up and the carbonate deposits can become replaced by sandstones and shales. The succession of the Herreria Formation (sandstones, shales and dolomite lenses), the Lancara Formation (carbonates) and the Oville-Formation (sandstones and shales) is an example of this process.

The second point is the interpretation of the observations made on the Lancara Formation itself. The overall picture shows that the Lancara Formation gradually thins to the north. This was caused by a subdued high along the León-line. In the southwestern corner of the studied area there has been either non-deposition of the Lancara sediments or erosion of the Lancara sediments in Lancara time. Eastwards, towards the Esla River there are no indications of any subdued highs. Whether the Pardomino High was active or not, cannot be established from measured sections. Too many of the sections east of the Bernesga are incomplete because of faulting.

The Lancara Formation consists mainly of two different lithologies; the Dolomite Member and the Griotte Member. The first is a succession of algal carbonate sediments while the latter shows the flourishing of a Cambrian fauna together with the gradual influx of siliciclastic material.

The basal oölitic dolomite beds of the Lancara Formation have probably been deposited under infratidal (below mean low tide) to intertidal conditions (between mean low and high tides). The oölitic dolomites are lenses interbedded between finely crystalline dolomites, devoid of any fossil material. Most likely they represent small beaches surrounding a carbonate mudflat area. Sporadic influx of clay might be responsible for the presence of shale streaks in the lower part of the Dolomite Member. Somewhat later the dolomites with the pinkish calcite nodules and the stromatolite marker bed were formed.

As for the genesis of the nodules it seems likely that we have to do with cavity-filling calcite. The straight intercrystalline boundaries and the subhedral crystals as well as the increase of the crystal size to the center are generally accepted criteria for cavity-filling calcite (Bathurst, 1958; Orme & Brown, 1963; and others). More difficult to explain is how the cavities came into being. Considering the very fine hostrock which forms the stromatolites and lies between these structures, it could be assumed that the sediment was very fine grained too. Primary vugs caused by the sheltering effect of larger grains, like for instance fossil fragments (the so-called 'umbrella-effect'), seems unlikely. Fossil fragments are estimated to make out less than five percent of the rock and we never found a fossil fragment (e.g. a trilobite) capping a nodule. Moreover geopetal structures could have been expected in such a case and these are absent in the nodules. Burrowing seems equally unlikely. The nodules are not interconnected and again we are faced here with the absence of sedimentary floors. The only possibility seems to be that the calcite is pseudomorph after another mineral. The drusy texture resulted from the filling up of a cavity formed by leaching. In an intertidal or supratidal environment, if we assume strong evaporation, the formation of gypsum could be expected. Illing et al. (1965) reported gypsum crystals from the sebkha Faishakh in the Persian Gulf. Two other points about the nodules are the rectangular outlines which can be observed and the dolomitic lining. According to Murray (1960), 'vugs exhibiting straight sides and rectangular re-entrants and projections are common, particularly in fine sucrose dolomite. These vugs are frequently associated with replacement anhydrite crystals of similar shape and size'. Figure 14, from Murray (1964), shows how anhydrite can replace a limestone. If this was also the case with the nodules we could assume the following line of events. First the formation of stromatolites and gypsum crystals. This was followed by dolomitization creating a lining around the nodules. Later on, perhaps at greater depth, the gypsum changed to anhydrite which could have pushed some of the dolomite aside or enclosed it. The replacement of the calcium sulphate by calcite probably took place after the Carboniferous orogeny since the calcite in the nodules have not been recrystallized as much as the sparry calcite cement which is present in the Limestone Member. It is uncertain whether the dolomitization was penecontemporaneous (i.e. happened in Lancara time) with the sedimentation. In this thesis a penecontemporary dolomitization is favored because the dolomitization followed so closely the stratification of the stromatolites and also because some of the sediments in the overlying Limestone Member seem to have been penecontemporaneously dolomitized. For an environmental interpretation of the Lancara stromatolites the occurrence of the pinkish calcite nodules might be important. Stromatolites are often believed to have been formed under intertidal or supratidal conditions; above mean high tide and only subject to spring- and storm-tide floodings (Logan, 1961; Logan et al., 1964; and others). Monty (1965, p. 377) observed stromatolites which grew below the intertidal zone in quiet places on the lagoon floor and on mud in very protected re-entrants of bays on the lee-side of the cays. J. H. Johnson (pers. commun.) is also of the opinion that stromatolites can be formed below low tide. For the Lancara stromatolites an intertidal environment seems most plausible considering the absence of fossil debris, and the possibility that the calcite nodules might have been evaporite nodules. The stromatolites also show similarity to stromatolites described by Roehl (1967) from the Bahamas and the Silurian Interlake Formation, Montana, U.S.A.

Higher up into the section are more finely crystalline dolomites. Towards the northern part of the Leonides they dominate the whole pre-griotte part of the section. Considering the absence of fauna and flora, the stromatolites, the observed sedimentary structures and the possibility that the calcite nodules are pseudomorph after gypsum or anhydrite it is concluded that the sediments were deposited in a warm, arid?, climate. The stromatolite bed and the overlying and underlying calcarenites can be interpreted as an intertidal, perhaps infratidal, intermezzo. These beds could for instance have been formed along a shoreline where the stromatolites were formed and swamped by a calcareous sand later on. Similar deposits have been described from the Interlake Formation, the Macumber Formation in the Maritime Provinces, Canada (Schenk, 1967) and other areas. Most investigators compare such sediments with the sebkha deposits of the Persian Gulf.

After the finely crystalline dolomites comes an important break in the lithology. The pelletal dolomites form a rather distinct unit in the western Leonides. Near Barrios de Luna they are correlative with dolomitized biolithites. To the east the pelletal dolomites are hard to trace. Many dolomites east of the Bernesga are pelletal dolomites often with 'birdseye' structures. It seems therefore that this facies gradually thickens eastward and intertongues with oölitic or simple crystalline dolomites. Pelletal grains alone seem to help little in making a distinction between intratidal or higher areas of deposition (Cloud, 1962; Roehl, 1967). The fact that we frequently found intraformational breccias in this unit might indicate an early lithification of this sediment. When combined with the birdseye-like cavities (with sedimentary floors) it points most of all at an intertidal-supratidal environment.

The general aspect of these dolomites suggest that their deposition could have taken place anywhere from the infratidal to the supratidal zone. Since 'birdseye' structures in these beds seem to increase in amount from LSC to LSG it could be concluded that the dolomites in the south were deposited in a slightly deeper environment. The increasing amount of 'birdseye' structures in the coarsely crystalline dolomites points at intertidal to supratidal conditions. This finds support in the authigenetic quartz which is a common feature in the coarsely crystalline dolomites. Grimm (1962) suggested that authigenetic quartz could be indicative for saline conditions. In the Lancara Formation there is a tendency of the quartz crystals to be concentrated in the medium-sized dolomite rather than in the coarse dolomite crystals. If the latter are the dolomitized equivalents of pore filling cement it could be argued that the surrounding sediment (now medium-sized dolomite) was deposited in a rather saline environment. It is difficult to determine the original character of the sediment. From the scant cross-bedding found in it, it could be assumed that these dolomites were originally calcarenites. Eastward from the Luna — Bernesga region these beds can no longer be traced with any accuracy.

The sediments of the Limestone Member have probably been deposited in an infratidal to intertidal environment. The abundant 'birdseye' structures in particular point at intertidal conditions (Shinn, 1968). The occurrence of authigenetic quartz suggests rather saline conditions. In this respect these limestones do not differ much from the underlying sediments. It is their facies, however, which does differ. These limestones and their dolomitized lateral equivalent contain many algal structures like stromatolites and oncolites. The whole aspect of these sediments suggest their deposition in a more turbulent environment. The many cavities in the Limestone Member indicate sub-aerial exposure of the Lancara sediments in Cambrian times. These cavities are karst-phenomena and contain sedimentary floors of exactly the same marine sediment that forms the surrounding wallrock. Such karst-phenomena (Roehl's subaerial diagenetic terrane) are common in carbonate sediments (e.g. Sander, 1936; Newell, 1953; Wolf, 1965d; Roehl, 1967). Roehl's publication is of interest in that it shows such a cavity, lined by a 'case hardened' rind (crust-layer) in recent rocks of Western Andros Island (Roehl, p. 2017, fig. 36), and Wolf (1965d) published a superb paper on similar open-space structures from algal reefs in Australia. Several of his photos and diagrams of the structure and their infilling (Wolf's fig. 3) could bear upon the Lancara Formation.

Since these cavities occur mostly in the Barrios de Luna region and particularly near LSF it is concluded that the surroundings of Irede must have been uplifted after the Limestone Member was deposited and before the sediments of the Griotte Member were laid down. In the eastern parts of the Leonides the time-equivalent strata are mostly dolomitized and cavities, like around Barrios de Luna were not observed.

The abrupt change from algal limestones to glauconitic bioclastic limestones must have been caused by a change in conditions. The occurrence of glauconitic pellets could be indicative for the temperature of the water. Porrenga (1967, p. 98) suggested: 'It is not unlikely that temperatures lower than about 15°C would favour the generation of glauconite'. We have to be careful, however, in using this statement on the Lancara's dark green, glauconitic, pellets. Röntgen-analyses have shown it to be muscovite-IM. Dapples (1967, p. 109) mentioned that glauconite does not appear stable under conditions of well developed folding. A folded arkose layer of the Nonesuch Shale (Proterozoicum) in Michigan contains grains considered on basis of their residual shape to have been glauconite. These pellets are now a mixture of chlorite and biotite. Perhaps the folding of the Lancara strata might have altered the glauconitic pellets too.

Nodular limestones and shales, rich in marine fossils are a common facies in a carbonate rock-sequence. They are known from the Devonian in the Ardennes, the Devonian in the West-Canadian Basin (Ireton Formation, and Waterways Formation) and other areas. Thes sediments are often deposited in an 'open marine carbonate-shale facies' in front of reefs (see Dooge, 1966, Appendix 6). Their nodular texture has been a matter of much discussion (Dooge, 1966, p. 32). Tectonic disturbance, submarine flow and brecciation, compaction, recrystallization and burrowing (Murray, 1965; Roehl, 1967, figs. 15B, C & D) have been suggested. Oele (1964) explained the disrupted nature of the limestones by solution processes. Thin sections of the griotte do show examples of pressure solution (fig. 55) and many of the very thin, reddish brown, shale streaks could be explained as being residual matter from an originally argillaceous lime mud. Some fossil fragments appear to have acted as a shield behind which the lime mud was sometimes preserved (fig. 55). Fossil debris is also more abundant in the dark argillaceous streaks than in the calcareous nodules. It could be explained by assuming that the bioclasts were originally more or less evenly distributed through the sediment but that due to pressure solution they are now more concentrated in the residual, argillaceous zones. It is not suggested in this thesis that pressure solution was the only process. Burrowing was cementery of Lancara de Luna. The red color of the griotte is due to finely dispersed hematite which griottes is due to finely dispersed hematite which occurs both in the limestones and in the shales. Early opinions on red beds in general were that the red material was transported as detritus from a hinterland (detrital-theory). The draw-back of that idea is that a recent analogue has not been found. Hinze and Meischner (1967) have recently investigated the terra rossa sediments at the Istrian coast (northern Adriatic). In this area terra rossa sediments occur inland and reddish brown sediment is formed in a fjord-like bay (Limski Kanal). Their conclusion is that in the transported erosional product the hematite is rapidly destroyed and an Fe^{3+}-hydroxide (FeOOH) is deposited in the sea. It does not result in detrital red sediments in the Adriatic Sea. The precipitation of Fe^{3+}-hydroxides in the present-day sediment of Limski Kanal seems to be due to a re-oxidation and reprecipitation process, close to the sedimentary interface. Walker (1967) has investigated recent red sediments from the Baja California and Paleozoic red beds of Colorado. He came to the conclusion that the red sediments in the Baja California are caused by the in situ formation of hematite pigment. To quote Walker (p. 361—363):

'The redistribution probably can be explained by variations in the redox potential (Eh) and pH of the interstitial fluids (Hem & Cropper, 1959; Garrels 1960, p. 110—165). Following deposition, intrastratal alteration of iron-bearing grains, particularly iron silicates, may occur wherever the grains are in contact with interstitial water provided that the hydraulic gradient is adequate to permit at least local removal of the soluble products to prevent saturation. The released iron can remain in solution as ferrous ions or be precipitated as ferric oxide, depending on the Eh and pH of the water. Where the factors are such that the interstitial environment lies in the stability field of ferrous ions, the iron will remain in solution and migrate with the interstitial water. Sediments in such areas will be drab colored and may become partly depleted of iron. On the other hand, where the Eh and pH are such that the interstitial environment lies in the field of $Fe(OH)_3$, and assuming there is enough oxidizing agent to keep it there, the iron will precipitate near its source, perhaps initially as amorphous ferric hydrate, but ultimately forming hematite. The sediments in the latter areas will become red and may be enriched by addition of iron derived from drab-colored sediments ...... Available data dealing with the Eh and pH of ground water (Germanov & others, 1960, p. 325; Baas Becking & others, 1960, p. 254; Back & Barnes, 1965, Pl. 1 and 2) indicate that the values commonly lie in the field of $Fe(OH)_3$. Some ground waters are reported to be oxygenated to depths of several hundreds to thousands of feet below the water table (Germanov & others, 1959, p. 329; Back & Barnes, 1965, Pl. 1). Assuming the Eh and pH of the interstitial waters are favorable, there apparently is no limit to the thickness of hematite-stained sediment that can result from intrastratal alternation of detrital iron-bearing grains...'

As for the Lancara griottes we have to keep in mind that they are:

1. marine sediments with a fairly rich fauna and up to 40% siliciclastic material, mostly shale;
2. a rather thin unit with a relative large areal distribution;
3. underlain by carbonate rocks which could well have had a significant amount of porosity and permeability in Cambrian times;
4. overlain by grey colored, brown weathering, glauconitic, marine shales and sandstones of the Oville Formation.

The increase of siliciclastic material could indicate either active erosion in an adjacent land area due to a climatological change (e.g. more rain in the hinterland) or a change in the current system in the sea bringing terrigenous material into the basin. Taking the amounts of shales, sandstones and glauconitic pellets of the Oville Formation into account a climatological change seems to be likeliest. This change could have caused erosion in a hinterland and temperatures in the sea favorable for the forming of glauconite. The red color of the griotte limestones could perhaps be explained by assuming the sedimentation of calcareous mud and ferri-hydroxides under mildly alkaline, slightly oxidizing conditions. The environment can have ranged from intertidal to shallow offshore marine. Given plenty of time and not too negative an Eh, ferri-hydroxides might have changed into hematite. The pressure solution processes which, undoubtedly, went on in the Griotte Member could have caused a relative increase of the residual hematite in the remaining sediment which resulted in the extreme red color of the present-day limestones and particularly of the shale streaks and stylolites between the nodules. During the compaction some of the iron might also have been squeezed into the underlying carbonates and these lower porous strata might owe some of their iron-content to these solutions.

Finally there is the problem of the absence of the Griotte Member in section LSF and the total disappearance of the Lancara between LSF and a point east of Salce. The author could not find definite proof in the field of a depositional edge of the Griotte Member west of LSC. The following observations make the idea of non-deposition of the Griotte Member in LSF, and of a high area between Irede and Salce, most likely.

1. The abundant karst phenomena in the Limestone Member of sections LSF, LSC, LSD, LSE and LSI. They are most abundant in LSF and LSC.

This strongly suggests the local uplift of an area between Salce and Irede. This uplift caused the development of a karst topography and it could well have resulted in the erosion of Lancara sediments around and west of Irede. The uplifted area covered the western and southwestern part of the Luna — Bernesga region: sections LSI, LSE and the sections around Barrios de Luna.

2. The fact that we found debris of Echinodermata and glauconitic pellets in a cavity of the Limestone Member. This means that at least in 'biosparudite-time' the algal limestones in LSF were already exposed.
3. A few meters above the algal limestones in LSF did we find Oville shales in the shrubs. The distance to the limestones could only be estimated (circa 4 m).

Besides these observations there are the considerations that elsewhere in the studied area the Griotte Member has never been pinched away by faulting, on the contrary, the faults occur at the very base of the Lancara Formation. No fault was observed at the base of the Griotte Member of section LSC, the closest section to LSF. Finally there is the fact that the Lancara Formation also seems to be reduced eastward from LSM. On the dust-road to Portilla de Luna only some scant vuggy dolomites crop out and from the red interval nothing is left but traces of red shales. This suggests that E of LSM we might have to do with a facies change. This idea seems to find support in the fact that higher in the Paleozoic Devonian strata (Huergas Formation and Portilla

Formation) have disappeared here too. North of Portilla de Luna the Santa Lucia Formation (lower to Middle Devonian) is overlain by (Frasnian) Nocedo sediments. Around Pontedo (section LSX) the griotte has probably been subaerial exposed. This is the reason why the Griotte Member in LSX contains *stromatactis*-like cavities. Since we did not find the cavity-fillings around Camplongo the subaerial exposure does not have to be interpreted as an uplift along the León-line. De Sitter (1965) postulates a dome which plunged from Asturia into a southern direction. This regional structure could also have been the cause of a temporary, local, uplift and consequent exposure of the griotte in Pontedo.

In a previous publication (van der Meer Mohr & Schreuder, 1967) it was suggested that the Lancara Formation formed a transgressive marine sequence. When the different lithofacies of the Lancara Formation are grouped according to Dooge's 'carbonate facies grouping' (Dooge, 1966, Appendix 7) the following approximate correlation can be made.

If the contact between the Griotte Member and the underlying strata would have been a gradational contact, a transgressive sequence could be postulated. The disconformable contact at the top of the Limestone Member in the Luna region could, however, indicate a temporary regression of the sea before the sediments of the Griotte Member were laid down.

	Griotte Member	Limestone Member	Dolomite Member
Lancara Formation, Cant. Mountains, Spain. Cambrian. (v. d. Meer Mohr)	Nodular argillaceous limestones and shales with trilobites, brachiopods and glauconite.	Oncolites, stromatolites and intrasparudites.	F-xtal dolomites, intraformational breccias and oölites on local beaches bordering bights.
Persian Gulf, recent. (Illing et al., 1965).	Lagoonal sediments: lime mud, pellets, pelycopods, gastropods and forams.	Algal 'reef' flat. Rubbery algal mats.	Sebkha lime mud and dolomites, gypsum and salt.
Rocky Mountains, Devonian. (Dooge 1966, app. 7).	Open marine carbonate shale (Groups 2—4).	Organic ecologic reef? (Groups 4A and 5A).	(Semi-)restricted carbonates (Groups 6, 7 and (8)).

CHAPTER V

AN IMPRESSION OF THE DISTRIBUTION OF SOME TRACE ELEMENTS IN A LANCARA SECTION (APPENDIX IV)

During the investigations it seemed useful to make a geochemical survey on the distribution of trace elements. The first aim was to find out whether there are any interesting deviations in the content of the trace elements in the Lancara Formation. Secondly there was the question whether a particular trace element would occur in a specific lithofacies. Thirdly it seemed worthwhile to compare the geochemical data from the Lancara section with data from other areas.

Since section LSD is by far the most interesting and complete section it was decided to use LSD for a geochemical pilot project. This project will be continued into a more regional survey on the distribution of trace elements in the Lancara Formation (van der Meer Mohr & Stephan, in preparation). The choice of the trace elements to be studied was restricted to four elements Cu, Co, Ni and Sr. Iron and manganese were left out since there is a thick unit of ferruginous sandstones and shales (Oville Formation and San Pedro Formation) overlying the Lancara Formation. These younger, ferruginous deposits could have changed the whole Fe-budget of the Lancara strata. Barium seemed unreliable too since many fault-zones in the Cantabrian Mountains contain veinlets of barite. Apart from the Cu, Co, Ni, and Sr determinations the MgO/CaO ratio of several dolomite samples was determined. All the specimen from the Limestone Member were analyzed on MgO in order to get an idea of the amount of dolomitization in these sediments. Since it can be assumed that high-magnesium calcite is no longer present in these Cambrian strata the MgO-content of a sample is here considered to be directly proportional to the dolomite content of the sediment.

The results of the survey (Appendix IV). — From the four elements chosen for this project, Cu, Co and Ni generally occur in higher quantities in fine-grained sediments (Krauskopf, 1967, p. 592, table 20—6). Strontium is mostly enriched in limestones, presumably because it can substitute for calcium. The preference of minor elements for fine-grained sediments can have various reasons. Four reasons are (according to Krauskopf, p. 593):

1. ionic substitution;
2. reactions of the trace elements with residual organic material;
3. adsorption on clay minerals;
4. precipitation with clay as hydroxides.

The Cu values in section LSD show hardly any correlation with the carbonate facies. The most important aspect of the Cu-values is that they increase where, in the finely crystalline dolomite beds, the percentages of insoluble residu increase. This insoluble residu is mainly an ochreous-brown argillaceous matter. The correlation with the residu is lost in the higher part of the sequence. In the biosparudite beds is a peak value for copper. The correlation with the insoluble residu could perhaps be explained by assuming adsorption of copper ions to the fine-grained material. According to Malan (1964, as quoted by Wolf, Chilingar and Beales, 1967, p. 91) copper, of algal structures in Northern Rhodesia, is not concentrated in the algal bioherms but in the interreef argillites. Malan concluded that this copper is syngenetic in origin. The data from the Lancara Formation seem to agree with Malan's observations.
The copper concentrations in the argillaceous Griotte Member are generally equal to those in the lower strata. Yet they could be expected to have been somewhat higher since there were possibilities for adsorption or reactions with organic matter. An explanation would be that under oxidizing conditions the copper went into solution and was transported away. In the Griotte Member the Co and Ni values might be higher than Cu because of the lesser solubility of cobalt and nickle.
The cobalt and nickle values do not show a correlation with the insoluble residu curve. Both elements seem to be more concentrated in the limestones of the two upper members than in the dolomites. In the Limestone Member there is a fair correlation with the strontium values. In the dolomites Co and Ni could have been substituted by Mg during dolomitization. According to Krauskopf (p. 517) nickle for instance can form an insoluble silicate. No definite conclusions can be made however. The samples were not treated for the purpose of differentiating silica and clay bound elements from adsorbed elements.
The strontium values show the highest peaks and a marked diference between the three members. The values in the Dolomite Members are generally low. This can have two separate reasons, a lower availability of strontium or the depletion of strontium through dolomitization (Friedman & Sanders, 1967, p. 333).
The latter possibility became evident when a fully dolomitized sample of the stromatolite marker bed yielded O ppm against about 100 ppm for a slightly dolomitized sample. Underlying the stromatolite bed is a shale which gave the highest values in the section. This anomalous amount of strontium can have been caused by the concentration of migrating strontium ions in the shale or by the syngenetic concentration of strontium in the shale. If the stromatolites were deposited in a hypersaline environment the strontium content in the seawater and in the sediment could have been high.
The Sr/Ca ratio of the oölite sediments in Great Salt Lake is 4,23/1000 atoms and is nearly equal to that of the water (4,20/1000 atoms). Odum mentioned that if the solubility products are much exceeded, and if the solutions have no possibility to exchange with a large reservoir, precipitation occurs in a closed system and the Sr/Ca rations of the precipitates are equal to those of the solution (Wolf et al. 1967, p. 88). Apart from the possibility that the Sr/Ca ratio was increased by evaporitic conditions there is the likeliness that the strontium was originally concentrated in the stromatolites by bacteria or that the algae somehow played a function in it. The last possibility seems very likely since there is a smaller strontium peak in the pelletal dolomite beds and the algal limestones have relative high strontium contents too. The strontium values in the basal, oncolitic and stromatolitic, part of the Limestone Member are below 100 ppm. This is most likely due to the partial dolomitization of the algal particles in this interval which is reflected in the higher MgO/CaO ratios. The middle part of the Limestone Member has higher strontium contents. This part contains abundant limeclasts which might have been derived from algal mud. There is a distinct drop of the amount of strontium under the top which again correlates with a high MgO/CaO value. This supports once more the idea that dolomitization can cause a depletion of the strontium contents. The Griotte Member shows more modest values for strontium than the Limestone Member. The amounts of strontium per sample decrease to the top of the Lancara Formation. Since strontium is generally believed to precipitate with aragonite and since the amount of calcite in the Griotte Member decreases towards the top the overall drop in the Sr-values towards the Oville Formation is understandable.
A comparison with other areas (fig. 62). — This is always risky since no two areas are the same nor were they tackled in the same way. Three often quoted studies of strontium variations in reef complexes are those by Flügel-Kahler (1962), Sternberg (1959) and Siegel (1961). The data from Flügel and Sternberg show both an increase of $SrCO_3$ towards the open basin. Siegel found that there was a maximum value for $SrCO_3$ on the leeside of the reef. Dooge (1966, appendix 6) does not give any specific values for the strontium contents of his different lithofacies. He limited the geochemical data in his diagram to two arrows. One arrow indicates a maximum value for Sr,

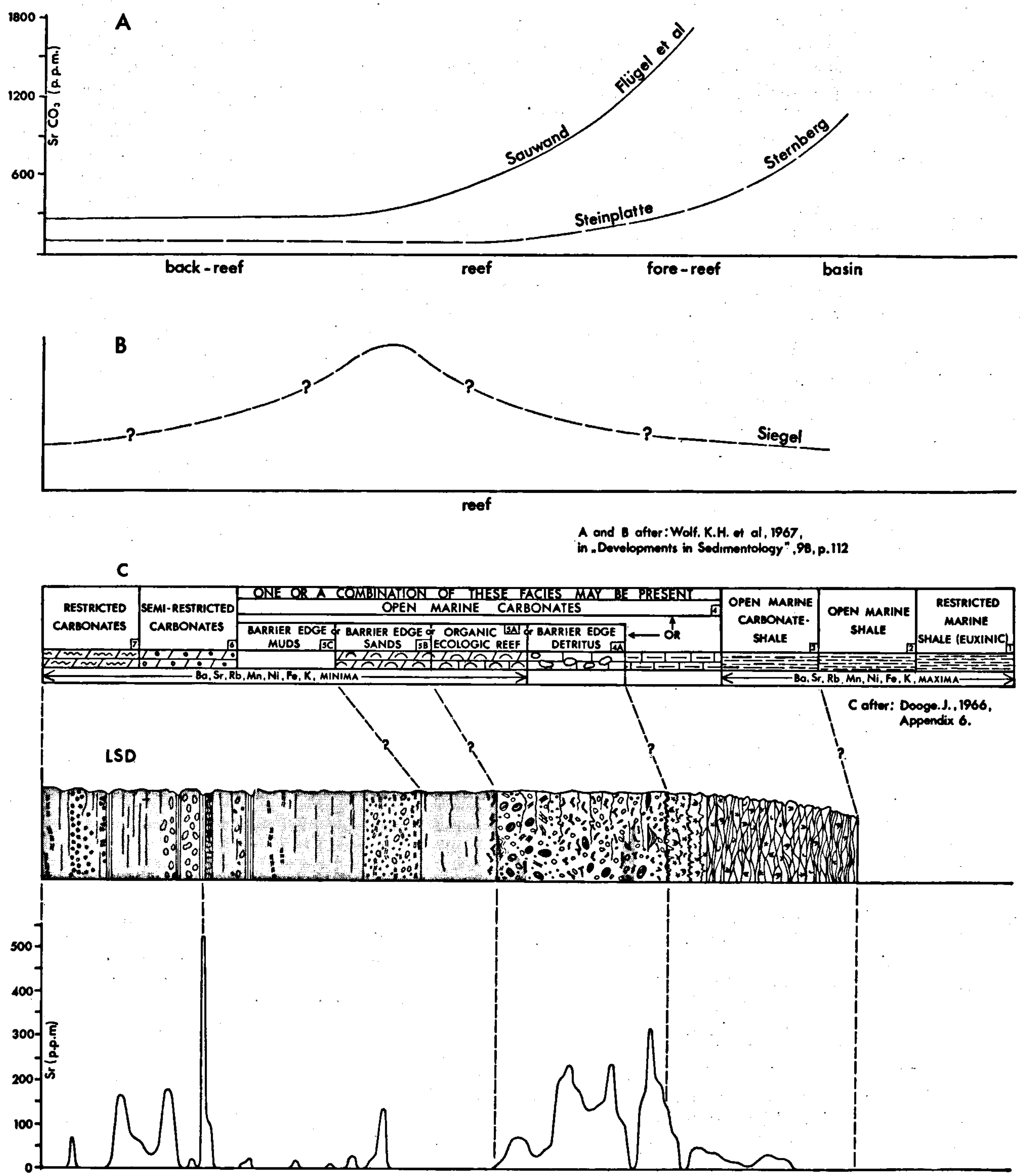


Fig. 62. A comparison between the distribution of strontium in the Lancara Formation and in other formations.

Rb, Mn, Ni, Fe and K. in the lithofacies 1, 2 and 3 (restricted marine shales, open marine shales and carbonate shales). The other arrow gives a minimum from the reef facies (5a) to his 'restricted carbonates' facies (7) (dolomites). In fig. 62 these different observations are compared with the Lancara Formation. The data from the Lancara Formation do not agree with those of Dooge. The nodular limestones in the Griotte Member are very similar in aspect to the limestones and shales in Dooge's facies 3. The griotte shows a decrease in Sr and not an increase. The color of the sediments in Dooge's facies 3 and 4 is gray to buff which points at more reducing conditions while oxidizing conditions are presumed for the Griotte Member. A difference in physico-chemical conditions might have had its influence on the presence or absence of the trace elements. The same goes for the algal limestones in the Limestone Member. These show a maximum while Dooge's diagram would suggest a minimum for Sr and Ni. Dooge's facies 5 to 7 contain dolomitized carbonate rocks. This dolomitization might explain his minimum for these facies. Siegel's diagram shows a peak value on the leeside of the reef and a decrease in Sr both to the fore-reef facies and the back-reef facies These Mg values decrease when Sr values increase. The distribution of $SrCO_3$ in the Sauwand and Steinplatte Reef Complexes coïncides with Dooge's geochemical data.

SAMENVATTING

De stratigrafie van de cambrische Lancara-Formatie vormt het onderwerp van dit proefschrift. Daarbij is voornamelijk aandacht besteed aan de petrografie en de petrologie van de dolomieten en kalken waaruit de formatie merendeels bestaat. Het studiegebied ligt in het Cantabrische Gebergte, in Noord-Spanje, en wordt in het westen begrensd door de Rio Luna en in het oosten door de Rio Esla.

In 1860 werd de Lancara-Formatie voor het eerst beschreven door Casiano de Prado. Zijn paleontologische gegevens werden later aanmerkelijk uitgebreid door Comte (1959) en Lotze & Sdzuy (1961). Een juister beeld van de dagzomen van de formatie werd verkregen door het gedetailleerde veldwerk van Rupke (1965), Sjerp (1966), Evers (1967), van Staalduinen (1969, in voorbereiding) en van den Bosch (1969, in voorbereiding).

Oele beschreef de sedimentaire strukturen en de petrografie van de Lancara-Formatie in het Esla-gebied. De Lancara-Formatie maakt deel uit van een groep siliciklastische sedimenten van predevonische ouderdom die tesamen de Luna-Groep vormen. In dit sedimentpakket vormt de Lancara-Formatie een uitzondering, doordat zij hoofdzakelijk bestaat uit kalken en dolomieten. De Herreria-Formatie, opgebouwd uit zandstenen en schalies, ligt onder de Lancara-Formatie en de schalies en glaukoniet-houdende zandstenen van de Oville-Formatie liggen erboven. De type-lokaliteit van de Lancara-Formatie ligt bij het geïnundeerde dorp Láncara de Luna. Omdat de lagen in de type-lokaliteit door de plooiing verstoord zijn, en vermoedelijk incompleet zijn, werd het beter geacht om een 'reference-locality' te kiezen nabij Barrios de Luna. De formatie kan in het gebied van de Rio Luna verdeeld worden in een Dolomiet-Pakket, een Kalksteen-Pakket en een Griotte-Pakket. Het Kalksteen-Pakket is elders in het gebied niet altijd aanwezig doordat de kalken gedolomitiseerd zijn. De dikte van de Lancara-Formatie varieert van 183 m in de 'reference-locality' tot circa 40 m in het noorden. Ten westen van de 'reference-locality' is de formatie afwezig. De Lancara sedimenten zijn hier, hetzij nooit afgezet, hetzij door erosie verdwenen. De erosie kan zowel voor als tijdens de sedimentatie van de knobbelkalken van het Griotte-Pakket hebben plaatsgevonden. Het Dolomiet-Pakket bestaat voornamelijk uit fijn kristallijne dolomieten met aan de basis wat oölieten. De opeenvolging bevat vrijwel geen fossielen. Aan de hand van de voorkomende sedimentaire strukturen (scheve gelaagdheid, intraformationele strukturen, varven-achtige gelaagdheid) en de organo-sedimentaire strukturen van algen is enigszins een indruk te krijgen van het milieu, dat geleken kan hebben op dat van de huidige sebkha-afzettingen in de Perzische Golf. Het is mogelijk dat de dolomitizatie bijna gelijktijdig met de sedimentatie plaats heeft gevonden. Het Kalksteen-Pakket bestaat uit een opeenvolging van algenkalken waarin veel stromalotieten en oncolieten voorkomen. Bij Barrios de Luna vindt men er ook lenzen van gelaagde, fibreuze calciet in. Deze calciet vult oude holten op die door erosie zijn ontstaan toen het sediment plaatselijk opgeheven werd boven het zeeniveau. Deze erosie komt ook tot uiting in een terra-rossa-achtige verwering van de bovenste sedimenten van het Kalksteen-Pakket in het Barrios de Luna-gebied. Deze sedimenten geven de indruk van afgezet te zijn in een turbulenter milieu dan de onderliggende, fijn gelaagde, dolomieten. Het Kalksteen-Pakket is te vergelijken met de 'algal flats' die in de Perzische Golf tussen de lagune en de sebkha voorkomen (Illing et al., 1965). Het Griotte-Pakket ligt met een scherp kontakt op het Kalksteen-Pakket. Het pakket bestaat uit rode knobbelkalken en schalies. Deze sedimenten hebben een rijke fauna en bevatten, vooral aan de basis van het pakket, glaukonietachtige korrels (Muscoviet-IM). De knobbelkalken kunnen door een kombinatie van faktoren zijn ontstaan (omwoeling, 'pressure solution' en brecciatie tijdens de plooiing). De rode kleur is veroorzaakt door fijn verdeelde hematiet. Het kan zijn dat het sediment in een oxyderend milieu werd afgezet, doch het is ook mogelijk dat de oxydatie pas in een veel later stadium plaats vond. Het is niet waarschijnlijk dat het siliciklastische materiaal in het sediment reeds roodgekleurd was ten tijde van de sedimentatie. Deze veronderstelling is gebaseerd op rapporten over de roodkleuring van sedimenten van de hand van Walker (1967) en Hinze & Meischner (1967). De knobbelkalken van het Griotte-Pakket zijn in een marien milieu afgezet en te vergelijken met een 'fore-reef' facies.

Er werd een kort onderzoek naar de verdeling van sporenelementen (Cu, Co, Ni en Sr) gedaan. Cu komt in de 'sebkha'-dolomieten het meeste voor waar de dolomiet veel siliciklastisch materiaal bevat. Het kopergehalte van de fossielrijke knobbelkalken is niet hoger dan dat van de onderliggende lagen. Vermoedelijk komt dit doordat koper in een oxyderend milieu betrekkelijk oplosbaar is; het kan dan uiteraard weggevoerd worden door het grondwater. Cobalt en nikkel zijn veel minder oplosbaar en dit kan de reden zijn waarom zij in ietwat hogere concentraties voorkomen dan het koper. Cobalt en nikkel vertonen evenals Sr een hoger percentage in het Kalksteen-Pakket dan in het Dolomiet-Pakket. Strontium kan uit de dolomieten verdreven zijn door het kleine magnesium-ion.

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