BIOSTRATIGRAPHY, PALAEOECOLOGY AND PALAEOGEOGRAPHY OF THE MAINLY MARINE AGER FORMATION (UPPER PALEOCENE – LOWER EOCENE) IN THE TREMP BASIN, CENTRAL-SOUTH PYRENEES, SPAIN

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SUMMARY

During the greater part of the Palaeogene the Tremp Basin was an area which underwent rapid subsidence as compared with the axial zone of the Pyrenees to the north, and the Ebro Massif to the south. As a result the sea occupied this area for a long time and deposition of the Ager Formation took place during the Late Paleocene and Early Eocene in a bay forming an appendix of the Atlantic Ocean. At the maximum of the transgression probably a connection with the Tethys existed. During this entire development the Tremp Basin was tectonically separated from the more southerly Ager Basin by the Montsech High which underwent much less subsidence. The southern side of the Tremp Basin, under the influence of this high, subsided less rapidly than the central part. This resulted in a considerably thinner succession along the southern side, consisting mainly of limestones, and a much thicker pile in the central part mainly built up of marls. Sediments deposited along the northern side of the basin for a greater part have been eroded. Where they have been preserved, they are less limy than those along the southern side. The northern margin moved in the course of time in northern or southern direction, in contrast to the stable Montsech High which formed a stationary southern margin.

The correlations within the formation are based on alveolinids and on lithostratigraphical characteristics. Hottinger's alveolinid biozonation undergoes one modification which has important consequences for the chronostratigraphy of the Mediterranean Palaeogene. The *Fasciolites oblongus* Zone namely does not appear to be a higher zone than the *F. trempinus* Zone, for *F. oblongus* lived contemporaneously with *F. corbaricus* and *F. trempinus; F. oblongus* lived in deeper water than the latter two, which explains that they are rarely found together in one sample. The occurrence of *F. oblongus* in the Ager Formation proves that the Ilerdian coincides for a large part with the Ypresian (Cuisian). Consequently the usually accepted Paleocene–Eocene boundary comes to lie within the Ilerdian, so that this stage cannot be maintained.

Data from all alveolinid species together have resulted in a better comprehension of the evolution of this group. The number of species and lineages proves to be smaller than has been thought. From the palaeoecology of the alveolinids it can be deduced that three possibilities were realized by the successive species of a lineage: (1) they remain restricted to some specific, shallow marine environment during their entire evolution, (2) they adapt themselves to many different, but mainly shallow marine environments and remain so during their further evolution, or (3) they migrate from shallow to deeper marine environments.

Fifteen facies types and 51 subfacies types are distinguished on palaeontological and/or sedimentological characteristics. Larger foraminifera, other microfossils and various groups of macrofossils are used for this, together with sedimentary structures and lithology. A large variety of facies types from fluvial and swamp deposits to marls of the deeper shelf occurs. Important facies types to be mentioned are lagoonal and tidal deposits, coral and algal reefs and related facies and various open marine facies.

Apart from some minor fluctuations the sea gradually extended over a progressively larger area during the deposition of the lower half of the Ager Formation becoming deeper at the same time. The relief of the sea bottom simultaneously became steeper. Half-way through the formation the transgression reached its maximum, after which the sea again became shallower and the area occupied by it smaller. The relief of the sea bottom then again was reduced. The maximum reef development occurred in the lower part of the *F. corbaricus* Zone, and was most extensive along the southern side of the basin. In the upper half of the same biozone reef growth was more and more hampered due to important influxes of clastic material. In the lower half of the formation the occurrence of sand and silt is always local, whereas it is found nearly everywhere in the upper half. Most of this material came from NE, E and SE directions.

The fauna and the flora point to a tropical climate. The Tremp Basin was situated at the northern margin of the tropics (zone of marginal reef growth). The maximum depth of the sea in the area studied was between 100 and 150 m. An important aid to the determination of the sea depth of various facies is the occurrence of glauconite which cannot have been formed above ca. 50 m depth in the Tremp Basin.

SAMENVATTING

Gedurende het grootste deel van het Paleogeen was het Bekken van Tremp een gebied dat snel daalde vergeleken met de axiale zone van de Pyreneeën in het noorden en het Ebro-massief in het zuiden. Daardoor kon de zee dit gebied lange tijd in bezit nemen en werden de mariene afzettingen van de Ager Formatie gevormd gedurende het Laat-Paleoceen en het Vroeg-Eoceen in een baai, die een uitloper was van de Atlantische Oceaan. Tijdens het maximum van de transgressie is er waarschijnlijk een verbinding met de Tethys geweest. Het Bekken van Tremp was tijdens deze gehele ontwikkeling struktureel geologisch gescheiden van het direkt ten zuiden hiervan gelegen Bekken van Ager door het Montsech-hoog dat een veel geringere daling onderging. De zuidflank van het Bekken van Tremp daalde onder invloed van dit hoog minder snel dan het centrale gedeelte. Dit resulteerde in een aanzienlijk dunner pakket sedimenten langs de zuidflank, voornamelijk bestaande uit kalken, en een veel dikker pakket van vnl. mergels in het centrale

gedeelte. De noordflank van het bekken is minder gespaard gebleven voor erosie en is, voor zover nog bewaard, minder kalkig ontwikkeld dan de zuidflank. Bovendien verplaatste de noordelijke rand zich in de loop van de tijd in noordelijke of zuidelijke richting, terwijl het Montsech-hoog, dat als zuidelijke rand fungeerde, zeer stabiel was.

De correlaties binnen de formatie berusten op alveolinen en lithostratigrafische kenmerken. De alveolinenbiozonering van Hottinger ondergaat één wijziging, die grote gevolgen heeft voor de chronostratigrafie van het mediterrane Paleogeen. De *F. oblongus* Zone blijkt namelijk geen jongere zone te zijn boven de *F. trempinus* Zone. *Fasciolites oblongus* leefde namelijk gelijktijdig met *F. corbaricus* en *F. trempinus; F. oblongus* kwam voor in een diepere faciës dan de twee laatste, waardoor ze meestal niet samen in één monster gevonden worden. Het vóórkomen van *F. oblongus* in de Ager Formatie bewijst dat het Ilerdien voor een groot deel het Yprésien (Cuisien) overlapt. Hierdoor komt de gewoonlijk gehanteerde grens tussen Paleoceen en Eoceen in het Ilerdien te liggen, zodat deze etage niet gehandhaafd kan worden.

Alle gegevens van de gevonden alveolinensoorten te zamen maken een beter begrip van de evolutie van deze groep mogelijk. Het aantal soorten en evolutielijnen blijkt geringer te zijn dan vroeger werd gedacht. Uit de paleoecologie van de alveolinen is af te leiden, dat de opeenvolgende soorten van een evolutielijn een drietal mogelijkheden ter beschikking staat: (1) zij blijven gedurende de gehele evolutie beperkt tot enkele specifieke ondiep-mariene milieus, (2) zij passen zich aan vele mariene, vnl. ondiepe milieus aan en blijven dat gedurende de verdere evolutie, ofwel (3) zij verhuizen van ondiepe naar dieper mariene milieus.

Er worden 15 faciëstypen en 51 subfaciëstypen onderscheiden op grond van paleontologische en/of sedimentologische kenmerken. Grootforaminiferen, andere microfossielen en diverse groepen macrofossielen worden hiervoor gebruikt naast sedimentaire structuren en de lithologie. Een groot scala van faciëstypen variërend van rivier- en moerasafzettingen tot mergelafzettingen van de diepere shelf is aanwezig. Hiervan kunnen als belangrijke faciëstypen genoemd worden: lagunaire en getijde-afzettingen, koraal- en algenriffen en genetisch verwante faciës, en diverse open-mariene faciës.

Kleine schommelingen daargelaten strekte de zee zich tijdens de afzetting van de onderste helft van de Ager Formatie geleidelijk aan over een steeds groter gebied uit en werd bovendien steeds dieper. De zeebodemtopografie werd hierbij steeds steiler. Halverwege de afzetting van de formatie bereikte de transgressie haar hoogtepunt, waarna de zee weer ondieper werd en een steeds kleiner areaal besloeg. De zeebodemtopografie werd toen weer afgevlakt. De maximale rifontwikkeling vond plaats in het onderste deel van de *F. corbaricus* Zone, en was het meest uitgestrekt langs de zuidflank van het bekken. In de bovenste helft van dezelfde biozone werd rifgroei steeds moeilijker door belangrijke toevoer van klastisch materiaal. In de onderste helft van de formatie is het vóórkomen van zand en silt steeds plaatselijk, terwijl in de bovenste helft vrijwel overal siliciklastisch materiaal gevonden wordt. De aanvoer van dit materiaal kwam vooral uit NE, E en SE richtingen.

De fauna en flora wijzen op een tropisch klimaat. Het Bekken van Tremp heeft zich aan de noordelijke rand van de tropen bevonden (zone van marginale rifgroei). De maximale diepte van de zee in het onderzochte gebied is 100 à 150 m geweest. Een belangrijk hulpmiddel bij het bepalen van de zeediepte van diverse faciës is het vóórkomen van glauconiet, dat in het Bekken van Tremp niet boven de ca. 50 m-dieptelijn gevormd kan zijn.

CONTENTS

CHAPTER I

INTRODUCTION

GEOLOGICAL SITUATION OF THE TREMP BASIN AND HISTORICAL GEOLOGY OF THE SOUTH-CENTRAL PYRENEES

The Tremp Basin, together with the Ager Basin, forms the easternmost part of the Palaeogene of the southern Pyrenean marginal trough. This trough is situated between the axial zone (consisting of Palaeozoic rocks folded and cleaved by the Variscan orogeny) in the north, and the Ebro Basin with Oligo–Miocene deposits in the south. The Ebro area was indeed characterized by a distinct positive topography during most of the Palaeogene. The Ebro Block did not change into a basin before the main phase of the Alpine orogeny of the Pyrenees (Pyrenean phase).

A short survey of the lithostratigraphic development of the post-Variscan deposits in the south-central Pyrenees has been given by Mey et al. (1968). The sequence starts with the largely fluvial molassic deposits of Late Carboniferous and Permian age in combination with important volcanic deposits (Nagtegaal, 1969). An unconformity separates these Palaeozoic rocks from the Triassic which is developed in Germanic facies. The Triassic is followed by marine Jurassic and Cretaceous sediments which consist mainly of limestones and marls and some dolomite. They were formed under rather stable conditions.

This picture changes rather abruptly in the Santonian with the deposition of many turbidites, mudflow sediments and olistostromes in the Vallcarga Formation (van Hoorn, 1970). Turbidites were also deposited during the Maastrichtian (Arén Formation), thus demonstrating continuing instability. Nearshore calcarenites and eolian quartz sandstones overlying this formation provide evidence of a distinct regression (Ghibaudo et al., 1973; Ghibaudo et al., 1974; Mutti et al., 1975). This complex is followed by the Tremp Formation (Upper Maastrichtian–Thanetian; in earlier literature the term Garumnian is used for this interval) which consists mainly of reddish-brown mudstones, sandstones and conglomerates of fluvial origin. To the west these deposits change into shallow marine deposits. Between the Esera River and the Noguera Ribagorzana River there is a frequent interfingering of marine and fluvial deposits. East of the latter river there was little marine influence whereas in the valley of the Isábena River five important ingressions have been found (Kooter, 1970).

A large transgression which supplied the deposits of the Ager Formation (Sparnacian–Ypresian) was followed by the deltaic complex of the Montañana Group (Ypresian–Lutetian). This interval included two phases of expansion of the sea, each followed by a regression. The sea never extended farther east than the villages of Roda de Isábena and Castigaleu (Nijman & Nio, 1975). An angular unconformity separates these deposits from the Upper Eocene Campodarbe Group which contains

fluvial and deltaic deposits. A more distinct angular unconformity, representing the main phase of the Pyrenean folding, separates these deposits from the Collegats Formation (uppermost Upper Eocene–Oligocene), which consists of a thick sequence of continental conglomerates near the source area changing into more finely grained fluvial sediments farther to the south. These are the demolition products of the rising Pyrenean orogene.

GEOGRAPHICAL SITUATION OF THE AREA STUDIED

The Ager Formation in the Tremp Basin has been investigated from Campo in the northwest and Benabarre in the west to Sant Salvador de Tolo in the east. The western part of this area is situated in the province of Huesca, the eastern part in the province of Lérida (Enclosure 1; Fig. 1).

Everywhere north of the line Campo – Arén – Tremp – Sant Salvador de Tolo the formation has disappeared due to erosion; the same is true in the Sierra del Montsech south of the Tremp Basin.

South of the Montsech mountains another, smaller Palaeogene basin occurs. This is the Ager Basin which was studied by J. Rosell's group (Universidad Autónoma de Barcelona). Already several studies have been published on this basin, sometimes dealing with the Tremp Basin as well (Villalta & Rosell, 1963; Crusafont et al., 1968; Ferrer et al., 1971, 1973; Rosell, 1973; Stevens, 1973; Mutti et al., 1973, 1974; Ghibaudo, 1976; Llompart, 1977). For literature on the western continuation of the Tremp Basin the reader is referred to the papers by Soler & Puigdefábregas (1970, 1972), Rupke (1972); Puigdefábregas (1975) and Puigdefábregas et al. (1975).

PREVIOUS WORK ON THE TREMP AREA

For a long time the south-central Pyrenees have been a subject of interest to geologists. Earlier investigations emphasized the regional features; stratigraphy and tectonics were broadly outlined, often accompanied by eloborate palaeontological inventories, e.g. Vidal (1875), Carez (1881), Dalloni (1910, 1930), Misch (1934), Selzer (1934), Almela & Rios (1947), Alastrué et al. (1957) and Mangin (1959). The most recent study of this kind is the publication by Garrido & Rios (1972).

In the course of time more specialized studies appeared, often of limited geographical or stratigraphical scope, e.g. Hottinger (1960, 1962), Hottinger & Schaub (1960), de Renzi (1965, 1968, 1975), Crusafont et al. (1966, 1968), Plaziat & de Renzi (1968), Luterbacher (1969, 1973), Kruit & Brouwer (1971), Mutti et al. (1972), Ferrer et al. (1971, 1973), Gaemers (1974), le Calvez (1975) and Plaziat (1975). Tectonic publications are mentioned in the following section, studies dealing with biostratigraphical and chronostratigraphical correlations in Chapter IV.

Of the above-mentioned authors only Ferrer et al. (1971, 1973) and Luterbacher (1973) attempted an environmental analysis of the marine Palaeogene deposits in the Tremp Basin.

TECTONIC COMPLICATIONS

The idea that large parts of the Pyrenees are allochthonous is not new. Dalloni (1910, 1930) already supposed that an important displacement to the south had taken place. Jacob & Fallot (1914) and Jacob et al. (1927) on the other hand believed in a large (thrust) movement to the north. Misch (1934) however preferred an entirely autochthonous interpretation. Seguret (1970) again breathed new life into the allochthonous concept. He supposed that two large nappes slid across the autochthonous rocks and across each other. Most later investigators have accepted his theory with only minor changes and amplifications (see Garrido & Rios, 1972; Garrido, 1973; Saenz de Santa Maria, 1976).

A deep boring drilled by the Spanish oil company Auxini in February 1975, provided new insights into the tectonics of the south-central Pyrenees. This boring (Isona no. 1-bis) is situated 9.5 km east and slightly north of Isona. It pierced a 3592 m thick Mesozoic succession of Upper Cretaceous to Triassic sediments; below this are Upper Eocene (Priabonian) marls and evaporites with a thickness of at least 722 m. This boring thus shows the existence of a nappe thrust over autochthonous sediments of Late Eocene age. This disproves previous ideas that no large nappe exists in the southern Pyrenees (Gaemers, 1974), or that the entire south-central Pyrenean unit (unité sud-pyrénéenne centrale) was thrust during the deposition of the middle part of the Upper Eocene (Seguret, 1970).

The Priabonian deposits under the thrust plane prove that gravitational sliding of the south-central Pyrenean unit did not occur before the latest Late Eocene. According to the ideas of Seguret (1970) the Cotiella nappe formed a whole with the south-central Pyrenean unit. In this case, the thrust plane of the Cotiella nappe should have originated at the same time as the thrust plane of the entire tectonic unit. Since the sliding of the Cotiella massif occurred ·simultaneously with the deposition of a thick Eocene marl sequence, the exact age of this event can be ascertained. Near Foradada the overthrust of the Cotiella massif dies out (Gaemers, 1974) and changes eastwards into an angular unconformity, which continues at least to the south of Merli (a small village northwest of La Puebla de Roda) in the marls of the Ager Formation; these marls are of Ypresian age (Pl. 1, Fig. 2). It follows that the overthrust of the Cotiella massif is also of Ypresian age; it is therefore much older than the Late Eocene thrusting of the south-central Pyrenean unit, from which it is evident that the two thrust planes are different and independent phenomena. Therefore there is no reason to doubt that the Cotiella sliding and the rotary movement of this sliding were of only local importance as explained by Gaemers (1974). Furthermore it would now appear likely
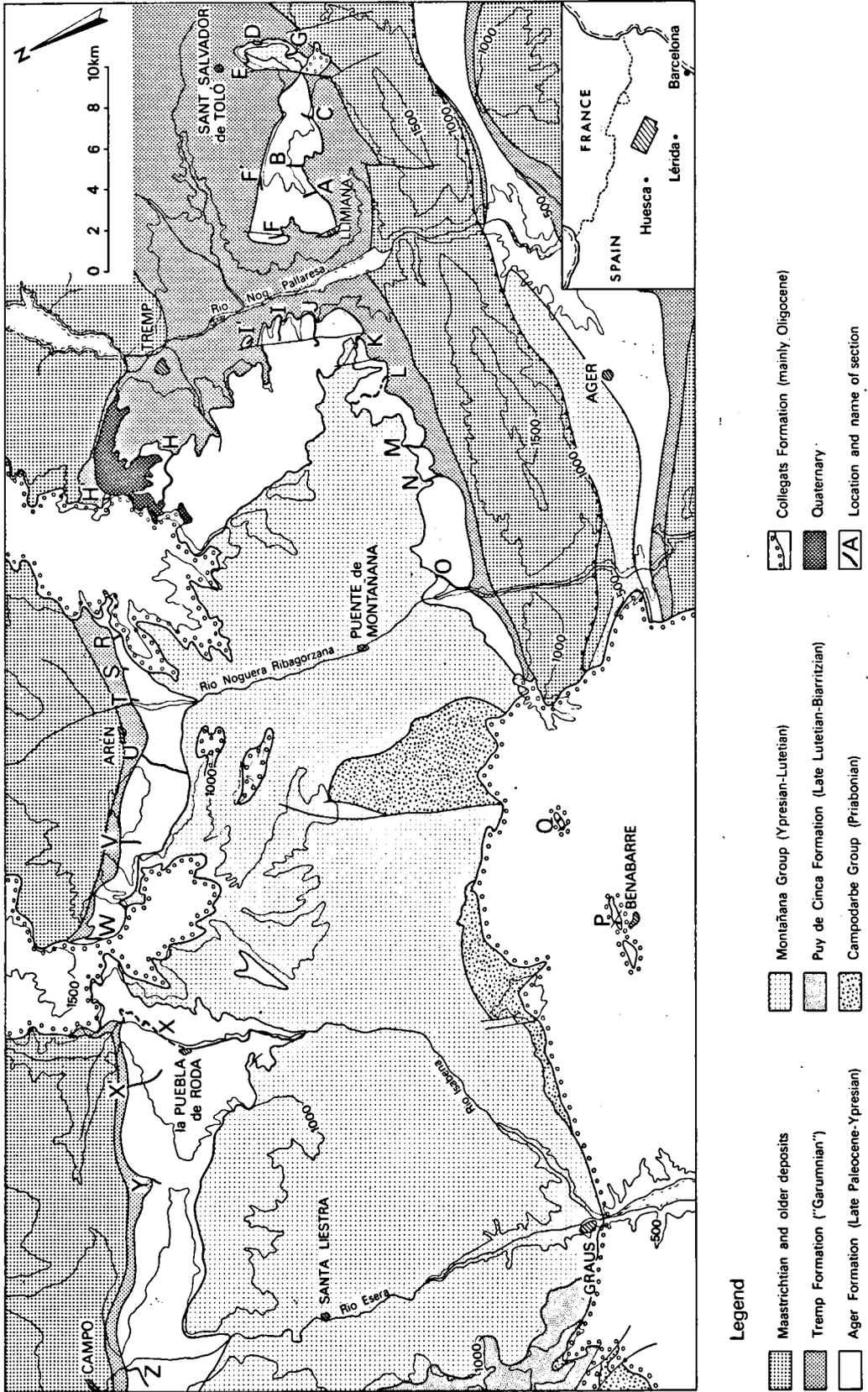
Fig. 1. Geological map of the area studied with location of the measured sections.

Legend

- Maastrichtian and older deposits
- Tremp Formation ("Garumnian")
- Ager Formation (Late Paleocene-Ypresian)
- Montañana Group (Ypresian-Lutetian)
- Puy de Cinca Formation (Late Lutetian-Biarritzian)
- Campodarbe Group (Priabonian)
- Collegats Formation (mainly Oligocene)
- Quaternary
- Location and name of section

that Seguret's south-central Pyrenean unit and his Gavarnie nappe constitute only one large nappe.

PETROGRAPHIC CLASSIFICATION OF THE SEDIMENTS

In the stratigraphic sections the carbonates are classified according to Dunham's (1962) system. Accordingly the name grainstone is used for mudfree calciclastic sediments. Dunham maintains that a calcarenite should be called a packstone if it contains more than 1% mud. Experience has shown that this 1% boundary is too strict, for only a few limestones meet this definition of grainstones. Therefore the 5% boundary suggested by van de Graaff (1971, p. 163) is used.

In the terminology of Folk (1959, 1962) the limestones occurring in the area of the present study nearly all belong to the biospar(rud)ites (calcarenites and calcirudites) and biomicr(ud)ites. In rare cases they can be classified as intraspar(rud)ites. According to Folk's classification the diversity of the carbonates is therefore rather limited. In the discussion of the several facies and subfacies types (Chapter V) Folk's system is used for the short lithologic descriptions.

A substantial part of the sediments in the Tremp Basin is a mixture of two or more of the following rock types: dolomite, limestone, clay, silt, sand, gravel and boulders. Dolomite, gravel and boulders are rare; nevertheless there is a large number of possible varieties and gradations between the other rock types. This sometimes makes identification and classification difficult.

METHODS AND TECHNIQUES USED

The outcrop area of the Ager Formation as shown in Fig. 1, was checked in the field in many places. Large parts were mapped on the relevant sheets of the Mapa de España, scale 1:50.000. The marked topography indicated on these maps does not always agree sufficiently with reality, for example in the neighbourhood of section G. The outcrop area between Campo and Serraduy (NE of La Puebla de Roda) is based chiefly on the maps of van Eden (1967, 1970). The Ager Formation on the southern side of the basin and on the northern side between Serraduy and Tendruy (small village NW of Tremp) was mapped in its entirety by the author with the help of aerial photographs and field work; there are no essential differences between these parts of the map and those made by Garrido & Rios (1972).

Most sections were measured on a scale of 1:100 or 1:200. Thick, monotonous sequences were recorded on a scale of 1:500 whereas some detailed sections with a succession of many thin strata were measured on a scale of 1:50. The data were noted in the field on check lists in order to save time and to standardize data collection.

Sampling was intensive, usually in proportion to the details within each section. Hard rock samples (mainly limestones and sandstones) as well as soft rock samples (mainly marls) were collected, although not all marls were sampled. If a stratum was rich in macrofossils, a small collection of the latter was often made and sometimes also loose fossils were collected. The weight of all rock samples and fossils collected amounted to about 1500 kg.

In addition to about 1400 thin sections several polished surfaces were studied if the structures were larger than a normal thin section. Sometimes staining of the samples with Alizarine Red-S was necessary in order to distinguish between calcite an dolomite. Many marl samples were treated with a diluted hydrogen peroxide solution so that they could be sifted more easily. The microfaunas and macrofaunas in the residues could then be studied.

The most frequent groups of larger benthonic foraminifera were counted in the thin sections. The counts were always made in or recalculated for a standard area of 6 cm².

In the stratigraphic sections the widths of the bars indicate the quantities of foraminifera in the accessory samples. Unintentionally the bars of the individual alveolinid species have different widths in some sections. This has no significance in this case; for these foraminifera the presence of a bar means only the presence of the species in the accessory sample without saying anything about the number of individuals.

STORAGE OF SAMPLES AND ADDITIONAL DATA

The rock samples, residues, thin sections, fossils and some sedimentary structures collected and studied were deposited in the collection of the Rijksmuseum van Geologie en Mineralogie, Hooglandse Kerkgracht 17, Leiden. In order to make the collection as compact as possible the hard rock samples were sawn into slices about 1–2 cm thick.

Additional data (mainly unpublished sections) were deposited in the same museum and in the files of the Department of Stratigraphy and Palaeontology, Geologisch en Mineralogisch Instituut, University of Leiden.

ACKNOWLEDGEMENTS

CHAPTER II

ABOUT THE EVOLUTION OF ALVEOLINIDS

GENERAL VIEW

The oldest known representatives of the Alveolinidae family are small, globular species of the genus *Praealveolina* which occur in the Lower Cenomanian. In younger strata *Praealveolina* gradually evolves into species with larger and more fusiform shells; moreover three other genera, viz. *Cisalveolina*, *Ovalveolina* and *Multispirina*, appear which may have evolved from *Praealveolina*. In the Turonian this latter genus again is the only representative of the family. *Subalveolina*, occurring in the Santonian and Lower Campanian, will have evolved from *Praealveolina* and is the latest representative of this Cretaceous group. These Cretaceous alveolinids form as a whole a distinct natural unit.

Except for some aberrant genera of local occurrence such as *Pseudedomia* Henson, Smout emend., no alveolinids have been found in the higher part of the Campanian and in the Maastrichtian. From Danian and Montian deposits alveolinids are completely unknown up to now. It is therefore highly unlikely that the Palaeogene alveolinids evolved directly from the Cretaceous species. Moreover the Palaeogene forms differ from the Cretaceous species in that they have a strongly developed postseptal canal and alternating chamberlets (Smout, 1963). Thus it is much more likely that the Paleo–Eocene forms arose from a miliolid ancestor. *Fasciolites* has been found from the Thanetian up to and including the Biarritzian (Middle Paleocene–Late Eocene). All alveolinids from the Tremp Basin belong to this genus which can be subdivided into two subgenera, viz. *Fasciolites* and *Microfasciolites* (see Gaemers, 1978). The evolution of these alveolinids starts with small, globular forms which gradually evolve into always larger and more elongated species. Thus the general pattern of evolution of these alveolinids is highly similar to that of the Cretaceous forms.

Younger alveolinids are *Borelis* which is known from Late Eocene times to the present day, *Bullalveolina* which is only known from the Oligocene, and *Alveolinella* which is known from the Miocene to recent. The latter genus is probably a descendant of *Borelis*. The origin of these three genera which seem to form a natural group is uncertain. Usually they are presumed to have miliolid ancestors because both the microspheric and megalospheric generations of *Borelis* have a milioline nepionic stage in contrast to most of the older alveolinids which have a planispiral megalospheric stage (Smout, 1963).

EVOLUTION OF THE ALVEOLINIDS OF THE TREMP BASIN

Hottinger's monograph of 1962 on the Palaeogene alveolinids of the Mediterranean area is an indispensable publication for the study of the alveolinids of the Tremp Basin. An important improvement of Hottinger's work with regard to earlier publications which deal with the same group of foraminifera is the use of standard magnifications in the photographs of the species: ten-fold, twenty-fold and forty-fold. This is especially important for the alveolinids, for the size is one of the most essential characteristics for the identification. However, if the successive species of a lineage increase considerably in size, it often happens that they are not all pictured at the same standard magnification. As a result the phyletic relationships between some species or groups of species are obscured. For example the species *Fasciolites (Microfasciolites) boscii* shown by Hottinger at a twenty-fold magnification was not identified as a member of the subgenus *Microfasciolites* (syn.: *Glomalveolina*) the species of which are usually shown at a forty-fold magnification.

In a previous publication (Gaemers, 1978) the present author tried to assemble the species from the Palaeogene
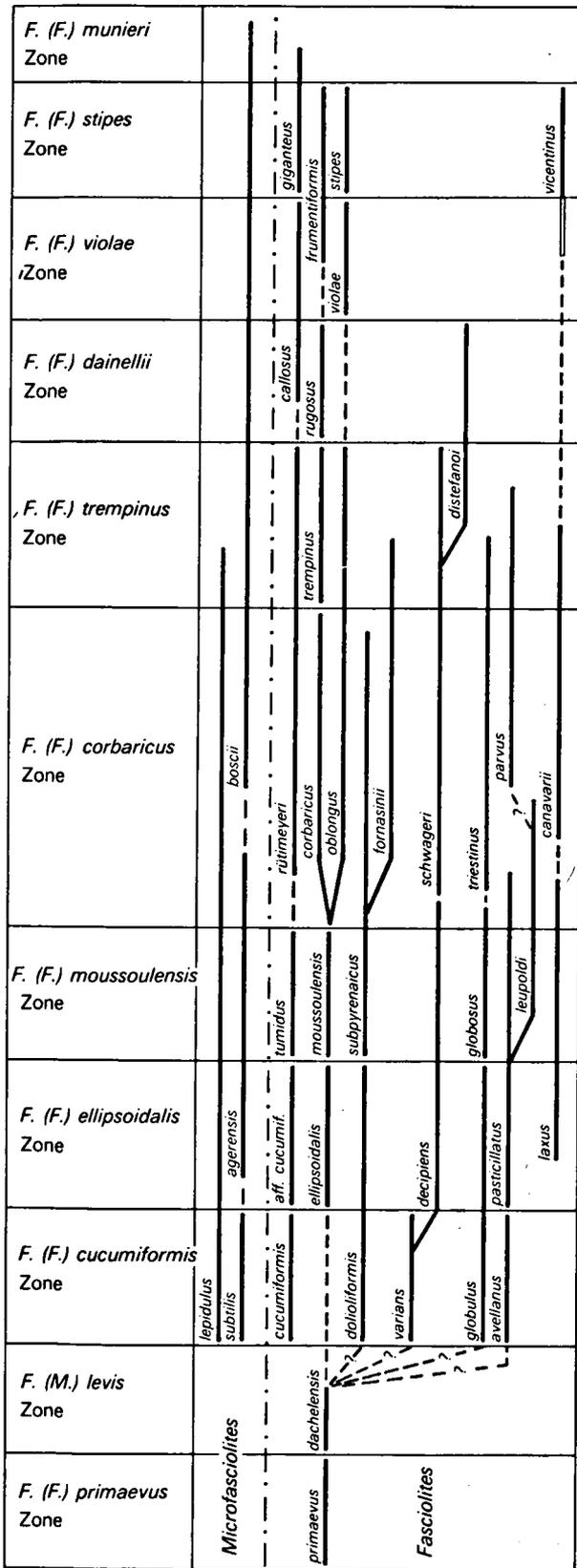
of the Tremp Basin in natural groups which are as extensive as possible. This arrangement with the addition of data of younger alveolinids collected from the literature provides a more elaborate scheme of the evolutionary development of some Palaeogene alveolinids (Fig. 2). One of the most important discoveries is the bifurcation of the lineage of *F. ellipsoidalis* after *F. moussoulensis*. In fact in the Tremp Basin transitional forms have been found not only between *F. moussoulensis* and *F. corbaricus* but also between the former species and *F. oblongus* (Gaemers, 1978, pl. 2, figs. 5, 6). These forms are intermediate with respect to their elongation index, the size of the chamberlets and the coiling. The chamberlets of *F. oblongus* are generally smaller than those of *F. moussoulensis*. The characteristics of the spirals of the latter species remain much more uniform during growth than those of *F. oblongus* which show two different ontogenetic stages: a younger, more elongated stage with distinctly thickened poles, and an older, more compact stage with tightly coiled spirals.

Parallel developments are obvious in all lineages. In the course of time the average size of the proloculus of megalospheric forms increases. We have to keep in mind that the variability of this characteristic is pronounced in most species. The sizes of the proloculus for successive species of a lineage tend therefore to show considerable overlap. Species which are not or only slightly flosculinized increase in size, and the elongation index increases simultaneously. Highly flosculinized species generally increase in size only (see for example the sequence *F. globulus* – *F. globosus* – *F. triestinus*). Moreover the number of chambers in a corresponding coil increases in the course of the evolution of the lineages. Finally the difference in size between the microspheric and megalospheric generations always increases as the development of the lineage progresses.

Although other characteristics can be affected by more accidental changes, the course of evolution seems to be fixed to a considerable degree. This does not mean however that the evolution of the alveolinids is completely determined beforehand. One cannot predict the future of a lineage entirely, because not only internal processes but also external, environmental circumstances influence the course of evolution. The internal processes in each individual animal and in the species as a whole as transmitted by propagation seem always to follow the same path. Once a lineage has started, it has to obey the laws of the internal processes. The above-mentioned parallel developments express the realization of these processes. Apart from the degree of flosculinization the only important difference found in the development of the various lineages is the rate at which the changes take

Fig. 2. Evolutionary lineages of the majority of the alveolinids occurring in the Tremp Basin. The connections between *F. varians* and *F. decipiens*, and between *F. schwageri* and *F. distefanoi*, which have been drawn as bifurcations, only signify a gradual transition between these species.

place. Probably population size is an important factor in this respect (see Chapter III).

Naturally animals tend to adapt themselves to the environment if conditions change during the lifetime of the lineage to which the species belong. This adaptation can lead to new features which however are superimposed upon the basic form determined by the internal processes. For instance the poles of alveolinids can be pointed to truncated. Microspheric forms of *F. ellipsoidalis* have fairly pointed poles, micro- and megalospheric forms of *F. moussoulensis* have truncated poles; those of *F. corbaricus* and megalospheric forms of *F. ellipsoidalis* have realized the intermediate possibility of rounded poles. The simultaneous increase in the size of the proloculus and of the entire test, plus the increase in the elongation index during the evolution take place irrespective of changes in the shape of the poles. The splitting of a lineage into two (or more) branches, which is called cladogenesis, is a matter of environmental conditions (in casu a geographical or ecological separation) and cannot therefore be deduced from the internal processes, which are guided by genetic principles.

Katagenetic developments, recorded for many animal groups such as bryozoans, gastropods, cephalopods and bony fishes (Gaemers, 1976), are not known from the alveolinids. Only progressive sequences have been observed and it is unlikely that retrograde tendencies wil be discovered in the future. It appears that among alveolinids (and probably among most foraminifera) size increase and increase of elongation once started continue unchecked until a lineage has reached the maximum size at which point it becomes extinct. From the available data it cannot yet be determined whether rejuvenation by means of neogenesis (Gaemers, 1976) occurs in this group – as has been found for the codfishes (Gaemers, 1976). If not, new lineages of alveolinids can only arise from the Miliolidae. Miliolidae are an example of foraminifera in which size increase seems to be checked. Perhaps the alveolinids have surpassed a certain threshold and the miliolids have not or not yet.

Thus the evolution of the alveolinids seems to differ in some respects from that of higher animal groups. Many questions still have to be solved before their evolution will be completely clear.

CHAPTER III

PALAEOECOLOGY OF ALVEOLINIDS AND OTHER LARGER FORAMINIFERA

GENERAL PALAEOECOLOGICAL NOTES ON LARGER FORAMINIFERA

Although larger foraminifera are used in many cases for biostratigraphic purposes, and have therefore been studied taxonomically for many years, only a few palaeontologists have concerned themselves with the palaeoecology of these fossils. Perhaps this is partly due to the scanty knowledge of the ecology of many groups of recent foraminifera.

A division into three main groups of associations of larger foraminifera is well-known for many Palaeogene deposits and can also be applied in the Tremp Basin, but more detailed information cannot be obtained from the literature. These groups of associations are the following:
1. The imperforate foraminifera associations, composed of Miliolidae, Alveolinidae and *Orbitolites*, or at least one or two of these groups.
2. The mixed perforate–imperforate foraminifera associations, in which species of the imperforate associations are usually found together with *Nummulites* and/or *Operculina*.
3. The perforate foraminifera associations. These include *Nummulites, Operculina, Assilina* and *Discocyclina*. Miliolids can still play an important role in these associations.

In a general way these foraminifera associations tell us something about water depth and temperature; the latter is closely related to the depth when we consider a

limited area like the Tremp Basin. A second important environmental factor for the distribution of the benthonic foraminifera associations is the kind of sediment deposited.

In order to unravel the influences of depth and bottom sediment it is important to find a sequence which shows gradually changing foraminifera associations while the sediment remains much the same. This is the case in section P and therefore this section can be used as a key section.

The sequence consists of pure limestones with occasionally more or less sandy beds. The lower part contains imperforate foraminifera associations, which lived in a shallow marine, fairly protected environment, judging from the entire faunal and floral composition. The middle part contains mainly mixed perforate–imperforate foraminifera associations which lived in somewhat deeper, more open marine environments. An important exception is noted in the upper part of this interval where an imperforate association predominates. Here the perforate elements have practically disappeared. Temporarily the sea became shallower, and reefs and fore-reef deposits could be formed. In the upper part of section P perforate associations are present which are indicative of deeper shelf waters; this is evident from the occurrence of glauconite and from the entire faunal and floral composition. *Discocyclina* and *Nummulites* are the most numerous genera here. Higher in this part of the section *Nummulites* generally decreases in number in contrast to

Discocyclina which becomes more abundant. From this and also from other data of the Tremp Basin it can be concluded that *Discocyclina* on the whole lived in deeper water than *Nummulites*.

Most larger foraminifera are not restricted to one type of sediment, but they always have clear preferences. We have to keep in mind that more species of each genus are involved and that not all necessarily occupied the same ecological niche. The following therefore is only a general impression of the main ecological requirements for some of the genera of larger foraminifera common in the Tremp Basin.

Orbitolites preferred a shallow marine environment which was protected against wave and tide actions; they appear in pure limestone deposits. Therefore the back-reef environment was most favourable. *Orbitolites* also occurs in limestones with a low sand or clay content. This genus was probably epiphytic like its recent counterpart *Sorites* (Hottinger, 1973). It is mainly associated with large numbers of miliolids and alveolinids.

Nummulites is most abundant in limestones and sandstones. In areas of extensive clay deposition it is usually rare. Sometimes large numbers of nummulite specimens are found in marls. An explanation for this could be that such marls were deposited at a much lower rate than most other marls. Nummulites generally lived in moderately deep shelf waters (ca. 15–50 m). When an important influx of sand entered the basin, these foraminifera seem to have replaced the alveolinid elements in the shallow environment. Nummulites could also live in deeper waters if mainly calcium carbonate and/or sand deposition took place instead of clay commonly found at these depths.

Operculina is observed chiefly in limestones and marls. It could only persist when the sand content was low. Typically large numbers of this genus can be found in moderately deep shelf waters, like the nummulites.

Assilina occurs mainly in marls and marly limestones that on the average were deposited at greater depths than those in which operculines are frequent. Assilines are not normally sand or pure carbonate dwellers. Glauconite can often be found together with assilines when the sedimentation rate was sufficiently low (in marly limestones).

Of *Discocyclina* two distinctly different forms occur in the Tremp Basin. One has markedly flattened discs and the central part is only slightly elevated. This form is mainly found in marls; it can also be found in marly and sometimes somewhat sandy glauconite-rich limestones intercalated as thin layers in the marls. These discocyclines often occur together with assilines but generally they live in deeper waters. In fact, marls with an abundance of discocyclines represent the deepest environment in the area studied (probably more than 100 m). The other form is characterized by inflated discs with a markedly thickened central part. It can be found in pure limestones or sandy limestones which are associated with reef development. This form also only lived in deeper waters, and is usually associated with

glauconite. Fore-reef deposits in the broad sense and deep reefs contain fairly large numbers of these fossils.

RECENT ALVEOLINIDS

Little is known about the ecology of recent alveolinids and of many other larger foraminifera. The sparse data available about the life habits of recent alveolinids chiefly concern the depth of the sea. Three recent alveolinid species are known from the Indo-Pacific region, viz. *Alveolinella quoyi* (d'Orbigny), *Borelis melo* Fichtel & Moll) and *Borelis schlumbergeri* (Reichel); *A. quoyi* is the species most often recorded.

According to Brady (1884) *Alveolinella quoyi* "most affects the shallow water of the coral reefs, and becomes rare at depths greater than 54 fathoms" (97 metres). He observed this species for example in the coral reefs of Honolulu (Hawaii) at a depth of 72 m. At Funafuti Chapman (1899) found this species at depths of 90 to 109 m. Cushman (1914) found *A. quoyi* around the Hawaiian Islands in waters about 113 metres deep. In 1921 he observed this species in the seas around the Philippines, where it is most abundant at depths between 18 and 70 m; one occurrence was recorded at the extreme depth of 582 m. Cushman (1933) mentions typical specimens of this species in Mokaujar Anchorage, Fiji, at a depth of 13 fathoms (23.5 m). Hofker (1930) recorded a range of 9 tot 45 metres for different stations in the Malayan Archipelago, whereas le Roy (1938) found a *Dendritina–Alveolinella* community in a protected shoal facies ranging in depth from 7 to 26 metres (Peper Bay, west coast of Java, Indonesia). Other authors who have found *Alveolinella* in reefs, back reef zones, reef flat channels and/or tropical lagoons are Gardiner (1906), Newell (1956), Cole (1957), Maxwell et al. (1961), Bandy (1964), Maxwell & Swinchatt (1970) and Chevalier (1973) (literature compiled by Ghose, 1977).

The occurrence of *A. quoyi* in bottom samples from deeper water surrounding oceanic islands can be explained by transportation of shells from shallower regions (Cushman, 1910). *Alveolinella* and also *Orbitolites* are considered by many authors to be characteristic constituents of a shallow marine environment of the tropics in and around reefs where the water is clear.

Borelis melo has been recorded off the Hawaiian Islands and near Ceylon (Brady, 1884). The limited amount of data does not justify an ecological interpretation.

The type material of *Borelis schlumbergeri*, described by Reichel (1937) as *Neoalveolina pygmaea schlumbergeri*, comes from Mayotte Island and Nossibé Island, northwest of Madagascar. Unfortunately no depth indications or other data are known. Specimens that can be included in the same species had already been found earlier by Möbius (1880) and Egger (1893). Möbius observed empty shells in a white carbonate mud at the bottom of the channel between the coastal reef and the Fouquets dam reef of the Isle of Mauritius.

Egger found his alveolinids in samples taken at depths of 137 m and 411 m to the west of Mauritius. Finally *B. schlumbergeri* was recorded by Hanzawa (1948) as being present in a sample from a depth of 82 m, south of Tarama-jima (Ryukyu Islands, Japan). From these data it seems probable that *B. schlumbergeri* lives in somewhat deeper water than *A. quoyi*, although we have to remember that currents may have transported empty shells to deeper waters.

FOSSIL ALVEOLINIDS

The fossil alveolinids listed in Table 1 seem in general to occupy the same ecological niches as their recent descendants. According to Hottinger (1960) fossil alveolinids flourished only within narrow facies ranges; fossil biocoenoses occur only in lime-rich deposits, which often contain numerous other porcellaneous foraminifera (mainly Miliolidae and *Orbitolites*) as well as many calcareous algae; alveolinids apparently could live on shallow sea bottoms which were poor in detritus (Hottinger, 1960, p. 271). Alveolinids evidently could not live in a brackish environment in contrast to miliolids, since alveolinids never occur in deposits which can be interpreted as definitely brackish (Hottinger, 1960). This is in accordance with the data of recent species, which have only been recorded from water of normal salinity.

Hottinger's description of the habitat indeed applies to the majority of the alveolinids in the Tremp area, but exceptions exist. It is certainly not true that alveolinids are always restricted ecologically to protected shelf areas, as Hottinger (1973, p. 443) stated, although for many species his view is applicable. Thanks to a detailed study of the facies of the marine deposits in the Tremp Basin, it is now possible to consider the palaeoecology of the different species and thus to obtain more precise information on this subject than ever before.

PALAEOECOLOGY OF THE FOSSIL ALVEOLINIDS IN THE TREMP BASIN

Table 1 shows the distribution of all important alveolinid species over the different (sub)facies types as compiled for the Tremp Basin. For three reasons however, this

Table 1. Ecologic distribution of the alveolinids occurring in the Tremp Basin. Subfacies IIc: lagoonal deposits; facies III: beach and barrier deposits; subfacies IVa-c: shallow tidal deposits; subfacies IVd, d': deeper tidal deposits; facies VI: shallow marine deposits with imperforate foraminifera associations; facies VII: back-reef deposits; subfacies VIIIb: *Lithothamnium* ridges; subfacies VIIIc, d: coral–algal reefs and coral reefs; subfacies VIIIe: deeper coral reefs; subfacies IXa: off-reef shoal limestones; subfacies IXb: reef channel limestones; subfacies Xa: shallow fore-reef deposits; subfacies Xb: deeper fore-reef deposits; facies XI: pure limestones with mixed imperforate–perforate foraminifera associations; facies XII: clayey limestones and marls with mixed imperforate–perforate foraminifera associations; facies XIII: fore-reef detrital limestones; facies XIV: marls and impure limestones with perforate foraminifera associations; facies XV: marls with *Turritella* community.

table must be used cautiously. In the first place some species appeared to be rare in the area, notably *F. (M.) subtilis*, *F. (F.) tumidus* and *F. (F.) laxus*. It is however probable that their palaeoecological distribution was more extensive than indicated by the few specimens found. Secondly many species will not have been observed in all environments in which they lived, because strata representative for these environments are not exposed in the Tremp Basin in all stratigraphic intervals. *F. (F.) subpyrenaicus* for instance could not be found in lagoonal deposits because the lagoonal environment is not represented in the existing outcrops of the stratigraphic range of this species. A special symbol is used in the table to indicate that it is highly likely that a species lived in more environments, as deduced from the known facies distribution of that species, and from the distribution of the most closely allied species. Thirdly it is not always possible to know whether the occurrence of a species in a (sub)facies was caused by transportation from other (sub)facies or not. Examples are the presence of *F. (F.) ellipsoidalis*, *F. (F.) laxus* and *F. (F.) canavarii* in facies IX.

Notwithstanding the above-mentioned restrictions a lot of information is available. In the following the separate species will be discussed first, and then the trends within the lineages will be considered.

F. (M.) lepidulus occurs in all imperforate and mixed perforate–imperforate foraminifera associations. Pure carbonate was preferred by this species but it could endure some sand or mud in the sediment.

The palaeoecological distributions of *F. (M.) pilulus* and *F. (M.) minutulus* are somewhat less extensive than that of *F. (M.) lepidulus*. *F. (M.) minutulus* shows some tolerance for sand, *F. (M.) pilulus* on the other hand seems to be restricted mainly to pure limestones.

In the *F. (M.) boscii* lineage *F. (M.) subtilis* represents the species which lived in the shallowest water. It is only known to occur in imperforate foraminifera associations. Its successor *F. (M.) agerensis* belonged to the typical mixed perforate–imperforate foraminifera associations, which lived in somewhat deeper waters than the imperforate foraminifera associations. Surely this species could tolerate a small amount of mud in the carbonate sediment, judging from its common occurrence in all subfacies of facies XII. *F. (M.) boscii* lived in even deeper seas and it is in fact the alveolinid species which lived in the deepest water in the Tremp Basin. It never occurs above the zone in which glauconite was formed (see also Chapter VII, section 5) in contrast to the other species which also lived in relatively deep waters; it is therefore a reliable indicator of a fairly deep sea. Apparently it could tolerate the sand and mud in the mainly calcareous sediment quite well.

It is likely that the three members of the *F. (F.) cucumiformis* lineage found in the Tremp Basin lived under the same conditions, for they all occur in the imperforate foraminifera associations (facies VI). Unfortunately the mixed perforate–imperforate foraminifera associations (facies XI) are poorly represented in the *F. (F.) cucumiformis* Zone, so that there was not

much chance of finding this species for which the biozone is named. The rarity of *F. (F.) tumidus* in facies XI however is a good indication that *F. (F.) cucumiformis* was also scarce in this facies. The latter species as well as *F. (F.) ruetimeyeri* could endure a considerable influx of sand. The few specimens of *F. (F.) tumidus* were found in pure limestones, but it is highly unlikely that this species was restricted to these sediments and could not tolerate sand. It is striking that all three species of this lineage seldom occur in large numbers in rock samples.

Typically both *F. (F.) ellipsoidalis* and *F. (F.) corbaricus* inhabit the clean calcareous bottoms of facies VI and XI, and occur in the neighbourhood of reefs. Probably *F. (F.) trempinus* had the same mode of life as these species. Reefs however are unknown in the exposures of the *F. (F.) trempinus* Zone in the Tremp Basin; for this reason the autochthonous occurrence of *F. (F.) trempinus* in reefs cannot yet be verified. The distribution of *F. (F.) moussoulensis* is more extensive. This species could also live under muddier bottom conditions. *F. (F.) oblongus* had the geatest tolerance for sand of all alveolinids in the Tremp Basin. It can be found in large numbers in calcareous sandstones rich in quartz sand. However, it is not restricted to such sediments: it also occurs in pure limestones. In the glauconitic sands of the Cuisian in the Paris Basin this species is the only alveolinid. Apparently it is the only species that could survive such bottom conditions. In the southern Pyrenees *F. (F.) oblongus* nearly always indicates deeper (and also colder) water. Usually it is found in glauconite-rich deposits, although it is not as accurate an indicator of deep water conditions as *F. (M.) boscii*.

There seems to be a striking difference between the occurrence of *F. (F.) oblongus* in the Paris Basin and in the Tremp Basin. Whereas this species lived in relatively deep and cold water (usually 50 metres or more) in the Tremp Basin, it occurs in the Paris Basin in deposits which are supposed to have been formed under much shallower conditions. If this is true, there are two possibilities which perhaps are not mutually exclusive. Firstly the sand influx may have been so large that *F. (F.) oblongus* and the nummulites superseded the other alveolinids completely. Secondly the temperature of the surface layers of the sea in the Paris Basin may have been lower than in the Tremp Basin. This is highly likely, since the Paris Basin is situated farther north than the Tremp Basin. Moreover, the communication of the Paris Basin with the North Sea was much larger than the narrow seaway to the Atlantic Ocean which indirectly connected it with the Tethys region.

Certainly the most successful group of alveolinids in the Tremp Basin, as far as distribution is concerned, is the *F. (F.) subpyrenaicus* lineage. The three species known from this lineage are all abundant in a large variety of facies and subfacies. Numerous *F. (F.) dolioliformis* specimens lived in normal saline lagoons up to and including the environments with mixed perforate–imperforate foraminifera associations. This

species could tolerate some mud and sand but preferred clean carbonate sediments. The same life conditions hold for *F. (F.) subpyrenaicus* and *F. (F.) fornasinii,* although both species have not yet been recorded in a lagoonal environment because there are no deposits of this milieu in the Tremp Basin from the time when these species existed. Moreover, *F. (F.) fornasinii* has a better tolerance for sand than the other two species of the lineage.

The species of the *F. (F.) decipiens* lineage which occur in the Tremp Basin are most abundant in the imperforate foraminifera associations, but *F. (F.) decipiens* and *F. (F.) schwageri* also occur in considerable numbers in the mixed perforate–imperforate foraminifera associations. It is not certain whether *F. (F.) varians* occurred in facies XI or not. All species of this lineage could endure only small percentages of sand or mud in a carbonate environment. It is interesting to note that *F. (F.) schwageri* is extremely abundant in various shallow marine limestones of facies VI, whereas *F. (F.) varians* and generally also *F. (F.) decipiens* are definitely more rare in this facies. It is striking that *F. (F.) schwageri* does not become abundant until *F. (F.) subpyrenaicus* has disappeared in the higher parts of the *F. (F.) corbaricus* Zone. This suggests that *F. (F.) dolioliformis* and *F. (F.) subpyrenaicus* were important competitors with respect to the members of the *F. (F.) decipiens* lineage, in contrast to *F. (F.) fornasinii.*

The *F. (F.) globosus* lineage is characterized by its very low tolerance for detrital particles in the sediment, the lowest compared with all other alveolinid lineages. Of this group *F. (F.) globulus* is still the least restrictive species in this respect: it is known to occur in lagoonal sediments up to and including limestones of facies XI. *F. (F.) triestinus,* the youngest member of the lineage in the Tremp Basin, seems as a rule to have lived in slightly deeper water, although it has not been found in a deeper environment than facies XI.

The *F. (F.) pasticillatus* lineage starts with *F. (F.) avellanus* which occurs almost exclusively in imperforate associations. Its descendant *F. (F.) pasticillatus* on the other hand is a characteristic species of the mixed perforate–imperforate foraminifera associations. This species is rare in pure imperforate associations and when it does occur the specimens closely resemble *Alveolina* sp. aff. *pasticillata* shown by Hottinger (1962, I, p. 91, fig. 46b). This form is characterized by thicker, somewhat more irregular coils with chamberlets which are larger than normal. *F. (F.) leupoldi* exists exclusively in mixed perforate–imperforate foraminifera associations. It can even be found rather frequently in the glauconite-bearing limestones of facies XIII. This species as well as *F. (F.) pasticillatus* shows a good tolerance for mud. On the whole *F. (F.) parvus* occupies the same palaeoecological niche as *F. (F.) leupoldi,* although it seems to be somewhat less sensitive to the depth of the sea since it can be found in imperforate foraminifera associations.

F. (F.) canavarii is a common species in limestones of the imperforate and the mixed perforate–imperforate foraminifera associations. There is some preference for the latter associations (facies XI). This is suggested mainly by the fact that dwarf forms of this species are more common in facies VI than in facies XI. In many cases dwarf forms have been found in the same samples as specimens of normal size. Transitional forms are also known. It can be concluded that the size is ecologically determined. Therefore there is no reason to separate these specimens into two species as Hottinger (1962) has done: he described the dwarf form as a new species, *Alveolina rotundata.* Although *F. (F.) laxus* is very scarce in the Tremp Basin, it seems highly likely that it occurred in the same facies as *F. (F.) canavarii* and that it had the same preference for facies XI. *F. (F.) canavarii* tolerated sand and mud admixtures in the limestone quite well. Once it was even found in a marl. The tolerance of *F. (F.) laxus* was probably less.

GENERAL PALAEOECOLOGICAL TRENDS WITHIN THE ALVEOLINID LINEAGES

The shallow marine limestones of facies VI contain by far the largest numbers of alveolinids in the Tremp Basin, followed by the somewhat deeper-water limestones of facies XI. The Middle Paleocene ancestors of these alveolinids also lived in shallow marine environments where calcium carbonate was deposited. Thus most descendants remained faithful to the mode of life of their forerunners.

Three groups with different ecological behaviour can be distinguished in the investigated lineages, as they appear in the Tremp Basin.

1. Barely specialized alveolinids which were abundant in many facies during their entire evolution. This group includes the *F. (F.) subpyrenaicus* lineage and also the species *F. (M.) lepidulus.* It is striking that these alveolinids, which must have occurred as large populations, show low rates of evolution.

2. More specialized alveolinids which did not markedly change their mode of life during their evolution. The sequence *F. (F.) ellipsoidalis – F. (F.) trempinus,* the *F. (F.) cucumiformis* lineage, the *F. (F.) decipiens* lineage, the *F. (F.) globosus* lineage and the *F. (F.) canavarii* lineage belong to this group. While the *F. (F.) cucumiformis* lineage is characteristic of the shallow marine facies VI, optimum conditions for the *F. (F.) canavarii* lineage were those of facies XI. Normally the lineages of this group have moderately high to high rates of evolution.

3. More specialized alveolinids which markedly changed their mode of life during their evolution. This group consists of the *F. (F.) ellipsoidalis – F. (F.) oblongus* sequence, the *F. (M.) boscii* lineage and the *F. (F.) pasticillatus* lineage. These three lineages changed from a shallow to a deeper marine habitat. The *F. (F.) pasticillatus* lineage changed the least in this respect. The most striking change in depth is found for the *F. (M.) boscii* lineage, but the difference with respect to the sequence of *F. (F.) ellipsoidalis – F. (F.) oblongus* is not great. The position of *F. (F.) moussoulensis* at the

beginning of the two sequences leading to *F. (F.) trempinus* and *F. (F.) oblongus* is rather peculiar. On the one hand it occupies the niche of the ecologically stationary *F. (F.) trempinus* branch, while on the other hand it is also found in an intermediate position in the ecologically shifting *F. (F.) oblongus* branch.

It is worth mentioning that those species which occupied the most aberrant palaeoecological niches of all alveolinid species, viz. *F. (M.) boscii* and *F. (F.) oblongus,* had the largest tolerance for sand. This tolerance cannot be an accidental phenomenon. As both species lived in deeper, and thus darker, water it is probable that their food consisted for the greater part of minute living animals and/or dead animals rather than the more vegetable diet of most foraminifera which mainly consists of diatoms, filamentous algae and other small plant material (Myers, 1943; Lipps & Valentine, 1970). Considerable amounts of sand supplied to an environment largely hinders the settlement of plants.

It is remarkable that the species which lived in deeper water had low rates of evolution in comparison with their ancestors who lived in shallow water. For two reasons it is likely that the populations of *F. (M.) boscii* and *F. (F.) oblongus* were larger than those of most other alveolinids: in appropriate facies in the Tremp Basin they occur in large numbers (there was no competition with related species) and they are common in areas such as the Paris Basin where no other alveolinids occur. Therefore it may be assumed that *F. (M.) boscii* and *F. (F.) oblongus* were more cosmopolitan species than most other alveolinids. This is in accordance with the results of the investigations of Boucot (1975a, b; 1977), who studied about 2000 genera and subgenera of brachiopods, rudistids and scleractinians. He found that cosmopolitan taxa have far larger stratigraphic ranges than endemic taxa. Thus there is a highly inverse correlation between the area occupied by a taxon and its evolutionary rate, which suggests that population size is the first order correlative of evolutionary rate.

This author agrees with Boucot that population size is a very important, if not the most important, factor in determining the rate of evolution. Population size however, does not depend only on the extent of the area occupied by a certain species as suggested by Boucot, but also on the number of individuals per unit surface and on the number of (sub)facies that this species inhabits. The barely specialized alveolinids of the *F. (F.) subpyrenaicus* lineage which occur in many (sub)facies are good examples in this respect.

Finally it has to be remarked that the simple relationship between the shape of the test and the sediment in which the alveolinids lived cannot be given by a general rule as implied by Hottinger (1962, p. 22). He states that the spherical forms are typical of pure limestones, and that the oval and more elongated forms inhabited more detrital facies. If this were true, the primitive alveolinids (which are spherical) should have lived in pure carbonate sediment, and most evolved species (which are usually clearly elongated) should have lived in more clayey or sandy sediments. The above discussion on the palaeoecology of the different alveolinid species proves that such a stringent relationship between shape and mode of life does not exist. It is however indeed likely that the more elongated forms had an advantage over the spherical forms in environments with distinct current action because they could not roll in all directions. In quiet environments all alveolinid forms are on an equal par.

PROBLEMS IN CORRELATION DUE TO FACIES CHANGES

The optimum development of alveolinids occurred in shallow marine calcium carbonate environments. They are scarce or absent in other shallow marine sediments and in deeper marine deposits except for some especially adapted species. Therefore it is difficult or even impossible to establish the biozonation of these latter deposits by means of alveolinids. Sediments of the southern side of the Tremp Basin are mainly in limestone facies. Here the alveolinids occur in sufficient numbers in most layers to permit reliable biostratigraphic correlations.

With the help of samples containing shallow and deeper living alveolinids the deeper facies where *F. (M.) boscii* and *F. (F.) oblongus* are present could be correlated stratigraphically with the shallow carbonate facies where most alveolinid species lived. Naturally one of the groups must be allochthonous in that case, but when it can be shown that it is only an allochthony of space and not of time the available data can be used for correlations without reservation.

On the northern side of the basin however, marls and sandstones predominate, especially in the upper part of the Ager Formation. In that area therefore we must use other fossil groups if accurate correlations are to be obtained. Another, less safe approach is to look for important sedimentary events which affected larger parts of the basin. For example, a sudden sand influx which presumably occurred simultaneously in many sections of the basin can be used as a stratigraphic marker. The stratigraphical position of facies fairly close to those containing the alveolinids can also be determined with the help of allochthonous specimens. Here again it is essential to be able to show that these fossils are allochthonous with respect to space, not with respect to time or to both time and space.

Experience indicates that only a few alveolinids have been reworked from older deposits. Reworking does occur, for instance in highly condensed sequences. The best example is section G; there we find alveolinids from different biozones together in one sample. Most sections represent a practically continuous sedimentation, or sedimentation alternating with non-deposition without clearly defined erosion. Each alveolinid association in these sections contains species which belong to the same biozone.

CHAPTER IV

BIOSTRATIGRAPHY AND CHRONOSTRATIGRAPHY

ZONATION ON THE BASIS OF ALVEOLINIDS

The vertical range of the alveolinid species, the taxonomy of which has been dealt with in Gaemers (1978), allows the establishment of alveolinid biozones in most stratigraphic sections, and provides biostratigraphic correlations of these sections as a base for the reconstruction of the history of the Tremp Basin.

The results of this previous study (Gaemers, 1978) deviate from those obtained by Hottinger (1960, 1962) in many respects, and as a consequence the position of the Ilerdian stage which was defined by Hottinger & Schaub (1960) has to be re-examined.

Biozonation on the basis of alveolinids, as established by Hottinger (1960), contains many biozones which correspond to relatively short intervals of time. During my previous investigations however, it was found that the relationships between alveolinid species had to be worked out in more detail. Many successive biozones introduced by Hottinger (1960) are not defined by successive species of one and the same lineage so that uncertainties are introduced into the biostratigraphic divisions. This is seen in particular in the transitions between the *F. cucumiformis* Zone and the *F. ellipsoidalis* Zone, the *F. trempinus* Zone and the *F. oblongus* Zone, the *F. oblongus* Zone and the *F. dainellii* Zone, and finally the *F. dainellii* Zone and the *F. violae* Zone. In these cases difficulties can be expected, because theoretically the chance is very small that a species boundary in one lineage will be placed at precisely the same level where a species boundary is placed in another lineage. There is almost always either a certain overlap or a time gap.

At present in fact it is customary in nearly all biostratigraphic research to use the most frequently occurring species with a presumably short stratigraphic range, without considering the relationships between the guide fossils which characterize successive biozones. In my opinion the only reliable, watertight approach for biostratigraphy is the use of evolutionary sequences of species within an interconnected area. Certainly many problems in stratigraphy can be solved by such an approach.

The best method is to use many lineages, especially in view of the fact that all lineages are finite (see Gaemers, 1976) so that the role for zonation purposes of one lineage has later to be taken over by another lineage. Another advantage of using more than one lineage in biostratigraphy is that there is better control, thus mistakes are made less easily.

As far as the *F. cucumiformis* and *F. ellipsoidalis* Zones are concerned no serious problems exist. It is a well-known fact that within the Tremp Basin typical specimens of *F. cucumiformis* do not or only rarely occur together with *F. ellipsoidalis*, unless stratigraphically older, reworked alveolinids have been mixed with autochthonous specimens. This has only been encountered in a few cases (e.g. in samples 43a and 43b of section X). Unfortunately the direct ancestor of *F. ellipsoidalis* is not known; for this reason there is no better alternative for the *F. cucumiformis* and *F. ellipsoidalis* Zones.

Many misunderstandings and incorrect biostratigraphic correlations have arisen as a result of the establishment of the *F. oblongus* Zone by Hottinger (1960) above the *F. trempinus* Zone and the 'Niveau de Coudures'. It is particularly unfortunate because the boundary between Ilerdian and Cuisian was placed by Hottinger and Schaub (1960) between the *F. trempinus* and *F. oblongus* Zones. Between these two biozones is the 'Niveau de Coudures'; however this new zone which was introduced by Hottinger (1960) is not a separate entity since the species *F. oblongus* and *F. ruetimeyeri*, occurring in this zone, have a large stratigraphic range. Furthermore it is highly unlikely that *F. coudurensis* is a species in its own right (see discussions of the former two species and of *F. canavarii*, Gaemers, 1978). Presumably the 'Niveau de Coudures' is part of the *F. trempinus* Zone (Gaemers, 1974).

In the Tremp Basin *F. oblongus* is very abundant; it has been found in the same stratigraphic horizons as *F. corbaricus* and *F. trempinus*. From this it is evident that the *F. oblongus* Zone coincides with the *F. corbaricus* and *F. trempinus* Zones together. It is more accurate to maintain the *F. oblongus* Zone in addition to the *F. corbaricus* and *F. trempinus* Zones than to say that the *F. oblongus* Zone does not exist (Gaemers, 1974), for in regions where *F. corbaricus* and *F. trempinus* are absent, as for instance in the Paris Basin, a less detailed age determination is still possible using *F. oblongus*. *F. corbaricus* and *F. trempinus* are of course to be preferred to *F. oblongus* as zone fossils because they permit a more detailed age determination.

The occurrence of *F. oblongus* together with *F. corbaricus* and *F. trempinus* has considerable impact on the chronostratigraphic concepts of the Palaeogene in the Mediterranean area and beyond. *F. oblongus* marks the Lower Cuisian; it occurs in the type section of the Cuisian at Cuise-la-Motte, France. There is general agreement among stratigraphers that the Cuisian stage is to be included in the Eocene, and lies in the lowermost part of that series. At least a part of the *F. corbaricus* Zone and/or the *F. trempinus* Zone of the Ilerdian stage, established by Hottinger & Schaub (1960) in the Tremp Basin, can now be correlated with the Cuisian of the Paris Basin and are thus to be considered as Eocene. The presence of other Lower Eocene alveolinids in the *F. corbaricus* and *F. trempinus* Zones of the Tremp Basin also supports this assumption. These species are *F. ruetimeyeri*, *F. fornasinii* and *F. schwageri*. Even *F. (M.) boscii* occurs in these zones. This species, which formerly was only known to occur in the Lutetian,

evidently has a large stratigraphical range. Thus considerable overlap occurs in Hottinger's system of alveolinid zonation.

Fortunately no real problems arise concerning the *F. dainellii* Zone. *F. rugosus*, the descendant of *F. trempinus*, occurs in this biozone which lies just above the *F. trempinus* Zone. *F. oblongus* is an ancestor of *F. violae*. There is a distinct difference in the elongation index of the two species, *F. violae* being much longer than *F. oblongus*. An intermediate form therefore can be expected in the *F. dainellii* Zone, which however has not yet been found in the fossil record (see Fig. 2). *F. dainellii* belongs to a group of highly flosculinized, spherical to slightly ovoid alveolinids and is a member of a different lineage than *F. oblongus* and *F. trempinus*. Nevertheless a zone between the *F. trempinus* (cq. *F. oblongus*) Zone and the *F. violae* Zone could be justified on the basis of the data on the evolution of the lineages of *F. trempinus* and *F. oblongus*.

Although I disagree with some of Hottinger's alveolinid zonations, most of his zones are still valid and of great value for biostratigraphy. His biozonation based on members of the ellipsoidalis group is particularly effective, since evolution proceeds faster in this lineage than in any of the other common groups of alveolinids. Therefore the most detailed division of the Upper Paleocene and Lower Eocene on the basis of alveolinids will be established using the successive evolutionary stages of this group. Most of Hottinger's alveolinid zones in the Upper Paleocene and Lower Eocene are accepted, although there were too many. All biozones from *F. ellipsoidalis* up to and including *F. trempinus* are valid because they are based on species of an evolutionary lineage.

OTHER BIOSTRATIGRAPHIC DATA FROM THE TREMP BASIN

Recent investigations in the fields of nannoplankton, planktonic foraminifera and ostracods have provided more data for age determinations.

Nannoplankton

Wilcoxon (1973) and Kapellos & Schaub (1973, 1975) studied the nannoplankton floras from the Campo and Tremp sections. Their nannoplankton zones are based on assemblages of species. This is customary in biostratigraphic work with these fossils, because most species have a large stratigraphic range.

This approach may not be sufficiently accurate. Until it is known exactly when the species appeared and disappeared, uncertainties will continue to exist. As the number of investigated species increases, more precision will be attained. Wilcoxon for instance distinguished fewer biozones in the Tremp section than Kapellos & Schaub.

If we compare the nannoplankton biozones with the revised alveolinid zonation, the most probable correlation is that shown in Table 2.

The differences with respect to the correlations of Kapellos & Schaub (1973, 1975) are:
1. the major portion of the *F. corbaricus* Zone correlates with the *M. tribrachiatus* Zone,
2. the *F. trempinus* Zone does not correlate with the *D binodosus* Zone,
3. the upper part of the *F. trempinus* Zone correlates with the lower part of the *D. lodoensis* Zone,
4. *F. oblongus* ranges from the *D. binodosus* Zone up to and including the lower part of the *D. lodoensis* Zone.

Unfortunately the Campo section does not offer many opportunities to verify these ideas, as alveolinids are almost absent in the stratigraphic interval involved. Only *F. oblongus* occurs at some levels, but the range of this species is too extensive to allow a precise correlation. The alveolinid zonation given for the Campo section by von Hillebrandt (1965) and Kapellos & Schaub (1973, 1975) is therefore largely conjectural except the lowermost part of the section.

The Tremp section along the road from Tremp to Puente de Montañana offers better opportunities for the correlation of nannoplankton and alveolinid biozonations. It is important to see which species were found by Kapellos & Schaub in their *Discoaster binodosus* Zone. Most species also occur in the *Marthasterites tribrachiatus* Zone, namely *Zygodiscus adamas, Micrantholithus attenuatus, Braarudosphaera bigelowi, Discoaster binodosus, Neococcolithes dubius, Sphenolithus radians* and *Marthasterites tribrachiatus*. Only two species, namely *Heliolithus kleinpelli* and *Discoaster mohleri*, do not occur so high in the succession. According to Perch-Nielsen (in Caro et al., 1975) the former species does not occur above the *Discoaster multiradiatus* Zone and the latter cannot even be found above the *Discoaster nobilis* Zone (= *Heliolithus riedeli* Zone). Perhaps the specimens of these two species were reworked. Moreover it cannot be seen from the publication of Kapellos & Schaub (1973) which part of the substantial portion of the section identified as the *D. binodosus* Zone contained these two species.

The lower part of the *F. corbaricus* Zone still corresponds in my opinion to the *D. binodosus* Zone (Tab. 2). Therefore at least part of that portion of the Tremp section identified as the *D. binodosus* Zone by Kapellos & Schaub will indeed correspond to the *D. binodosus* Zone. On the basis of the data given by Kapellos & Schaub however it remains quite likely that a considerable part of their *D. binodosus* Zone in the Tremp section belongs to the *M. tribrachiatus* Zone. That the lower part of the *F. corbaricus* Zone can be correlated with the *D. binodosus* Zone is proven by the occurrence of *F. corbaricus* ca. 550 m above the base of the *F. cucumiformis* Zone in the Campo section (von Hillebrandt, 1965), for according to Kapellos & Schaub (1973) the *D. binodosus* Zone extends from ca. 285 m to ca. 880 m above the base of the *F. cucumiformis* Zone.

In the Tremp section a correlation of the *F. trempinus* Zone with the *D. lodoensis* Zone has not been confirmed. The stratigraphically youngest nannoflora discovered so far (Kapellos & Schaub, 1973) belongs to

the *M. tribrachiatus* Zone. The top of the *F. trempinus* Zone very probably is therefore missing in the Tremp section. This idea is supported by the fact that marine development within the Tremp Basin becomes much thicker and more complete towards the west. *F. oblongus* has been found in strata which are much younger in the Campo section than the strata in the vicinity of Tremp. Thus it is very probable that *F. trempinus* also extends higher stratigraphically than is indicated by the marine succession in the Tremp section, a possibility which has been suggested earlier (Gaemers, 1974).

The Cuisian of the Paris Basin comprises only the upper part of the *M. tribrachiatus* Zone and the lower part of the *D. lodoensis* Zone with certainty (Kapellos & Schaub, 1973, 1975). This does not imply that the range of *F. oblongus* covers only this interval. The type section of the Cuisian represents only a very short time

	this publication	Martini, 1970	Berggren, 1969	Premoli Silva & Bolli, 1973	Von Hillebrandt, 1965	stratigraphic range of some stages
EOCENE middle	*F. violae*	*Discoaster sublodoensis*				Ilerdian Hottinger & Schaub, 1960
EOCENE middle	*F. dainellii*	*Discoaster lodoensis*	*Acarinina densa*	*Globorotalia pentacamerata*	*Globorotalia caucasica*	
					Globorotalia palmerae/Acarinina aspensis	
EOCENE lower	?——?		*Globorotalia aragonensis*	*Globorotalia aragonensis*	*Globorotalia aragonensis*	Cuisian Dollfus, 1880
EOCENE lower	*F. trempinus*	*Marthasterites tribrachiatus*	*Globorotalia formosa*	*Globorotalia formosa formosa*	*Globorotalia formosa*	
EOCENE lower					*Acarinina angulosa*	
EOCENE lower	*F. corbaricus*	*Discoaster binodosus*	*Globorotalia subbotinae/ Pseudohastigerina wilcoxensis*	*Globorotalia subbotinae*	*Globorotalia lensiformis*	Ypresian Dumont, 1849
PALEOCENE upper	*F. moussoulensis*	*Marthasterites contortus*	*Globorotalia velascoensis/ subbotinae*	*Globorotalia edgari*	*Globorotalia subbotinae*	? Sparnacian Dollfus, 1880
PALEOCENE upper	*F. ellipsoidalis*				*Globorotalia marginodentata*	
PALEOCENE upper	*F. cucumiformis*	*Discoaster multiradiatus*	*Globorotalia velascoensis*	*Globorotalia velascoensis*	*Globorotalia velascoensis*	Thanetian Renevier, 1873
PALEOCENE middle	*F. (M) levis*	*Heliolithus riedeli*	*Globorotalia pseudomenardii*	*Globorotalia pseudomenardii*	*Globorotalia pseudomenardii*	
PALEOCENE middle	*F. primaevus*					
	alveolinids	nannoplankton	planktonic	foraminifera		
	taxon-range-zones (partly lineage-zones)	concurrent-range-zones				

Table 2. Correlations of biozonations of alveolinids, nannoplankton and planktonic foraminifera, and the stratigraphic range of some important stages.

interval (Bignot & Moorkens, 1975), whereas the range of *F. oblongus* is definitely much greater. This species therefore is a rather poor guide fossil. The absence of the *D. binodosus* Zone in the Cuisian of the Paris Basin only means that the Eocene was non-marine there at that time, so that *F. oblongus* obviously could not have lived there at that time. It can be concluded that the nannoplankton data given by Kapellos & Schaub do not contradict the revised alveolinid zonation.

Planktonic foraminifera
Different investigators have already studied planktonic foraminifera in the Tremp Basin, viz. Gartner & Hay (1962), von Hillebrandt (1965, 1975), Luterbacher (1969) and Ferrer et al. (1973). An interpretation of these data is a difficult task, because nearly all authors who study planktonic foraminifera use a different biozonation, and because the terminology for many species has changed in the course of time for taxonomic reasons. In this study the zonation of Premoli Silva & Bolli (1973) as described in Caro et al. (1975) is followed.

Another difficulty is the fact that the planktonic foraminifera in most sections of the Tremp Basin could not be isolated from the samples. However, in the centre and the northern part of the Tremp Basin where marls predominate sufficient specimens could be collected at certain horizons. The southern part of the basin is mainly developed in limestone facies. In thin sections planktonic foraminifera are not rare but they could not be identified at the species level. For this purpose loose specimens are necessary.

The Tremp section again is the section which has been studied the most. Gartner & Hay (1962) have identified *Globorotalia pseudomenardii*, but this finding is contradicted by later investigators. This identification must be based on a mistake which resulted in an age which was too old. Von Hillebrandt (1965), Luterbacher (1969) and Ferrer et al. (1973) mention planktonic foraminifera, belonging to the *G. subbotinae* Zone, from a rather limited stratigraphic interval which corresponds with the lower part of the *F. corbaricus* Zone.

In the Sant Adria and Aren sections the *G. subbotinae* Zone could also be demonstrated (Luterbacher, 1969; Ferrer et al., 1973), but a correlation with the alveolinid zones is not possible because alveolinids are lacking in these intervals in either section. The proven range of the *G. subbotinae* Zone must be greater here, perhaps extending somewhat further back in time than in the Tremp section.

Von Hillebrandt (1965) has studied the Campo section where planktonic foraminifera are more abundant. In spite of this it is still difficult to delineate the biozones precisely. Very probably the boundary between the *G. edgari* and *G. subbotinae* Zones (this is the boundary between the *G. subbotinae – G. marginodentata* Zone and the *G. lensiformis* Zone of von Hillebrandt) is situated close to where the top of the *F. moussoulensis* Zone can be expected (but again alveolinids are lacking). This is indicated by the fact that *Globorotalia aequa* disappears at this point and *G. lensiformis* appears.

All things considered planktonic foraminifera from the Tremp Basin can be of little help for the solution of the biostratigraphic problems.

Ostracods
Investigations of the ostracod faunas in the Tremp Basin have been carried out by Ducasse (1972), Tambareau & Villatte (1974), Tambareau (1975) and Carbonnel (1975). The Thanetian–Ilerdian boundary seems to be very sharp because many species make their first appearance in the Lower Ilerdian (Tambareau, 1975). The relationship between Ilerdian and Cuisian as indicated by the ostracods is however not yet clear enough because of the limited number of sections studied.

Fish remains
Shark and ray teeth are very scarce in the Tremp Basin. Although some shark teeth were found only one is preserved well enough for a species identification. This is a large tooth of *Lamna obliqua* (Agassiz, 1843) found near Sant Adria in a loose piece of limestone (coll. RGM 175 888). This sample undoubtedly belongs to the upper part of the Ager Formation, as no younger marine Tertiary strata occur in the area around Sant Adria. The most probable age is Early Eocene (Ypresian) as the species occurred predominantly during this interval; in rare cases it can be found in the Upper Paleocene (Casier, 1946; Arambourg, 1952).

Sample J-26 (section at Guardia de Tremp) from the *F. moussoulensis* Zone has yielded a complete tooth plate from the middle part of the jaw of *Myliobatis* cf. *striatus* Buckland, 1837 (coll. RGM 175 889). Up to now *M. striatus* is only known to occur in the Eocene (Ypresian). Large ray teeth, including those of *M. striatus*, have not yet been mentioned from the Upper Paleocene. On the basis of the alveolinids however, a Late Paleocene age is most likely for the *F. moussoulensis* biozone; sample J-26 however occurs in its upper part.

CORRELATIONS WITH OTHER STRATOTYPES

Several authors have already tried to find the relationships between the Palaeogene stages defined in western Europe. For this study the investigations of Moorkens (1973), Kapellos & Schaub (1973, 1975), Caro et al. (1975) and Bignot & Moorkens (1975) are the most important.

Most problems in the determination of the biostratigraphic relationships between the stratotypes are caused by the differences in palaeontological contents. The type section of the Ilerdian is rich in nummulites and assilines, but poor in alveolinids and planktonic foraminifera. Calcareous nannoplankton occurs in sufficient numbers. Fortunately numerous alveolinids can be found in most horizons of the sections south of the Tremp section, where Hottinger (1969, 1962) was able to establish a substantial part of his alveolinid zonation.

In the Sands of Cuise-la-Motte, the type section of the Cuisian, alveolinids and nummulites abound, but the

number of species of both groups is very restricted. There is a reasonable number of species of calcareous nannoplankton but an age determination based on planktonic foraminifera is difficult. From the occurrence of *Globorotalia formosa gracilis, G. marginodentata, G. subbotinae* and *G.* ex. gr. *wilcoxensis* – '*esnaensis*, independently identified by many authors (see Bignot & Moorkens, 1975), no precise conclusions can be derived. The *G. subbotinae* Zone as well as the *G. formosa formosa* Zone has received consideration. It is not very likely that the *G. aragonensis* Zone is represented (Bignot & Moorkens, 1975). The stratotype of the Cuisian undoubtedly contains nannoplankton of the *M. tribrachiatus* Zone (Kapellos & Schaub, 1973, 1975). When the data of alveolinids, planktonic foraminifera and calcareous nannoplankton are considered together, the Cuisian corresponds partly with the uppermost part of the Ilerdian (Tab. 2).

The stratotype of the Ypresian includes the Yper Clay and the Sands of Mons-en-Pévèle. *Nummulites planulatus* is very frequent in these deposits, but alveolinids are absent. With the aid of nannoplankton the *M. tribrachiatus* Zone could be demonstrated by many authors. In borings taken at Ooigem and Kallo the *D. binodosus* Zone was demonstrated in the lower part of the Yper Clay; at Kallo the *D. lodoensis* Zone was found in the uppermost part of the Sands of Mons-en-Pévèle (Bignot & Moorkens, 1975). The assemblage of planktonic foraminifera, which is practically the same as that present in the type section of the Cuisian, occurs in most of the Sands of Mons-en-Pévèle and the upper part of the Yper Clay (Bignot & Moorkens, 1975). When all data are taken into consideration there is no doubt that the Ypresian and the Ilerdian overlap one another considerably (Tab. 2).

The Sparnacian, defined by Dollfus (1880) in the Paris Basin, consists mainly of lagoonal–lacustrine fresh-water and brackish deposits; only the top contains some very shallow marine deposits (Plaziat, 1975). A direct comparison with other areas is therefore very difficult and it would be better to develop a new stage with a new stratotype consisting of a sequence of open marine deposits to replace the Sparnacian. Certainly the Sparnacian corresponds with a part of the Early Ilerdian.

The stratigraphic position of the Thanet Beds with *Cyprina morrisi*, the stratotype of the Thanetian, is still difficult to determine because most of the planktonic foraminifera and nannoplankton are reworked from Upper Cretaceous rocks and lower parts of the Paleocene. The discovery of *Heliolithus riedeli* by Bramlette & Sullivan (1961) suggests that the Thanetian belongs to the biozone of the same name (Bignot & Moorkens, 1975).

The Landenian, defined by Dumont in 1839, and emended by him in 1849, unfortunately contains only few planktonic microfossils. The scarce findings of planktonic foraminifera in the 'Tuffeau de Lincent' make it difficult to come to an explicit determination of the stratigraphic position. This stage probably belongs to the

G. pseudomenardii Zone and it probably correlates with the Thanetian (Bignot & Moorkens, 1975).

THE PALEOCENE–EOCENE BOUNDARY

According to the definition of Schimper (1874) the Paleocene contains the 'Sables de Bracheux, Travertin ancien de Sézanne', and 'Lignite et Grès du Soissonnais' which represent the Thanetian and the Sparnacian. Therefore the Paleocene has to include these stages in any case, and the upper boundary of the Paleocene has to be drawn above the Sparnacian (Hottinger, Lehmann & Schaub, 1964). Obviously difficulties will arise because the Sparnacian has not been defined by (purely) marine deposits, but it is wise to respect the original definition of the Paleocene as far as possible in order to avoid unnecessary confusion. Therefore the division of Blondeau et al. (1965) who place the Sparnacian within the Ypresian has to be rejected. Moreover the fact that the Sparnacian and the Cuisian of the Paris Basin fall in the same sedimentary cycle cannot be used as a valid argument, since transgressions and regressions may not occur simultaneously throughout the whole world, and the Paris Basin is only a small, unimportant basin on a world-wide scale.

When the Paleocene–Eocene boundary as accepted by specialists of planktonic foraminifera and calcareous nannoplankton is considered, rather close agreement exists among most investigators. Nannoplankton specialists usually draw this boundary between the *M. contortus* Zone and the *D. binodosus* Zone, while many specialists of planktonic foraminifera use the *Pseudohastigerina* datum proposed by Berggren (1964, 1971) which is defined by the first appearance of *Pseudohastigerina wilcoxensis* (Cushman & Ponton). Unfortunately this species has not yet been found in the Tremp Basin, but from all available data it appears likely that the above-mentioned boundaries of nannoplankton and plantonic foraminifera nearly coincide with the boundary between the *F. moussoulensis* and the *F. corbaricus* Zones (Tab. 2). These boundaries do not contradict the definition of the Paleocene by Schimper. In consequence the Paleocene–Eocene boundary, as it is generally recognized at present, distinctly lies in the Ilerdian (Tab. 2).

If the Paleocene–Eocene boundary is shifted to the base of the Ilerdian, the enlarged Eocene will occupy a time span which is no longer in proper proportion to that of the shortened Paleocene; furthermore little or nothing will be left in the Upper Paleocene so that the Thanetian, which is universally regarded as Middle Paleocene, would automatically become Upper Paleocene (Curry, 1975).

There is however at present no good reason for shifting the Paleocene–Eocene boundary. The Ilerdian in the sense of Hottinger & Schaub (1960) consists of a lower part which belongs to the Upper Paleocene and an upper part which belongs to the Lower Eocene. Since a lower-rank stratigraphic unit (stage) may not belong to

two internationally accepted higher units (series), the Ilerdian cannot be accepted as an international stage unless the series boundaries are changed. The attempt to adapt the Paleocene–Eocene boundary to the original concept of the Ilerdian stage, which was proposed by Pomerol at the special session 'Le contenu de l'Ilerdien et sa place dans le Paléogène' on 18 November 1974 in Paris (Pomerol, 1975), must be rejected. The concept of the Ilerdian stage is essentially based on a succession of zones of larger foraminifera, which cannot be recognized on a world-wide scale (Luterbacher, 1975). Relative age determinations in this area based on planktonic foraminifera are difficult, and good correlations with these fossils are even impossible. It is therefore to be regretted that many participants of the session at Paris were tempted to choose a Paleocene–Eocene boundary at the base or at the top of the Ilerdian (Anonymous, 1975).

A considerable gap exists between the stratotypes of the Sparnacian and the Cuisian (Tab. 2). Stratigraphically the base of the Cuisian is situated distinctly higher than the base of the Ypresian. For these reasons and also because of the superposition of the Cuisian on essentially non-marine deposists, the Cuisian does not provide a well-defined series boundary as proposed by Hay (1969).

The base of the Ypresian approximates the Paleocene–Eocene boundary the best (Bignot & Moorkens, 1975). Therefore it would be an important contribution toward an international stratigraphic scheme if this base could be established by a well-defined boundary stratotype. The Ypresian of Dumont (1849) is to be preferred to the Cuisian of Dollfus (1880) because of priority, its greater usefulness (the type section of the Cuisian comprises only a very small interval), the greater certainty that it is free of ambiguities and its greater suitability for wide-spread application.

CONCLUDING REMARKS

For want of clear, international decisions on stratigraphic boundaries and stratotypes (apart from some good exceptions), many ambiguities have permeated the stratigraphic literature resulting in considerable confusion and many contradictions. If all available stratotypes of the type localities are considered, it is seen that large hiatuses or overlaps often exist between stages. A continuous stratigraphic classification system covering all geological history cannot be obtained in this way. Therefore many stages were subsequently enlarged in order to reach a balanced system. This has led to many different concepts about most stages, none of which has an official status unless an internationally accepted agreement has been reached.

In order to avoid confusion and vagueness it is essential that in the future every stratigrapher follows insofar as possible the recommendations of the International Subcommission on Stratigraphic Classification (ISSC), which are given in the International Stratigraphic Guide (editor: Hedberg, 1976). The Summary

of an International Guide to Stratigraphic Classification, Terminology and Usage (1972) was the predecessor of this publication. In many cases boundary stratotypes must be redefined for the existing stratotypes in order to fix the boundaries exactly. These boundary stratotypes ought to lie within an interval with continuous marine sedimentation. One of the greatest sources of confusion namely lies in the fact that geologists have established stage boundaries on facies changes. As a result it is impossible to tell whether or not marine biozones which border on non-marine sediments are genuine range zones or assemblage zones. In other words: do these zones terminate at the facies boundary or not. It is much more likely that these biozones are more extensive than their apparent range in the rock sequence.

Schaub (1968) compares the relationship between a stage and its stratotype with the relationship between a species and its type specimen (holotype, lectotype, neotype). He maintains that the holotype and the stratotype do not serve to define the species or the stage in its entirety, but to fix them. It is of course impossible for one specimen or one section to include all properties of the species or stage. Every species nevertheless has been fixed in time by evolutionary development. It is necessary to know when the precursors and the successors appeared so that the exact time interval within which a species existed can be determined. Only when this has been established can a reliable biostratigraphy be set up. Similarly it is necessary to know where stage boundaries are situated, otherwise hopeless confusion among geologists will result. In this sense the comparison between a stage and a species can be continued. Schaub states that this is not necessary because, according to him, a stratotype does not serve to define the entire time interval of the stage but only to fix it in cases of doubt. This idea must be rejected, since proceeding from this principle means in fact that cases of doubt will continue to exist because then not all time intervals will be established officially. According to the recommendations of the ISSC, boundary stratotypes have to be designated together with the unit stratotypes. It is however not necessary that they occur in the same locality.

The Ilerdian cannot be considered as an international stage, in spite of Schaub's designation (1969) of the Campo section as parastratotype, because

1. it is highly probable that the *F. trempinus* Zone continues above the marine deposits of the Tremp section; *F. trempinus* has not been found in the Campo section, although marine sedimentation continued for a much longer time in the Campo area than farther to the east,

2. the *F. oblongus* Zone is not a zone lying above the Ilerdian but is a part of it,

3. planktonic foraminifera are too scarce in the entire area,

4. there is considerable overlap with the Ypresian,

5. overlap with the Cuisian is highly probable,

6. the Paleocene–Eocene boundary as originally defined lies within this stage.

On account of the fact that the Sparnacian is not a suitable alternative, a new stage should be established between the Thanetian and the Ypresian. This stage has to be defined on the basis of nannoplankton and planktonic foraminifera of known evolutionary development. It would of course be useful if benthonic foraminifera were also present, but this is not a necessity. The difficulty is to find a suitable area which contains a continuous sequence of marine sediments and also meets these requirements.

The lower part of the Ilerdian occupies most of the gap between the Thanetian and the Ypresian. It is however not really suitable as a stage as suggested by Gaemers (1974), because not enough data are available on the planktonic foraminifera, and because no marine deposits occur below the *F. cucumiformis* Zone in the province of Lerida.

Nevertheless the Tremp area will always be an important area for Palaeogene stratigraphy because this region has the great advantage that there is a continuous marine sedimentation around the Paleocene–Eocene boundary.

CHAPTER V

FACIES DESCRIPTIONS AND INTERPRETATIONS

INTRODUCTION

Fifteen facies and 51 subfacies have been distinguished on lithologic and sedimentary features, and fossil content. Field observations were coupled with the study of thin sections.

In most facies large benthonic foraminifera are numerous. The qualitative and quantitative data on these fossils furnish a good opportunity to reconstruct the general framework so that the mutual relationships between the different facies types will become clear to a large extent. Specific fossils which are characteristic of a subfacies usually belong to a larger or smaller group of macroscopic fossils which are often recognizable in the field. The frequency of the larger macrofossils is such that they will not appear in a thin section and only rarely in an arbitrarily taken sample. The presence of these important fossils therefore usually can only be ascertained in the field. The smaller characteristic macrofossils occur frequently, but not always, in thin sections; usually a magnifying glass is needed to recognize them with certainty in the field. Some facies types contain no or only a few fossils, or mainly only the remains of allochthonous organisms; then lithological and especially sedimentary characteristics form the basis of an identification.

The successful ecological concept of biocoenosis, introduced by Möbius in 1877, cannot be used in palaeontology. Only a part of the biocoenosis is preserved in the sediment, for many organisms do not leave fossil remains or are transported to other environments; moreover alien elements can be added by transportation after death; therefore the · term thanatocoenosis is used in palaeontology to indicate all the fossils present in the sediment at a particular location (Brouwer, 1967).

A biocoenosis is a community of organisms which form a dynamic equilibrium with each other and with the environment. Petersen (1913, 1915), Caspers (1950) and Thorson (1957, 1958) were the pioneers in the study of the animal communities on the shelf bottom. From the beginning it has been common practice to name communities after species which are characteristic and common there. Worms, molluscs and echinoderms are the most important groups for distinguishing the different communities (see also Toulemont, 1972).

Molluscs and echinoids usually fossilize easily, whereas only the few worms with calcareous or arenaceous tubes have parts which fossilize; ophiuroids and other starfishes only occur as fossils in very exceptional cases. For the definition and description of fossil communities, which always contain fewer species than the original living communities, we must therefore rely upon those molluscs and echinoids, supplemented with other fossilized groups, which form the autochthonous part of the thanatocoenosis. Consequently fossil communities will of necessity sometimes be named after other animal groups than their recent counterparts. This could imply that the boundaries between fossil communities will not coincide with those of the corresponding original communities, so that the space occupied by fossil and recent communities is not always comparable.

Communities always grade into each other. The absence of sharp boundaries makes it difficult for ecologists as well as palaeoecologists to set up a good division. Each organism has its own distribution which normally does not coincide with that of others nor with the chosen community boundaries. For these reasons we have to keep in mind that these boundaries are arbitrary. Boundaries can best be drawn there where marked changes in faunal and/or floral composition occur. The determination of boundaries is often even more difficult in palaeoecology than in ecology because the allochthonous elements tend to obscure the differences between communities.

DIAGENESIS

The state of preservation of fossilized parts depends highly on the kind of material of which the fossil consists. Aragonite has usually been greatly affected by early diagenesis in the Tremp Basin; often it has even dissolved completely. This explains the occurrence of

many internal and external moulds and the calcite replacement of many coral colonies, as well as of many molluscs. Consequently the fossils consisting of calcite are often easier to collect and to identify than aragonitic ones, so that the occurrence of calcitic fossils is easily overemphasized.

Another example of early diagenesis is seen in the skeletons of nummulitid foraminifera (*Assilina, Operculina* and *Nummulites*) which have been replaced to different degrees by chert. Neither other foraminifera nor other fossils nor the surrounding sediment were affected. The process starts with the formation of small globules of chert which consist of radial fibres. These globules preferably originate in the thickest parts of the walls of the shells. By growth and increase in number they can merge and replace more than half of the original amount of calcite material. Eventually the cavities between the walls may be filled with chert. In this way a continuous piece of chert is formed inside the shell, whereas the outer parts of the skeleton remain unaffected (Pl. 5, Figs. 1, 3–5). This replacement always occurs in impure limestones of the *F. corbaricus* Zone around the upper boundary of the glauconite formation, mainly in subfacies XIVa, but also in subfacies XIIIa and c, XIIb and c, and XIa when they are associated with subfacies XIVa. It is most frequent in sections O and L.

This early diagenesis probably followed the pattern which is postulated as the main process for the formation of deep-sea chert: in situ dissolution of biogenous opal with silica reprecipitated inorganically as authigenic disordered alpha-cristobalite (Weaver & Wise, 1974; Keene & Kastner, 1974). This material in turn gradually recrystallizes to form chalcedony. Most probably the biogenous opal is supplied by diatoms (Weaver & Wise, 1974), which dissolve more rapidly than radiolarians or other siliceous fossils such as sponge spicules.

THE DIFFERENT FACIES AND SUBFACIES TYPES

Facies I. Continental deposits

Sediments belonging to this facies are always very poor in fossils. Fossils characteristic of environments with normal marine salinity are always lacking. This facies is only known to occur in the *F. cucumiformis* Zone.

Subfacies Ia. Coastal swamp deposits. – These deposits consist of dark gray marls, mudstones and (some) siltstones without stratification and are irregularly mottled with rust-brown spots. In some places (section I') calcium carbonate concretions occur. In rare instances some euryhaline organisms, such as gastropods of the Cerithidae family, can be found.

The rust-brown spots are due to differential oxidation–reduction processes caused by oxidation of plant roots. Coleman et al. (1970) describe recent clays with the same characteristics in Malaysian mangrove swamps. Haseldonckx (1972a and b, 1973) has studied pollen floras of the Ager Formation. Here elements from coastal swamps predominate: Taxodiaceae, Nyssaceae, *Sabal* and Myricaceae (fresh water coastal swamp dwellers) and *Nypa* (brackish water mangrove swamp dweller). Pollen grains of coastal swamp plants are much more numerous in the Ager Formation than those of mangrove swamp plants. Therefore it is likely that the fresh water swamps occupied much larger areas than the brackish swamps. Some of the swamp deposits are certainly of brackish origin; this is the case for example when Cerithidae are present. The floral elements indicate a tropical climate.

This subfacies is present in sections H, H', I, I' and S.

Subfacies Ib. Fluvial deposits. – These deposits consist of grey to dark grey quartzose sandstones and conglomerates with channels; fossils are scarce; mainly *Microcodium* fragments and remains of higher plants are found. Clay galls frequently occur.

This subfacies is present in only two places. In section S (sample 149) a variety of sedimentary structures was found. Clearly symmetrical wave ripples indicate a deposition in shallow water, whereas rain prints prove that the area dried out temporarily. The base of section H' consists of coarser sediments in which current action dominated (mega cross-bedding and small-scale cross-bedding, parallel lamination).

These deposits have only been found in the *F. cucumiformis* Zone. They are associated with lagoonal and swamp deposits.

Facies II. Lagoonal deposits

A large variety of lagoonal deposits with a highly variable fossil content occurs in the Tremp Basin. To a large extent this is a reflection of different salinities. In the exposures described here they are limited to the *F. cucumiformis* Zone and the *F. trempinus* Zone.

Subfacies IIa. Deposits containing a Serratocerithium community. – These are dark clays and marls containing Cerithidae. Sedimentary structures are lacking. The best exposure of this subfacies is section I' (*F. cucumiformis* Zone). A gastropod fauna rich in individuals but poor in species is present. Most numerous are the cerithids of the genus *Batillaria* represented by several species, including *B. (Vicinocerithium) goniophora* (Deshayes), and *Serratocerithium*. Furthermore another cerithid, *Tympanotonos*, has been found in small numbers together with some other gastropods such as *Volutilithes, Pyrazus, Sycostoma* and *Ampullella semipatula* (Deshayes).

Nowadays cerithids dominate in quiet lagoons which are connected with the sea, and in sheltered shallow bays in the tropics and subtropics where the salinity is usually higher or lower than in the open sea. For two reasons a higher salinity is very probable for the cerithid community in the Tremp Basin. Firstly the subfacies is associated with the dolomites and dolomitic limestones of subfacies IIe. Secondly the warm climate gave rise to considerable evaporation from the lagoons. This

subfacies thus can be interpreted as a hypersaline lagoonal environment.

This subfacies has been found in the *F. cucumiformis* Zone of sections H′ and I′.

Subfacies IIb. Deposits containing Crassostrea and Cubitostrea communities. – The dark grey clays and marls contain Ostreidae. These deposits are most characteristic when the oysters are extremely abundant. This is the case in several locations in the *F. trempinus* Zone.

In this zone the species *Cubitostrea multicostata* (Deshayes, 1832) occurs. The specimens of this species closely resemble those from the type locality of the Cuisian (Cuise-la-Motte, Paris Basin). The exterior ornamentation of the valves, the outline of the valves and the hinge are similar. The French specimens however have a shallower, larger and more protracted muscle scar, which is situated farther towards the umbo.

Often the soft sediments of the *F. trempinus* Zone are covered with weathering layers; then only loose specimens of *Cubitostrea* shells can be found, in which case the two valves are frequently still joined together. Serpulid worms are sometimes encrusted on the inner and outer surfaces of the thick valves.

Another area where large quantities of oysters can be found is immediately to the east of section I′. Here a sudden change occurs from marls rich in cerithids to marls with many large specimens of *Crassostrea angusta* (Deshayes). In the section itself oysters are usually scarce and small. Unfortunately the degree of exposure of these marls is poor, so that the oysters have not been found in situ; the oysters however must come from the marls, because they have been found on the steep slopes of an isolated small hill consisting entirely of marls. The outer surfaces of the shells were often perforated by clionid sponges suggesting low rates of sedimentation. At least some layers of these marls must be crowded with oysters, for many clusters of oysters that grew together have been collected. Nevertheless oyster reefs of either *Crassostrea* or *Cubitostrea* have not been encountered.

The study of the ecology of recent oysters has revealed that "*Crassostrea* seems to be the most euryhaline oyster genus" (Stenzel, 1971, p. N1038) whereas "*Ostrea* is polyhaline to euhaline and less euryhaline than *Crassostrea*" (Stenzel, 1971, p. N1039). The occurrence of many specimens of *Crassostrea* in the immediate neighbourhood of the *Serratocerithium* community suggests that these animals also lived under hypersaline conditions. Recent specimens of *Crassostrea virginica* and *C. rhizophorae* however do not live in sea water with a salinity of more than 40 pro mille; they even prefer distinctly lower salinities (Stenzel, 1971). It is therefore probable that the *Serratocerithium* and *Crassostrea* communities flourished under slightly hypersaline conditions.

For the *Cubitostrea* community a reliable estimate of the salinity is difficult because no recent representatives of *Cubitostrea* are known. In any case it may be supposed that the *Cubitostrea* community lived under conditions that differ in some respects from those of the *Crassostrea* community. The *Cubitostrea* community often consists of only a few species. In these cases it is likely that the salinity deviated from that of normal sea water. Apparently *Cubitostrea* could also live in sea water of normal salinity, for it has also been found in less restricted communities which are richer in species.

Transitions between subfacies IIa and IIb occur in which oysters and cerithids are of nearly equal abundance (section N, *F. trempinus* Zone). These sediments are often sandy. Subfacies IIb has been found in the *F. cucumiformis* Zone of sections H, H′ and I′ and in the *F. trempinus* Zone of sections N and O (at other locations only loose oysters were collected).

Although oysters can inhabit an enormous variety of facies and subfacies, the association of the above-mentioned marls, which contain oysters almost exclusively, with other lagoonal deposits leaves no doubt as to the lagoonal conditions of subfacies IIb.

Subfacies IIc. Deposits containing only imperforate foraminifera. – These deposits consist of grey to dark grey marls and limestones and contain many Miliolidae, often Alveolinidae and rarely *Orbitolites*. Other fossils are scarce. This subfacies has only been found in the *F. cucumiformis* Zone of sections H, I, I′, S and Z.

If only Miliolidae are present there may have been some deviation from the normal salinity of the open sea. The salinity was normal if one of the other groups of foraminifera occurred together with the miliolids. This subfacies represents the seawardmost development of lagoonal environments in the Tremp Basin. Transitions to subfacies IIb, d, f and g have been found.

Subfacies IId. Deposits containing many ostracods. – In these deposits consisting of grey limestones and (silty) marls, Ostracoda predominate. The next most numerous group is that of the small benthonic foraminifera. Some oogonids and stalk fragments of Characeae (fresh water green algae) have been washed into these deposits. Other fossils are scarce. This subfacies has only been encountered in the *F. cucumiformis* Zone of section Z (sample 365a, 366). Association with dolomites of subfacies IIe suggests that hypersaline conditions existed.

Subfacies IIe. Dolomitic deposits. – These deposits consist of light grey dolomites and occasionally sandy or clayey and dolomitic limestones. The pure dolomites are microcrystalline (crystals with strikingly uniform sizes between ca. 10–20 μm) and mottled by small burrows. At one level in the *F. cucumiformis* Zone of section Z, where most deposits of this subfacies occur, chert has developed. Fossils are rare. Evidence of slumping suggests a slope upon which the dolomites must have been deposited. The subfacies is also present in section I′; in section I there is one thin layer. It has only been found in the *F. cucumiformis* Zone.

The dolomites can be interpreted as primary. No transmutation phenomena have been found and the

dolomite is always restricted to specific, distinct layers. A high pH is commonly associated with the precipitation of magnesian carbonates (Peterson & von der Borch, 1965). These authors have discovered modern inorganic deposition of chert in a lagoonal environment comparable with subfacies IIe. They found considerable fluctuations in the pH, which in the lagoon can easily exceed 10 during active photosynthesis by *Ruppia maritima* Linnaeus while beneath the surface of the sediment it can be as low as 6.5 due to rotting plant remains. Detrital quartz grains can dissolve in high pH solutions and reprecipitate during low water levels as a result of the reduction in pH and the higher concentrations of brine.

The energy necessary to transform the quartz into opal-cristobalite is supplied by solar radiation. A warm or hot climate is inferred. Like Peterson & von der Borch this author found detrital quartz grains with irregular shapes caused by corrosion. Halos of fine-grained silica and carbonate surrounding the grains are sometimes very clear. Undoubtedly the quartz grains furnished the material for most of the chert. The chert in subfacies IIe was formed predominantly in and around fossils (foraminifera and siliceous sponges). Sometimes it developed as pseudomorphs of gypsum crystals, which together with the formation of dolomite, indicate an evaporitic hypersaline environment.

Subfacies IIf. Deposits containing many fragments of Microcodium. – These deposits consist of grey sandstones, siltstones and limestones and contain *Microcodium* fragments. Other fossils are rare. The sandstones consist mainly of poorly sorted and often angular quartz grains. This suggests transportation over a short distance.

Microcodium is a fresh water alga, of which the precise systematic position is still unknown (Bodelle & Campredon, 1968). In the Ager Formation this alga has always been transported and fragmented, but in the underlying Tremp Formation it can be found in situ. It is uncertain whether the fragments of *Microcodium* in the Ager Formation originate partly from algae that lived simultaneously in the hinterland or whether they all have been reworked from the Tremp Formation. The occurrence of Upper Cretaceous pebbles in the *F. cucumiformis* Zone, suggests that at least some of the *Microcodium* fragments have been eroded from the Tremp Formation. The lack of marine fossils and the stratigraphic position between other subfacies make it highly probable that subfacies IIf is lagoonal.

This subfacies is present in sections I', S, T, U and Y and is only known to occur in the *F. cucumiformis* Zone. Transitions exist to subfacies IIg.

Subfacies IIg. Deposits containing many remains of land plants. – These deposits are mainly dark grey marls and some grey limestones which are sometimes sandy. Remains of land plants are characteristic constituents of these deposits. Sometimes fragments of Characeae are present. These sediments may have been deposited under fresh water conditions if other fossils are absent. If miliolids are present they were formed in lagoons which were at least brackish.

This subfacies occurs in many sections (sections H, H', I, I', R, S, T and U), but is always limited to the *F. cucumiformis* Zone.

Facies III. Beach and barrier deposits
Only a few layers within the Tremp Basin can be assigned to this facies.

Subfacies IIIa. Mollusc-rich beach deposits. – Grey and brown quartzose sandstones, conglomeratic sandstones and conglomerates with many molluscs make up this subfacies. They sometimes occur at the base of the *F. cucumiformis* Zone or at the top of the *F. trempinus* Zone. The top of section X contains the best example of this subfacies. Here a rich mollusc assemblage can be found in which pelecypods dominate markedly over gastropods; it includes single valves of members of the Veneridae and Solenidae families, oysters, mussels and *Nassarius*-like gastropods. The molluscs and also the other fossils present are all shallow marine elements which can live close to the coast. All fossils are allochthonous. The majority of the valves of the pelecypods are oriented with their convex side upward. The orientation of these fossils as well as the composition of the mollusc fauna indicates a normal beach environment.

Other occurrences of this subfacies are near the bases of sections R, S and U.

Subfacies IIIb. Beach and barrier deposits. – These deposits consist of well-sorted grey quartzose sandstones and calcarenites with parallel (=horizontal) lamination (Pl. 3, Fig. 3). Some small current ripples are associated with the horizontal lamination, which is disturbed by burrow activity in some places. Low-angle cross-bedding has also been observed. The fossils (mainly foraminifera) are fragmented or at least rounded. The parallel lamination is clearly visible thanks to the alternation of thin layers of coarse, more fossiliferous material, and finer, more inorganic material (mainly quartz grains). This subfacies occurs in the *F. cucumiformis* Zone of sections S and H, and at the top of the *F. corbaricus* Zone of sections A, B and M.

These deposits evidently represent a high-energy environment. The palaeogeographic and stratigraphic positions with respect to other subfacies indicate a normal beach environment for deposits in the *F. cucumiformis* Zone, and a barrier environment for those in the *F. corbaricus* Zone. The latter deposits alternate with mottled muddy sandstones, which are less well-sorted. The boundaries between them are sharp. A comparison with the shore-face storm deposits described by Kumar & Sanders (1976) seems obvious. Only the basal gravel which they interpret as lag gravel formed during maximum storm intensity is absent in the area studied, but this may be due to the lack of coarse material. The burrow-mottled sediments were deposited

seaward of the wave base during fair weather. The laminated sandstones are presumed to have been deposited under storm conditions.

Subfacies IIIc. Evaporitic beach deposits (Pl. 6, figs. 1, 2). – These deposits are represented by a light brown biomicritic limestone (packstone) which contains bird's-eyes and pseudomorphs of gypsum crystals (Pl. 6, Figs. 1, 2). This subfacies was encountered only once, namely in the *F. cucumiformis* Zone of section P (sample P5). The limestone consists mainly of imperforate foraminifera (miliolids, alveolinids and *Orbitolites*) but some other foraminifera occur as well. Apart from foraminifera fossils are scarce. Irregular spots of sparry calcite (bird's-eyes) lie together at specific levels. Some of the spots, especially the larger ones, have several sharp and straight boundaries (Pl. 6, Fig. 1). They can be recognized as former crystals, which have been replaced by smaller calcite crystals. The shapes of the different sections through such crystals indicate gypsum as the original material.

The structures in this limestone prove that this deposit was formed under supratidal and evaporitic conditions. Bird's-eyes and gypsum crystals nowadays are both formed in the supratidal zone of the Persian Gulf (Curtis et al., 1963; Illing et al., 1965; Lucia, 1972).

Facies IV. Tidal deposits (IVa–d) and shallow deposits with scour and tool marks (IVe)
Except for subfacies IVe the division of this facies has been made chiefly on the basis of associations of large benthonic foraminifera. In most cases this provides a satisfactory classification, but sometimes it is somewhat artificial.

Tidal influences are of course not limited to subfacies IVa–d, but they are clearly visible here due to the type of sediment (mostly sandy or silty) and/or the sedimentary structures that are present. Other (sub)facies where tidal action played an important role are facies III, V, VI, IX, X and XI and subfacies VIIIa and b.

Subfacies IVa. Shallow tidal deposits containing a community with few species. – This subfacies is characterized by light to dark grey calcareous quartzose sandstones, siltstones and in rare instances conglomerates with only a few fossil remains (chiefly oyster fragments and remains of land plants). The layers usually appear as planar beds. The most common sedimentary structures are small-scale cross-bedding and megacross-bedding (both also as herringbones), and horizontal and vertical burrows. Other structures, i.e. flaser and linsen structures, clay galls, small channels, load coasts and *Ophiomorpha* burrows are less frequent. In rare cases transported gastropods, other pelecypods, ostracods and echinoid remains can be seen; they are nearly always fragmented.

This subfacies has been found in the *F. cucumiformis* Zone of sections C, E, F, G, H, H', I', J, K, M and O, and in the *F. trempinus* Zone of sections A, B, G, J, K,

M and O. In the *F. trempinus* Zone these sediments are closely associated with lagoonal deposits (mainly subfacies IIb). They can be considered as small marine ingressions into the lagoons. In the *F. cucumiformis* Zone subfacies IVa can also be associated with lagoonal deposits but usually it occurs together with subfacies IVb and facies VI. Essentially all deposits of subfacies IVa were formed under tidal conditions.

Subfacies IVb. Shallow tidal deposits containing a community somewhat richer in species. – These deposits consist of light grey and grey biosparitic (and less commonly biomicritic) calcarenites (grainstones and packstones) as well as quartzose sandstones, siltstones and clays with imperforate foraminifera and megacross-bedding. Usually the bedding is planar. Herringbones of large and small-scale cross-bedding, which are frequently encountered, are proof of ebb and flood currents. Clay galls are common, especially in the *F. trempinus* Zone.

Channels, shallow as well as deeper ones, are also often seen in this subfacies but they rarely cut into deposits of other (sub)facies. Vertical burrows usually dominate over horizontal ones. At one place a nice grazing trail has been found (Pl. 3, Fig. 5.). Parallel lamination, fining upwards, and low-angle mega-cross-bedding are observed much less frequently. A large variety of transported fossils is present, mainly foraminifera, pelecypods (mainly oysters), gastropods, echinoids, ostracods and crabs; different groups of calcareous algae and bryozoans as well as remains of land plants, worms and fishes are minor constituents transported from adjacent environments.

This subfacies is the most wide-spread of all tidal deposits. It has been found in the *F. cucumiformis* Zone of sections A, B, C, E, F, F', G, H', I, I', J, K, L, M, N, O, T and Y. It is present in the *F. ellipsoidalis* Zone of sections B, F, G, N, P and Z, in the *F. moussoulensis* Zone of sections G and N, in the *F. corbaricus* Zone of sections B, G, L, M and N, and in the *F. trempinus* Zone of sections A, B, C, E, G, J, K, L, M, N and O.

Transitions to subfacies VIb, d and e occur frequently. Most of the transported fossils probably come from these subfacies. Facies VI and subfacies IVa, and to a lesser degree subfacies IIb, are associated with subfacies IVb which is a distinct tidal environment with more connections with the open sea than subfacies IVa.

Subfacies IVc. Wadden-like tidal deposits. – These deposits consist of grey to dark grey quartzose sandstones, quartz-bearing calcarenites, siltstones, marls and conglomerates. Characteristic structures are channels cut into the underlying sediments which often have a different lithology (pl. 2, Figs. 2, 3, 4). Clay galls frequently form the lag of these channels. Other important sedimentary structures are small-scale and megacross-bedding as well as flaser and linsen structures (Pl. 1, Fig. 1). Horizontal lamination is rarely seen. Horizontal and vertical burrows are numerous; several bedding planes have been penetrated by many kinds of

horizontal burrows of varying diameters. Many of the animals which inhabited these burrows fed also on imperforate foraminifera, the remains of which are often concentrated in the burrows. Fragments of land plants are common; some bedding planes are strewn with them. Minute fragments of the fresh water algae *Microcodium* are numerous in many layers. These fossils were transported from other, neighbouring environments together with the less common remains of various foraminifera, fragments of echinoids, pelecypods (notably oysters), ostracods, gastropods, dasycladaceans, etc. Some oysters are probably autochthonous. Burrowing animals clearly thrived in this environment.

All sedimentary and palaeontological evidence favours wadden-like environment for this subfacies, which is most closely related to subfacies IVa and b.

The most typical and extensive development of subfacies IVc occurs in the *F. cucumiformis* Zone of section X. The only other section where it can be found is section W. Here, in the same biozone, coarse conglomerates form part of the tidal sequence. They consist of more or less angular, poorly sorted pebbles, cobbles and boulders. The largest boulder measured is a sandstone boulder 60 cm long. Size and sorting of the grains suggest a very short transport. Therefore these conglomerates are probably the demolished remnants of a cliff in the immediate neighbourhood.

Subfacies IVd. Deeper tidal deposits. – Light grey to grey calcarenites, quartzose sandstones and siltstones are the constituents of this subfacies. The calcarenites are sometimes white; sandstones and siltstones rich in black rock-derived material are dark grey. The most frequently occurring sedimentary structures are planar large and small-scale cross-bedding and trough megacross-bedding (both megacross-bedding types often occur as herringbones). Vertical and horizontal burrows are numerous. Many beds contain clay galls. Less frequently vertical, and sometimes horizontal, *Ophiomorpha* burrows, made by *Callianassa* lobsters have been found, chiefly east of the Noguera Pallaresa River; furthermore horizontal lamination, flat shallow channels, and channels with rounded profiles, low-angle megacross-bedding, small-scale current ripples, flaser and linsen structures, and load casts are seen occasionally. The most abundant fossils are oysters, many of which are juvenile specimens, other pelecypods, echinoid remains, serpulid worms, gastropods, ostracods, and remains of crabs and land plants. Usually the fossils are fragmented. Occasionally many other fossils are present, for example various calcareous algae and bryozoans, foraminifera and corals. These fossils are nearly always fragmented and allochthonous. Among the frequent fossils many molluscs (especially the oysters), crabs, serpulids and some echinids are probably autochthonous. Burrowing animals without hard skeletal parts flourished in this environment.

A typical inhabitant of this environment is a small fibulariid sea urchin that resembles the recent species *Echinocyamus pusillus*. The fossil species has been found in thin sections, mainly from section B. The radial partitions which serve as internal supports are clearly visible. Probably this is the species *Eoscutum doncieuxi* (Lambert), which was found in the Ilerdian regressive deposits in the French Pyrenees and described by Crochet et al. (1976). In the Tremp Basin it also occurs in the regressive sequence. The recent *Echinocyamus pusillus* lives in fine and medium-grained, well-sorted sands. Off the coast of Brittany it occurs chiefly at depths between 20 and 70 m (Toulemont, 1972). When the coast is somewhat protected and hence the water less turbulent this species can also be found at much shallower depths. It is therefore not a good depth indicator.

Subfacies IVd occurs predominantly in the *F. corbaricus* Zone; it occurs in sections A, B, C, D, E, G, J, K, L, M, N, O, U and X. In the *F. ellipsoidalis* Zone it occurs in sections D, E and X', in the *F. moussoulensis* Zone in sections D and E, and in the *F. trempinus* Zone in sections B, E, J, K, N and O.

Usually this subfacies is associated with facies XI (chiefly with subfacies XIa). In rare instances it is associated with facies XIII and XIV (in sections L, N and O). Its presence in the *F. cucumiformis* Zone of section X (sample 21a, b) is rather peculiar. Here a slightly quartz-bearing biosparitic calcarenite with a fossil assemblage extremely rich in species which have been washed together from various shallow and deeper (sub)facies lies intercalated between the shallow water deposits of subfacies VIc and d and IVc. It can be interpreted as a small but rather violent marine ingression. The erosive base of this layer supports this conclusion (Pl. 2, Fig. 1).

The sedimentary structures in particular help to determine the environment of this subfacies. Especially the herringbones indicate that it has strongly been influenced by tidal currents. On the basis of the fossils it can be demonstrated that these sediments were deposited in a somewhat deeper sea than the previously mentioned subfacies of facies IV. The trough-shaped megacross-bedding was formed by lunate megaripples. The presence of many of these structures proves that in many places the velocities of the sea currents were high (Reineck & Singh, 1973, p. 35).

Subfacies IVd'. Deeper tidal deposits with large channels. – This subfacies is a special case of subfacies IVd; it consists of light to dark grey, more or less quartz-bearing calcarenites at the top of the *F. corbaricus* Zone and the base of the *F. trempinus* Zone in section E. Channels which are the largest of the whole Ager Formation extend many metres down into older deposits. This is partly due to the relatively low rates of sedimentation and subsidence in this area, but it is also the result of the special position in the palaeogeographic setting (see Chapter VI). In spite of these large structures, these deposits fit well within the tidal complex of subfacies IVd.

Subfacies IVe. Shallow deposits with scour and tool

marks. – These deposits consist of dark grey, more or less silty marls alternating with grey and dark grey sandstones and siltstones. The base of the sandstones and siltstones always cuts erosively into the marls. Many interesting scour marks can be observed together with tool marks and other structures, i.e. parallel lamination and load casts; occasionally small-scale cross-bedding and horizontal burrows are also seen. Fossils are absent except for some transported remains of land plants, some foraminifera and oyster fragments.

Within the wide variety of scour marks present we can distinguish flute marks (Pl. 3, Figs. 1, 2), longitudinal furrows and ridges, pillow-like scour marks, and flute rill marks (terminology according to Reineck & Singh, 1973). Slightly meandering flute rill marks can change into normal flute marks. These structures can differ in size: small-scale (widths expressed in mm) and larger scale (widths expressed in cm). Associated with these scour marks are different types of tool marks. Most numerous are slide marks: long, straight grooves which are formed by the continuous dragging of objects in the direction of the current along the sea bottom. Narrow slide marks (width <1 cm) formed by small objects normally cut sharply into the soft sediment; therefore they are also called groove marks. Wider slide marks (up to 5 cm or more) made by larger objects usually have a more rounded profile (Pl, 3, Fig. 2). In some beds there may be many small prod marks; they can be as much as 1 cm long and 1 to 2 mm wide. In addition some bounce marks with widths of up to about 1 cm have been observed. All scour and tool marks have been preserved as moulds on the lower surface of lithified sands and silts.

The measured orientation of the flute marks varies from 190° to 256°, thus indicating that the direction of the current was approximately S to WSW. In individual beds however, the directions of the scour and tool marks normally do not vary more than 30 degrees. In exceptional cases the difference may be more than 45°. Often the slide marks run parallel to the scour marks.

The alternation of marls and sandstones or siltstones with scour and tool marks allows no other interpretation than that occasional small turbidity currents moved downwards along a palaeoslope which was the site of a normally quiet sedimentation of marls. Otherwise the marked and sudden changes in current velocities cannot be explained. Unfortunately there is no clear direct evidence of a turbidite origin of the sandstones and siltstones. None of these beds is built up of a distinct turbidite sequence; fining upwards is indistinct, if present at all. Probably this is due to the fact that most beds are thin and are composed of small grains.

These sediments can not have been deposited in deep water, because they lie intercalated between shallow marine deposits (tidal deposits and sheltered deposits). The presence of numerous *Thalassinoides* burrows in some of the tidal sediments is additional proof of a shallow sublittoral environment (Frey, 1975, p. 17). The oldest turbidite deposits were in fact formed directly on lagoonal marls with an oyster bed. We have to accept therefore that these sediments were deposited in a marine environment not more than some metres deep.

Facies V. Deposits with sand waves and other large sedimentary structures
Sand waves are giant ripples which are about 10 m high. Sometimes they can reach a height of 20 m. Their wavelength is several hundred metres. Two types can be distinguished in the Tremp Basin: one consists exclusively of bioclastic material, the other mainly of non-calcareous detrital grains.

Subfacies Va. Sand waves consisting of bioclasts (mainly imperforate foraminifera). – This subfacies is characterized by white biocalcirudites to biocalcarenites (grainstones) with giant-sized megacross-bedding. Only one such giant ripple has been found in the Tremp Basin. It occurs in the *F. ellipsoidalis* Zone of section X immediately N of Serraduy, where it is excellently exposed over a length of about 100 metres along the eastern side of the Isábena River (Pl. 2, Fig. 1). Perpendicular to the river bank is a small valley where it can be seen in cross-section (Pl. 2, Fig. 2). Neither the western side of the Isábena River valley nor the northern side of the small valley contains remnants of this large sedimentary phenomenon. The greatest height of the giant ripple in the outcrop is 10 m. In the Isábena River valley the thickness gradually decreases towards the south. In the small valley the sand wave wedges out rapidly towards the east (Pl. 2, Fig. 2). A horizontally layered lag deposit, which increases upwards in fineness as indicated by the fossils (samples 41 and 42), forms the base of the sand wave in the Isábena River valley. In the small valley the giant ripple cuts directly into the underlying wadden-like deposits. In both places there is a distinct angular unconformity.

The giant ripple has been built up mainly of alveolinids and miliolids. In addition there are often fragments of colonies of the red algae *Lithothamnium* and corals, as well as broken and rounded molluscs. As would be expected the fineness of the bioclasts increases upwards: large alveolinids and large fragments of other fossils occur at the base of the sand wave whereas at the top only miliolids and small alveolinids can be found.

From the apparent gradual change in the slope of the cross-bedding of the giant ripple from S to N along the Isábena River it can be inferred that the direction of the maximum slope in the sand wave turns. This is confirmed by the orientations of the dips. In the southern and central part of the exposure the orientations measured were almost exactly eastwards, in the norhern part (in fact the central portion of the giant ripple) the direction measured was southeasterly. Thus the crest of the giant ripple was not straight but lunate. The main current direction was from NW to SE.

The depth of the sea must have been at least as great as the height of the ripple: 10 m or more. Vertical and lateral facies changes in the Ager Formation near Serraduy make it improbable that the giant ripple was formed at a depth of more than 30 m. The entire

sequence of which this structure forms a part is clearly transgressive. The lunate ripple is underlain by wadden-like deposits and the superposed strata indicate a gradually deepening sea. This agrees well with the development of recent sand ridges in the southern North Sea, which is mainly transgressive during the Holocene (Jelgersma, 1961; Hageman, 1969). An important difference however can be found in the orientation of the crest compared with that of the main current. The crest of the giant ripple of Serraduy was approximately perpendicular to the currents, whereas the recent sand ridges in the North Sea lie more or less parallel to the main current. The enormous size of the lunate ripple proves that the current velocities were very high. It can only be a high order phenomenon (see Folk, 1976).

Subfacies Vb. Sand waves and other large sedimentary structures (mainly with perforate foraminifera). – Light grey to grey calcareous quartzose sandstones and bioclastic calcarenites (grainstones) make up this subfacies. The grain size is coarse to medium. Giant cross-bedding and megacross-bedding are the most characteristic structures. Tabular megacross-bedding predominates markedly over trough megacross-bedding. Long vertical escape burrows which often run through an entire megaset frequently occur in the megaripples. Horizontal burrows are frequent. The presence of both types of burrows demonstrates that rapid sedimentation alternated with non-deposition or slow sedimentation. The burrows are the only sure proof of the existence of autochthonous animals. Other remains of organisms are practically all allochthonous. Large benthonic for-aminifera, especially nummulites and discocyclines, are numerous. Furthermore mollusc and echinoid fragments and fragments of cyclostomatous and cheilostomatous bryozoans (e.g. *Biflustra*) occur. The presence of many discocyclines and *Biflustra* specimens proves that this subfacies developed in relatively deep water, in any case distinctly deeper than subfacies Va. Megacross-bedding sometimes changes vertically and laterally into small-scale cross-bedding (see Nio, 1976, fig. 4a). Beds containing this type of alternation show many clay galls. Loading structures and convolute bedding point to rapid burial of unconsolidated rocks with loose packing. The thickest sand wave sequence lies on a convolute bedding at least 1.50 m thick (see Nio, 1976, fig. 4b).

This subfacies has only been found in the *F. corbaricus* Zone and the *F. trempinus* Zone of section X, in the immediate vicinity of the village La Puebla de Roda. A more detailed description is presented by Nio (1976) who distinguished an initial sand wave facies, a sand wave facies and a post-sand wave facies, which have all been included in our subfacies Vb.

Some critical remarks however are in order concerning Nio's threefold division. From the photographs in his publication it is clear that the so-called post-sand wave facies (marked C) consists of two different sedimentary complexes, which must have originated in two different ways. The first (called type a here) consists mainly of tabular megacross-beddings of highly variable thicknesses and irregular bases due to scouring processes. The megasets were deposited on a horizontal or only slightly sloping sea bottom (see Nio, 1976, figs. 5a, 7a and b and 8; in figs. 7a and b only the upper sequence marked C belongs to this type).

The second complex (called type b here) is characterized by its regular features. The thicknesses of the preserved parts of the megacross-beddings vary much less. The boundaries between the megasets are remarkably straight and not horizontal (in other words: they do not run parallel to the base and top of the complex) but slope upwards or downwards with dips of up to 15° (see Nio, 1976, figs. 7a and b; only the lower sequence marked C belongs to this type).

Judging from the photographs no essential differences can be seen between the formation of the post-sand wave facies and that of the initial sandwave facies figured by Nio (1976, figs. 4a and b). In the case of the initial sand wave facies one would expect a general increase in the current velocities and consequently an increase in the thicknesses of the megasets. In the post-sand wave facies one would expect exactly the opposite.

Sometimes a lateral change from giant ripples (facies B2 of Nio) into Nio's post-sand wave facies C occurs (see Nijman & Nio, 1975, fig. 15a). There are also transitional zones between types a and b of facies C (see Nijman & Nio, 1975, figs. 15a, b). It is however remarkable that most sedimentary structures described as sand waves persist over long distances (see Nijman & Nio, 1975, figs. 14a, b). The gentle slopes on which the megasets of type b of facies C were deposited sometimes dip in a direction which is opposite to that of the underlying giant ripple (to the right in fig. 15b, Nijman & Nio, 1975); together with the gentle slopes often continuing for hundreds of metres without a decrease in the steepness of the slopes, this is a strong argument against a post-sand wave filling of the lower parts between the crests of sand waves.

There is another reason for not believing that Nijman & Nio's post-sand wave facies originated as a deposit on a slope of the giant ripples, said slope leading to a marked reduction in the current velocities after the formation of the giant sets. Sedimentation of the upward and downward sloping megacross-beddings certainly occurred under high-energy conditions, otherwise the heights of the sets up to 1.50 m cannot be explained. Nio (1976) on the other hand assumes distinctly lower current velocities for these deposits. His main argument is his observation that the current directions are highly variable. The spread of the measurements of the cross-beddings was not less than 150° (the extremes being 180° (S) and 330° (NNW).

These data can perhaps be explained by using a quite different sedimentary model. If the directions of the megacross-beddings were randomly oriented within the sediment body, as would be expected had relatively low-energy conditions prevailed, no distinct regular structure could have been formed. Since the structure of

the type b complex is regular and simple, the only possible solution is that all current directions played a specific role in a large-scale sedimentary process. This is the case for instance when sand ridges are formed in an environment governed by tidally induced currents. Sand ridges lie with their crests roughly parallel to the maximum current and can grow by lateral and vertical accretion. On one side the sediment is transported up the slope by one tidal current and on the other side it is transported down the slope by the opposite tidal current. In such a sedimentary regime differences of 150° between the current directions can easily occur.

Facies VI. Shallow marine deposits containing imperforate foraminiferal associations (carbonate platform)

This facies is wide-spread in the basin, occurring in all sections. Six subfacies can be distinguished by their different fossil content. Transitions between these subfacies frequently occur, especially between subfacies VIc, d and e. The facies occurs predominantly in the *F. cucumiformis* Zone and is well represented in the *F. ellipsoidalis* Zone and the *F. trempinus* Zone.

Subfacies VIa. Deposits containing almost exclusively foraminifera. – These deposits consist of light grey to grey biomicritic limestones (packstones), which are sometimes sandy or silty, and grey to dark grey marls. Horizontal burrows frequently occur, and vertical burrows are not rare. The fauna consists almost exclusively of alveolinids, miliolids and *Orbitolites*. The remaining faunal elements are mainly other foraminifera and fragments of oysters and echinoids, and in rare instances fragments of gastropods, bryozoans and other pelecypods. Allochthonous fragments of land plants are common in the marls. Fragments of calcareous algae are scarce.

On the northern side of the basin the deposits are associated with quiet deposits of other subfacies of facies VI. On the southern side of the basin they seem to have been deposited under higher energy conditions. Here they are usually associated with the tidal deposits of subfacies IVb. Sometimes they gradually pass into the deposits of the latter subfacies.

Subfacies VIa can be interpreted as a shallow marine restricted environment. It has been found almost exclusively in the *F. cucumiformis* Zone.

Subfacies VIb. Deposits containing many oysters and echinoids. – These deposits consist of light grey to grey biomicritic, sometimes biosparitic, limestones with a variable quartz sand content. The limestones are mainly packstones as well as some grainstones and wackestones. Occasionally they are silty. The limestones are often nodular. Some grey marls can also be included in this subfacies. Horizontal and vertical burrows are common. Small-scale cross-bedding or clay galls may be encountered in rare cases.

Oysters are the characteristic fossils. Sometimes clusters can be found, especially in the marls; they are

numerous in this subfacies. Imperforate and rotaliid foraminifera and fragments of echinoids, including their spines, are also common. The presence of large numbers of these fossils in this subfacies and their scarcity in neighbouring areas suggest that they are autochthonous. Remains of land plants, and fragments of crabs, pelecypods and some gastropods often occur. Other fossils are scarce.

Transitions to subfacies VId and e and the tidal deposits of subfacies IVb frequently occur. In most limestones, the influence of currents can be inferred from the texture of the limestones and the rounding of many of the fossils. Micritisation caused by algal boring through the outer coils of alveolinids and other foraminifera is often seen, suggesting low rates of deposition and interrupted sedimentation.

This subfacies represents a shallow marine, mainly rather high-energy environment less restricted than subfacies VIa. It is most widely distributed in the *F. cucumiformis* Zone and *F. ellipsoidalis* Zone.

Subfacies VIc. Deposits containing a Pseudomiltha community. – These deposits consist of grey to dark grey, sometimes light grey, biomicritic limestones (packstones), argillaceous limestones and marls, and are usually nodular or irregularly bedded. Sometimes a small amount of sand has been mixed into the sediment. Large shells of *Pseudomiltha corbarica* (Leymerie) (Pl. 4, Fig. 7) in position of life, i.e. burrowed vertically into the sediment, are the characteristic fossils of these deposits (for a detailed description see Plaziat, 1972, p. 33). Most numerous are the imperforate foraminifera. In addition to rotaliid and valvulinid foraminifera there are echinoid fragments, oysters, other pelecypods, gastropods, ostracods, and remains of land plants. In the typical deposits of this subfacies however, *P. corbarica* predominates markedly over the other molluscs. In many cases dasycladaceans (green algae) occur together with this species, so that many gradual transitions to subfacies VIe can be found. Horizontal and vertical burrows are common. Inorganic sedimentary structures are rare. Geopetal structures are perhaps most frequent.

Sometimes subfacies VIc passes into the tidal deposits of subfacies IVb. In that case *P. corbarica* lived on mud-free bottoms consisting of bioclasts. Some small-scale cross-bedding and flaser and linsen structures may then also occur. The typical deposits however, never show evidence of currents and have been deposited in a quiet environment. Thus this subfacies represents a protected shallow marine environment, although it is not lagoonal as suggested by Ferrer et al. (1973), for fauna and flora indicate normal salinities.

It occurs in the *F. cucumiformis* Zone and the *F. ellipsoidalis* Zone of many sections. In the *F. moussoulensis* Zone it is rare.

Subfacies VId. Deposits containing a rich mollusc assemblage (Pl. 5, Fig. 2). – These deposits consist of light grey to grey biomicritic limestones (packstones) and grey to dark grey marls; sometimes they contain small

quantities of sand, silt or clay. These deposits are characterized by a rich mollusc assemblage of pelecypods and gastropods. All fossils occurring in the former subfacies, except *P. corbarica*, can be found in subfacies VId. On the whole the fauna and flora of this subfacies are indeed more varied: serpulid worms, *Acicularia* (a green alga) and some corals also occur in this subfacies. There are often dasycladaceans and the codiacean alga *Halimeda*, so that transitions exist to subfacies VIe. Usually there is no evidence of currents, but occasionally biosparitic limestones (grainstones) composed of allochthonous fossils suggest current activity.

This subfacies can be interpreted as a shallow marine environment more open marine than the previously described subfacies but still rather protected. It occurs in the *F. cucumiformis* Zone of nearly all sections. It is common in the *F. ellipsoidalis* Zone and much rarer in the higher zones.

Subfacies VIe. Deposits containing many green algae (Pl. 6, Fig. 3). – These deposits consist of grey to dark grey biomicritic limestones (packstones) and marls which are sometimes sandy or silty. They contain many remains of green algae, viz. dasycladaceans (including *Neomeris* and *Belzungia*), and the codiacean *Halimeda*, which may have formed extensive submarine meadows, together with brown and other green algae of which no traces remain. *Belzungia* is known from the Danian of the French Pyrenees and the lower Lutetian of Libya and Egypt (Pfender & Massieux, 1966; Massieux, 1966). In the *F. trempinus* Zone the internodes of the udoteacean green alga *Ovulites* are common (Pl. 6, Fig. 3). Sometimes they are extremely abundant and dominate over all other fossils. These algae are also known to occur in the Sparnacian of the French Pyrenees (Deloffre, 1970) and the Ypresian of the northern part of the Corbières region (Massieux, 1965). *Ovulites* is closely related to the recent genus *Penicillus*. A striking fossil which often accompanies *Ovulites* in the Tremp Basin is a small calcareous sponge resembling the genus *Barroisia*.

Recent species of *Neomeris* are only known to occur in the littoral zone and the uppermost part of the infralittoral zone (0–10 m depth) and are restricted to seas where the isocrymes do not fall below 20 °C (Konishi & Epis, 1962). At present *Penicillus* also lives in warm, shallow marine environments and the same is true of *Ovulites*.

This subfacies usually occurs in combination with subfacies VIc or d and it has therefore roughly the same geographical, stratigraphical and ecological distribution.

Subfacies VIf. Deposits containing Velates and/or Beisselina. Light to dark grey biomicritic limestones (packstones), which are sometimes sandy, silty or clayey, and grey to dark grey marls make up this subfacies. It represents the transition between the five foregoing subfacies and facies XI, and is characterized by a fossil assemblage rich in species. It includes the same remains as those found in subfacies VId, but can be distinguished from the latter by the presence of the gastropod *Velates schmiedeli* and/or the cheilostome bryozoan *Beisselina*. Sometimes *Pseudomiltha corbarica* also occurs.

Subfacies VIf is localized almost exclusively on the southern side of the Tremp Basin. Its widest geographical distribution is in the *F. ellipsoidalis* Zone.

Subfacies VIc, d and e combined. – A fossil community extraordinarily rich in species occurs in the *F. trempinus* Zone of sections A, B, C, K, N and O. In the slightly sandy, grey to dark grey nodular limestones (packstones) the molluscs in particular are represented by many species of many families. Species of the following pelecypod families are common: Cardiidae, Carditidae, Mytilidae, Lucinidae (among others *Pseudomiltha*) and Ostreidae. The two valves are almost always still joined together. Species of the gastropod families of Cerithidae and Volutidae frequently occur, as well as *Globularia* aff. *sigaretina, Ancilla, Seraphs* and *Rimella*. Among the megafossils there are many large sea urchins (*Conoclypus*); furthermore smaller echinoids, crabs, serpulid worms and brain corals are not rare. In thin sections a multitude of fragments of different dasycladaceans can be observed together with many foraminifera, ostracods and bryozoans.

These limestones with a rich fauna and flora, representing numerous species and individuals, were deposited in a shallow marine environment which was protected against strong tidal currents although the flow of sea water was suffient to provide enough food and oxygen. A sheltered bay therefore is the most probable environment for these deposits.

Facies VII. Back-reef deposits
As a rule sediments are assigned to this facies when the relationship with reefs in the immediate neighbourhood is evident from field observations and when there is no evidence of strong currents. The connection with reefs seen in the field is especially important if no reef debris occurs, for in that case there are no specific field or microfacies characteristics of this subfacies.

The foraminifera association consists mainly of imperforate elements (alveolinids, miliolids and *Orbitolites*) but some nummulites may also be present.

We have to remember that deposits assigned to other facies may also have been formed in a back-reef environment, for example subfacies VIc, e and f, and subfacies XIb and d. A direct relationship between these subfacies and the reefs has however not been discovered during the field work.

Subfacies VIIa. Back-reef deposits without reef debris. – These are light grey to grey, sometimes dirty white, biomicritic limestones (packstones), occasionally with intraclasts. Foraminifera are the most abundant fossils. Skeletal parts of echinoids as well as gastropods, pelecypods, ostracods and fragments of the fragile red alga *Lithoporella* are encountered frequently. Less

common are dasycladaceans, *Acicularia* and remains of crabs, serpulids and various bryozoans. The spaces between the fossils are mainly filled with lime mud, and there is not much fragmentation of the fossils; obviously the sediments were deposited in a low-energy environment.

Association with reefs (facies VIII), off-reef shoal limestones (subfacies IXa), or back-reef deposits with reef debris (subfacies VIIb), suggest a back-reef environment; otherwise these deposits would have been incorporated in facies VI or XI. They occur in the *F. moussoulensis* Zone of sections C and P, and in the *F. corbaricus* Zone of sections C, G and Q.

Subfacies VIIb. Back-reef deposits with reef debris. –
This subfacies consists of light grey to grey biomicritic limestones (packstones and some wackestones) usually without sand grains or intraclasts. Some burrows occur. The same fossils as in subfacies VIIa can be found although fauna and flora are more varied. Fragments of colonies of corals and/or the red alga *Lithothamnium* are often abundant suggesting the close proximity of reefs. The components of this material reflect the composition of the reefs. Most fossils however are not fragmented, which indicates a low-energy environment.

Transitions to subfacies IXa and XIa occur. The back-reef deposits often change laterally into reefs and off-reef shoal limestones. In the *F. corbaricus* Zone subfacies VIIb occurs along the entire southern side of the Tremp Basin. Moreover this subfacies is present in the *F. moussoulensis* Zone of sections C, G and P. Along the northern side of the basin it has only been found in the *F. corbaricus* Zone of section X′. The reef debris in the *F. trempinus* Zone of section O is the only indication of reef growth during that interval.

Small patch reefs on a shallow platform of alveolinid limestones, do not give rise to well-developed fore-reef and back-reef deposits which can be distinguished from other platform sediments. This is the case in the *F. cucumiformis* Zone of sections J, K and L, and in the *F. ellipsoidalis* Zone of sections L, N, O and P.

Facies VIII. Reefs
Many geologists only consider a limestone body a reef when it is composed entirely of boundstones. In this concept animal and/or algal colonies grow on top of one another continuously without leaving much space for detrital lime sediment. The only reefs in the Tremp Basin that answer this requirement are the algal ridges (subfacies VIIIb) which were formed by the coralline red alga *Lithothamnium*. The interstitial space between the colonies is minimal.

In the various fossil coral reefs or coral–algal reefs a lot of interspace can exist between the colonies so that no horizontally and vertically continuous boundstone is formed. The interspaces contain packstones, wackestones or grainstones, and if a sample is taken only from this part of the reef, it is impossible to make the correct environmental interpretation. Nor can one small thin section through a coral or algal colony prove

the existence of such reefs. They can only be discovered by field observations. Unfortunately these reefs are not easily visible in outcrops in contrast to the massive *Lithothamnium* reefs. Their most characteristic aspect is that their bedding is irregular or nodular (Pl. 1, Figs. 3, 4, 6). The large and small knobs represent coral colonies. Their bedding planes, if discernable at all, are usually undulating (Pl. 1, Figs. 3). The different types of coral reefs and coral-algal reefs are characterized by different species of corals which unfortunately could not be identified because a coral specialist could not be found.

Recent coral reefs as a rule lack a massive framework of coral colonies. Apart from the large structures between the reefs sensu stricto such as channels and lagoons, there are cavities and interspaces between the colonies on a much smaller scale, which are filled with lime mud and sand containing small skeletons (foraminifera, molluscs, etc.) (Maxwell, 1968). If we could observe such recent reefs in cross-section they would resemble the fossil coral reefs of the area studied.

The difficulty involved in recognizing fossil reefs is evident from the literature. Only a few of the reefs on the northern side of the Tremp Basin have been identified by Garrido & Rios (1972). In the publications of Ferrer et al. (1971) and Ferrer et al. (1973), which focus on the marine Palaeogene deposits of the Tremp Basin, reefs are not mentioned at all.

Subfacies VIIIa. Patch reefs on shallow platforms. –
This subfacies includes light grey to grey boundstones and biomicritic limestones (packstones) and is characterized by a fauna and flora rich in species and individuals. Coral colonies are abundant whereby hemispherical and platy forms predominate. They are often encrusted by *Lithothamnium*. Various groups of foraminifera, including *Reophax* and sessile types, occur together with the three imperforate groups. Remains of oysters, other pelecypods, including boring species gastropods, ostracods, echinoids, crabs, worms and some bryozoans indicate a rich animal community. In addition to the red algae (*Lithothamnium* and *Lithoporella*) the green algae are also well-represented by Dasycladaceae, *Halimeda* and *Acicularia*.

These reefs are always associated with limestones which contain pure associations of imperforate foraminifera. They are always small, both in extent and in thickness. The absence of undeniable fore-reef deposits with distinct palaeoslopes is characteristic. The limited size and the position of these reefs prove that they are patch reefs, which often have developed on the reef flat behind the algal ridge or which were otherwise protected against strong wave and current actions.

They have been found in the *F. cucumiformis* Zone of sections J and L, in the *F. ellipsoidalis* Zone of section N, in the *F. moussoulensis* Zone of section P, and in the *F. corbaricus* Zone of section Q.

Subfacies VIIIb. Lithothamnium ridges. – These ridges consist of light grey boundstones and contain tightly

clustered *Lithothamnium* colonies which have a roughly spherical shape and are usually 0.5–2 cm across (Pl. 4, Fig. 4). The scarce interstitial spaces are filled with lime mud (sometimes marl) in which small allochthonous fossil fragments occur. They belong to the following groups: foraminifera, gastropods, pelecypods, *Corallina*, *Lithoporella*, ostracods, echinoids, crabs, bryozoans and corals. The red alga *Lithothamnium* forms the bulk of the volume of reefs; some worms which lived in calcareous tubes (*Haliotus*-like worms and others) as well as sessile foraminifera lived on and in the algal colonies. Sometimes autochthonous corals also occur. Other autochthonous organisms are lacking; thus this subfacies is poor in species.

In some places a distinct slope with dips of up to 30° can be observed on the seaward side of the algal reefs (Pl. 1, Fig. 5). At one locality (about 50 m east of sample locality A29 of section A) it could be demonstrated that a fossil algal ridge emerged after its formation and remained so for some time. Its top is covered by a thin reddish weathering layer which is clear evidence of this event that must have been caused by a slight tectonic uplift. This residual sediment contains small crystals of gypsum, which indicate an evaporitic environment. Several small fissures in the algal ridge were formed by subaerial solution (karst).

The recent counterparts of the *Lithothamnium* reefs are the algal ridges (*Lithothamnium* ridges) which form the most exposed parts of modern reef complexes (see for instance Maxwell, 1968; Adey & Burke, 1976). These algal ridges develop best where the breakers have their greatest strength. This is generally the case on the windward side of islands. These algae (and also certain vermetid gastropods) form the only organic framework capable of resisting the strongest oceanic breakers because of their compact construction. The algal ridges are formed no more than several metres below the high-tide level. During ebb tide large portions can lie above the water-level. They protect the reef flat against strong wave action.

Lithothamnium ridges have been found in the *F. ellipsoidalis* Zone of sections L and W, and in the *F. corbaricus* Zone of sections A, P, Q and X'.

Subfacies VIIIc. Coral–algal reefs. – In these grey to dark grey boundstones and biomicritic limestones (packstones and wackestones), coral and algal colonies appear in about equal proportions. A well-exposed example has been found about 50 m east of sample locality A29a (section A; see Pl. 1, Fig. 6). These reefs represent the transition between the algal ridges (subfacies VIIIb) and the coral reefs of subfacies VIIId. Their presence therefore is indicative of intermediate depths and wave strength. The faunal and floral composition of these reefs is also intermediate, and for this one is referred to the descriptions of subfacies VIIIb and d. In this connection it should be mentioned that the coral is almost exclusively hemispherical and that encrusting bryozoans are relatively common.

Examples of subfacies VIIIc have been found in the *F. corbaricus* Zone of sections A, B, M and P.

Subfacies VIIId. Coral reefs (Pl, 1, Figs. 3, 4). – The reefs consist of light grey to dark grey boundstones and biomicritic limestones (packstones and wackestones) with a fauna and flora rich in species and individuals. The accompanying foraminifera association of these reefs and their surrounding rocks is usually a mixed imperforate–perforate one (alveolinids, miliolids and *Orbitolites* with some nummulites and an occasional transported discocycline). Hemispherical coral colonies (among others brain corals) predominate over the branching types. The largest colony observed had a diameter of 70 cm (sample C37). In one case (section X') platy corals occur which are embedded in a marl. Sessile foraminifera are abundant. Boring pelecypods can frequently be found in the coral colonies (Pl. 3, Fig. 4). Many animals lived between the corals: large oysters and other pelecypods (the valves are still often joined together), gastropods (sometimes *Velates*), solitary corals, echinoids, ostracods, different groups of bryozoans, serpulid and *Haliotus*-like worms, crabs and fish remains. Red algae, i.e. encrustations of *Lithothamnium* and *Lithoporella*, and the internodes of *Corallina* as well as green algae (dasycladaceans and *Halimeda*) also occur.

These reefs flourished where wave action was not very strong, thus usually in water at least several metres deep. Their distribution is the greatest in the *F. corbaricus* Zone where they have been found in sections A, B, C, K, N and X'. In addition they occur in the *F. cucumiformis* Zone of section H' and in the *F. moussoulensis* Zone of section X'.

Subfacies VIIIe. Coral reefs of deeper water. – These reefs consist of dark grey boundstones and biomicritic limestones (packstones); they may contain glauconite. In addition to many hemispherical coral colonies, branching types are also relatively abundant. Encrustations by *Lithothamnium* and borings by pelecypods are common. Foraminifera, ostracods, oysters, pectinids, *Spondylus* and other pelecypods, *Velates* and other gastropods, *Porocidaris* and other echinoids, solitary corals, crabs and some bryozoans lived between the coral colonies. Sponges seem to be more common than in the shallower reefs. The foraminifera association of the reef and both the lateral and vertical adjacent sediments contain more perforate than imperforate elements. *Nummulites*, *Operculina*, *Assilina* and *Discocyclina* occur. The presence of these foraminifera together with *F. (M.) boscii* suggests a depth of at least 40–70 metres. Many fragile branching coral colonies prove that quiet conditions prevailed.

The only places where this reef type has been identified with certainty is in the *F. corbaricus* Zone of sections J and L. Transitions to the shallower reefs of subfacies VIIId have all been incorporated in the latter subfacies; they are characterized by the occurrence of some glauconite and discocyclines.

Facies IX. Calcarenitic deposits, strongly influenced by tidal currents, in between and around reefs

The deposits of the two subfacies distinguished are very similar. The off-reef shoal limestones are more often sparitic and have a greater variety of sedimentary structures than the reef channels. Differences between the fossil contents of the two subfacies are usually only quantitative: as a rule *Corallina* and *Lithoporella* (Pl. 7, Fig. 2) are more frequent in the off-reef limestones, whereas massive and branching corals, *Lithothamnium*, dasycladaceans, *Halimeda* and *Acicularia*, sessile foraminifera and encrusting calcareous tubes of worms (*Haliotus* and others) are more frequent in the reef channels. Moreover fragmentation of the fossils is more pronounced in the off-reef limestones which indicates a longer average transport for the particles in the latter subfacies. In many cases an unambiguous identification of these subfacies is possible with the help of the vertical and lateral facies changes.

Subfacies IXa. Off-reef shoal limestones (Pl. 7, Fig. 2). – This subfacies consists of white to light grey, sometimes grey, biosparitic limestones (grainstones) and biomicritic limestones (packstones), which occasionally contain some sand and in rare instances some intraclasts. The most frequent sedimentary structures are shallow and somewhat deeper channels and vertical burrows. Furthermore horizontal burrows, small-scale and megacross-bedding (both sometimes as herringbones) and fining upwards of the fossil debris can be seen. Often micritisation of the exterior of fossils (mainly foraminifera) caused by boring algae is found, indicating low sedimentation rates. Most fossils are fragmented. In addition to the above-mentioned fossils the following groups are also frequently encountered: foraminifera, ostracods, echinoids, oysters, other pelecypods, *Velates*, other gastropods, many types of cheilostomatous bryozoans, crabs, solitary corals, serpulid worms, fish remains (rarely), the red alga *Distichoplax biserialis* and remains of land plants.

Depending upon the depth at which these deposits were formed the foraminifera association will be entirely imperforate or mixed imperforate–perforate. Usually the imperforate elements predominate. *Nummulites* is often abundant. *Operculina, Assilina* and *Discocyclina* are usually much more rare.

Foraminifera and encrusting and articulate coralline algae form the bulk of the volume of these limestones. This agrees with the observations of Forman & Schlanger (1957, p. 619 and pl. 4) on the Tertiary limestones of Louisiana and Guam, which also have been interpreted as off-reef shoal limestones.

Off-reef shoals are most frequent in the *F. corbaricus* Zone, i.e. in sections A, B, C, D, E, G, J, K, L, M and N. They are furthermore found in the *F. cucumiformis* Zone of sections E, K and V, in the *F. ellipsoidalis* Zone of section X and in the *F. moussoulensis* Zone of sections G, K, P and W.

Subfacies IXb. Reef channel limestones. – These

deposits consist of white to light grey, sometimes grey, biomicritic limestones (packstones) and biosparitic limestones (grainstones). The only sedimentary structures observed are channels and vertical burrows. The same groups of fossils occur as in the off-reef shoal limestones. The fragments of the coral and *Lithothamnium* colonies in particular are larger in the channels than in the off-reef shoals. An important reason for this is certainly that the reef debris in the channels travelled a shorter distance with respect to the source. Imperforate or mixed imperforate–perforate foraminifera associations can occur, depending upon the depth at which the reef channels lie.

Reef channels are found most frequently in the *F. corbaricus* Zone, in sections C, K, M, N, P, Q and X'. Furthermore they occur in the *F. ellipsoidalis* Zone of section W and in the *F. moussoulensis* Zone of sections B and P.

Facies X. Reef-breccia limestones (fore-reef deposits sensu stricto)

These deposits for the most part are composed of coral colonies and/or colonies of red algae. The remainder consists of other floral and faunal elements derived from the reef communities. If the degree of exposure of the rocks is sufficient these limestones can be recognized in the field by the distinct palaeoslopes which dip towards the centre of the basin (Pl. 1, Fig. 5). Sometimes channels have developed. These limestones are highly resistant and therefore they often form perpendicular walls which are not accessible without special equipment and experience. The same indeed applies to many reef exposures.

As there is a gradual transition from shallow to deeper reefs, only an arbitrary subdivision of the fore-reef deposits can be made. The foraminifera association and the stratigraphic position between adjacent sediments furnish the most conclusive indications. Distinct fore-reef deposits are absent when there are patch reefs on the shallow platform (reef flat).

Subfacies Xa. Shallow fore-reef deposits (Pl. 7, Fig. 1). – These deposits consist of white to light grey, sometimes grey, biomicritic limestones (packstones). Biosparitic limestones (grainstones) are much less common. Glauconite is usually absent. Depending upon the reefs from which the debris has derived, fragments of *Lithothamnium* colonies or coral colonies or both are present. Imperforate foraminifera always predominate markedly over the perforate elements; often they are the only large benthonic foraminifera present. The frequently observed micritisation of the fossil fragments caused by boring algae indicates interruptions in the enlargement or shifting of the fore-reef area. All fossil groups mentioned under subfacies VIIIb, c and d can be expected.

These fore-reef deposits often change laterally into off-reef shoal limestones. Subfacies Xa has been found in the *F. cucumiformis* Zone of sections H' and V, in the *F. ellipsoidalis* Zone of section W, in the *F. moussoulensis* Zone of section X', in the *F. corbaricus*

Zone of sections A, B, K, M, N, P and X', and in the *F. trempinus* Zone of section J.

Subfacies Xb. Deeper fore-reef deposits. – These deposits consist of light grey to grey biomicritic limestones (packstones) in which glauconite often occurs. These deposits are composed of the debris of shallow and deeper reefs, and all of the organisms mentioned for these subfacies can be expected. Perforate foraminifera usually predominate over the imperforate. Alveolinids (with the exception of some specimens of *F. (M.) boscii*), most miliolids and *Orbitolites* usually show rounding by transportation and are thus obviously allochthonous – in contrast to the perforate foraminifera, of which nummulites are generally the most numerous. In order of decreasing importance discocyclines, operculines and assilines can also be found.

Sometimes these deposits contain the cheilostomatous bryozoan *Biflustra,* in which case they grade into those of subfacies XIIIb. Transitions to subfacies XIIIc are also seen; these fore-reef deposits contain numerous thick spines of regular echinoids (section A). The deeper fore-reef deposits are always associated with the various subfacies of facies XIII and XIV. They have only been found in the *F. corbaricus* Zone in the sections A, I, K, L and Y.

Facies XI. Deposits consisting mainly of pure limestones with mixed imperforate–perforate foraminifera associations (Pl. 6, Fig. 4)
This facies is widespread in the Tremp Basin. All subfacies of facies XI have been found in all alveolinid biozones. The various subfacies of this facies occur in the *F. cucumiformis* Zone in sections along the northern side of the basin, whereas they are nearly absent along the southern side in this biozone. The opposite is the case in the *F. trempinus* Zone. In general it is true of all subfacies that they have developed more extensively along the southern side than along the northern side of the basin.

Subfacies XIa, b, c and d show many resemblances with subfacies VIb, c, d and e, respectively. In addition to the differences in the foraminifera associations the subfacies of facies XI always contain additional faunal elements compared with the resembling subfacies of facies VI.

Horizontal and vertical burrows occur in all subfacies. Nummulites are the most common perforate foraminifera, followed by *Operculina; Discocyclina* and *Assilina* are rare. Transitions between the subfacies are frequently observed.

Subfacies XIa. Deposits containing many oysters and echinoids (closely allied to subfacies VIb). – These deposits consist of light grey to grey, sometimes dark grey, biomicritic limestones (packstones) and more rarely biosparitic limestones (grainstones); they are sometimes sandy or silty. Some marls have also been included in this subfacies. The limestones are sometimes nodular. Sedimentary structures, except burrows, are usually scarce. In some places megacross-bedding (sometimes as herringbones) and channels are clear indications of strong currents in this subfacies. Such deposits are transitions to the tidal environment (subfacies IVb and d). Where these structures are missing the presence of many small fossil fragments and the usually small quantities of lime mud between the fossils are often suggestive for a high-energy environment.

In addition to foraminifera, oyster fragments and/or echinoid fragments predominate in the thin sections. Whole shells of oysters and irregular echinoids are common. Entire skeletons of the sea urchins *Conoclypus* sp. and *Opissaster* aff. *minor* Lambert have been found. The cheilostomatous *Beisselina* is the most frequently occurring bryozoan. Other fossils are generally much less common. Of these in particular the foraminifer *Reophax* and sessile foraminifera are worth mentioning. Carditidae, Cardiidae, Pectinidae and *Crassatella* sometimes occur; the two valves may still be joined together. Furthermore other pelecypods, gastropods, ostracods, crabs, various cheilostomatous bryozoans, corals (chiefly colonies), serpulid worms, *Lithothamnium, Lithoporella, Corallina, Halimeda, Acicularia,* dasycladaceans and remains of land plants are found, chiefly as fragments.

Subfacies XIa is usually associated with subfacies IXa, facies VI, VII and XII and subfacies XIVa. Transitions exist to subfacies IXa, XIIa, b and c, VIb, VIIb, XIVa and b and XIIIb.

Subfacies XIb. Deposits containing a Pseudomiltha–Velates community (closely allied to subfacies VIc). – These deposits consist of light to dark grey biomicritic limestones (packstones) which are often nodular. Some clayey limestones and marls belong to this subfacies. The joint occurrence of *Pseudomiltha corbarica* (Leymerie) (usually in position of life) and *Velates schmiedeli* Chemnitz is characteristic for these deposits. These molluscs and oysters occur in considerable numbers. Carditidae, Cardiidae, Pectinidae (the two valves often are still joined together) and *Turritella* are much more rare. Sometimes entire skeletons of the echinoids *Ditremaster* sp. and *Amblypygus* sp. ex gr. *dilatatus* Agassiz have been found. Fragments of echinoids as well as various foraminifera and ostracods are common. Other fossils which often occur as fragments are other pelecypods and gastropods, various cheilostomatous bryozoans, some cyclostomatous bryozoans, crabs, coral colonies, serpulid worms, *Lithothamnium, Lithoporella, Halimeda, Acicularia,* dasycladaceans and remains of land plants. The rare occurrence of terebratulid brachiopods and of spines of the regular echinoid *Porocidaris* indicates a transition to subfacies XIIa or b. Subfacies XIb is often associated with the latter two subfacies, with facies VI, and also with subfacies IXa and IVd.

The absence of sedimentary structures formed by currents, the presence of pelecypods in situ and the kind of sediment are indicative of a low-energy environment.

Subfacies XIc. Deposits containing a rich mollusc assemblage (closely allied to subfacies VId). – These deposits consist of light to dark grey, sometimes slightly sandy biomicritic limestones (packstones) which may be nodular. They are characterized by a rich mollusc fauna; especially gastropods are abundant. The families of the Volutidae, Cardiidae, Ostreidae and Pectinidae could be identified with certainty as well as the genus *Clavilithes* and' the species *Bicorbula vidali* (Cossmann). Brain corals sometimes occur in situ. In one place a specimen of the large irregular echinoid *Conoclypus* was found. Except for *Pseudomiltha, Velates* and the specifically mentioned echinoids of the previous subfacies all fossil groups of subfacies XIb can be found in subfacies XIc. Moreover solitary corals, other brachiopods and other worms occasionally occur.

The lack of cross-bedding and other sedimentary structures formed by currents as well as the kind of sediment suggest a low-energy environment for subfacies XIc. It may be associated with the same subfacies as subfacies XIb.

Subfacies XId. Deposits containing many green algae (closely allied to subfacies VIe). – These deposits consist of grey to dark grey biomicritic limestones (packstones) which are often nodular. Some marls also belong to this subfacies. The green algae *Halimeda* and dasycladaceans are abundant. Entire skeletons of the echinoid *Opissaster* aff. *minor*, molluscs of the families Carditidae and Volutidae, and brain corals have been found and surely belong with certainty to the autochthonous fauna. Usually this subfacies occurs in association with subfacies XIb or XIc.

Facies XII. Deposits consisting mainly of clayey limestones and marls with mixed imperforate–perforate foraminifera associations

The subfacies of this facies can be divided into two groups. One group comprises subfacies XIIa, b and c, which are characterized by abundant and varied faunas. The other group, represented by subfacies XIId, has a rather poor fauna. A considerable proportion of the fauna of the first group consists of epifaunal elements. The only sedimentary structures are horizontal and vertical burrows. All types of transition between these subfacies exist. Even the fossils for which the communities are named may occur together in one bed. Nevertheless the subfacies can usually be distinguished fairly easily. Fossils, which are mainly restricted to these subfacies and which therefore are characteristic for them, are the Chamidae, many representatives of the Pectinidae, *Eutrephoceras* aff. *lamarcki* and a terebratulid brachiopod (*Terebratula montolearensis* Leymerie). The cheilostomatous bryozoan *Beisselina* is not restricted to subfacies XIIa, b and c, but is most numerous there, from which it may be concluded that it lived there under optimum conditions.

Subfacies XIId does not differ essentially from subfacies XIVd. The stratigraphical position between

other subfacies is the principal means of distinguishing both subfacies.

The unexposed parts of the sections, which alternate with the limestones of facies XI, probably are mainly marls and marly limestones and are interpreted as belonging to facies XII.

Subfacies XIIa. Deposits containing a Spondylus community. – These deposits consist of grey to dark grey, sometimes light grey, biomicritic limestones (packstones) which are usually irregularly bedded and sometimes nodular. These limestones are often clayey. Some marls also belong to this subfacies. Nummulites and/or operculines are usually the most numerous perforate foraminifera, miliolids are always the most numerous imperforate ones. Alveolinids, *Orbitolites* and especially assilines are less common. In the field pelecypods and gastropods are most conspicuous. Of the epifauna the pelecypods *Spondylus eocenus* Leymerie (Pl. 4, Fig. 8), Chamidae, Pectinidae, oysters and *Mytilus* are the most important representatives. The two valves are nearly always still joined together. The following gastropods are epifaunal: Cypraeidae (? *Gisortia*), *Xenophora, Clavilithes* and *Rostellaria*; the same mode of life can be presumed for their fossil relatives; these fossils are however less common. Other pelecypods present are mainly shallow burrowers like Cardiidae, Carditidae, Lucinidae, *Crassatella* and *Fimbria*. Other gastropods are Naticidae, *Seraphs, Ancilla* and *Rimella*. Brain corals and boring pelecypods are rare. Terebratulid brachiopods are more frequent in this subfacies than in other subfacies. Small radially ribbed brachiopods are rare. Regular and irregular echinoids were abundant. This can be deduced from the occurrence of many loose plates and spines (including those of *Porocidaris*; see Pl. 4, Fig. 9). Entire skeletons of sea urchins are as a rule rare and belong mostly to *Maretia aragonensis* Cotteau and *Ditremaster* cf. *alarici* (Tallavignes) (Pl. 4, Fig. 2). Other fossils occurring in this subfacies are various foraminifera (including sessile ones), ostracods, different types of cheilostomatous bryozoans (vinculariiform and adeoniform, sometimes also lunulitiform types) and some cyclostomatous bryozoans (including *Entalophora*), fragments of crabs, various serpulid worms, some solitary corals, some massive and branching coral colonies, fish remains (rare) and pieces of dasycladaceans and *Halimeda*. The foraminifer *Reophax*, fragments of *Lithothamnium* and *Lithoporella*, and remains of land plants can all be considered allochthonous.

Transitions to subfacies XIa, b, c and d, and subfacies VIc, d and f exist. In that case *Pseudomiltha corbarica* and/or *Velates schmiedeli* are often found together with the above-mentioned fauna and flora. In some places where an impoverished *Spondylus* community lived in more agitated water (for instance in section N) the bryozoans are nearly or completely absent in the limestones which in such a case are light grey and without clay. Transitions to subfacies XIIIb and XIVb and facies XV can also be seen. Then glauconite may be

present, and *Biflustra* fragments, *Conocrinus* internodes or *Turritella* may be found. In these apparently deeper water deposits the lunulitiform bryozoan *Lunulites* is often abundant, whereas this species is absent in shallower environments.

The *Spondylus* community with its many epifaunal elements lived in areas where the sedimentation rate was low. The presence of fossil fragments and the usually high concentrations of the fossils make it probable that some erosion occurred. Living species of the families of the Spondylidae, Chamidae and Ostreidae are cemented by secreted shell material to a hard substratum (Moore, 1969; Stanley, 1970). This can be a firm bottom or the skeleton of another organism. The valves of our fossil species of the Spondylidae and Chamidae are unequal but not as asymmetrical as those of many recent representatives of these families. Nevertheless a similar mode of life is highly likely for these species. The long spines of *Spondylus eocenus* were useful as a protection against predators (for instance fishes), like those of recent species.

In the majority of the cases the *Spondylus* community lived under quiet conditions, i.e. was not disturbed by waves or strong currents. The various types of bryozoans which surely are definitely autochthonous prove this. This subfacies therefore represents an environment below wave base, with the possible exception of the impoverished *Spondylus* community of section N. The minimum depth of this subfacies was therefore at least ca. 15 m. The lower limit is less easily to fix. If the conditions of a solid sea bottom, low sedimentation rate and low energy are fulfilled, the *Spondylus* community can be expected in a considerable part of the photic zone.

The abundance of species and the presence of the large shells of the free-swimming nautiloid *Eutrephoceras* aff. *lamarcki* (Deshayes) indicate open sea conditions. The presence of shells of this nautiloid mainly in this subfacies and in subfacies XIIb and c is probably due to the transitional position of facies XII between the shallower limestones and the deeper marls. The empty shells probably stranded here, as facies XII often seems to have acted as a threshold between the open sea environments and the shallow water realm.

Subfacies XIIa is found in association with subfacies XIIb and c, XIa, b, c and d, XIVb and c and facies XV. The largest distribution of this subfacies is in the *F. moussoulensis* Zone where it occurs in sections A, B, I, J, L, M and O. It is also found in the *F. ellipsoidalis* Zone of sections F, J, K, O, U and V, in the *F. cucumiformis* Zone of section U, in the *F. corbaricus* Zone of sections I, J, M, N, U, X and X', and in the *F. trempinus* Zone of section K and east of section X.

Subfacies XIIb. Deposits containing a. Schizaster – Linthia – Ditremaster community. – These deposits consist of grey to dark grey biomicritic limestones (packstones and some wackestones), which are irregularly bedded or nodular, dark grey marls and in rare instances siltstones. Nummulites and operculines are

usually the only perforate foraminifera. Miliolids are always the most numerous imperforate foraminifera. Alveolinids and *Orbitolites* are less common. Echinoids are abundant, in their number of individuals as well as in their number of species. Most specimens are preserved as complete skeletons (without spines). *Schizaster* aff. *vilanovai* Cotteau (Pl. 4, Fig. 3), *Linthia hovelacquei* Cotteau (Pl. 4, Fig. 1), *Maretia aragonensis* Cotteau and *Ditremaster gregoirei* Cotteau are the most common species. Other irregular echinoids found are *Trachyaster* aff. *raulini* Cotteau, *Schizaster* aff. *biarritzensis* (d'Archiac), *Conoclypus* cf. *cotteaui* Lambert and *Conoclypus marginatus* Desor. Complete skeletons of regular echinoids are rare. This is also the case in other environments and might be due to the differences in the mode of life of irregular and regular echinoids: regular echinoids always belong to the epifauna and irregular ones usually to the infauna. Three regular echinoid species have been found, viz. *Rhabdocidaris* aff. *pouechi* Cotteau, *Thylechinus pegoti* Cotteau, and *Porosoma rousseli* (Cotteau). It is not impossible that the loose spines identified as *Porocidaris serrata* d'Archiac (Pl. 4, Fig. 9) belong to the same species as the complete skeletons (without spines) which have been identified as *Rhabdocidaris* aff. *pouechi*.

Many molluscs form part of this community, i.e. Pectinidae, Cardiidae, Chamidae, Ostreidae, *Crassatella*, Naticidae, *Rimella* and many others. In contrast to subfacies XIIa the gastropods are clearly in the minority compared with the pelecypods. Other fossils that occur are various foraminifera, ostracods, different types of cheilostomatous bryozoans (vinculariiform and adeoniform types) and cyclostomatous bryozoans, crabs, various serpulid worms, sponges, some solitary corals and massive coral colonies, fish remains (rare) and fragments of *Halimeda* and dascycladaceans. The foraminifer *Reophax* as well as fragments of *Lithothamnium, Lithoporella, Corallina, Acicularia* and land plants are rare; where encountered they represent allochthonous elements.

An exceptionally well-preserved fauna which can be considered as a variant of the *Schizaster – Linthia – Ditremaster* community can be seen fairly high up in the *F. corbaricus* Zone of section X, immediately west of the village La Puebla de Roda. Here the irregular echinoids *Ditremaster* cf. *nux* (Desor), *Brissopsis* sp. and *Isopneustes* sp. occur. Many pelecypods have been found: large oysters, Pectinidae (including *Chlamys*), Chamidae, Limidae and Mytilidae (all epifaunal elements) as well as Musculinae (semi-infaunal). The presence of sponges consisting of funnel-shaped cups on relatively thin stems, and of complete skeletons of crabs of the species *Xanthopsis dufouri*, with pincers and articulate legs still attached, indicates quiet conditions during deposition. Association with subfacies XIVb and c suggests that this variant of the community lived in rather deep water.

The *Schizaster – Linthia – Ditremaster* community lived under about the same conditions as the *Spondylus* community. The sedimentation rate was somewhat

higher, and no significant erosion took place, as can be seen from the presence of complete echinoid skeletons and the smaller proportion of cemented pelecypods. Other environmental conditions agree with those of the latter subfacies. Many of the echinoid species listed for this subfacies probably also occurred in adjacent environments. There however they will be difficult to locate because there is less chance that they will have been preserved as complete skeletons and because they were probably less common. Thus originally the contrast with other (sub)facies was probably less than it seems to be now.

Transitions to subfacies XIa, b, c and d and subfacies XIVa exist. The presence of *Pseudomiltha* and/or *Velates* indicates the transition to subfacies XIb, that of *Ditrupa* to subfacies XIVa. Subfacies XIIb may be associated with subfacies XIIa and c, XIa, b, c and d, and with subfacies XIVa, b and c. In the latter case glauconite may be present.

Subfacies XIIb occurs in the *F. ellipsoidalis* Zone of sections F, H, J, K and V, in the *F. moussoulensis* Zone of sections F, J, K, L. O, V and X, in the *F. corbaricus* Zone of sections F, J, M, O, V and X, and in the *F. trempinus* Zone of section J.

Subfacies XIIc. Deposits containing a Patallophyllia community. – These deposits consist of dark grey marls and grey to dark grey biomicritic limestones (packstones) which are sometimes slightly sandy. The limestones usually show irregular bedding. As a rule nummulites are the most abundant perforate elements, but occasionally operculines, assilines or discocyclines may predominate. Miliolids are the most frequent imperforate foraminifera. The characteristic fossil is the solitary coral *Patallophyllia* (Pl. 4, Figs. 5, 6). Various molluscs occur, including pelecypods of the Cardiidae, Carditidae, Ostreidae and Teredinidae families and *Crassatella* (the two valves are often still joined together); Naticidae, *Turritella, Sigmesalia* aff. *duvali* (Rouault) and *Rimella* are common gastropods. Other fossils in this subfacies are various foraminifera, ostracods, echinoids (*Schizaster* sp.; *Porocidaris* spines; in general fragments of the skeletons), various cheilostomatous bryozoans (adeoniform, vinculariiform and lunulitiform types) and cyclostomatous bryozoans, other solitary corals, some coral colonies, various serpulid worms, crab remains, small radially ribbed brachiopods, fish remains (rare) and fragments of *Halimeda* and dasycladaceans. Allochthonous elements are fragments of *Lithothamnium*, driftwood containing Teredinidae (boring pelecypods) and other remains of land plants.

Lunulites bugei Reguant is a common fossil in subfacies XIIc, just as in subfacies XIId, XIVa, b and c. It belongs to the lunulitiform bryozoans, which have a peculiar mode of life and hence are of special ecological interest. Lagaaij (1963) studied these bryozoans extensively, especially the species *Cupuladria canariensis* (Busk) which is known from the Miocene to the present. The larvae settle on small, solid particles, for instance on coarse quartz grains, pellets, small fossil fragments or foraminifera. "The ideal biotope for the lunulitiform Bryozoa is therefore a small particle (quartz and/or carbonate sand) bottom. They never occur on a bottom consisting entirely of clay and are never found encrusting rocks, large pebbles, piles, larger shells, or other such large objects" (Lagaaij, 1963, p. 181). Therefore it is understandable that lunulitiform bryozoans are usually absent in the marls of the typical *Turritella* facies. The substrate particle is incorporated in the colony, so that the adult colony is free of the sediment. They can escape a shallow burial in the sediment by crawling upwards. All other bryozoans remain attached to a hard substratum. Lunulitiform bryozoans can therefore inhabit areas where other bryozoans cannot live.

The minimum depth at which the larvae of lunulitiform bryozoans can settle and develop into adult colonies depends on the degree of the water turbulence at the bottom, i.e. upon the level of the wave base and the strength of bottom currents; the larvae cannot settle on a bottom where the sand grains tend to shift under the influence of water movement (Lagaaij, 1963, p. 187).

The *Patallophyllia* community thus lived in a low-energy environment below wave base. The sedimentation rate was usually higher than that in the environment of the *Schizaster – Linthia – Ditremaster* community, but was still relatively low. The average depth was probably greater than that of the two preceding subfacies, although the maximum depth will not have differed much from that of these subfacies.

There are often transitions to facies XV, in which *Turritella* as well as *Patallophyllia* are numerous. Transitions to facies XI and subfacies XIVa and b also exist. Subfacies XIIc may have been associated with facies XV and with subfacies XIIa, b and d, XIa, b, c and d, XIVb and c and VIIIe.

Subfacies XIIc occurs in the *F. ellipsoidalis* Zone of sections F, H', J, U and V, in the *F. moussoulensis* Zone of sections F, I, R and U, and in the *F. corbaricus* Zone of sections F, H, I, J, M, O, R, U and X.

Subfacies XIId. Deposits containing a fauna poor in species. – These deposits consist of dark grey marls and some clayey biomicritic limestones (packstones and wackestones). Nummulites are the most abundant perforate foraminifera, miliolids the most abundant imperforate ones. Furthermore *Orbitolites, Operculina, Assilina* and *Discocyclina* can occur. Oysters are probably the most common pelecypods; in addition Carditidae and occasionally Limidae have been found; the two valves are often still joined together. Other less common fossils are gastropods, other foraminifera, ostracods, echinoids (mainly fragments), adeoniform, vinculariiform and sometimes lunulitiform cheilostomatous bryozoans, cyclostomatous bryozoans, serpulid worms and in rare instances scaphopods. The number of species is always small.

These sediments show the greatest affinity with the other subfacies of facies XII. The conditions under which these deposits were formed were probably about

the same as those for the *Patallophyllia* community.

Transitions are known to subfacies XIb and XIVb. Subfacies XIId occurs in association with facies XI and subfacies XIIb and c. Subfacies XIId occurs in the *F. cucumiformis* Zone of sections H' and S. in the *F. ellipsoidalis* Zone of sections H, I and J, and in the *F. moussoulensis* and *F. corbaricus* Zones of sections I and J.

Facies XIII. Fore-reef detrital limestones (deeper fore-reef deposits)

These deposits consist of an accumulation of shells which are in general broken. Remains of large benthonic foraminifera, echinoids, bryozoans and red algae dominate, although their mutual proportions can differ markedly. For this reason three subfacies can be distinguished which gradually merge into one another. The faunal and floral composition of this facies is usually more diverse than that of the fore-reef detrital limestones from Louisiana and Guam described by Forman & Schlanger (1957), who found assemblages in which large benthonic foraminifera predominated substantially over all other groups.

The broken fossils have usually retained their angular edges, which indicates that they were transported over short distances only. This can also be deduced from the usually sudden transitions to other facies. The characteristic fossils of facies XIII are usually found in much smaller quantities in adjacent environments, suggesting that they actually lived on the fore-reef slopes, although it is extremely difficult to find any fossils in position of life. Without doubt this was due to the low sedimentation rate, coupled with some current action. The most common sedimentary structures are channels and megacross-bedding; vertical and horizontal burrows also occur. The frequent occurrence of glauconite indicates that these deposits were formed in fairly deep water (Chapter VII, section 5). It occurs as sand grains and as filling in fossils.

Nummulites are usually the dominant group of perforate foraminifera. Miliolids are frequent and alveolinids, especially *F. (F.) oblongus*, are often common. Where the sea was deeper *Discocyclina* predominates. *Operculina, Assilina* and *Orbitolites* are usually less important. Thus as a rule a distinct mixed imperforate–perforate foraminifera association occurs, even though these deposits were formed in relatively deep water. The imperforate foraminifera could live here at greater depths than usual because the sediment consists mainly of pure limestones without clay.

Most fossils can be found in all three subfacies: the red algae *Lithothamnium, Lithoporella, Corallina* and *Distichoplax biserialis*, the green algae *Halimeda* and dasycladaceans, foraminifera (including sessile ones), ostracods, various cheilostomatous and cyclostomatous bryozoans, irregular and regular echinoids, oysters (chiefly juvenile specimens), Pectinidae, boring and other pelecypods (the two valves often still joined together), gastropods, serpulid worms (including *Haliotus*) and fragments of crabs and corals (solitary ones and colonies).

This facies is confined to the *F. corbaricus* Zone.

Subfacies XIIIa. Deposits containing a community of various cheilostomatous and cyclostomatous bryozoans (Pl. 7, Fig. 4). – These deposits consist of light grey to grey biomicritic and biosparitic limestones (packstones and grainstones), which are sometimes slightly sandy. Large benthonic foraminifera and cheilostomatous and cyclostomatous bryozoans predominate in this subfacies, among which the vinculariiform types are most numerous (chiefly *Idmonea* s.l.), followed by the adeoniform types (*Beisselina*). Sometimes some fragments of *Biflustra* are present. Terebratulid brachiopods and small, radially ribbed brachiopods occur commonly. Spines of *Porocidaris* are scarce. Fragments of massive and branching coral colonies, *Acicularia*, and the foraminifer *Reophax* are allochthonous. They are derived from the reefs, just like many fragments of red algae.

Many *Lithothamnium* colonies however will have been autochthonous and they contributed to the formation of a firm sea bottom upon which the bryozoans could attach themselves. The many vinculariiform bryozoans indicate that it was a quiet sea and that the depth of the sea was considerable (Stach, 1936; Lagaaij & Gautier, 1965). The latter two authors only found high percentages of these bryozoans below a depth of 120 m. It is impossible to suppose that little or no current action occurred. The composition of the fauna and flora makes it highly likely that continuous currents existed which did not change much in direction. Strong currents would jeopardize the many fragile epifaunal organisms too much. Low current velocities must have prevailed (less than about 20 cm/sec; see Schopf, 1969, table I).

Transitions occur to facies X and subfacies XIIIc and XIVa. Subfacies XIIIa has been found in association with subfacies XIIIc, Xb, VIIId and e. IXa and XIVa and d. It occurs in the *F. corbaricus* Zone of sections J, K, L, M, N, O, P, Q and X'. The most extensive development of this subfacies occurs in section P.

Subfacies XIIIb. Deposits containing a Biflustra community (Pl. 7, Fig. 3). – These deposits consist of light grey to grey biosparitic and biomicritic limestones (grainstones and packstones), which sometimes are sandy. If the sand contains numerous black rock-derived grains, the limestones are dark grey. Large benthonic foraminifera, the cheilostomatous bryozoan *Biflustra* and echinoid fragments predominate in this subfacies. *Biflustra* fans can form complete tapestries on bedding planes, when they are washed together. The upper layer of zoecia of the flat lying fans is often partly filled with lime mud, thus forming clear-cut geopetal structures (Pl. 7, Fig. 3). The lower layer seems to have been much more difficult to fill. It was usually free of sediment at first and became filled later with clear sparry calcite. When the upper layer is filled entirely with lime mud and the lower layer is still entirely free of sediment, as frequently happens, the geopetal structures can easily be

misinterpreted, for one is inclined to think that the filled layer is the lower one.

Other bryozoans are of minor importance. Molluscs are more abundant than in subfacies XIIIa and c. Fragments of massive coral colonies and red algae, *Acicularia*, dasycladaceans and *Reophax* are debris from adjacent reefs.

This subfacies often contains more grainstones than subfacies XIIIa. In these grainstones in particular the fossil fragments are more rounded; this indicates a more agitated environment, which was probably on the average somewhat shallower than that of subfacies XIIIa.

Biflustra belongs to the eschariform type of bryozoans. Stach (1936, p. 62) wrote: "This type is adapted for life in sublittoral zones at depths of at least 10 fathoms. ... It may extend to deeper water, but not to the littoral zone".

The species *Biflustra savartii* which is known from the Eocene to the present, nowadays has a tropical distribution and lives at a depth of at least 100 m (Lagaaij, 1952, p. 19, 20). According to Schopf (1969) recent eschariform bryozoans occur in environments with moderate current velocities and a low rate of sedimentation. The sedimentary characteristics of subfacies XIIIa confirm that the fossil *Biflustra* lived under similar circumstances. Schopf (1969, p. 243) wrongly incorporated *Biflustra* in the flustriform group, which consists of bryozoans with chitinous, very flexible skeletons adapted to littoral environments.

Transitions occur to subfacies IXa, XIIIc and XIVa. Subfacies XIIIb has been found in association with subfacies IXa, XIIIc, XIVa and d, and sometimes with subfacies IVd. It occurs in the *F. corbaricus* Zone of sections A, I, J, K, L, M, N, O and Q. The most typical and most extensive development of this subfacies occurs in sections L and M.

Subfacies XIIIc. Deposits containing a community of many irregular echinoids. – These deposits consist of light grey to grey biomicritic and biosparitic limestones (packstones and grainstones), which are often sandy. The sand frequently contains many black rock-derived grains which give the limestones a dark grey colour. Large benthonic foraminifera and echinoid fragments predominate over all other fossils and even the echinoid fragments can be less numerous; in that case this subfacies approximates the fore-reef detrital limestones of Forman & Schlanger (1957). It is not easy to find whole skeletons of echinoids and therefore species identification is difficult; only one complete skeleton of an irregular echinoid has been found, i.e. the schizasterid *Linthia* sp. ex gr. *aragonensis* Cotteau, Although the echinoids have never been found in situ and are nearly always broken, they must have lived in large numbers in this environment, for the fragments are usually more numerous here than in adjacent (sub)facies. The number of echinoid fragments is roughly inversely proportionate to the rounding of the fossil fragments. Thus the echinoids seem to have preferred the quieter parts of this subfacies.

The absence or rare presence of bryozoans in this subfacies can often be attributed to the very sandy nature of many of the limestones. Probably the sedimentation rate was commonly too high and the currents were too strong for these animals to be able to settle. This subfacies formed at the same depths as the two preceding subfacies. Transitions to subfacies XIIIa and b and XIVa and facies X can be seen. Subfacies XIIIc has been found in association with subfacies XIIIa and b, IXa and b, XIVa and d, Xb and VIIId and e, and sometimes with subfacies IVd. It occurs in the *F. corbaricus* Zone of sections I, J, K, L, M, N, O, P and Q. The most typical development of this subfacies occurs in section Q and the most extensive occurrence has been found in sections K, L and O.

Facies XIV. Deposits of marls, impure limestones and some sandstones containing perforate foraminifera associations

The foraminifera associations of these deposits are called perforate foraminifera associations, although miliolids commonly occur and alveolinids are not rare in subfacies XIVa and c. Many of the miliolids and some of the alveolinids have been transported from shallower environments and the autochthonous alveolinids are limited to a few deep water species.

The autochthonous elements of all subfacies include the following fossils: large benthonic foraminifera, small benthonic ones (more rare than in shallower deposits), ostracods, echinoid fragments (including *Porocidaris* spines), gastropods and pelecypods (including *Ostrea* and *Turritella*), serpulid worms, crab fragments, cyclostomatous bryozoans (chiefly *Idmonea* s.l.) and the cheilostomatous bryozoan *Beisselina*. Planktonic foraminifera and remains of lands plants, both allochthonous fossils, can be found in all subfacies.

Horizontal and vertical burrows are usually the only structures in these sediments. Glauconite occurs as filling in fossils and as sand grains, when the sedimentation rate was low. The presence of glauconite indicates that the formation of this facies took place in rather deep water (see Chapter VII). This authigenic mineral is however often absent because of a sedimentation rate which was too high. Unfortunately not all deposits belonging to facies XIV can be assigned with certainty to one of the four subfacies because the ecological guide fossils are sometimes rare.

Subfacies XIVa. Deposits containing a Ditrupa community (Pl. 8, Fig. 1). – These deposits consist of light grey to dark grey sandy, silty or clayey biomicritic limestones (packstones), grey to dark grey marls which are often silty and some grey sandstones. The limestones are sometimes partly sparitic; the fossils in these limestones are frequently rounded. Moreover sedimentary structures such as channels and megacross-bedding are more common here; these

deposits were subjected to relatively strong current action.

The fauna usually consists of a limited number of species. Nummulites predominate in the limestones which contain many angular or rounded fossil fragments and consequently have a coarse-grained structure. Operculines and discocyclines are generally common. In marls and limestones with a more micritic matrix and fewer fossil fragments the assilines predominate. In these latter deposits operculines and discocyclines are common as well. The large benthonic foraminifera are practically always by far the most abundant of all fossils. The characteristic worm *Ditrupa* with its slightly and regularly bent tubes consisting of two distinct layers, a calcitic and an aragonitic one (Pl. 8, Fig. 1), is usually sufficiently numerous to be present in thin sections; the species is *Ditrupa plana* (J. Sowerby). In the coarse-grained, nummulite-dominated limestones the concentration of the tubes of *Ditrupa* is greater because of the lower sedimentation rate of these sediments. Sometimes they may also have been washed together.

Other fossils which regularly occur are echinoid fragments, pelecypods, gastropods and different species of serpulid worms. Vinculariiform, adeoniform and lunulitiform bryozoans have been found. It is not likely that they are all autochthonous.

One whole specimen of the regular echinoid *Rhabdocidaris* aff. *pouechi* Cotteau has been found. Other autochthonous fossils are the pelecypods of the Carditidae, Cardiidae, Veneridae, Arcidae, Pectinidae and Musculinae, and *Crassatella*. Except for the representative of the Musculinae which is a semi-infaunal element, and the usually epifaunal Pectinidae, all are infaunal pelecypods which lived in the uppermost part of the sediment.

Other fossils, which occur mainly as fragments, are definitely allochthonous and came mainly from reefs; these are fragments of massive and branching coral colonies, *Lithothamnium*, *Corallina*, *Lithoporella*, *Distichoplax biserialis*, *Acicularia*, dasycladaceans, sessile foraminifera, *Reophax* and radiolarians. They represent only a small proportion of the total number of the fossils.

At present the distribution of the genus *Ditrupa* is known to be world-wide in tropical to temperate latitudes. The recent species *Ditrupa arietina* (O. F. Müller) is known to occur in the northern part of the North Sea, the Skagerrak, the Cattegat, the Channel and the northern Öresund (Hartmann-Schröder, 1971), and near the Atlantic and Mediterranean coasts of France and Spain (Toulemont, 1972, Picard, 1965; Rioja y Lo Bianco, 1931), as well as in the Atlantic Ocean, the Mediterranean Sea, the Red Sea, the Andaman Sea (at 785 fathoms) and around the Philippine Islands (Fauvel, 1953). Recent *Ditrupa* sp. has also been reported off the Japanese coast at 71 fathoms (Cheng, 1974). The European finds are better documented and are usually in shallower water. Off the coast of Brittany *D. arietina* has been found at depths ranging between 60 and 85 m in the *Astrorhiza limicola* community and in the *Maldane*

glebifex – *Amphiura filiformis* – *Amphiura chiajei* subcommunity (Toulemont, 1972). Picard (1965) found this species off the French coast near Marseille at depths ranging between 32 and 78 m, and occasionally between 105 and 113 m. Finally, Pérès (1959) records living specimens at depths ranging between 91 and 210 m in the waters around Corsica and the sea between Tunisia and Malta. As far as this author knows a modern analogue of the abundant occurrence of *Ditrupa* found in the Tremp Basin exists only in the northern part of the present North Sea. Large masses of *Ditrupa* also occurred in the Sands of Kattendijk which were deposited in the Early Pliocene North Sea in the neighbourhood of Antwerp (Belgium).

Like all other serpulid worms *Ditrupa* is a suspension feeder; it differs however in that it is not encrusted on a hard substrate. Instead the tubes are loose and rise above the soft sediment bottom. Off the coast of Brittany this species lives on and in very fine to medium-grained sand bottoms (grain diameters between 0.05 and 0.5 mm) with a highly variable pelitic content (Toulemont, 1972). The sediments in which Picard (1965) found *Ditrupa* are described as heterogeneous, that is to say sediments with sand, silt and clay mixed together. In both areas *Ditrupa* occurs only in the transitional zones between domains containing mainly sand or clay deposits.

These data agree well with those of the *Ditrupa* community in the Tremp Basin. The sediments in which *Ditrupa* has been found here are usually also heterogeneous and also represent the transition between the more sandy and the more clayey areas. The tidal difference in the Mediterranean Sea is small, that of the Atlantic Ocean near Brittany is certainly greater. *Ditrupa* always inhabits places where the tide-induced currents are weak or absent and therefore it can live at shallower depths in the Mediterranean Sea. Sedimentary and palaeontological evidence proves that the tidal influences were strong in the Tremp Basin, so that the depth at which the *Ditrupa* community lived was certainly as great as that in Brittany.

Transitions occur to subfacies XIIIb and c, XIVb, XIIb and c and IXa, and facies XI and XV. Subfacies XIVa has been found mainly in association with subfacies XIVb and c and facies XIII. It is also associated with subfacies XIIb and c, XIa and IXa, and facies XV. Its widest distribution is in the *F. corbaricus* Zone: it occurs in sections F, H, I, J, L, M, O, P, Q, U, V, X and X', it also is seen in the *F. moussoulensis* Zone of sections F, V, Y, and Z, and the *F. ellipsoidalis* Zone of section V.

Subfacies XIVb. Deposits containing a Conocrinus community (Pl. 8, Figs. 2, 3). – These deposits consist of grey to dark grey marls and dark grey to light grey clayey, silty and sandy biomicritic limestones (packstones). The most abundant large benthonic foraminifera are assilines, operculines and discocyclines. Nummulites are rare. The abundance of cheilostomatous bryozoans is striking. There are many specimens of

many species of the vinculariiform, adeoniform and lunulitiform types. Cyclostomatous bryozoans are also seen (chiefly the vinculariiform *Idmonea* s.l.). The loose internodes of the sea lily *Conocrinus doncieuxi* Roux, 1978 are often sufficiently numerous to appear in thin sections. Whole skeletons of these animals have never been found. Small radially ribbed brachiopods are common, terebratulids are much more scarce. Among the pelecypods the pectinids must be mentioned. The worm *Spirorbis* has also been found. Radiolarians are rare allochthonous elements.

As a rule the bryozoans are abundant in those beds containing large concentrations of fossils. In these usually thin layers the majority of the fossils has been broken and/or rounded. These deposits contrast with the more commonly occurring marls in which fragmentation is not as pronounced. The nature of these fine sediments and the fauna indicates that the currents were usually weak.

A recent relative of the fossil *Conocrinus* is *Rhizocrinus lofotensis* M. Sars, 1864*. This species is characterized by its small and fragile stem and calyx. The internodes of the stem are obviously more slender than those of the fossil species. The recent animals fall apart easily and the same may be presumed for the fossil *Conocrinus*. Therefore it is not strange that a complete fossil skeleton or at least a major portion of one has never been found, although they were somewhat more robust. The recent species lives together in large numbers; the fossil species must have had the same gregarious way of life, otherwise the abundance of skeletal parts of these sea lilies remains unexplained. *R. lofotensis* prefers to live on a firm mud bottom where it anchors itself with its cirrhi; extra attachment points are furnished by empty shells, spines of sea urchins, etc. (Sars, 1868). High sedimentation rates cannot therefore be endured. It may be assumed that the fossil *Conocrinus* made the same demands on its environment.

The recent species lives at considerable depths. It has been found by Sars off the Lofoten Islands (Norway) at depths ranging between 100 and 300 fathoms. It is also known to occur in deep waters in the tropics, since it has been found before the coasts of Surinam and British Guyana on muddy bottoms at depths of ca. 500–600 m (J. Walenkamp, pers. comm.). It is however not possible

that the fossil *Conocrinus* should have lived at such great depths in the Tremp Basin: the abundance of large benthonic foraminifera proves that it must have lived in the photic zone. The *Conocrinus* community often alternates with the *Ditrupa* community which contains many molluscs which are normally confined to the photic zone. Thus the *Conocrinus* community certainly lived at depths comparable with those of the *Ditrupa* community. It is therefore impossible for this sea lily to have lived in really shallow waters.

The only way in which such concentrations of broken and rounded fossils could have been formed at these depths is through severe storms or temporarily strong currents. The fine sediment particles are then washed away to deeper parts of the basin and a lag deposit consisting of the coarser fossil fragments is left.

The most frequent transitions are those to facies XV. There are also transitions to subfacies XIVa and c and XIIa and c. Subfacies XIVb has been found in association with these same facies and subfacies. It occurs in the *F. corbaricus* Zone of sections H, U, X and X', in the *F. moussoulensis* Zone of sections R, U and Z, and in the *F. ellipsoidalis* Zone of section U. It is striking that it has only been found on the northern side of the Tremp Basin.

Subfacies XIVc. Deposits containing a mollusc-rich community (Pl. 8, Fig. 4). – These deposits consist of grey to dark grey, often silty marls and grey to dark grey, sometimes light grey, biomicritic limestones (packstones, rarely wackestones) which can be silty, clayey and sometimes sandy. The most abundant large benthonic foraminifera are assilines and operculines. Discocyclines may also be common. Molluscs are the most important group of organisms. There are usually numerous species. The number of specimens is rather variable. Probably this subfacies can be subdivided into more subenvironments after a more detailed study, since different mollusc assemblages seem to occur. The pelecypods are the most varied. The following families and genera have been identified: Carditidae, Cardiidae, Veneridae, Musculinae, Nuculidae, Arcidae, Pectinidae, *Ostrea* (many juvenile specimens), *Crassatella, Pholadomya* and *Thyasira*. The two valves are often still joined together. Gastropods are represented by Turridae, *Turritella,* Buccinacea, *Sigmesalia* aff. *duvali* (Rouault) and *Athleta* (? *Volutispina*). Many other unidentified species of pelecypods and gastropods also occur. The scaphopod *Dentalium* is occasionally seen. Other fossils are vinculariiform and lunulitiform bryozoans, the solitary coral *Trochocyathus, Spirorbis* and other serpulid worms, small radially ribbed brachiopods, sponges and fish remains (rare). Fragments of massive coral colonies are scarce and are undoubtedly allochthonous.

Nuculacea are discriminating bottom sediment feeders (Stanley, 1970; Boekschoten, 1963). Most of the other pelecypods are suspension feeders. Cardiidae, Carditidae and Veneridae are largely restricted to bottoms which belong to the photic zone. This can be due to their

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*) After completing the text I found a picture of an internode of *Conocrinus doncieuxi* in Roux, 1978a (pl. 2, fig. 2) which is evidently the same species that I have found in the Tremp Basin. This new species will be described in Roux (1978b). Roux (1976) described two new recent species belonging to the genus *Conocrinus*, viz. *C. cherbonnieri* and *C. cabiochi*, which occurred at depths of about 300–500 m and about 2000 m, respectively. Therefore the depth range of *Conocrinus* is considerable (see also Roux & Montenat, 1977). The two recent species of *Conocrinus* and the recent *Rhizocrinus lofotensis* seem to live under about the same ecological circumstances. Probably the genera *Conocrinus* and *Rhizocrinus* are synonymous (Roux, 1976); if so, then the name *Conocrinus* deserves priority because it is the older one.

dependence on a sufficient supply of phytoplankton (Boekschoten, 1963; Yonge, 1928). *Thyasira* is a pelecypod which usually lives in deeper waters; it is a characteristic element of many deep-sea clay bottoms at present, but it has also been found before the Rhône delta in water 20 m deep by van Straaten (1960). The depth to which light penetrates sea water depends highly upon the transparency of the water, and this is determined mainly by the concentration of the suspended material. It is highly unlikely that light penetrated beyond about 150 m, in view of the large accumulations of clay in the northern part of the basin.

In some marls small thin-shelled pelecypods and gastropods are the only molluscs. These beds were probably deposited at considerably higher rates than those containing the larger, thicker-shelled molluscs. Rapidly deposited clay is much softer and contains much more water between the clay particles than slowly deposited clay. Small thin-shelled molluscs do not sink into the muddy bottom as easily as the larger species do (Stanley, 1970). Therefore although the sediments are mainly marls, which barely differ from one another lithologically, their sedimentation rate may have varied greatly.

Transitions occur to facies XV and subfacies XIVb and d and XIIc. Subfacies XIVc has been found in association with facies XV, subfacies XIVa, XIIIa and c, XIb and sometimes with subfacies IVd. Its widest distribution is in the *F. corbaricus* Zone in sections H, I, L, N, O, U, X and Y. It also occurs in the *F. moussoulensis* Zone of sections H, H', R, U and Y, in the *F. ellipsoidalis* Zone of sections H and H', and in the *F. trempinus* Zone of section X.

Subfacies XIVd. Deposits containing a fauna poor in species. – These deposits consist of dark grey and grey marls and some biomicritic limestones (packstones), which are often silty and sometimes sandy, and some sandstones with clay galls. Assilines and operculines are the most important large benthonic foraminifera. Nummulites and discocyclines may also occur. Oysters, many of which are juveniles, are probably the most common molluscs in this subfacies. Sometimes they are clearly found in situ. Furthermore some *Turritella*, Carditidae and a few other pelecypods and gastropods may be present. Bryozoans, terebratulid brachiopods and fish remains are rare. Fragments of *Lithothamnium* and coral colonies can only be allochthonous elements.

The circumstances were far from favourable in this subfacies; this can be concluded from the fact that the fauna is poor in species. The only possible reason for this can be that the sedimentation rate was too high.

Transitions occur to subfacies XIVc and XIIc. This subfacies is associated with facies XV and subfacies XIVa and IVd. It occurs in the *F. corbaricus* Zone of sections I, J, K, L, O, U and V, in the *F. ellipsoidalis* Zone and/or *F. moussoulensis* Zone of sections H and H', and in the *F. trempinus* Zone of section X.

Facies XV. Deposits containing a Turritella community

This facies consist of grey to dark grey, in rare instances light grey, marls and biomicritic limestones (packstones). The marls are often silty and the limestones are mainly clayey and/or silty. The marls predominate markedly over the limestones in this facies. They are generally much thicker than the limestones. The most frequent structures are horizontal burrows, followed by load structures. Vertical burrows are rare, as is cross-bedding. A perforate foraminifera association occurs in which assilines and operculines are the most abundant elements. Discocyclines are much scarcer and nummulites occur only occasionally. Miliolids are the only imperforate elements.

The characteristic fossil of subfacies XV is the gastropod *Turritella trempina* Carez, which can be replaced by *Turritella figolina* Carez (see de Renzi, 1968). The latter species can be distinguished from the former by its sharper, more protruding carina. The number of specimens found is highly variable. These gastropods occur in such quantities in some beds that they lie piled up one on top of the other; the remaining interspace is then filled with marl and other, smaller fossils. On the other hand the number of turritellids can be so small that the marls in question are easily confused with marls of other facies, like those of subfacies XIVb and c. Thus gradual transitions to these subfacies exist, and also to subfacies XIIc.

The most typical fossil assemblage which causes the least confusion with other assemblages of other facies is a fauna with few species which contains in addition to *Turritella* some gastropods and pelecypods, foraminifera, ostracods, serpulids and remains of irregular sea urchins. Other assemblages in the Tremp Basin which belong to facies XV have a richer fauna. In addition to the faunal elements already mentioned the following fossils may also be included in this assemblage: bryozoans (especially *Lunulites*, but also some *Beisselina*, and fragile vinculariiform types), the solitary coral *Trochocyathus*, small radially ribbed brachiopods, sponges, regular sea urchins and the worm *Spirorbis*. Special groups of molluscs that should be mentioned are *Sigmesalia* aff. *duvali*, Naticidae and Strombidae (gastropods) and Carditidae, Mytilidae, Nuculanidae and *Crassatella* (pelecypods). Allochthonous elements are shark teeth (rare), boring pelecypods of the Teredinidae family and remains of land plants.

Various recent turritellids can endure high sedimentation rates. The most comprehensive ecological study on a *Turritella* species has been written by Sartenaer (1959). Sartenaer, and also van Straaten (1960) and Picard (1965), found large quantities of living specimens of *Turritella tricarinata communis* Risso quite close to the mouth of the Rhône River, where other molluscs are very rare or even absent. It can occur in large numbers there because it does not need to compete with other organisms. This *Turritella* species is well adapted to environments in which fine sediments are rapidly deposited (see also van Straaten, 1970, p. 112). Small tentacles along the mantle margin ensure that only desirable sediment particles can intrude into the mouth.

The species can also easily escape burial under new sediment by crawling upwards to the new sediment surface (Sartenaer, 1959; van Straaten, 1960). Turritellids are infaunal deposit feeders; this mode of feeding is common to only a few groups of gastropods; they filter by a process of ciliary feeding and eat finely sifted bottom sediments (Cox, 1960). *T. tricarinata communis*, a deposit feeder like other turritellids, thus lives in a special ecological niche not open to other molluscs or macro-invertebrates; it requires large quantities of finely grained bottom material and cannot withstand too much turbulence in the water (Sartenaer, 1959, van Straaten, 1960).

For these reasons it is not accidental that *Turritella* is most abundant in those parts of the Tremp Basin where the thickest and most finely grained sediment masses developed. Therefore there is no reason to doubt that the above-mentioned fossil species lived under the same sedimentary conditions as the recent *T. tricarinata communis*. In other facies other turritellid species sometimes occur. These species demand another type of environment. Such turritellids are also known to exist today. *T. triplicata* (Brocchi) for instance also lives along the French Mediterranean coast, but prefers sandier environments (see Picard, 1965).

The richer assemblage indicates a distinctly lower sedimentation rate than that presumed for the poor assemblage. Nevertheless this sedimentation rate is nearly always still much too high for the formation of glauconite, since this mineral is seldom found.

The depth at wich this facies developed is rather variable. The upper limit is determined by the wave base and by strong currents. In the Mediterranean Sea where tidal and current actions are limited *T. tricarinata communis* can be found in large numbers in up to 10 m

of water (Sartenaer, 1959; van Straaten, 1960). In the Tremp Basin with its stronger tidal and current actions the upper limit for the occurrence of numerous *T. trempina* and *T. figolina* was certainly much lower. A minimum depth of 20 m seems reasonable.

The deepest recent occurrence of *Turritella* is 210 m (Pérès & Picard, 1958). Van Straaten (1960) found *T. tricarinata communis* in water more than 120 m deep before the Rhône delta, but it is no longer abundant below 50 m. According to Sartenaer (1959) a dramatic decrease in the number of specimens of this species occurs at about 35 m in the Gulf of Fos. This *Turritella* prefers to live in the biocoenosis of the coastal terrigenous mud, which shows a striking decrease in number of specimens of all organisms below 85 m (Picard, 1965).

The lower limit for the occurrence of numerous *T. trempina* and *T. figolina* must also be lower in the Tremp Basin than in the present Mediterranean. The deposits in which these species are abundant and/or the fauna exhibits the highest diversity are thus the shallowest members of this facies. The deepest members display an impoverished fauna, qualitatively as well as quantitatively whereby the turritellids are also much more rare.

Frequently *Turritella* and *Patallophyllia* are associated with one another. Such a community forms the transition to subfacies XIIc. Facies XV is found mostly in association with this subfacies or subfacies XIVc and b. Occasionally it is associated with subfacies XIVa and d, XIIa and XIa. It has been found only in the northern and central parts of the basin. It occurs in the *F. ellipsoidalis* Zone and *F. moussoulensis* Zone of sections H, H', R and U, and in the *F. corbaricus* Zone of sections H, I, R, U and X.

CHAPTER VI

PALAEOGEOGRAPHY OF THE SUCCESSIVE PHASES AS DEFINED BY THE ALVEOLINID BIOZONES

GENERAL REMARKS

Introduction
One attempt to reconstruct palaeogeographic maps of the Tremp Basin has preceded this study. Ferrer et al. (1971) published an isopach map for the entire Ager Formation, and facies maps covering mainly the same stratigraphic intervals used in the maps of the present publication.

No attempt was made in the present study to draw an isopach map for the entire formation because not enough data concerning the upper part of the formation were available. Nevertheless our results make it clear that Ferrer's isopach map is based on too few data.

Compared with my interpretation the interpretation of the facies presented by Ferrer et al. is generally that of a much shallower basin. In their opinion large areas were

covered by beaches, lagoons and sheltered bays, leaving comparatively little space for open marine environments. This interpretation cannot be maintained when the ecology of recent representatives of important fossil species is taken into account. Ferrer et al. were led to assume so many shallow, protected environments on account of the presumed presence of bars built up of nummulite shells. Such bars would have acted as barriers protecting the sheltered marine environment. The present author has not however found any evidence that the nummulite accumulations encountered have formed submarine ridges. These accumulations always occur in planar sediment bodies in which no sedimentary structures have been observed.

None of the various reef types which do occur were identified by Ferrer et al. Independently Gaemers (1971) and Garrido & Rios (1972) discovered the reefs on the

northern side of the basin. The reefs on the southern side were first mentioned by Gaemers (1974).

Evidence for erosion in the hinterland
Conglomerates have been found chiefly in the *F. cucumiformis* Zone. In the Tremp Basin they always have a polymict composition. Most frequent are pebbles and cobbles of sandstones, limestones and white quartz. The sandstones and limestones can often be identified by means of their fossil content as originating from the Arén Formation or from the Tremp Formation. Other Cretaceous pebbles also occur. At least some erosion of the Tremp Formation must have taken place. This formation contains many conglomerates which include numerous pebbles from older formations. On the basis of the conglomerates therefore it cannot be proven that deposits older than the Tremp Formation furnished the coarse material for the Ager Formation.

The sand fraction which occurs in many beds in the area studied consists predominantly of black rock particles; under the microscope lighter and darker areas and white spots are visible in these particles. Often these black grains are so numerous that the colour of the sandstones becomes grey to very dark grey. Sometimes these rock fragments reach the size of fine gravel; in one case distinct radiolarians were observed in such a fragment. These particles therefore can only come from the Lower Carboniferous black radiolarites which are highly resistant to weathering. These radiolarites had however already been attacked by erosion during Late Carboniferous, Permian and Early Triassic times, and occur as sand grains and pebbles in large amounts in the deposits formed during those times (pers. comm. P. J. C. Nagtegaal). Thus it is not necessary that Lower Carboniferous sediments were eroded in the Early Tertiary. It is indeed probable that the Triassic Bunter furnished this material. The radiolarite fragments also occur in some Cretaceous deposits, but there they are too scarce to be an important supply for the Ager Formation.

Muscovite occurs in many sandy deposits of the Ager Formation. the frequent occurrence of biotite and muscovite flakes in the upper part of the *F. corbaricus* Zone and the *F. trempinus* Zone on the northern side of the basin is worth mentioning. They are often large and always appear fresh. Biotite especially is not very resistant to weathering and it is therefore inconceivable that this mica was involved in more than one sedimentation cycle. During Early Eocene times the biotite must have been eroded from the northern to northeastern hinterland, biotite being absent on the southern side of the basin. The biotite and much of the muscovite can only have originated from the axial zone of the Pyrenees where many granites occur. These old intrusive rocks must therefore have been exposed at least in some places during the Early Eocene.

Moreover the occurrence of mica suggests that "winnowing and/or by-passing are not being carried out efficiently" (Doyle et al., 1968, p. 381). The large quantities of mica in the upper half of the Ager Formation on the northern side of the basin indicate that much mica was supplied, and little mica was washed

A	- Aren	I	- Isona
Ag	- Ager	PM	- Puente de Montañana
B	- Benabarre	PR	- la Puebla de Roda
C	- Campo	T	- Tremp
G	- Graus	ST	- San Salvador de Tolo

	facies	I-II	deposits of rivers, swamps and lagoons
o	„	III-IVa,b,c,e	beaches and barriers, shallow tidal deposits and shallow turbidites
•	„	IVd	deeper tidal deposits
	„	Va	sand waves mainly with imperforate foraminifera
	„	Vb	sand waves etc. mainly with perforate foraminifera
▲	„	VI	shallow marine deposits with imperforate foraminifera
	„	VII-VIII-IXb-X	back-reef, reefs, reef channels and fore-reef
+	„	IXa	off-reef shoals
—	„	XI	pure limestones with imperforate and perforate foraminifera
I.	„	XII	marls and clayey limestones with imperforate and perforate foraminifera
▽	„	XIII	fore-reef detrital limestones (pure limestones of the deeper fore-reef)
□	„	XIVa	deeper marls and impure limestones with *Ditrupa* community
▪	„	XIVb,c,d	other deeper marls and impure limestones with perforate foraminifera
—	„	XV	marls and clayey limestones with *Turritella* community
↷	slumping of facies XIV		
⤳	turbidites		

isopachs in metres
uninterrupted isopachs: best known isopachs
dashed isopachs: extra polated isopachs

Legend for Figures 3–12.

away (Doyle et al., 1968). From this it can be concluded that resedimentation was unimportant and the sedimentation rate was relatively high.

The study of the nannoplankton has revealed that 90% or more of the specimens were reworked from the Cretaceous. Most of this material originates from the Upper Cretaceous (all stages are represented), and some of it even comes from the Albian and pre-Albian. It is therefore not unreasonable to suppose that the bulk of

the large quantities of clay in the Ager Formation was furnished by Upper Cretaceous rocks. Moreover this conclusion makes it more probable that coarser material of the same interval also contributed directly to the sediments of the Ager Formation.

Remarks concerning the horizontal sections (Enclosures 2 and 3)

One horizontal section connects the measured vertical
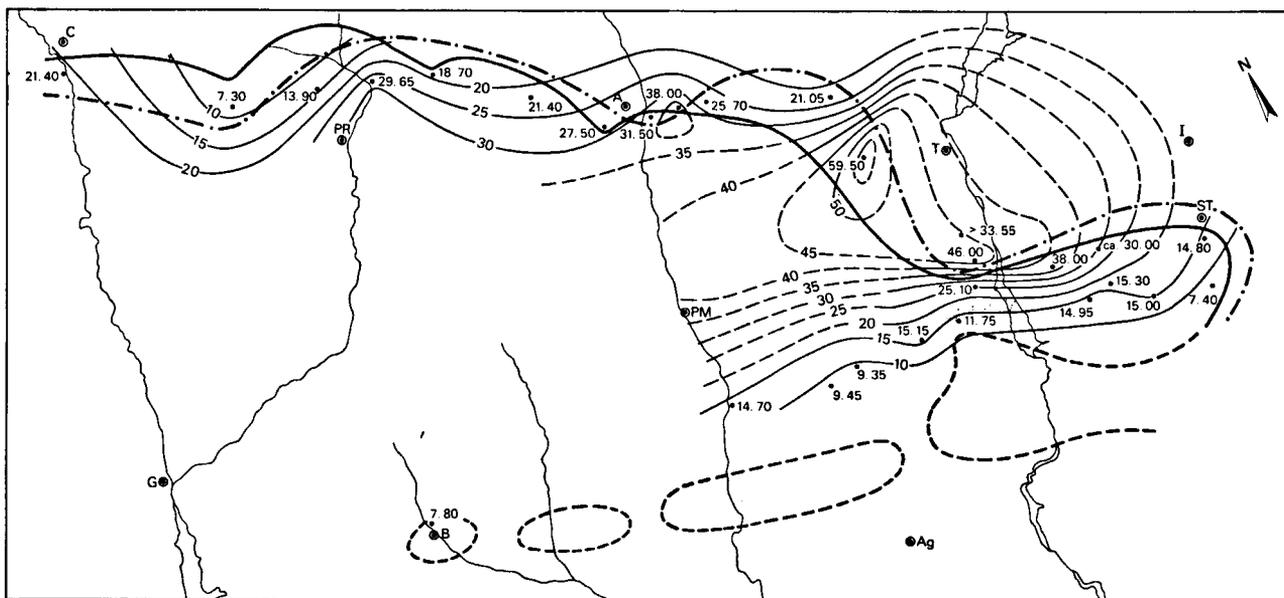
Fig. 3. Isopach map of the *F. cucumiformis* Zone. Continuous heavy line: northern coast line of the Tremp Basin for the lower part of the zone. Heavy dashed line: hypothetical southern coast line of the Tremp Basin for the lower part of the zone. Heavy dashed-dotted line: northern coast line of the Tremp Basin for the middle part of the zone. All coast lines mark the maximum extension of the land for the relevant time interval. Legend on p. 194.
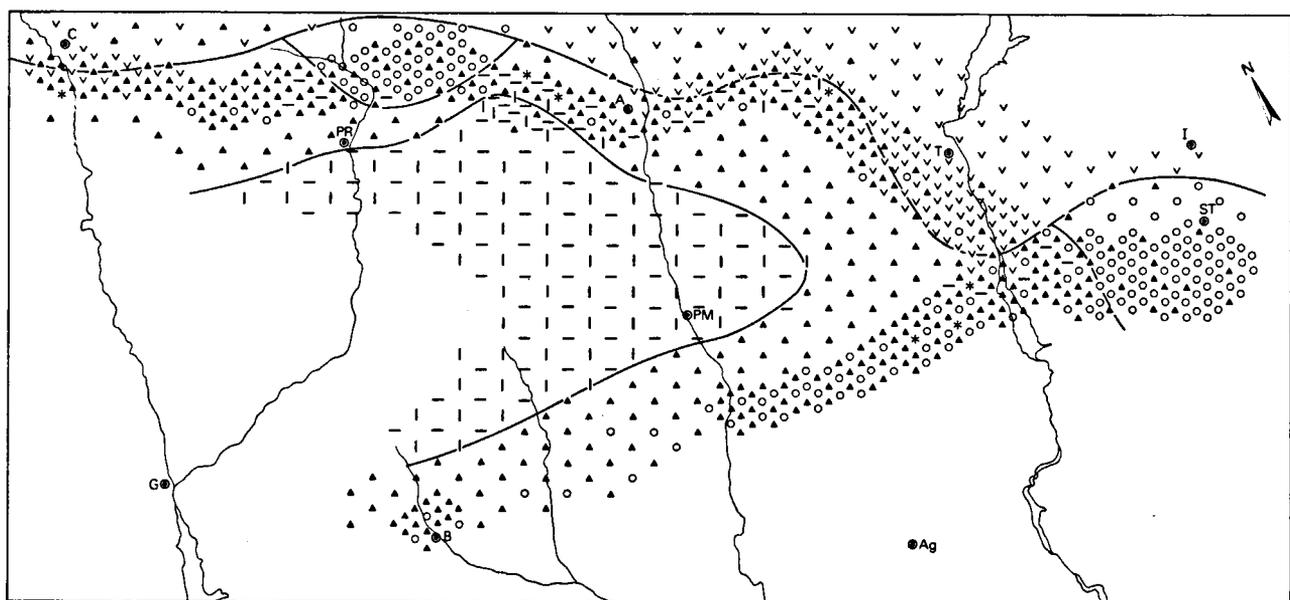

Fig. 4. Facies map of the *F. cucumiformis* Zone. Legend on p. 194.

sections along the southern side of the basin (Enclosure 2. Two smaller horizontal sections are nearly perpendicular to the first one, running in a north–south direction (Enclosure 3). Data along the northern side did not suffice to make a horizontal section. It is to be noted that the measured sections as a rule tend to represent a more basinward development towards the top. This is particularly the case in sections X, H, L and O. This explains the relatively thick development of the *F. corbaricus* and *F. trempinus* Zones in sections L and O with respect to the thicknesses in adjacent sections in the horizontal section of Enclosure 2. Also the seemingly large and unexpected facies changes in these biozones between sections L and O and the adjacent sections can be explained by the same phenomenon.

Mode of construction of the facies and the isopach maps
A palinspastic reconstruction is not necessary because the Tremp Basin has not suffered considerable shortening. Usually the dip of the strata is less than 15–20°. The area with the steepest dips lies between Campo and Merli where the base of the Ager Formation dips to the south at an angle of 45°; near Merli even steeper dips of about 60° occur locally.The younger deposits of the formation immediately south of this zone already dip much less.

A slight N–S shortening persevered throughout the deposition of the Ager Formation. Due to this, the shortening is somewhat greater for the lower biozones than for the upper ones. This shortening is connected with the fact that the basin subsided more rapidly along the long axis than along the borders (see also Chapter VII, section 7.

Facies maps (Figs. 4, 6, 8, 10, 11). – The symbols used for the different facies and subfacies types are closely spaced where the Ager Formation crops out. The configuration of the facies symbols in that area is primarily based upon the distribution of the facies in the individual sections. The extent of each biozone in a section can be indicated by a line on the map. The centre of these lines representing the relevant biozone can be plotted on the map. The facies symbols have been grouped around these centres in proportion to the importance of each facies represented. In this way many clusters of facies symbols appear on the map which are connected with one another by filling the interspaces with a gradually changing symbol pattern. In a reliable way this can only be done for rapid facies changes if the clusters lie close together. No attempt has been made to fill the interspaces between separate clusters if a too large distance between the clusters did not allow a reliable interpretation.

A wide spacing is used outside the outcrop area where no data could be collected. Only the presumably most important facies types and the supposed general trend have been indicated in such areas.

The result is a set of palaeogeographic maps showing a qualitative as well as quantitative picture of the facies. Continuous heavy lines have been used on the facies maps to indicate the more important and more rapid facies changes so that the distribution of the predominant facies types or groups of facies types becomes more obvious, thus designating the general palaeogeographical trends.

Isopach maps (Figs. 3, 5, 7, 9, 12). – The thicknesses of the biozones have been measured as accurately as possible. If no or not enough alveolinids occurred in the relevant interval the thickness was estimated with the aid of palaeoecological and lithological data. The extent of each biozone in a section can be indicated by a line on the map. For all sections the centre of these lines representing the relevant biozone have been plotted on the map with a dot. The measured thickness of the biozone is given in metres at each point. Continuous isopachs were drawn whenever the density of data allowed the reconstruction of sufficiently accurate isopachs. Dashed lines were used for those parts of the basin where insufficient or no data were available but where an extrapolation could be made by taking into account the general palaeogeographical picture.

PALAEOGEOGRAPHY OF THE SUCCESSIVE PHASES

Fasciolites cucumiformis Zone (Figs. 3, 4)
In most of the Tremp Basin the Ager Formation lies directly on the fluvial red beds of the Tremp Formation. The latter sediments consist mainly of sand and clay deposited in the channels of meandering rivers and the backlands, respectively. From this it can be concluded that the landscape had a very low relief. In the western-most part of the basin the marine sediments of the Devotas Formation (Kooter, 1970) underlie the first strata of the Ager Formation; they always indicate extremely shallow water conditions, thus confirming the presence of a low relief.

Therefore it is quite understandable that the transgression which led to the deposition of the marine sediments of the Ager Formation rapidly advanced eastwards over most of the area studied. With the degree of biostratigraphic accuracy attainable no difference in time can be found between the beginning of the transgression in the eastern part of the area.

An important land area was situated north of the northern outcrop area. Thanks to the intercalation of continental deposits between marine deposits in a number of sections, shore lines could be drawn for the lower and middle parts of the *F. cucumiformis* Zone (Fig. 4). In the upper part of this interval there was again a marked transgression (although not as extensive as in the beginning) which extended beyond the outcrop area. Probably the then existing shore line was for the most part already beyond the area covered by the map.

The land immediately north of the line Campo – Gurp must have had a somewhat more marked relief than that north of the line Gurp – Sant Salvador de Tolo. This can be deduced from the influx of coarser siliciclastic material which is especially pronounced in sections W

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and X. In section W poorly rounded boulders up to 60 cm in diameter occur, which can only have been transported over short distances. It is presumed that the coarse conglomerate in which these boulders occur originated from a cliff of conglomerates of the Tremp Formation situated immediately north of the section. A more limited influx of siliciclastic material was noted in sections S and T. Here pebbles are never more than 10 cm across. In addition an influx of coarse fluvial material was found in section H' near Gurp (diameter of the pebbles: up to 13 cm). Not far to the south in section

H near Tendruy a siliciclastic influx of a different nature has been found which can in no way be connected with the earlier influx at the base of the *F. cucumiformis* Zone. In section H the largest and coarsest siliciclastic influx occurs in the upper half of the biozone. In other sections along the northern side of the basin than those already mentioned some sand and silt occur but they are of lesser importance. In summary, there are at least four separate sources of siliciclastic material lying not far to the north or northeast of the northern side of the basin.

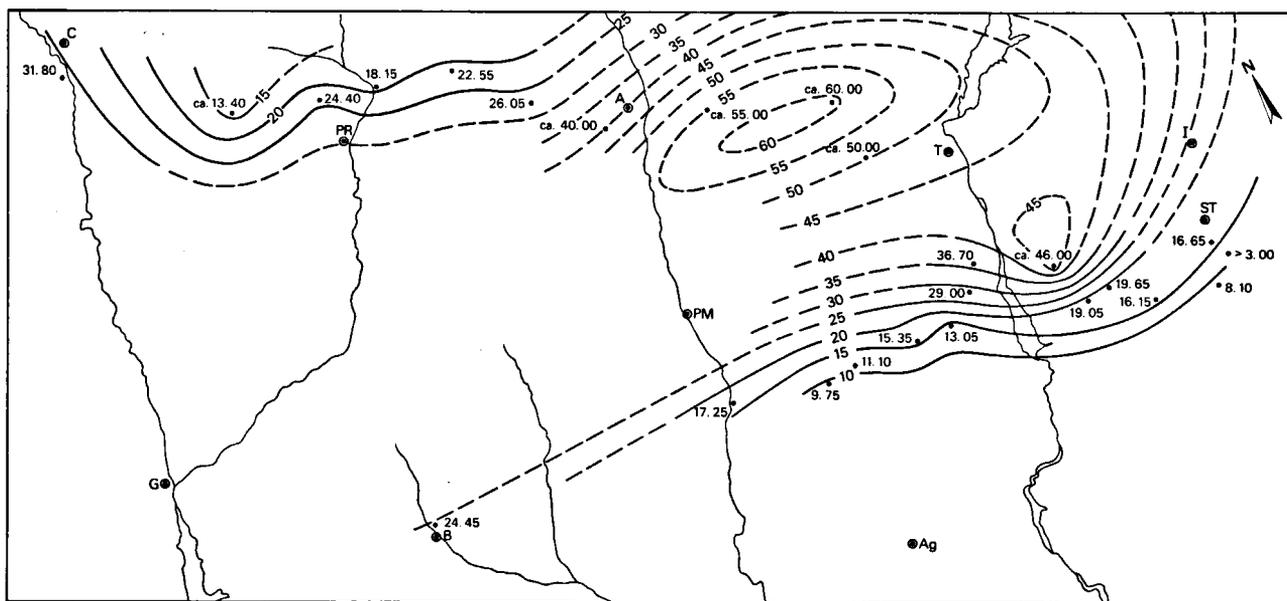On the southern side an extensive, continuous area of

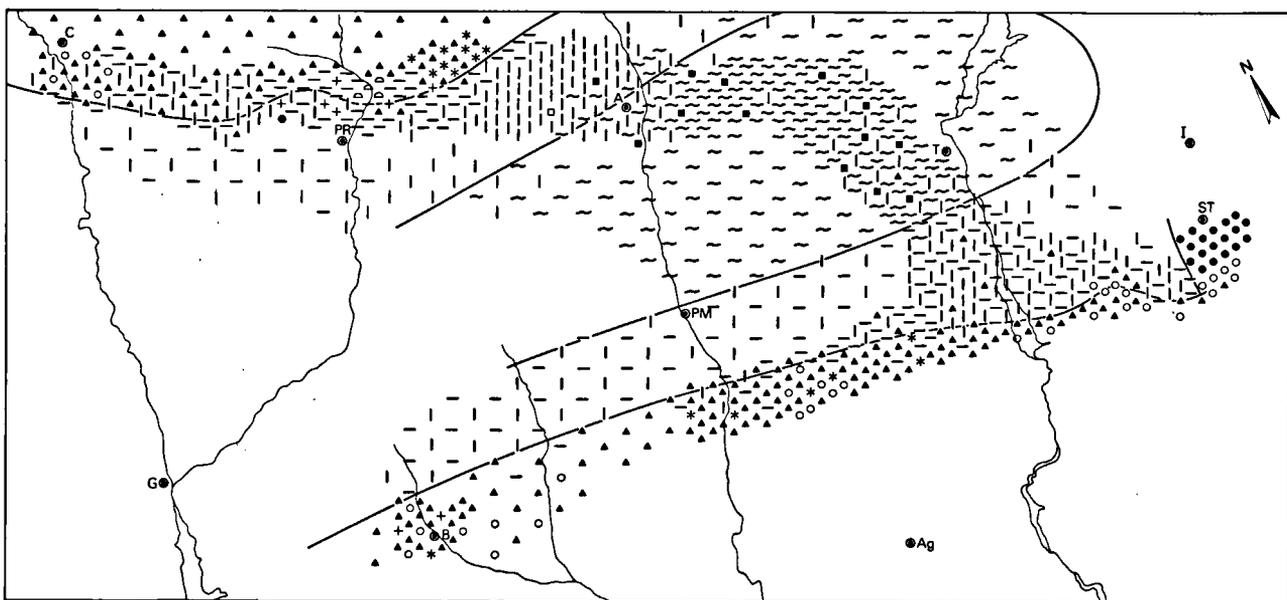Fig. 5. Isopach map of the *F. ellipsoidalis* Zone. Legend on p. 194.

Fig. 6. Facies map of the *F. ellipsoidalis* Zone. Legend on p. 194.

siliciclastic influx is situated to the east of the Selles barrage lake (Noguera Pallaresa River); sections A to G belong to this area. The thickest development and the coarsest material occur in sections G and E; to the west the influence of the detrital influx diminishes gradually. Section K represents a special case. Whereas the siliciclastics of the former area must have originated from a source to the east, the conglomerate in section K can only have come from a source somewhere in the south. The sections north and west of section K namely contain no or hardly any siliciclastics; the adjacent sections to the east only contain more finely grained sediments. The conglomerate in section K thus points to a supply from the Montsech High.

West of Tremp and in sections I and I' fine-grained swamp and lagoonal deposits dominate. Thin dolomitic beds indicate evaporitic conditions. The general trend of the isopachs (Fig. 3) suggests that the swamps and lagoons covered a large area east of these localities (Fig. 4). This is in accordance with the accepted picture of roughly E–W running palaeomorphological elements, viz. the northern edge of the Tremp Basin and the Montsech threshold which forms the southern edge of the basin.

Apart from two areas where siliciclastic sediments of tidal origin prevail (N of La Puebla de Roda and S of Sant Salvador de Tolo) and the area W and SW of Tremp where mainly swamps and lagoons occur, shallow marine limestones along the southern side, and shallow marine limestones and marls along the northern side of the basin dominate in the outcrop area. These deposits belong for the most part to facies VI. They can change gradually into carbonates of subfacies IVb, so that no sharp boundary between these two facies can be drawn. Only locally did some small patch reefs develop on this carbonate platform. At one location (N of Benabarre) it can be proven that temporarily this shallow platform was slightly above the high-tide level under evaporitic conditions, because gypsum pseudomorphs have been found. This suggests the existence of a series of low islands, consisting of foraminiferal sands, and lying in the prolongation of a peninsula; outcrops of older sediments on the peninsula may have furnished the material for the conglomerate of section K. This rather hypothetical shore line is indicated by a dashed line (Fig. 3). The main fault in the Montsech, which is an upthrust fault, however caused an important N–S shortening between the Tremp and Ager Basins which has not been taken into account on the map.

Normally one would expect isopachs to run parallel to the shorelines. This is not the case with our reconstructed northern shore lines which cut the isopachs clearly. This is due to the fact that whenever subsidence was pronounced the sedimentation rate was even higher at some places, so that continental deposits were formed during shorter or longer intervals. The differences in the rates of subsidence are primarily controlled by tectonics; the filling of the basin with sediments is largely determined by the relief thus formed. In the Tremp Basin the subsidence is a largely synsedimentary phenomenon which usually predominates

over the sedimentary filling, but in some cases is nullified or surpassed by a pronounced sedimentation. The best example of the latter situation can be found in that part of section H where very shallow deposits overlie turbiditic sediments with scour and tool marks at their base. The average SW direction of the currents which scoured out the flute marks is practically perpendicular to the shore lines and points towards the centre of the basin. This fits well within the general palaeogeographic picture.

Fasciolites ellipsoidalis Zone (Figs. 5, 6)

The sea clearly extended over a larger area during this interval than during the former one. The area where shallow marine deposits have been found is less extensive, and continental deposits are absent in the outcrop area. For this reason shore lines cannot be drawn. Probably they lie outside the map area for the larger part (Fig. 5).

Shallow marine deposits occur in a zone from Campo to northeast of La Puebla de Roda, and in a zone parallel to and directly north of the Montsech. The demonstrable influx of siliciclastic material is much more restricted than that of the *F. cucumiformis* Zone. The area of the main occurrence of this material is situated south of Sant Salvador de Tolo. Here tidal deposits predominate (Fig. 6). Section G contains the coarsest sediments, including some conglomerates. The associations of larger benthonic foraminifera prove that the tidal deposits of section G were formed in shallow water, and those of the more northerly sections D and E in somewhat deeper water. The occurrence of some sand and silt in sections A, B, C and F can be attributed to the same source as that in the tidal deposits of sections D, E and G. The source area must have been situated not far to the south or southeast of section G. The pure quartz sands consisting mainly of rounded and well-rounded grains in section Z south of Campo on the other hand can only have come from a northern source area.

In the northern shallow area many biosparites and biosparrudites with megacross-bedding occur in the lower part of the biozone. The presence of these deposits proves that this area was heavily exposed to currents and tides. The most impressive sediment body developed under high current velocities is the giant lunate ripple of section X at Serraduy; this 10 m high megacross-bedding must have been built up by a current flowing towards the SE (see Chapter V, section 3.5). A smaller megacross-bedding in the more westerly section X' indicates a current with a NE direction. The occurrence of massive *Lithothamnium* ridges east of Serraduy in section W is compatible with this picture, for such ridges offer good resistance to strong wave and current movements, and in fact need such an extreme environment.

During the deposition of the upper part of the biozone quieter conditions prevailed in the northern shallow area mainly because the basin deepened somewhat in this

region. Here the pelecypod *Pseudomiltha* is often encountered in life position.

The southern shallow zone is characterized for the most part by a horizontal and vertical alternation of more sheltered biomicrites (*Pseudomiltha* often occurs in situ) and more exposed biomicrites and biosparites which obviously were influenced by tidal currents. No sharp boundaries can be drawn between these sediment types. On this more or less protected carbonate platform some small patch reefs were built by coral colonies. In rare cases small *Lithothamnium* reefs occur. Only in sections A, C and K can a distinct deepening of the basin be inferred from the deposits in the upper part of the biozone.

Bordering on the above-mentioned shallow marine areas is a 6–10 km wide zone in which mixed imperforate–perforate foraminifera associations dominate (facies XI and XII, see Fig. 6). The most frequently occurring, distinct communities in this zone are those of *Spondylus* and *Patallophyllia*. Subfacies XIa and XIc are
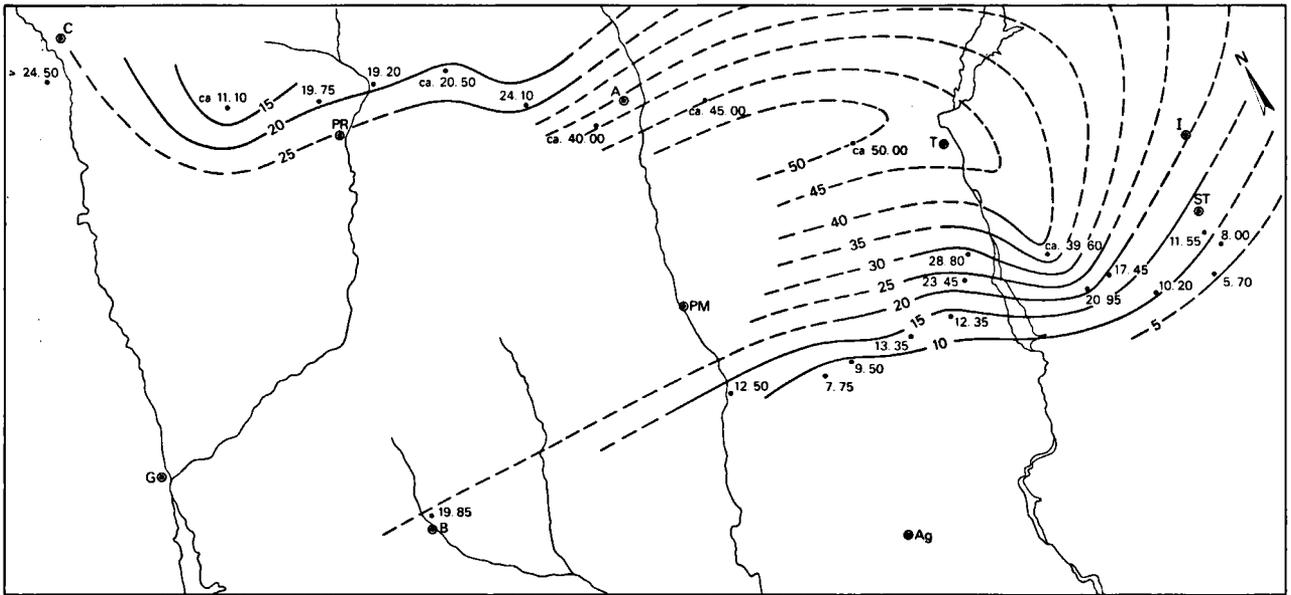

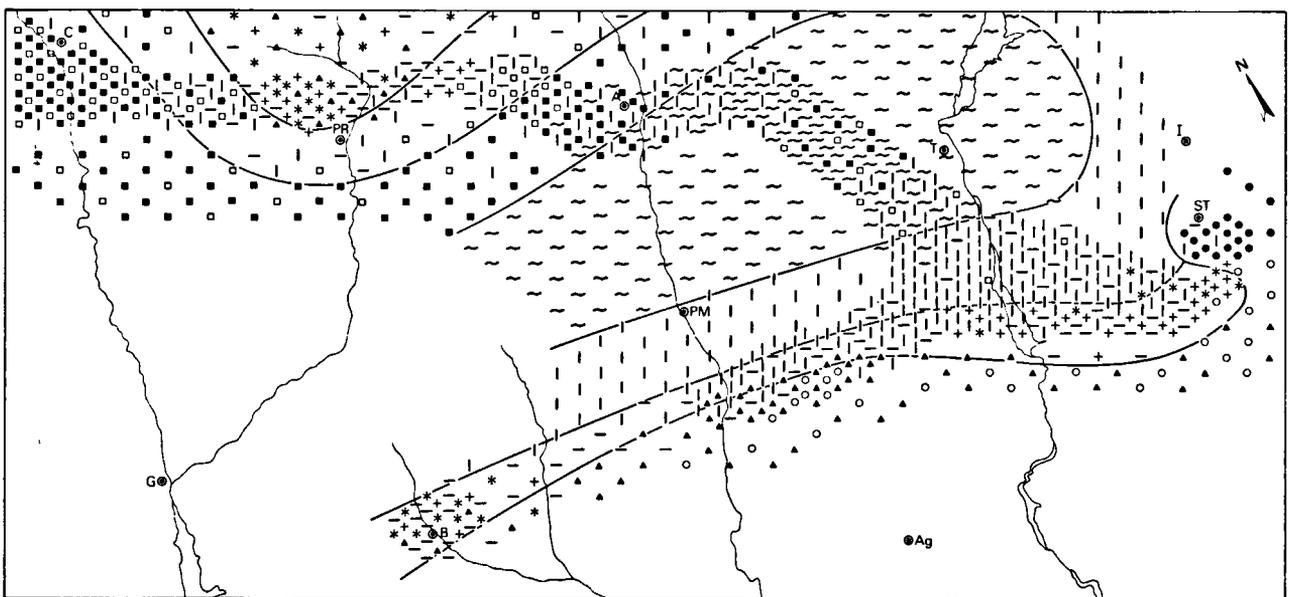Fig. 7. Isopach map of the *F. moussoulensis* Zone. Legend on p. 194.

Fig. 8. Facies map of the *F. moussoulensis* Zone. Legend on p. 194.

important east of the Noguera Pallaresa River. The most extensive development of the *Schizaster – Linthia – Ditremaster* community has been found in section K, whereas the *Halimeda*-rich deposits of subfacies XId are by far the most extensive in sections I and F. It is remarkable that the latter subfacies occurs near the only striking anomaly in the isopach pattern (Figs. 5, 6). The biozone here is represented by a thicker succession. The occurrence of many specimens of *Halimeda* suggests that a local depression existed and that the bottom was well-protected against currents, for this alga flourishes in sheltered conditions. Therefore it can be assumed that subsidence was even more rapid than deposition at this place.

The *Turritella* community dominated in the centre of the basin where the highest sedimentation rates occurred. This facies (XV) is rare outside the 40 m isopach (see Figs. 5, 6).

The most important facies boundaries (Fig. 6) do not deviate much from the general isopach pattern (Fig. 5). Probably the isobaths also followed the isopachs rather closely. For this reason the palaeogeography of the *F. ellipsoidalis* Zone is less complicated than that of the *F. cucumiformis* Zone. Compared with the latter biozone the transgression advanced mainly towards the northeast. Certainly the submarine relief was somewhat more pronounced than during the deposition of the preceding biozone.

Fasciolites moussoulensis Zone (Figs. 7, 8)
The sea again advanced during this interval, although it made much less progress than during the preceding intervals. Shallow marine areas occupy somewhat less space in the outcrop area than those of the former biozones. The northern shallow area directly north of La Puebla de Roda tends to become somewhat isolated. The southern shallow area has shifted a little towards the south over its entire length.

The only part of the basin where sand has been found is in the southeast. The highest concentration of sand occurs in section E, directly south of Sant Salvador de Tolo. Smaller quantities have been found in sections D, F and G. This distribution points to an eastern provenance for these siliciclastics. The direction of the supply of this material has therefore changed compared with that of the preceding biozone. Apart from some thin silt beds the sediments consist of limestones and marls.

Reef development increased somewhat in the western part of the basin. Section X' contains a coral reef with encrusting coralline algae, and in section P another coral reef has been found. They must have grown in deeper and quieter water than *Lithothamnium* reefs. The reefs only occur where the zone is 20 m thick or less.

The symmetry which existed to a large extent in the *F. ellipsoidalis* Zone between the northern and the southern sides of the basin has almost disappeared. Along the northern shallow zone there is only a narrow strip in which facies XI and XII predominate (not indicated on the map, Fig. 8). This is bounded to the south by a wider zone where facies XIV plays the

principal role. This zone in turn passes into an area dominated by the *Turritella* community which occurs in the central part of the basin. This community and the *Patallophyllia* community are often united to one larger community.

The southern shallow zone is bordered by a 6–10 km wide zone where mixed imperforate-perforate foraminifera associations dominate. This area can be divided into two parts: a somewhat shallower southern part in which more limestones have been deposited, and a somewhat deeper northern part with more marly sedimentation. In the southern part off-reef shoal limestones and reefs are dominant in the westernmost and easternmost parts (sections G and P); in sections A and B and sections K up to and including section O the *Spondylus* and *Pseudomiltha – Velates* communities are important; the *Schizaster – Linthia – Ditremaster* community is common as well. In the northern part the *Patallophyllia* community is more significant, forming the transition to the central area with its *Turritella* marls. This latter facies rarely occurs where the zone is 35 m thick or less.

In summary the northern side of the basin shows an important development of facies XIV, whereas facies XI and XII are well-developed along the southern side. This means that the deepest part of the basin was not situated in the centre where the thickest sequence occurs (Fig. 7), but farther towards the north. The relief of the sea bottom was therefore much steeper on the northern side of the basin than on the southern side. On the whole the submarine relief was indeed more pronounced than in the *F. ellipsoidalis* Zone. Important facies boundaries follow the isopachs fairly well. The most striking deviation is the protrusion of the 40 m isopach near section F. The presence of fossils characteristic of facies XIV, viz. tubes of *Ditrupa* and internodes of *Conocrinus*, in several strata of this section suggests the continued existence of the local depression mentioned for the preceding biozone.

Lower part of Fasciolites corbaricus Zone (Figs. 9, 10)
The *F. corbaricus* Zone corresponds to a much longer episode in which much thicker sediments were deposited than in the underlying biozones (see Chapter VII, section 2). It is necessary to split this zone into two parts of approximately equal thicknesses because many important palaeogeographical changes took place. Even one half of the *F. corbaricus* Zone lasted much longer than one of the three older biozones (see Chapter VII), so that more palaeogeographical changes took place; in point of fact it would necessitate more than the one facies map given (Fig. 10) to represent the development of the basin in as much detail as in Figs. 4, 6 and 8, successively.

During the first half of this long interval the transgression again gained ground, in particular not long after the start of this interval, followed by a certain equilibrium between the subsidence and the filling of the basin.

In the northern area where shallow marine carbonate sedimentation occurred these carbonates are restricted to the base of the lower part of the *F. corbaricus* Zone. It

consists of two areas which perhaps were connected with one another in the north where the Ager Formation has now disappeared by erosion. The larger area is situated NW of La Puebla de Roda; the approximate maximum extension is indicated by the heavy line immediately north of this village (Fig. 10). It is remarkable that a shallowing development occurred culminating in reef development near the top of this limestone sequence. This is just the opposite of the general trend of deepening of the basin. The local and very short shallowing even led to the formation of a

Lithothamnium ridge. On three sides (W, S and E) of the shallow carbonate area a pronounced relief must have existed, because the sediments of facies XIV which were deposited in distinctly deeper water lie close by, interfingering with the shallower deposits. The deposition of pure limestones terminated suddenly, changing into the muddy sediments of deeper facies. It follows that a rapid subsidence of this area occurred at that moment.

The smaller northern area with limestone deposition covers an area about 5 km long extending along the
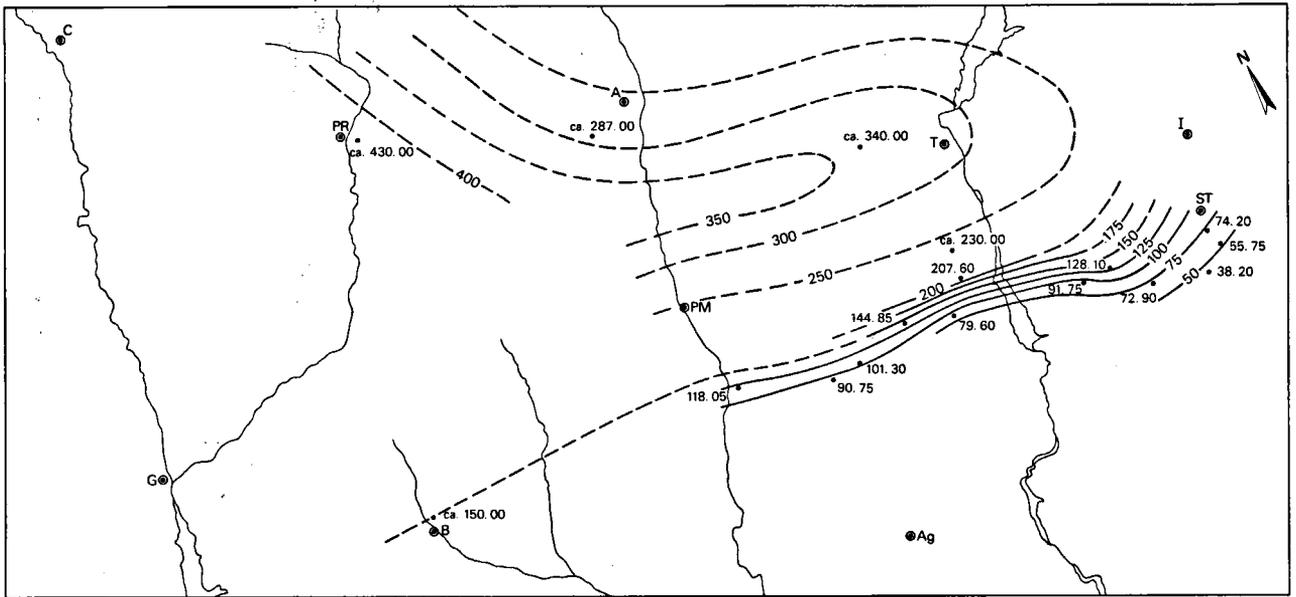

Fig. 9. Isopach map of the *F. corbaricus* Zone. Legend on p. 194.
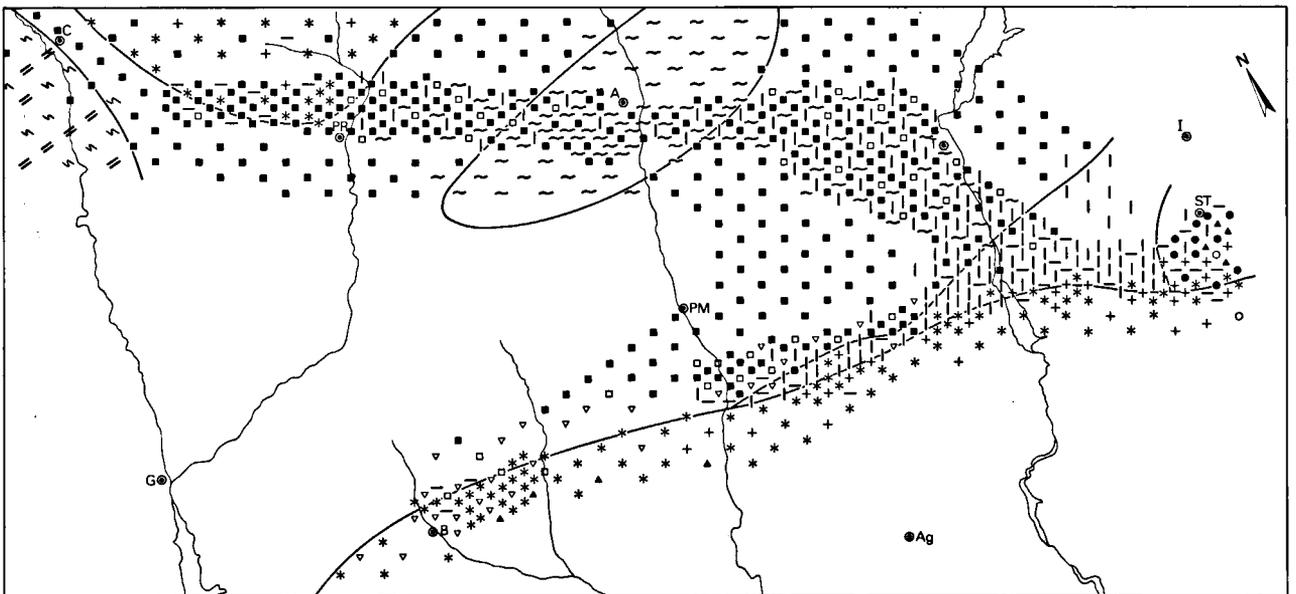

Fig. 10. Facies map of the lower part of the *F. corbaricus* Zone. Legend on p. 194.

outcrop area immediately west of Arén. Because it existed for an even shorter time and because of its small thickness in a thick sequence, it could not be marked adequately on the facies map. Here also there is a shallowing sequence with a coral reef on top, followed abruptly by deeper marls.

The entire northern shallow area thus was characterized by a marked instability and this realm shifted far towards the north. The isopach pattern on the northern side of the basin (Fig. 9) also indicates that this part of the basin had lost its stability: thick successions were deposited pointing to rapid subsidence.

In contrast, the southern area with shallow marine carbonate deposition was mainly stationary. Many reefs flourished here; they form a continuous belt at least 50 km long and several km wide situated on the northern side of the Montsech threshold (Fig. 10). Thus the lower part of the *F. corbaricus* Zone is characterized by the most exuberant and most extensive reef growth in the Tremp Basin. Many types of reefs developed in this belt. In the westernmost part (section P) there are *Lithothamnium* ridges and coral–algal reefs. These reef types are dominant up to the Noguera Ribagorzana River. Coral reefs become more important towards the east. They dominate almost everywhere east of this river. The only exception is section A where a *Lithothamnium* ridge and coral–algal reefs occur. Apparently the breakers were more forceful or more effective here than everywhere else along the eastern part of the reef belt due to the shallowness of the sea near section A. The *Lithothamnium* ridge was even above sea level for some time (see Chapter V, section 3, 8). The dominance of algal reefs in the western part of the belt can be explained by a combination of factors, viz. the shallowness of the sea and the greater exposure to surf action than farther eastwards. The latter circumstance probably resulted from the lack of sheltering shallow areas farther towards the west. Moreover the relief of the sea bottom was stronger in the west than in the east as shown by the rapid westward wedging out of the strip where the mixed imperforate–perforate foraminifera associations predominate (Fig. 10). There the reef complex borders directly on the deeper facies (XIII and XIV).

In the eastern and middle parts of the basin the reef belt could maintain its position during the entire interval. In the western part near Benabarre the reef complex definitely makes way for the deeper fore-reef detrital limestones (facies XIII). This means that this part of the reef belt shifted towards the south in the time interval embracing the upper half of the lower part of the *F. corbaricus* Zone.

In the entire interval treated in this section the occurrence of sand is mainly limited to the area S of Sant Salvador de Tolo. The largest influx of sand occurs in section E, with smaller but still appreciable quantities in sections D and G. To the west a rapid decrease reduced the sand portion to almost nothing in sections B and C. This sand distribution indicates a supply from the east. Another area where sand occurs is situated in the

west. The bioclastic fore-reef detrital limestones of section P contain a significant percentage of pure quartz sand. In section Q this sand occurs in smaller quantities in the same deposits. The source area must have been situated in the west or southwest. A southern origin is ruled out because the reefs are located there, a northern origin because of the deeper, muddier sediments in that direction, and an eastern origin because the sand differs in composition from that in the east and also because almost no sand occurs between sections O and B.

Palaeocurrent measurements of megacross-beddings in sections A, E and K are concentrated in the sector between the south and northwest. These cross-beddings were formed by ebb- and flood-currents. NW to NNW ebb-current directions were determined in section O. The nearly easterly direction measured in section P suggests a current parallel to the reef belt and agrees with the western provenance of the sand in the same section.

In the greater part of the area the deeper-water deposits of facies XIV dominate. This means that the basin as a whole was deeper than during the preceding intervals. In the centre of the basin (around Arén) the *Turritella* marls are the most important facies. Probably the basin here was even somewhat deeper. The deepest part of the basin lies on the western border of the area studied, where turbidites occur. This is the region of the lower part of the shelf and of the continental slope which forms the transition to the oceanic deep sea. South of Campo are large slumps and olistoliths (Gaemers, 1974, figs. 2, 3). The olistoliths consist of shallow marine limestones with an abundant fauna and flora; they are often reef limestones. Their source area was situated only some km towards the northeast, from which it is evident that very steep palaeoslopes existed here.

In summary, the palaeogeography of the Tremp Basin in this interval is characterized by a rather deep shelf bordered by high, steep reefs. During the later half of the interval the western part of the basin subsided so markedly that the narrow elongated bay changed into a more open, funnel-shaped sea with its widest opening directed towards the ocean.

Upper part of Fasciolites corbaricus Zone (Figs. 9 and 11)

The beginning of this interval is marked by an important change in the supply of sediment. Sudden influxes of sand took place practically simultaneously in numerous locations where thus far no or very little sand had been deposited. Notwithstanding various interruptions this influx continued until the end of the deposition of the Ager Formation, and even continued in younger continental deposits which followed.

There are two separate areas one of which is situated around section H, northwest of Tremp where large quantities of sand occur, indicating that the sand must have derived from at least two sources.

In the northwest, between Merli and Arén, is an area which must have received much sand from a northern or northeastern source. Perhaps the complicated Turbón

structure north of the Tremp Basin is connected with the supply of this detrital material. In the lower part of the interval are the largest accumulations of sand. Near La Puebla de Roda the most obvious structures developed at that time are giant cross-beddings. These structures, as well as megacross-beddings forming parts of large sediment bodies, probably originated in an environment with strong, tide-induced currents (see Chapter V, section 3.5). During the formation of these large sediment bodies the sea must have been rather deep (many tens of metres at least), since below and above

these deposits thick sediment sequences occur which belong to facies XIV. An important transgression during that space of time as suggested by Nio (1976) is certainly out of the question. Nio highly underestimated the depths at which the underlying beds were formed. Subsidence and deposition near La Puebla de Roda remained in fairly close equilibrium during the interval corresponding with the upper part of the *F. corbaricus* Zone. Probably even a regressive tendency existed; this can be deduced from the large sediment bodies migrating basin-inwards in the course of time. This is in
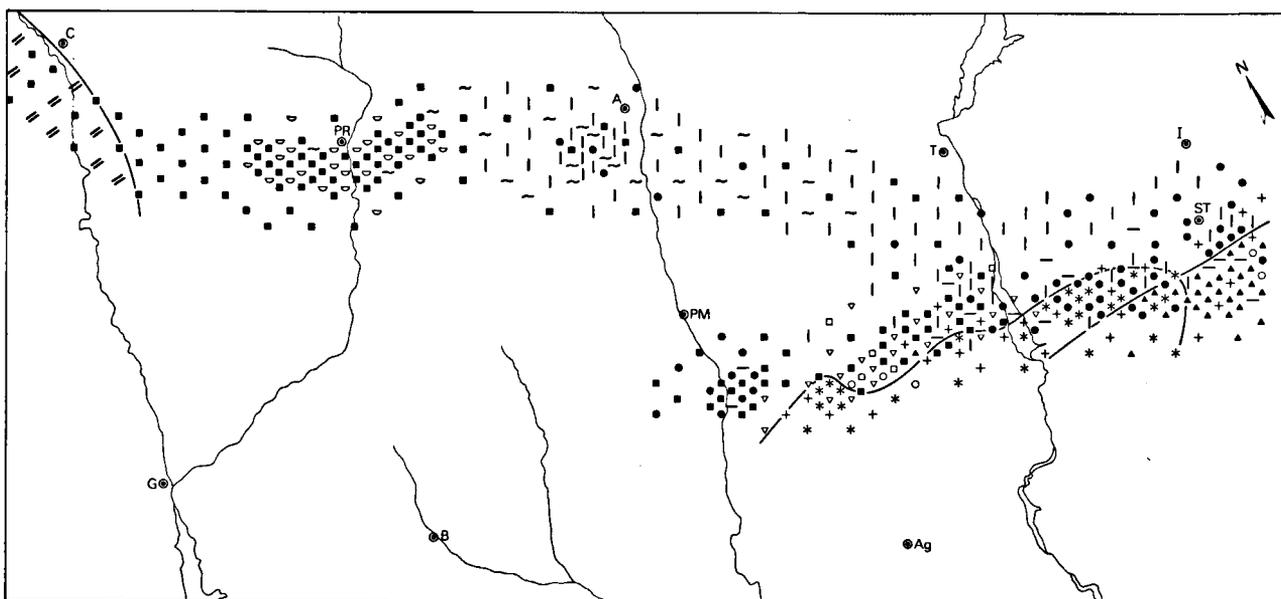

Fig. 11. Facies map of the upper part of the *F. corbaricus* Zone. Legend on p. 194.
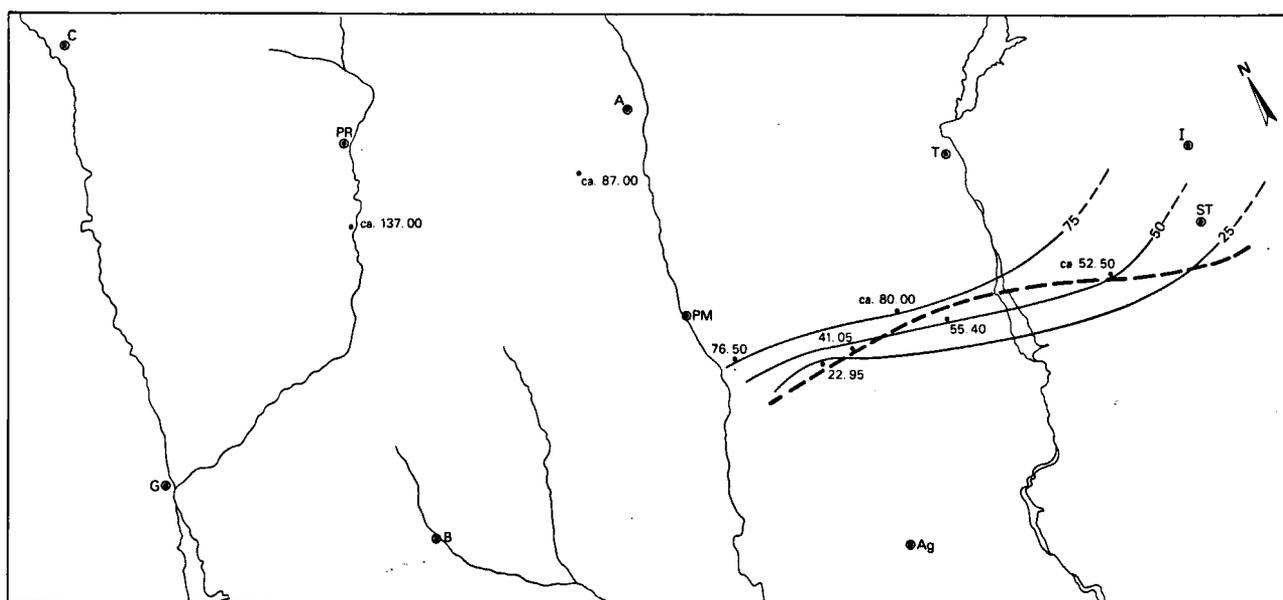

Fig. 12. Isopach map of the *F. trempinus* Zone. Legend on p. 194.

accordance with the regressive trend in all other measured sections.

In the southeast there is another area with a large sand influx. Although it is continuous, two separate sources must be responsible for the sand supply. This is evident from the grain size distribution and the differences in the amounts of sand in the area. One source can be postulated east of sections D and E where larger quantities of sand occur than in the adjacent sections. Four other sections, viz. J, K, A and B, contain more and coarser sand than the immediately adjacent areas. This sand can only have come from the south or south-east.

Reefs could not flourish along the northern side of the basin because the sedimentation rate was too high. Along the southern side coral reefs could grow only during the time when no or almost no sand was supplied. Important reef growth occurred in a belt at least 20 km long. The probable continuation of this reef belt west of section N unfortunately cannot be demonstrated because of erosion of the Ager Formation or coverage by younger sediments. The thickest reef development is located near Sant Esteve de la Sarga (section N) and can be attributed to the favourable combination of slight subsidence and limited sand supply.

The deepest part of the basin undoubtedly was situated in the west where turbidites were deposited. Apart from the sandy deposits discussed above, chiefly marls and silts of facies XII, XIV and XV were deposited outside the shallow marine zone where calcium carbonate deposition dominated.

Fasciolites trempinus Zone (Fig. 12)

The regression which started in the preceding interval continued during the deposition of the F. trempinus Zone. Before the end of this interval continuing sedimentation led to the filling of the shallow sea in the greater part of the basin. Only in the westernmost part of the area near the Esera River did marine sedimentation continue.

The influx of clastic material was considerable so that pure and almost pure limestones could barely develop. They are only observed in the lower half of the F. trempinus Zone, except for one bed in section B in the upper half of the exposed part of this zone. The most important occurrence of these limestones is on the southern side of the basin, west of the Noguera Pallaresa River. In this area there is some indication that several small coral reefs existed. In sections J and O a thin fore-reef and a back-reef deposit were found.

The limestones can be divided into two groups. The first consists of nodular limestones deposited in a quiet, sheltered environment. These sediments contain predominantly a large number of autochthonous species from which it is evident that (weak) currents provided

sufficient oxygen and food. The second group consists of limestones with cross-beddings and channels formed by strong tidal currents. The number of species in these limestones is limited, and the fossils identified are often allochthonous. Transitions between the two groups occur.

All transitions can be found from pure carbonate tidal deposits up to and including pure siliciclastic tidal deposits. The more calcareous tidal deposits dominate in the lower half of the interval, and the more siliciclastic ones in the upper half. As a rule on the southern side of the basin most of the measured megacross-beddings were formed by ebb-tide currents. The only exception is section A where more flood-tide directions were measured.

On the northern side of the basin in particular, thick siliciclastic sequences were deposited which indicate an important influx of sand from the north or north-east. Much smaller quantities of sand occur on the southern side of the basin. Probably this sand came from a source in the southeast, in view of the grain size distribution in that area. Deposition of clay played a much more important role in this part of the basin.

The prevailing regressive trend in the deposits of the F. trempinus Zone can be demonstrated by the differences between the lower and the upper parts of this biozone. During the deposition of the lower part open marine conditions prevailed, whereas tidal deposits were more important in the upper part when lagoonal environments covered large areas.

Three different areas can be distinguished in the palaeogeography of the Tremp Basin during the deposition of the F. trempinus Zone. South of the heavy dashed line in Fig. 12 only shallow marine and lagoonal deposits occur. The marine sediments contain only imperforate foraminifera associations. North of the dashed line mixed imperforate–perforate foraminifera associations also occur (facies XI and XII) which indicates that temporarily a somewhat deeper sea existed. From about the Isábena River towards the west is the third area where the sea was even deeper when the first beds of the F. trempinus Zone were deposited. In this area facies XIV also occurs. The transition from marine to continental conditions took place later in that area than in the more easterly regions. The boundary between the marine Ager Formation and the mainly fluvial Montañana Group east of the Isábena River can be considered as isochronous, because the sea withdrew very rapidly from this entire area.

On account of the poor degree of exposure of the F. trempinus Zone in many places, it is impossible to make as accurate a facies map as for the other biozones. The isopach map is only fragmentary because not enough measurements of total thicknesses are available for this biozone.

CHAPTER VII

GENERAL PALAEOECOLOGICAL AND PALAEOGEOGRAPHICAL PICTURE

INTRODUCTION

The aim of this investigation is a reconstruction of the Late Paleocene–Early Eocene Tremp Basin. Much has already been said about the conditions of deposition in the discussions of the different (sub)facies types. In this chapter an attempt is made to discuss the main features and to estimate the different parameters as accurately as possible. Unfortunately nearly all important factors which combine to produce the environment can only be determined in an indirect manner, such as temperature, depth, salinity, pH, oxygen content, current and wave actions, light intensity, clearness of the water, etc. Fossil faunal and floral elements can provide fairly detailed and accurate information about most of these factors. Sedimentary structures are an important aid in determining other factors (for example, directions of currents).

All of these factors are interrelated in different manners, some more directly than others. A problem in this respect is that often no simple, unambiguous relationship exists between an organism and its environment. For example, the depth at which an animal lives is often dependent on the temperature. In that case we have an equation with two unknowns, depth and temperature. Resolution is only possible if we can also obtain data from other organisms. The total fossil environment with its multitude of unknown factors naturally demands even more data before it is sufficiently known. Detailed studies, such as the work of Lagaaij (1963) on the ecology of the lunulitiform bryozoan *Cupuladria canariensis*, are of great help in determining the relationships between the different factors. Thus it is evident from Lagaaij's study for example that the maximum depth at which this bryozoan occurs is determined mainly by the temperature of the bottom water.

Most facies types of the area studied contain a large variety of species so that a reasonably accurate idea of the environmental factors can be obtained. Facies with a scarcity of fossils can then be interpolated fairly precisely once the relationships with the highly fossiliferous facies are known from a regional study. The entire reconstruction moreover will become even more reliable if different independent data are mutually corroborative (Brouwer, 1967, p. 88, 89).

SEDIMENTATION RATES AND DURATION OF THE DIFFERENT INTERVALS

On the basis of the correlations between the zones based on nannoplankton and planktonic foraminifera, and benthonic foraminifera as given in Tab. 2, and comparison of the biozonation of planktonic foraminifera with the time scale in Berggren's table 52.40 (1971), a time interval of about 5 millions years can be deduced

for the deposition of the entire Ager Formation east of the Isábena River.

The thicknesses of the successive biozones (see Enclosures 2 and 3) already suggest that the time intervals represented by these zones are of unequal length. Convincing support of the idea that considerable differences really must have existed can be obtained from the distribution of the *Turritella* facies. The *Turritella* species occurring in this facies needs a rather high sedimentation rate in order to compete with other organisms so that they are not replaced by them. When the distribution of the *Turritella* facies in a certain biozone is compared with the isopach pattern of that biozone, an isopach can be found which represents the critical boundary outside of which the rate of sedimentation was not sufficiently high for the *Turritella* species to live. The minimum sedimentation rate necessary for the occurrence of *Turritella* remained the same supposing the way of life of this *Turritella* species to remain unchanged during the deposition of the entire Ager Formation. If the critical boundaries for the *Turritella* facies lie at different isopachs in the different biozones it thus can only mean that the biozones comprise time intervals of unequal lengths; and this is in such a manner that the lengths of the time intervals are proportional to the thicknesses of the biozones at the critical boundary.

Comparison of the data collected in the facies and the isopach maps of the *F. ellipsoidalis* Zone (Figs. 5, 6) shows that the *Turritella* facies is restricted to the areas where the isopachs only rarely surpass values of 40 m. In the *F. moussoulensis* Zone the critical boundary of this facies is at the 35 m isopach (Figs. 7, 8), but a markedly different value is found for the *F. corbaricus* Zone, namely ca. 250 m (Figs. 9, 10, 11). For other facies types similar differences are noted when the *F. corbaricus* Zone is compared with the *F. ellipsoidalis* or the *F. moussoulensis* Zone. Thus it can be concluded that the *F. corbaricus* Zone lasted 6 to 7 times longer than each of the other two biozones.

This agrees quite well with the average thicknesses of these biozones. Therefore the average thicknesses of all individual biozones have been taken as a measure of the length of the time intervals represented by these biozones. A simplified estimate which approximates the measured thicknesses satisfactorily is that the *F. trempinus* Zone (as far as it is represented in the eastern part of the basin) would represent about the same amount of time as the three lowest biozones together, whereas the *F. corbaricus* Zone would represent an interval which lasted twice as long as that of the *F. trempinus* Zone. The time intervals represented by the *F. cucumiformis* Zone, the *F. ellipsoidalis* Zone and the *F. moussoulensis* Zone would not differ markedly from one another. The time interval of the *F. ellipsoidalis* Zone probably was slightly longer than that of the *F.*

moussoulensis Zone judging from the distribution of the *Turritella* facies. This facies is restricted mainly to the area where the isopachs surpass values of 40 m for the former and 35 m for the latter biozone. The time intervals of the *F. cucumiformis* Zone and the *F. ellipsoidalis* Zone probably were about equally long.

From the above the duration of the intervals of all individual biozones can be estimated. For the *F. cucumiformis* and *F. ellipsoidalis* Zones a value of 430 000 years is found, for the *F. moussoulensis* Zone 380 000 years, for the *F. corbaricus* Zone 2.5 million years and for the *F. trempinus* Zone in the eastern part of the basin 1.25 million years.

The preceding results can be used to estimate the mean rates of sedimentation as well as more specific rates for different facies.

The thinnest sequence found in the basin is section G, ca. 3.5 km south of Sant Salvador de Tolo. The sequence from the base of the *F. cucumiformis* Zone to the top of the *F. corbaricus* Zone measures 59.40 m. The estimated space of time for this interval is 3.75 millions of years. The mean rate of sedimentation which can be estimated from this is the low value of 1.58 cm/thousand years. Cross-bedded strata in this section prove that often much higher rates must have existed. From this it can be concluded that many hiatuses occur in this sequence; this idea is supported by the occurrence of many channels at different horizons, which at the same time indicates considerable erosion.

The thickest sequences in the Tremp Basin are the Tendruy–Sant Adria section (section H) and the Tremp section (several km west of Tremp). The latter section has been described by Luterbacher (1973) and by Ferrer et al. (1973); both give a thickness of 900 m. It has appeared that the thicknesses of all sections which were measured again during the present study are always found to be smaller than those given by Ferrer et al. The thickness of the Tremp section comprising the entire Ager Formation is therefore estimated to be about 800 m. The mean rate of sedimentation for this section amounts to 16 cm/thousand years in that case, thus ten times as rapid as the rate of section G. Hiatuses caused by non-deposition or erosion are hardly to be expected in the Tremp section because the strata generally changed gradually.

For the estimation of the sedimentation rates of specific facies types or the rate necessary for the formation of glauconite, it is necessary to find sequences in which that facies type is present as continuously as possible. The upper part of the *F. corbaricus* Zone in sections K and N is most suitable in this respect for glauconite. The duration of this interval was about 1.25 million years. Glauconite-bearing deposits predominate markedly in these sections, and the remaining parts of the sections consist mainly of reefs and related sediments which also developed at comparably low rates of sedimentation (in some deeper reefs glauconite occurs in situ). The thicknesses of the upper part of the *F. corbaricus* Zone are 39.50 m and 44.50 m for sections K and N, respectively. The calculated estimations of the

sedimentation rates are 3.16 and 3.56 cm/thousand years, respectively, which are low (1–10 cm/thousand years is considered the range for low rates of sedimentation; see Schopf, 1969).

The highest sedimentation rates can be expected in the *Turritella* facies which generally occurs in the thickest sections. The most continuous formation of deposits of this facies type is in the *F. ellipsoidalis* Zone of section H' at Gurp. The estimated thickness of this interval is about 60 m. Some thin intercalations of more slowly deposited sediments are however also present. The thickness of a completely continuous sequence of the *Turritella* facies would therefore certainly have been greater and can be estimated at about 80 m. A rate of sedimentation of about 18.5 cm/thousand years can be calculated from this. This is a moderate rate (10–100 cm/thousand years is considered the range for moderate rates of sedimentation; see Schopf, 1969).

The conclusion drawn is that the rates of sedimentation in the Tremp Basin were never really high. The transparency of the sea water may therefore have been good to very good in most places so that light could penetrate down to great depths of at least 100–150 m.

CURRENTS

In the northern hemisphere, between 0 and 40° latitude, the atmospheric and oceanic circulations follow a clockwise pattern due to the Coriolis force which is generated by the rotation of the earth. Such a pattern must also have existed in the Atlantic Ocean during the Palaeogene. Since the Tremp Basin is an east-west running basin with a wide opening to the Atlantic Ocean in the west, it is highly probable that it was a part of this oceanic circulation pattern. A consequence of this is that a sea current from (north)west to (south)east would have entered the basin along its northern side, and would have left the basin along its southern side running in the opposite direction.

The strength of this current however could impossibly be great. In any case it would not be able to form megacross-beddings or giant cross-beddings on the sea bottom. By far the greater part of these structures will therefore have been formed by tidal currents. Measurements of the directions of the mega ripples along the southern side of the basin reveal that ebb-tide currents are overrepresented here; this supports the idea of a roughly E–W running current which intensified the influence of the ebb-tides.

The above-mentioned outline seems to be the most probable model in the event that the basin only opened to the Atlantic Ocean. From the palaeogeographical reconstruction of the *F. cucumiformis* Zone it appears certain that this situation did exist during that interval. The same geographical situation must have existed at least during the upper part of the *F. trempinus* Zone.

For the interjacent interval nothing can be said with certainty because the sea extended too far beyond the outcrop area of the Ager Formation. It is however

probable that during at least a part of this interval, namely at the time of maximum transgression, a connection with the Tethys (Mediterranean Sea) existed, because not far to the east, in the Sierra del Cadi and in the vicinity of Oliana, deposits of the same age also developed under clearly marine conditions. During that time the Tremp Basin would have formed part of a strait between the Atlantic Ocean and the Tethys, by which Spain was isolated from the western European continent. This is a much more complicated palaeogeographical situation, and it is therefore difficult to say in how far and in which respect the current pattern differed from the above-mentioned model. The only thing that can be said is that there is a greater likelyhood of higher current velocities in the event that the Tremp Basin was part of such a connecting seaway.

CLIMATOLOGICAL EVIDENCE

During Eocene times the Pyrenees were situated on the thirtieth degree of northern latitude (Smith et al., 1973, text-fig. 6, map 1). At present this would mean a location on the extreme margin of the tropics. On a world-wide scale the Paleocene–Eocene climate was on the average clearly warmer than it is now, for no extremely cold climates existed at that time. A wider tropic belt must have hemmed the equator, and the other climatic belts must have shifted towards the poles. Therefore the area studied was definitely located within the tropics. The coral reefs and the thick and compact *Lithothamnium* ridges are the most striking witnesses of such climatological conditions.

Nevertheless the Tremp Basin must have been in the zone of marginal reef growth as defined by Schlanger & Konishi (1975), judging from the composition of the encountered fauna and flora. This is due mainly to the fact that the Tremp Basin was connected with the eastern part of the Atlantic Ocean. At tropical latitudes the eastern sides of the oceans are generally colder than the western sides (Lees & Buller, 1972); these regional differences can be explained by the oceanic circulation which in its turn is influenced by the rotation of the earth on the climate. Reef growth was relatively weak in the Tremp Basin, although reefs and related facies covered large areas during some episodes. The production of coral was low so that the reefs could not contribute much material to deeper facies. As a result the production of indigenous material in deeper water was not obscured by transported coral and algal colonies and the shells of other reef inhabitants as would happen when vigorous reef growth occurred (Schlanger & Konishi, 1975, fig. 4). A fortunate consequence is that many facies types can be distinguished much more sharply and clearly than in the zone of optimum reef growth. The specific character of the deeper facies bordering on the reefs thus is clearly evident in the Tremp Basin.

A peculiarity of the area studied is that typical coral–algal as well as bryozoan–algal facies (Schlanger & Konishi, 1975) have been found. In the terminology of Lees & Buller (1972) these are called the chlorozoan and the foramol associations, respectively. Hermatypic corals and calcareous algae (for instance *Halimeda*) are abundant in the coral–algal facies whereas brachiopods, bryozoans and barnacles are scarce. In the bryozoan–algal facies the opposite holds. Red algae and foraminifera are about equally abundant in both facies, and molluscs are somewhat more important in the bryozoan–algal facies (Schlanger & Konishi, 1975, fig. 2a; Lees & Buller, 1972, fig. 1).

Generally the coral–algal facies in the area studied represents the shallower, warmer waters and the bryozoan–algal facies the deeper, colder waters. This can easily be explained by the well-known dependence of hermatypic corals on intense sunlight and relatively high water temperatures (Wells, 1957). In tropical areas characterized by the vigorous growth of coral and algal reefs bryozoans are abundant at depths of several tens of metres (Maxwell et al., 1961; Maxwell, 1968). In higher latitudes bryozoans can inhabit shallower depths because of the lack of competition of reef corals.

It is not accidental that reef growth in the Tremp Basin was most extensive during the time that submarine relief was most pronounced. In the present-day marginal reef growth zone, coral and algal reefs can grow only on relief elements that clearly rise above their surroundings. On the weakly sloping parts in between the bryozoan–algal facies dominates (Carrigy & Fairbridge, 1954; Maxwell et al., 1961; van Andel & Veevers, 1965; Maxwell, 1968).

AUTOCHTHONOUS GLAUCONITE, AN IMPORTANT EXPEDIENT IN PALAEOECOLOGICAL RECONSTRUCTIONS

The authigenic mineral glauconite can be formed in water with a pH slightly higher than 7, under mildly reducing conditions, if turbulence and sedimentation rates are not too high. The temperature range suitable for the formation of this mineral is fairly limited. Probably the minimum temperature is about 15 °C and the maximum 20 °C. As a result the depth interval in which glauconite can be formed is also rather limited. In temperate seas glauconite originates mainly at depths of about 30 m. In tropical areas it is formed at much greater depths. The deepest occurrence of autochthonous glauconite would be 250–500 m (all above-mentioned data from McRae, 1972; Buurman, 1973). The statement of Kohler (1977) that the maximum depth is 800 m is not very likely because the required temperature will not be reached easily at that depth under present circumstances.

Within such a limited area as the Tremp Basin where uniform climatic conditions can be assumed to have existed we may proceed from the assumption that throughout the basin the upper limit for autochthonous glauconite remained approximately the same. Along the northern side of the basin this limit was probably somewhat higher because of the influence of the current entering from the Atlantic Ocean. Whenever the

sedimentation rate was not too high during most of the formation of the marine sediments of a certain section, then the parts with autochthonous glauconite of such a section must have been formed in deeper waters and the parts without this mineral in shallower waters (the lower limit of the occurrence of glauconite will never have been reached in the area studied, except perhaps in the extreme western part – mainly west of the Esera River). Sometimes glauconite was transported to shallower waters. Then it was often more or less oxidized. The most obvious example of allochthonous glauconite has been found in the *F. cucumiformis* Zone of section X (samples 21a, 21b). Here a glauconitiferous layer containing many transported fossils from a large variety of marine environments lies between shallow marine deposits with imperforate foraminifera associations (facies VI). The glauconite of this layer is largely oxidized into a brown-coloured mineral.

In the tropical part of the present eastern Atlantic Ocean (between latitudes 10° N and 10 °S) temperatures of 20 °C usually prevail at depths of 50–100 m (Corcoran & Mahnken, 1969; Voigt et al., 1969). Above 50 m higher temperatures exist, so that no glauconite can be formed there. The Tremp Basin was situated at a more northern latitude but because it was part of a strait or a narrow appendix to the Atlantic Ocean it will upon the whole have been warmer than the open ocean at the same latitude due to its more sheltered position. Therefore the minimum depth of the occurrence of glauconite can be estimated at about 50 m.

Facies XIII and XIV nearly always developed below this critical boundary. Facies XV can occur above as well as below this depth; this can only be deduced from indirect sources, for the rate of sedimentation of the *Turritella* marls was too rapid for the formation of glauconite. The presence or absence of glauconite in thin, intercalated layers which were deposited slowly make a depth determination possible. Some reefs (subfacies VIIIe) must have flourished in waters deeper than about 50 m, judging from the presence of autochthonous glauconite which colours parts of the skeletons of many corals. The regular occurrence of this mineral and the accompanying faunal elements in subfacies Vb suggest a depth of formation of about 40–50 m for this subfacies with its giant cross-beddings. Facies XI and XII sometimes developed within the depth range of this mineral but generally they developed in shallower water. All other facies never contain autochthonous glauconite and developed at depths of less than 50 metres.

OTHER TEMPERATURE/DEPTH DATA

In most facies types large benthonic foraminifera predominate. At present the tropics are the only area where this is the case. This distribution together with the occurrence of coral reefs, algal reefs, calcareous green algae and many other tropical groups of organisms in the Tremp Basin make only one conclusion possible, namely that this area was situated in the tropical climate zone.

This means that the temperatures of the sea water in the shallow and protected parts of the basin will easily have reached value of 30 °C. Near beaches and in lagoons where evaporitic conditions prevailed, even higher temperatures can be expected.

Corresponding with recent examples (see for instance le Roy, 1938) facies with imperforate foraminifera associations (viz. subfacies IVa, b, c; Va; VIa–f; VIIa, b; VIIIa–c and IXb) are indicative of the shallowest and warmest parts of the sea (depths of 0–25 or 30 m). In fact subfacies IVa–c, VIIa, b and VIIIa–c are generally confined to the upper part of this range, whereas subfacies Va is strictly limited to the lower part of this range. As a rule coral reefs (subfacies VIIId) and off-reef shoal limestones (subfacies IXa) will also have developed above depths of 25–30 m, although they often contain a mixed perforate–imperforate foraminifera association. The perforate elements here are usually allochthonous.

Mixed perforate–imperforate foraminifera associations (facies XI and XII) occur in deeper waters, although a considerable overlap with the preceding association exists. Le Roy (1938) for instance found an *Operculina – Ozawaia* community at depths greater than 18 m. Differences in environmental protection are the cause of this overlap. Perforate elements can inhabit shallower depths in the open sea than in more or less sheltered environments, and the opposite is true for the imperforate elements, such as most alveolinids and *Orbitolites*. The lower boundary of the mixed perforate–imperforate foraminifera association generally coincides with the upper limit of the occurrence of glauconite, namely ca. 50 m. Only in rare instances somewhat greater depths can be assumed.

The perforate foraminifera associations (facies XIII, XIV and part of facies XV) consequently inhabited sea bottoms at depths greater than 50 m as already described. The recent bryozoan species *Biflustra savartii* is known to live below ca. 100 m; subfacies XIIIb is characterized by a *Biflustra* community. Subfacies XIIIa contains the most diverse bryozoan fauna of the Tremp Basin; according to Schopf (1969) nowadays the largest numbers of species of bryozoans occur between depths of 50–100 metres. Therefore a maximum depth of about 100 m can be supposed for subfacies XIIIa and XIIIb on the grounds of the bryozoans. Subfacies XIIIc is generally so closely connected with the other two that it must have been limited to the same depth interval. The presence of large benthonic foraminifera and various groups of molluscs which are limited to the photic zone suggests that the sea in the area studied was rarely deeper than about 100–150 m. The temperature certainly was not below 15 °C at the normal maximum depths, since glauconite always occurred whenever the rate of sedimentation was sufficiently low.

A three-dimensional model can be drawn in which the position of the various (sub)facies types with respect to one another and with respect to the depth of the sea is given (Fig. 13). As many subfacies as possible are included in this block diagram (only subfacies IVe, Va and Vb are not represented), so that the true

relationships are somewhat strained: the relative spaces occupied by the subfacies were sometimes larger in fact than depicted here. Many subfacies moreover have only been found in a limited stratigraphic range. Fig. 13 therefore is a theoretical diagram, for which data concerning the development of the entire Tremp Basin were used.

It has been attempted to indicate the most frequently occurring relationships between the different (sub)facies types, but it should be remembered that one subfacies in nature often also bordered on other subfacies. The thicknesses of various subfacies shown in the model have been made to agree with the estimated sedimentation rates of these subfacies.

TECTONICS AS CAUSE FOR THE EXISTENCE OF THE PALAEOGENE TREMP BASIN

It may be asked why the Tremp Basin existed and why it has the shape it actually has.

The Tremp Basin forms the easternmost part of a large east-west trending basin structure which can be followed to the Bay of Biscay. The smaller Ager Basin, having an axis parallel to that of the Tremp Basin, can be considered a similar basin which joins the large structure. The basins are separated by the Montsech threshold. North of the Tremp Basin is a positive area, and north of that the southern French marginal trough. The latter two units also have an east–west directed axis.

In cross-section therefore the picture is that of an accordeon-like structure on which smaller undulations may have been superposed outside the Tremp Basin. The direction of this structure agrees completely with the direction of the greatest compressional force due to the collision of Africa and Europe between which Spain was pinched.

During the formation of the Ager Formation the compression was apparent partly as the slow but persistent deepening of the Tremp Basin which was the greatest near the axis of the basin. As a result some N–S shortening of the basin occurred; when this could no longer happen (in the course of the Eocene) the other possibility of shortening, namely nappe formation, took place.
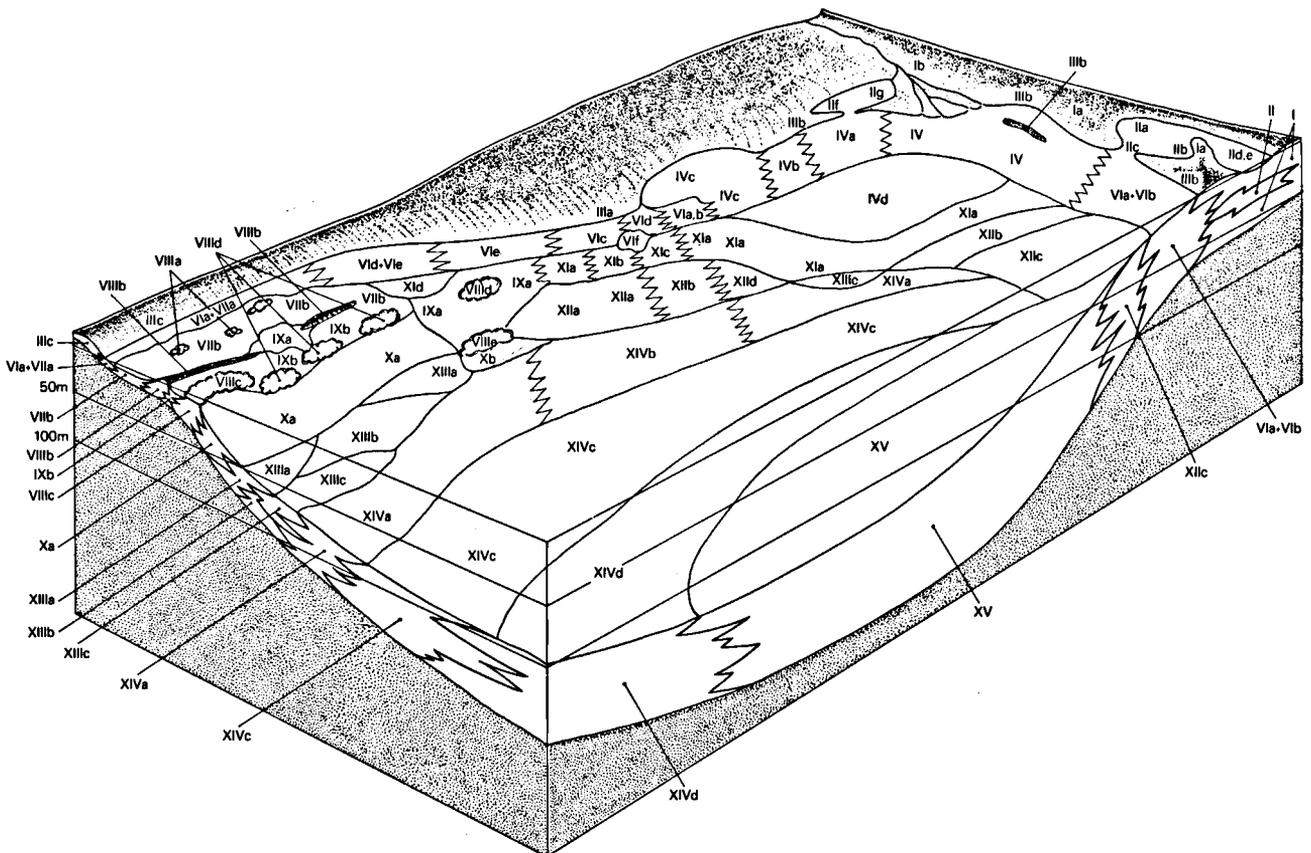

Fig. 13. Three-dimensional model in which the most frequently occurring relationships between the different (sub)facies types are shown. The thicknesses of various subfacies have been made to agree with the estimated sedimentation rates of these subfacies.

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