THE STRUCTURAL GEOLOGY AND PETROLOGY OF THE MESOZOIC CALCAREOUS SEDIMENTS WEST OF LAC DUE BOURGET (SAVOIE).

by

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ABSTRACT

The Mesozoic rocks of the area consist chiefly of limestones which range in age from Middle Jurassic to Lower Cretaceous.

Previous research is summarised. Little detailed work has been done on the lithology of the Mesozoic succession and the limestones have not previously been the subject of detailed petrographic study. The general geology of the area is described with emphasis on the lithology. The lithological divisions have been mapped on a scale of 1:20,000. Three mountain ridges cross the area from north to south. Thrust faults occur on the western sides of at least two of them.

In the laboratory, the limestones were studied by means of thin sections and etched polished surfaces. Several specimens were analysed chemically for magnesia, lime and ferric oxide; insoluble residues were also determined. The calcilutities are described and their possible modes of origin are discussed. A scheme of nomenclature is presented for calcarenites, based on three components:

pellets, ooliths and bioclastic fragments. The depositional characters of each rock type are outlined. Diagenetic modifications involving deposition and redistribution of calcite due to "mechanical" processes are distinguished from those due to "physico-chemical" processes. In partially and completely silicified rocks it is suggested that there were possibly four phases of silicification. The textures of dolomites and dolomitic limestone are described and their origin discussed. In both silicification and dolomitisation the selective nature of the processes is demonstrated. Dedolomitisation is shown to be an important process which has produced a variety of replacement textures. The occurrence of dedolomitised rocks was not formerly recognised in the Jura and the replacement textures have not been described previously in Western Europe or America.

Systematic petrographic studies were made of each formation and possible depositional environments are deduced. Some formations, which show rhythmic sedimentation, were the subject of more detailed studies.

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PART II

Frontispiece.

The Charvaz Ridge, looking north, with the Lierre Ridge in ghe foreground.

The Charvaz Ridge, looking east.

PART I

CHAPTER I

INTRODUCTION

The Jura Mountains form a crescent on the map which extends from Baden in Switzerland to Grenoble in France. On the convex side of this crescent there are areas of essentially flat lying rocks which are known as the plateau Jura or "Jura tabulaire" in contrast to the folded Jura or "Jura plissé" of the Jura proper (Fig. 1). The Jura rocks are Mesozoic in age, and consist dominantly of unmetamorphosed limestones with subordinate marls. They are separated from the basement rocks by Triassic sediments with thick salt and anhydrite formations.

Along the greater part of their length the Jura Mountains are separated from the Alps by the Molasse plain. Towards the southern end of the French Jura however, the sweep of the crescent brings the Jura rocks into contact

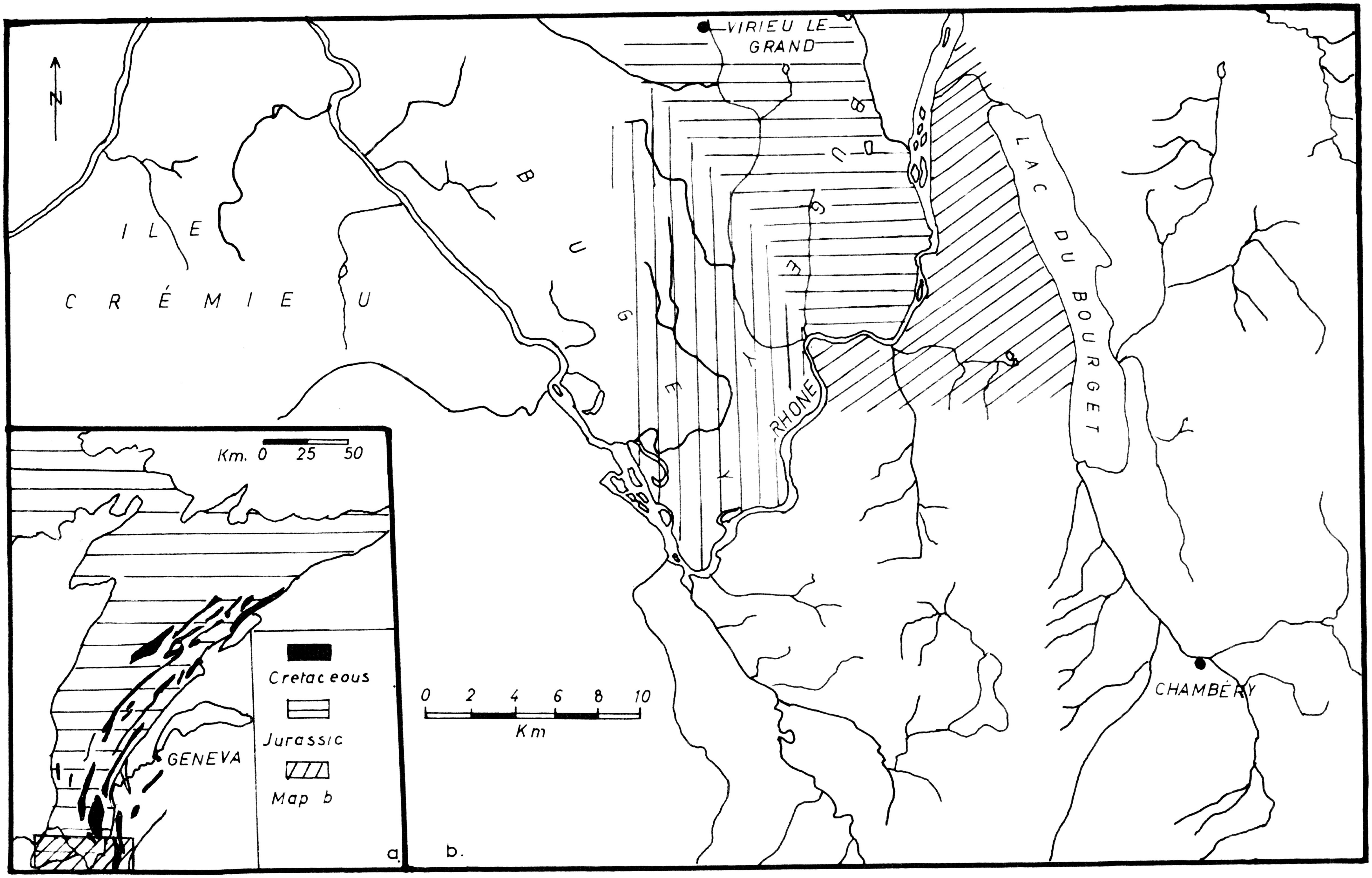


FIG.1. LOCATION OF THE AREA STUDIED

a Simplified geological map of the Jura Mountains.

b Map showing the area studied by students from IMPERIAL COLLEGE. Oblique shading: area studied by the author; horizontal shading: area studied by S. Taha; vertical shading: area studied by other students.

with the subalpine front in the Grand Chartreuse.

Research by Imperial College in the southern part of the French folded Jura was initiated by Dr. D.V. Ager in 1956, with the purpose of ultimately building up a regional picture of facies changes and palaeoecology. As a part of this project the author commenced work in the summer of 1957 in the area to the west of Lac du Bourget in the western part of Savoie. At the same time, the late S. Taha commenced his research in the area immediately to the west and north-west, centred around Vivien le Grand in the adjacent part of the province of Ain. It was intended that the work of Mr. Taha and the author would be combined to give a broader regional picture of the geology. The premature death of Mr. Taha early in 1959, in the later part of the second year of his research, has not made it possible for the regional aspects of the work to be presented at this stage. However, reference will be made to certain aspects of Mr. Taha's research in various sections of this thesis.

The area described in this thesis lies towards the southern end of the French folded Jura in the western part of the province of Savoie. It is bounded naturally on the east by the Lac du Bourget, and on the north and west by the river Rhone (Fig. 2). Topographically the area consists of three long essentially north to south mountain ridges separated by flat or gently undulating areas of lake and river alluvium, glacial deposits and Tertiary Molasse. These ridges are from east to west; the Charvaz Mountain ridge, the Lierre Mountain ridge and the Parves Mountain ridge. The Mesozoic rocks are on the whole well exposed, but some parts of the area are heavily forested. The various members of the succession commonly develop characteristic topographic features which allow them to be traced with confidence on air photographs, even through the forest areas. The topography of the region is partly pre-molasse in age, since the Molasse is generally believed to have been deposited in tectronic basins surrounded by the newly risen mountains. The pre-molasse surface is only exposed in one locality in the area, that is, at Chevelu. The topography has been modified by the Pleistocene glaciation which has left a veneer of boulder clay and erratics of schist and gneiss particularly on the lower slopes of the ridges and on the Moloese country.

The work involved in the preparation of this thesis consisted of two summer seasons (1957 and 1958) in the field, in the course of which the Mesozoic rocks were subdivided stratigraphically into a number of formations on the basis of lithology, and then their distribution mapped on the scale of 1 to 20,000. In the course of the first field season, rock specimens were collected from all members of the stratigraphic succession, and were subsequently studied petrographically in the laboratory. On the basis of this preliminary laboratory study it was decided that certain parts of the succession would be amenable to detailed petrographic study. Such a study would be a contribution to sedimentary petrology in general, and in particular would serve as background for later regional studies of facies changes at these levels throughout the Jura. Field mapping continued during the second field season, and extensive collections of specimens were made from the selected formations. Laboratory study of these specimens continued throughout the second year of the research.

The thesis is in three parts. The first part deals with the field aspects of the work, that is, the stratigraphic succession, lithologies and structure; while the second part is concerned with the laboratory study and gives a petrological account of the Mesozoic limestones. These aspects of the work are brought together in the third part, which comprises detailed petrographic studies of the individual formations and conclusions as to their depositional environments.

CHAPTER 2

REVIEW OF PREVIOUS WORK

The area between the Lac du Bourget and the Rhone has attracted numerous workers in the field of geology Localities such as la Balme gorge, Vions, Chanaz and the Col du Chat have become classic, especially for the study of Callovian and Portlandian - Purbeckian faunas.

In 1844, members of the Geological Society of France visited the area and Chamousset published an account of this excursion. In the Col du Chat the Neocomian was described as consisting of white limestones, marls and sandstones with green grains. The last probably refers to the glauconitic calcarenites of what is here called the Bourdean Beds since there are in fact no sandstones in the Mesoic succession of the area. In the Upper Jurassic, white limestones and dolomites were recorded. Chamousset wrongly applied the term "oolitic limestones" to the bioclastic calcarenites of the Middle Jurassic. In 1854, Pillet and Girod published a geological memoir on the area centred around Chanaz. They recognised the presence of Bathonian, Callovian, Oxfordian, Corallian and the Neocomian. The absence of the Portlandian - Purbechian from their succession was probably due to the scarcity of macrofauna. Pillet (1863) recorded a fresh water fauna in the Purbechian of the Mont due Chat and also recognised the Valangenian stage in the Lower Cretaceous. This had previously been classified as Upper Jurassic. Lory (1864) noted the presence of corals, Diceras and Nerinea in the white limestone of the Col du Chat. In the same year Ebrary (1864) recognised the Bajocian stage at Chanaz. Choffat (1878) in his memoir on the Callovian and Oxfordian of the Southern and Western Jura described in some detail the succession between Lucey and Puthod and at the Col du Chat. Hollande (1880, 1884) published two volumes which dealt with the stratigraphy of much of Savoie. By covering larger areas, he attempted some stratigraphical correlation. He recorded for instance a bed rich in Ostrea in the Purbeckian of the Mont du Chat, Colombier, and other localities, though use of this genus for correllation cannot be considered as having much value.

The Geological Society of France held its extraordinary session in the Jura in 1885. Excursions under the leadership of Pillet and Hollande were made to La Balme gorge, Vions and Chanaz. Pillet (1885) who recorded observations made on this occasion paid special attention to the Purbeckian fauna. These, however, were confined to the macrofauna, particularly to the gastropods. A more complete list of fresh water fossils from the Purbeckian of Yonne was given by Maillard (1885). In a note in the "Revue Savoisienne" Hollande (1885) described the Purbeckian of the Mount du Chat as consisting of alternations of fresh water and marine beds. From further study at Bregnier - Cordon (Ain) he concluded that this alternation of marine and fresh water beds is typical of the Jurassic - Cretaceous boundary of Savoie and Ain. His conclusions were later confirmed by the study of micro-fauna by Donze (1958).

More detailed work was carried out later by Hollande (1885), who gave a list of macrofossils and described the lithology of the Jurassic and Lower Cretaceous at Chanaz, Vions and the Grand Colombier at Culoz. Hollande's account includes thicknesses of the various lithological groups, which had hardly been mentioned earlier. He further showed that the "white oolitic" limestone at Chanaz and the Col du Chat is of Lower Kimmeridgian age, but that it occupies a different stratigraphical level at Culoz. Although true oolites of Lower Kimmeridgian age have not been recorded by the writer, Hollande's observation demonstrates that rapid facies variation exists in the Mesozoic limestones of the area. Hollande further maintained that the Portlandian varies in thickness from 30 and 35 metres at Vions and Chanaz respectively to 45 metres at Columbier. It is surprising that from the study of macrofossils he claimed an accurate delimitation of this stage in spite of the fact that even with more recent studies of the micro-fauna the delimitation of the Portlandian is rather difficult in this part of the Jura. A few years later in 1888 Revil published a paper on the Middle and Upper Jurassic of the Mont du Chat. Although his structural account was shown to be incorrectly by Aymé (1951), his section on the stratigraphy of the Jurassic is undoubtedly the best yet produced. The so-called "oolitic limestone" in the Kimmeridgian of the Col du Chat was stated to thicken considerably at Chanaz. This apparent thickening is now known to be due to oblique faulting.

The geological mapping of the area was carried out by Riche, Doŭmi and Hollande between 1894 and 1899, and the official geological map was published in 1901 (No. 169, 1 : 80,000). Hollande was concerned with the mapping of the sub-alpine region and part of the Jurassian region which includes the area surveyed by the author. Hollande (1898) maintained that a synclinal structure existed at Billieme in the Hauterivian. The present writer regards this structure as a thrust fault bringing these beds against the Upper Jurassic. Aymé (1951) has also shown that Hollande's geological mapping of Charvaz mountain was an oversimplification of the structure.

In a comprehensive work on the "Géologie des Chaine Jurassiennes et Subalpines de la Savoie" Révil (1911 - 13) devoted some sections to the geology of Mont du Chat and that of Mont Tournier. In these anticlines, Révil, showed that the amplitude and intensity of the folding is generally less than it is in the Sub-alpine chain further east. He also concluded that orogenic movements affecting this part of the Jura were numerous and lasted until Pleistocene times. The concept of continuity of orogenic movements is very important and is in agreement with the conclusions reached by the writer.

An important work on the Callovian ammonites of the Mont du Chat ridge was published by Lemoine (1932). Blondet (1935) described several species of the genus Cecotraustes from the Bothonian of Chanaz.

The work of Favre and Richard (1927) on the Kimmeridgian to Purbeckian succession of Pierre-Chatel and la Balme gorge is by far the most detailed scientific work so far carried out in the area. Besides observing field characters of each formation they gave an account of the petrology of the Portlandian-Purbeckian, and from the study of sections they located the fresh water horizons at the top of the Jurassic. They have, however, wrongly denied the presence of dolomites in the basal Kimmeridgian and did not record the extensive dedolomitisation in these horizons.

In a paper concerned with the revision of the Chambéry map (No. 169, 1 : 80,000), Giot (1947) pointed out that the folds in the Mont du Chat and Montage de Lierre have more affinity with those in the Sub-alpine zone than with the typical Jura folds found further west in Bugey. Vatan (1947) who was also responsible for the revision of the map of the Chambéry region dealt mainly with the Molasse and with the Quaternary deposits. His paper merely recorded some field characters of these deposits. Gidon, who is at the present officially in charge of a project for resurveying the Chambéry region, has produced a series ofpapers which have dealt mainly with the stratigraphy and some structural aspects of the area. In the Chevelu region, he described a "décoiffement" structure which he maintained brought the 'Urgonian'to rest on the Molasse. The writer disagrees with Gidon on some structural details in the area, which will be dealt with in the appropriate chapter. Gidon's interest in the area is, however, confined to the revision of the structure set out in the Chambéry map (Sheet 169, 1902), and other maps and sections, since published.

His published works have not dealt in detail with the petrology of the limestones which forms the principal subject of this thesis.

The fresh-water beds of the Purbeckian were studied recently by Donze (1958) in the Col du Chat and at Vions. Donze has shown that the Purbeckian facies at these localities differs markedly from that described by Favre and Richard (1927) at la Balme gorge. The latter is closer to that occurring in the Fier gorge. The localities chosen by Donze for the study of the Purbeckian beds are widely separated. Further palaeontological work is needed at intermediate localities to make possible the construction of a more precise palaeogeographical picture.

Among the major syntheses dealing with the Jura the two volumes of Margerie (1922 - 1936) are of considerable value to the structural geologist. They include maps and sections, and comprehensive bibliographies covering the whole of the French Jura. The chapter on the Jura mountains in Arkell's "Jurassic Geology of the World" is a useful summary, especially the section on the southern Jura which includes the area studied by the author. The excellent work of Heim (1919) "Geologie der Schweiz", although concerned mainly with the Swiss Jura is a valuable reference since many of the samples of folding well illustrated in sections by Heim are encountered in the southern Jura in

France. The memoir by Moesch (1867) and the monographs by de Loriol (1876 - 1904) are valuable standard works for the stratigrapher and palaeontologist. From this brief survey it is apparent that the structure and stratigraphy have been more well described but virtually no petrographical work has been done on the limestones of the area.

CHAPTER 3

THE MESOZOIC SUCCESSION

The Mesozoic succession presented in this chapter has been established mainly on the lithological basis. A representative collection of fossils made by the writer and other members of Imperial College resulted in the recognition of the stages presented in Table (1). The Faunas have been identified by Dr. D.V. Ager, Dr. L.R. Cox, Dr. H. Dighton Thomas and Dr. J.H. Callomon. In published literature on the area stages seem to have been recognised mainly by comparison with adjacent localities where the fauna is either relatively more abundant or has been studied in greater detail. No lithological divisions have been proposed by French geologists in this region. In this thesis, formations are named after "type localities" where the succession has been studied in detail. This was carried out by the writer in the area between the Lac du Bourget and the Rhone and by the late S. Taha in the area centred around

TABLE 1

THE MESOZOIC SUCCESSION

Formation	Division	Stage	Thickness (metres)
Chambotte Limestone		Barremian (?) ('Urgonian')	31 - 47
Bourdeau Beds	Upper Lower	Hauterivian (?)	32 - 60 89*
Parves Beds	Upper Middle Lower	Valenginian- Berriasian (?) Purbeckian-Portlandian	40 55 116
Virieu Limestone	Upper Lower	Portlandian- Kimmeridgian	125 - 300 40
Gignon Limestone		Oxfordian (?)	30
Chavoley Beds		Oxfordian (? some Callovian)	200
Chanaz Beds	Upper Middle Lower	Callovian- Bathonian Bathonian	40 20 15
Lucey Beds	Upper Middle Lower	?Bajocian	20 25 23

*Where a single figure is quoted the thickness is that measured at the type locality or where the formation was studied in detail.

Virieu le Grand (Fig. 1).

In the northern part of the Charvaz ridge, virtually the whole of the Mesozoic succession is reasonably well exposed, and this is where it was first studied by the author. In the course of mapping, however, it was found that some formations, namely the Parves and the Bourdeau Beds, are better exposed in the southern part of the area and thus the type localities for these formations were chosen there. The succession is summarised in Table (1). Field evidence for each formation will be described in turn.

The Lucey Beds

This formation is named after a village on the left bank of the Rhone in the neighbourhood of which it is well exposed and where it is easily accessable.

In the type locality the Lucey Beds constitute a major cycle of sedimentation which begins with a coarse-grained clean-washed calcarenite, becoming progressively finer grained upwards. A fairly thick succession of calcarenites and cherts follows. Higher up in the cycle events must have followed in a reverse order thus the cycle

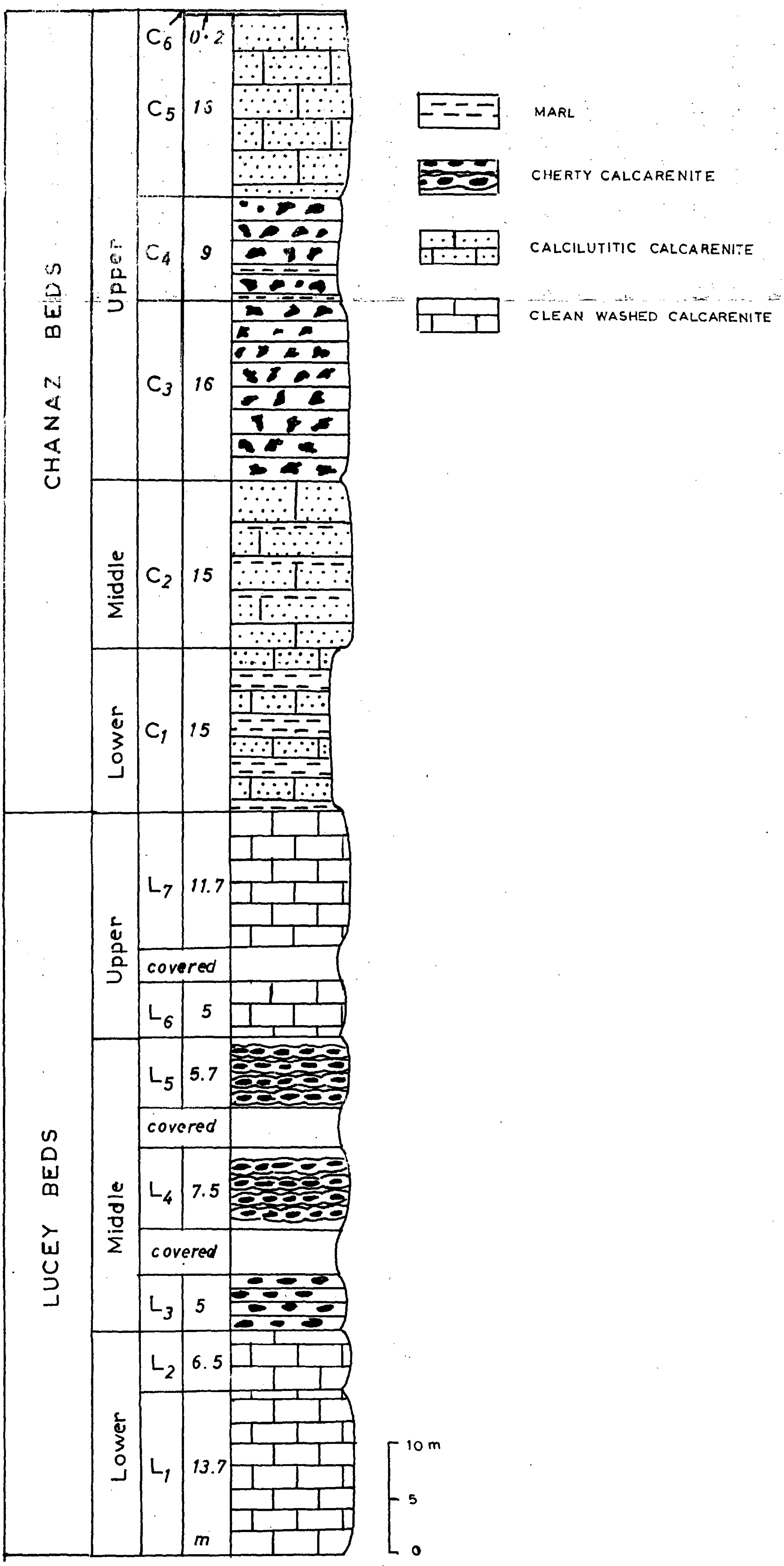


FIG. 3.— *Vertical section of the Lucey and Chanaz Beds south of Chanaz.*

ends as it began with clean-washed, coarse-grained calcarenite. The skeletal components of the bioclastic calcarenites, which constitute the main part of the Lucey Beds, weather differentially. This makes it possible to distinguish in the hand specimen fragments of crinoids and bryozoa amongst the other constituents. These fragments often stand out in relief on the weathered surfaces giving them a typical granular appearance, which in fine-grained bioclastic calcarenites can easily be mistaken for dolomite. It is convenient to recognise three subdivisions. Each of these will be described in turn.

1. <u>Lower Lucey Beds</u> This subdivision consists of a coarse or medium-grained calcarenite (L_1), and a fine to very fine-grained calcarenite (L_2). (See Fig.3). The lower group (L_1) is cross-bedded, while the upper group (L_2), shows wavy bedding surfaces and fairly uniform bedding thicknesses ranging from 25 to 30 cm. The coarse calcarenites of the former group form thick beds truncated by concave surfaces which also truncate the cross-laminations (Fig. 4). Each cross-bedded unit usually begins with a thick bed of very coarse calcarenite. This is followed by finer-grained

calcarenite which forms cross-laminations ranging from 3 cm. to 10 cm. in thickness. The unit ends with fine-grained arenaceous and laminated calcarenite.

2. Middle Lucey Beds. This unit consists of fine-grained calcarenites with cherts. In the field it is possible to recognise three subdivisions. These vary in bedding thicknesses, the type of chert and the presence or absence of very thinly bedded arenoceous layers (see Fig. 3).

(L_3) In this sub-division bedding thickness is fairly uniform (17 - 20 cm). The fine-grained limestones are interbedded with arenaceous layers each of which is about 2 cm. in thickness. The middle part of each limestone bed is siliceous. The 'chert' nodules usually occupy about 1/3 of the thickness. In spite of the nodular character of the latter, bedding surfaces are planar, and this is probably related to the presence of arenaceous and slightly argillaceous layers. When these layers are absent, wavy bedding surfaces become dominant.

(L_4) In this sub-division the average bedding thickness is greater than in (L_3). Thicknesses vary between 45 and

FIG. 4A. The Lower Lucey Beds, north of Lucey

FIG. 4B Cross-bedding in the Upper Lucey calcarenites, west of Col du Chat

150 cm. Two generations of chert are found (i) nodular chert arranged parallel to the stratification and related to the wavy bedding surfaces and (ii) tabular chert, cutting across the stratification. These are parallel to vertical joints, which are well developed in this formation, and are obviously related to the joints. These cherts are therefore regarded as post-tectonic and must have formed later than the nodular cherts.

(L_5) this last sub-division is characterised by sphaeroidal cherts which show concentric structures. Bedding thicknesses are fairly uniform ranging from 50 to 60 cm.

3. Upper Lucey Beds. The uppermost division of the Lucey consists of very fine to fine-grained calcarenite below and coarse to very coarse-grained calcarenite above. In the lower group (L_6), particle size increases progressively upwards, and bedding thicknesses range from 40 cm. to 105 cm. In the upper group (L_7), bedding surfaces are indistinct. Instead, stylolites with columns up to 2cm. in height are of frequent occurrence. In the Col du Chat, however,

cross-bedding is well developed (Fig.4B).

The Lucey Beds have yielded the following fossils:

1. Lower Lucey Beds.

Rhactorhynchia sp.

Crustacean fragment

2. Middle Lucey Beds.

Pecten sp.

Lobothyris buckmani (Davidson)

Isastraea explanulata (Mc.Coy)

Isastraea sp.

3. Upper Lucey Beds.

Isocrinus cf. *I. andreae* Desor

Parallelodon (*Beushausenia*) sp.

Posidonomya? sp.

The Lucey Beds are exposed in continuous outcrop in the escarpment which extends from Chanaz to Lucey. It is extremely resistent to weathering and thus often forms almost vertical cliffs. The escarpment increases in height progressively southwards from Chanaz, but decreases in height again as it approaches Lucey. Exposures are thus only accessible in the neighbourhood of Chanaz and Lucey. In the southern part of the area another important outcrop along a steep escarpment extends from just north of Monthoux to la Vacherie and beyond. In this outcrop the Lucey Beds are involved in thrust-faulting which cuts out part of the succession. An excellent section is, however, exposed south of the Col du Chat. Lithologically the Lucey Beds here are similar to those exposed in the Chanaz-Lucey escarpment, but certain beds show a marked increase in thickness. As in the type section arenaceous layers are important up to the basal part of the Middle Lucey but are absent from the upper part. The calcarenites of the Upper Lucey measured here 42 metres compared with 20 metres north of Lucey. The increase in thickness is mainly in the fine-grained calcarenites which amount to 26 metres compared with 10 metres in the northern outcrop.

More striking lateral variations are displayed west of the area studied by the author, namely, in Bugey. In the neighbourhood of St. Bois, the Middle Lucey consists mainly of coarse-grained limestone rich in corals, terebratulids and rhynchonellids. In this locality J.W. Murray (private communication) measured some 20 metres of this coral-rich facies. The siliceous limestones which amount to 26 metres at the Col du Chat are only 4 metres thick in St. Bois. East of the latter, in the neighbourhood of Chazy Bons (Fig. 2), the coralline facies is again encountered. S. Taha (private communication), who mapped this area, recorded 12 metres of dolomitised coral reef facies at Cuzieu and 13 metres in the vicinity of Billième. The siliceous limestones here are only 7 metres thick. Thus during the Middle Lucey times, coral reefs must have existed in Bugey. They coralline facies thins out in an easterly direction and is absent from the area between the Rhone and Lac du Bourget. The overlying limestones with Chert increase in thickness in the same direction and at the Col du Chat reach 26 metres.

The Chanaz Beds

This formation is well exposed just south of the name village of Chanaz, in the northern extremity of the area. The excellent exposures and the ease of accessibility here have made it a classic locality, especially for the study of the Bathonian and Callovian fauna which the Chanaz Beds have yielded.

The Chanaz Beds differ from the Lucey Beds in being

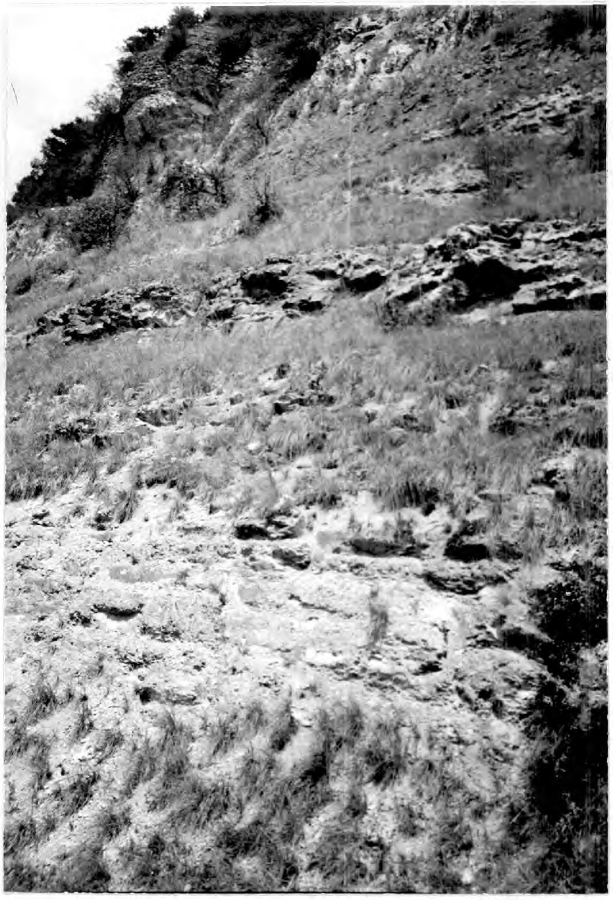


FIG. 5 The Chanaz Beds, south of Chanaz. The shaly beds at the base are the Lower Chanaz Beds. The Upper Chanaz cherty calcarenites form the cliffs at the top.

more argillaceous and the cross-bedding, so typical of the Lucey Beds, is absent from this formation. In the Chanaz area it is possible to distinguish three divisions (Fig. 3), each of which makes a markedly different topographic feature.

1. Lower Chanaz Beds. This division consists of a rhythmic alternation of dark grey argillaceous limestone and shales. In the lower part shale and limestone are almost equal in proporations. Towards the top the latter becomes more important. Fossils include:

Lima cf L. rigidula (Phillips)
Goniomya V-scripta (Sowerby)
Pholadomya crassa (Agassiz)
Pholadomya lyrata (J. Sowerby)
Morrisceras (?) sp.
Procerites sp.
Lytoceras sp.

2. Middle Chanaz Beds. This division consists of very thick-bedded* grey argillaceous calcarenites interbedded with some marly horizons. The latter are extremely rich in brachiopods ammonites, lamellibranchs and echinoids. The fossils are well preserved and these beds together with the uppermost sub-division of the Upper Chanaz Beds, constitute the most fossiliferous horizons in the Mesozoic succession of the area. They are readily recognisable in the field and serve as a useful marker horizon. They have been, for instance, of considerable value in ellucidating the structure in the thrust zone of the Monthoux region (see map). Details of the section measured at Chanaz is given in the table below:

		Thickness in cm.
15.	Grey argillaceous calcarenite	700
14.	Grey calcarenite with ammonites, brachiopods and lamellibranchs	3
13.	Grey argillaceous calcarenite	100
12.	Calcarenite with echinoids	30

*terms for thickness of stratification are those proposed by Ingram (1954)

11.	Grey calcarenite with brachiopods scattered throughout	180
10.	Calcarenite extremely rich in terebratulids and rhynchonellids	20
9.	Grey calcarenite	80
8.	Calcarenite rich in rhynchonellids	4
7.	Grey calcarenite with rhynchonellids near the base	200
6.	Grey argillaceous calcarenite	50
5.	Marl extremely rich in rhynchonellids and terebratulids	20
4.	Grey calcarenite speckled with iron oxide; scattered oysters	100
3.	Marl extremely rich in rhynchonellids and terebratulids	18
2.	Grey calcarenite with brachiopods	30
1.	Grey argillaceous calcarenite, poorly fossiliferous	170

The Middle Chanaz fauna includes:

Acanthothiris cf. *A. spinosa* Lamark

Stiphrothyris spp.

Parkinsonia sp.

(see also below).

3. <u>Upper Chanaz Beds</u>. These beds form the highest part of the escarpment at Chanaz and in fact it retains this position along the greater part of the escarpment facing the Rhone between Chanaz and Lucey. This is due in part to its siliceous nature, which makes it extremely resistent to weathering, and partly because it is succeeded by succession of marls and limestones. Exposures of these beds are difficult to reach for the greater part of its outcrop. Some good exposures are, however, easily accessible both at Chanaz and immediately to the north-east of Lucey. The following lithological groups have been recognised in the field (see Fig. 3 for thicknesses).

(C_3) This group consists of grey fine-grained calcarenite with cherts and sub-ordinate shales. The cherts form irregular nodules scattered at random. These silicified limestones differ from those in the Lucey Beds in the irregular nature and random orientation of the chert nodules in relation to the stratification, and in the predominance of flat bedding surfaces. Bedding thicknesses are generally greater than those of the Lucey Beds, ranging from 30 cm. to 100 cm.

(C_4) This group is similar to that described above except that shales become more important, forming beds between 5 and 15 cm. compared with 0.5 to 2 cm. partings in (C_3).

(C_5 and C_6) These lithological groups, which form the top of the Chanaz Beds, are not exposed in the northern part of the area. In the southern part of the Charvaz ridge, however, between Monthoux and the Col du Chat, the limestones with cherts are overlain by very thick-bedded argillaceous calcarenites free from chert. These are followed by a ferruginous, oolitic limestone extremely rich in ammonites and brachiopods. Locally, this uppermost fossiliferous limestone is extremely rich in iron and was formerly exploited for iron ore in the Chanaz area. Although fragments of these ferruginous beds are widely scattered at the latter locality, nowhere is their outcrop exposed at the present time. These celebrated beds have been the subject of important palaeontological papers by Lemoine (1932) and several other workers, who showed that they represent a part of the Callovian stage.

Fossils, collected from various levels of the Chanaz Beds, from the areas studied by the author and by S. Taha, comprise the following:

Chomatoseris aff. *c. complanata*(Defrance)

Corynella (?) sp.

Morphoceras inflatun (Quenstedt)

Ochetoceras sp. indet.

Oppeliidae indet.

Alligaticeras sp. indet.

Parkinsonia sp. indet

Perisphinctid indet.

The Chanaz Beds have a similar areal distribution to the Lucey Beds. In their southern outcrop, however, they extend beyond Monthoux where their outcrop is repeated by strike faulting. The lower part of the Chanaz Beds usually produces gentle slopes in contrast to the cliff-forming Middle and Upper Chanaz.

The Chavoley Beds

These beds are extensively quarried for cement in the strike valley which extends north-west and south-east of

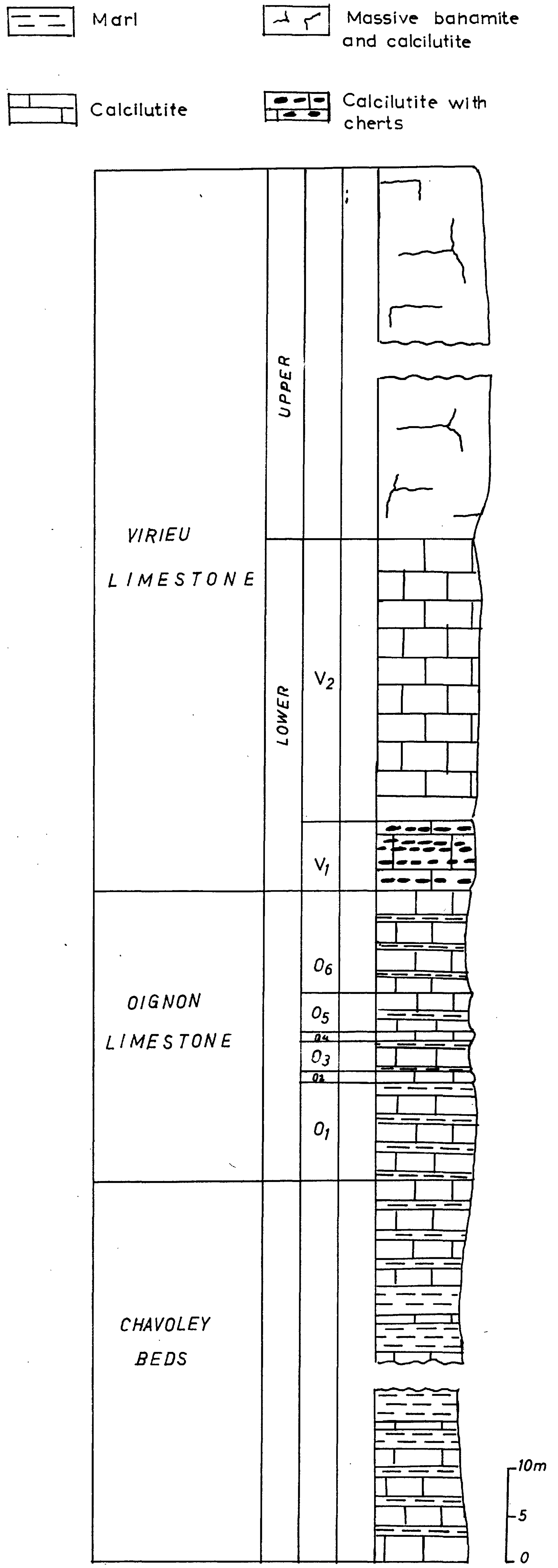


FIG. 6.— *Vertical section of the Chavoley Beds and Oignon Limestone at Chanaz and the Virieu Limestone at la Balme.*

the name village of Chavoley in the department of Ain. They were studied by S. Taha who collected rich ammonite fauna from these quarries.

In general terms the Chavoley Beds consist of rhythmic alternations of marls and medium-bedded calcilutites. Lithological subdivisions are based on the relative proporations of these lithologies. These include: (Fig. 6).

(Ch_1) In this group calcilutites are subordinate to marls, but are present in sufficient quantity to produce a significant feature.

(Ch_2) This sub-division consists predominently of marls. These form thin laminae ranging from 1 to 2 mm. These thinly laminated beds invariably give rise to low-lying country.

(Ch_3) Calcilutites predominate over marls in this division, and exhibit typical conchoidal fracture.

The Chavoley Beds are rich in fossils, especially ammonites and brachiopods. These are generally well preserved and easy to extract. They tend to be concentrated at certain levels rather than being uniformly distributed throughout the formation. The Chavoley fauna includes:

Ornithella cf. O. moeschi (Mayer)
Ataioceras cf. A. lothari (Oppel)
Discophinetes cf. D. Schilli (Oppel)
Perisphinctes spp.
Dichtomosphinctes (?) sp. indet.
Trimarginites trimarginatum (Oppel)
O. (?) semifalcatum (Oppel)
Oppeliidae indet.
Creniceras sp.
Amoeboceras sp.
Euaspidoceras sp. indet.
Sowerbyceras sp. indet.
Trimarginites sp. indet.
Dichotomoceras sp.
Taramelliceras sp.
Grossouvria sp. indet.
Alligaticeras sp.
Tulitidae sp.

In the area mapped by the writer, the Chavoley Beds outcrop in a strike vallgy extending from Chanaz to Jongieux.

FIG. 7 The Oignon Limestone at Oignon hill.

They also outcrop north and south of Monthoux where they form an almost horizontal feature which separates the steep scarp of the underlying Chanaz and Lucey Beds from the escarpment of overlying resistant formations.

The Oignon Limestone

On the southern flank of the Mollard de L'Oignon (Ain) south east of Chavoley, this formation is fully exposed (Fig. 7), and was studied by S. Taha. It has been measured at Chanaz in a quarry immediately to the north of this village. It consists of rhythmic alternations of bluish calcilutites and shales. This formation is extremely well bedded, and this together with its bluish colour and rusty brown weathering gives it a very distinctive appearance in the field (Fig. 7). Variation in the limestone/shale ratios permit the recognition of three main groups in the field. These from the base upwards include (see Fig. 6 for thicknesses):

1. (O_1) In this division the limestone/shale ratio is about 5 : 1. The calcilutites have fairly uniform bedding thicknesses ranging from 10 to 15 cm.

2. (O_2 - O_5) This consists of very thick-bedded (1 to 1.2 metres) calcilutites interbedded with calcilutite and shale alternations. In the rhythmic alternations, the limestone/shale ratios are lower than above, because of the increase of the thicknesses of the shaly horizons.

3. (O_6) In this division the limestone/shale ratios are relatively high. Higher ratios have resulted from the increase in thickness of the limestones which range from 30 cm to 100 cm.

In the quarry outside Chanaz, the top of the Oignon Limestone is marked by a marly horizon with pyritised nodules. The marls are relatively rich in fossils, mainly brachiopods. The total thickness exposed here is 30 metres. In the type area, where about 40 metres have been recorded by S. Taha (private communication), a pisolitic limestone about 4 metres in thickness occur at the top of the Oignon Limestone. At Chanaz, the marly horizons with pyritised nodules noted above is probably the lateral equivalent of the pisolite. In this locality a brecciated or conglomeratic limestone marks the base of the Lower Virieu. Similarly, breccias have been recorded by S. Taha above the pisolitic horizon in Bugey.

Fossils are fairly common in the Oignon beds. They are usually well preserved and relatively easy to extract. These include:

<u>Dichotomosphinctes</u> aff. <u>D. auriculatus</u> Arkell
<u>Belemnites parallelus</u> Phillips
<u>Acanthorhynchia</u> cf. <u>A. spinulosa</u> (Oppel)

The lithology of the Oignon Limestone is fairly constant in the area studied. Exposures at Chanaz, Lucey and the Col du Chat show almost identical bedding thicknesses, texture, colour and limestone/shale ratios. It forms an extensive outcrop from Chanaz to the neighbourhood of Jongieux. To the east of the latter locality a thrust-fault, brings the Oignon Limestone to the summit of the western escarpment of the Charvaz Mountain. This outcrop extends across to the Col du Chat and beyond. The observed thickening of this outcrop is not stratographical but due to the development of zig-zag folds to be described later.

Some significant changes at the top of the Oignon Limestone can be demonstrated by comparison with neighbouring areas. In the west, between Milieu and Vérizieu (about

25 km. west of Chanaz), the writer has observed some 8 metres of pisolitic limestone at the top of the Oignon Limestone. Here the pisoliths are exceptionally large (1 - 2 cm). East of Chavoley, a pisolite was also observed but here it is only 4 to 5 metres thick. In fact, S. Taha (private communication) was able to use the pisolite as a marker horizon in some structurally complex fault zones. The pisolite observed in the Chavoley region is generally finer-grained than that noted in the neighbourhood of Millieu. J.W. Murray (private communication) noted that the pisolitic limestone occurs to the north of Premeyzel but not to the south and east of that locality. Thus, it appears that a general decrease in the thickness of the pisolite and grain size of the pisoliths exist from east to west in Bugey. A line can be drawn from Premeyzel north-eastwards to Vions, north-west of which the pisolitic facies is found. To the south-east of this line, which is in fact sub-parallel to the sub-alpine front, the pisolite is absent. As noted above, the marls with pyritised nodules could be its lateral equivalent, and the breccias noted both at Chavoley and at Chanaz might have formed contemporaneously, thus marking the instability of the sea floor just before the

shallow water facies of the overlying Virieu Limestone was deposited. Further work, however, is needed in order to establish the possible correlation of these facies and the nature of the breccias need further investigation.

The Virieu Limestone

This limestone forms part of the Virieu Mountain in the province of Ain. Its easily-accessible outcrops opposite La de Virieu, have been studied by S. Taha who recognised a lower division or "Bedded Virieu" and an upper division or "Massive Virieu".

The Virieu Limestone is exposed in a continuous section in the magnificent la Balme gorge. At this locality, the division made by S. Taha is recognised and further sub-division is possible. (Fig. 6).

Lower Virieu Limestone. This division is differentiated from the Upper Virieu mainly by the nature of its bedding. It consists mainly of pale grey calcilutite with chert horizons in the lower part(V_1), but cherts are virtually absent from the upper part (V_2), (see figure 6). The lower sub-division (V_1) is 8.8 metres thick. The upper sub-division forms a vertical cliff where it was only possible to make a rough estimate of about 30 metres. Favre and Richard (1927) measured some 37 metres of limestone free of chert at Pierre-Châtel, immediately to the north of la Balme. Two types of bedding surfaces are displayed in the Lower Virieu; flat bedding surfaces of consistent nature divide the limestone into very thick beds. These range from 1.5 to 5 metres in thickness. There are also wavy bedding surfaces with amplitudes between 1 and 3 cm. These divide the limestone into much thinner beds ranging from 5 to 15 cm. in thickness. These wavy bedding surfaces are characteristic of the upper group, (V_2).

Fossils are not uncommon in the Lower Virieu. They are generally of uniform distribution, but there are also some concentrations at certain horizons. Immediately to the north of la Balme, one flat bedding surface near the base of the Lower Virieu is crowded with extremely well preserved brachiopods. The fauna of the Lower Virieu includes:

Solenopora sp.

Isastraea sp.

Epithyris sp.

Trichothyris sp. nov.

Lobiodothyris zieteri (de Loriol)

Septaliphoria pinguis (Roemer)

Ornithella sp.

Stolmorhynchia sp.

Belemnites sp.

Actinostromaria sp.

Inoceramus cf. *I. cunningtoni* Cox

Ataxioceras spp. indet.

Upper Virâsu Limestone

The most characteristic feature of this division is the virtual absence of stratification. It consists mainly of white and yellowish limestones with some brownish masses of coarse-grained dolomite near the base. The limestones comprise calcilutites and calcarenites. The latter differ in many respects from calcarenites observed in lower formations. As stated earlier the skeletal components in the Lucey Beds, for instance, weather differentially giving rise to granular surfaces. Except for some coral colonies which weather differentially, the calcarnites of the Upper Virieu Limestone give rise to smooth weathered surfaces. In the field it is possible to differentiate only one type of calcarenite in this formation, namely that cemented with sparry calcite, and even this latter type requires careful examination preferably on damp surfaces. Another characteristic feature of this formation is the relative abundence of cavities, some of which are several centimetres wide, especially in the lower dolomitised horizons. These cavities are filled with coarse clear calcite. Clear calcite is also common in the upper part of this division, but here it generally fills entire fossils or fossil fragments. The upper Virieu Limestone in this part of the Jura is extremely rich in corals and to some extent, in lamellibranchs. The fossils listed below include also those determined in thin sections:

<u>Clypeina jurassica</u> Favre

<u>Textularia</u> sp.

<u>Quinqueloculina</u> (?) sp.

Triloculina sp.

Actinoporella podolica Alth

Acicularia sp.

Solenopora sp.

Montlivaltia sp.

Myriophyllia sp.

Thamnastraea sp.

Calamophyllia sp.

Aplosmilia ? sp.

The Virieu Limestone forms a continous outcrop from Chanaz to Jongieux. In the northern part of this outcrop the Upper Virieu is only 126 metres thick compared to 200 metres at la Balme gorge. The Virieu Limestone constitutes the summits of the Charvaz mountain and its cliffs mark the highest part of the Charvaz ridge and extends to the Col du Chat and beyond, towards the Mont du Chat. At the Col du Chat the Upper Virieu measures 260 to 300 metres while at the Mont du Chat, Gidon (unpublished Ms.) recorded some 400 metres. The Virieu Limestone also forms the major part of the northern estremity of the Lierre ridge. This is the only locality apart from la Balme where cherty horizons were recorded in the Lower Virieu. Revil (1888), however, maintained that some cherts occur both at the Col du Chat and at Chanaz.

The Parves Beds

These beds are magnificently exposed in la Balme gorge. Their outcrop continues northwards into the Parves Mountain after which this formation is named. The gorge of la Balme and the Parves Mountain, especially in the neighbourhood of Pierre-Châtel are, celebrated localities for the Portlandian-Purbeckian succession, which corresponds in part to the lower division of this formation.

The outcrops of the Parves Beds are very extensive and are generally well exposed, a continuous outcrop extends from north to south in the central part of the Charvaz ridge. It also outcrops in the escarpment facing Jongieux, and extends northwards to the east of Chanaz. A less continuous outcrop exists in the Montagne de Lierre, and good exposures are easily accessible in the isolated hill of Vions.

In the field, at first sight, much of this formation might appear to consist of calcite mudstone or calcilutite.

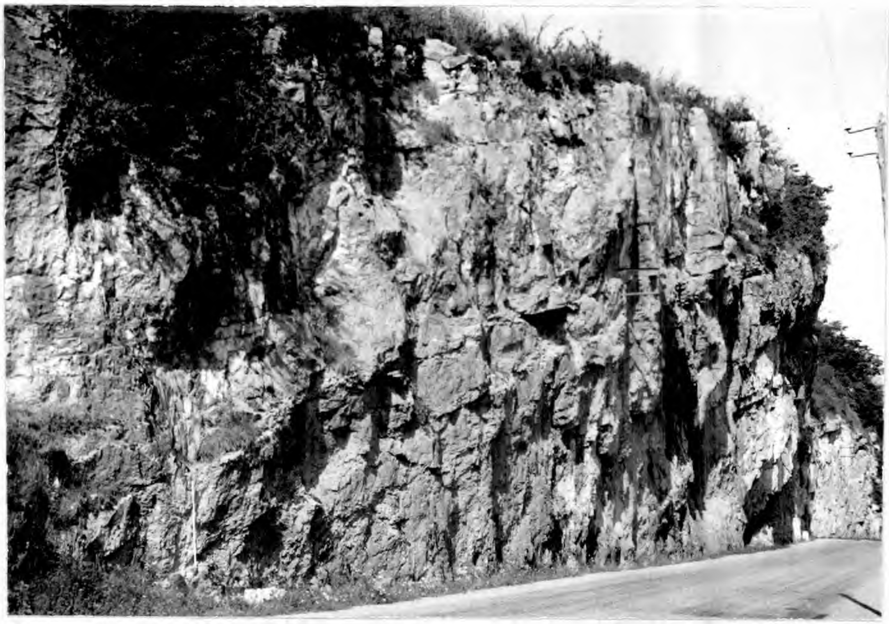


FIG. 8A. The Middle Parves Beds (massive at the top) and the Lower Parves Beds, La Balme gorge.

FIG. 8B. The Upper Breccia Group in the Lower Parves Beds, La Balme gorge.

After careful examination, however, it becomes apparent that although calcilutites are important in this formation, they are generally less abundent than calcarenites. The latter are similar in appearance to those of the Virieu Limestone and are designated in the field as pellet limestones to distinguish them from the bioclastic calcarenites of the Lucey and Chanaz Beds.

The Pavres Beds are well stratified (Fig. 8) and thus they are easily distinguished from the underlying almost unstratified Upper Virieu. It is worth noting, however, that although calcarenites or pellet limestones are important in this formation, cross-bedding, typical of the Lucey and the overlying Bourdeau Beds is virtually non-existent.

The formation is divided into three units, each of which is further sub-divided. Some of thse sub-divisions have distinctive lithologies and serve as useful marker horizons. Reference to these will be made in the course of the systematic descriptions.

Lower Parves Beds This division consists of thick-bedded, pale grey calcilutites or pellet limestones alternating with thinly bedded dolomites or dolomitic limestones. These

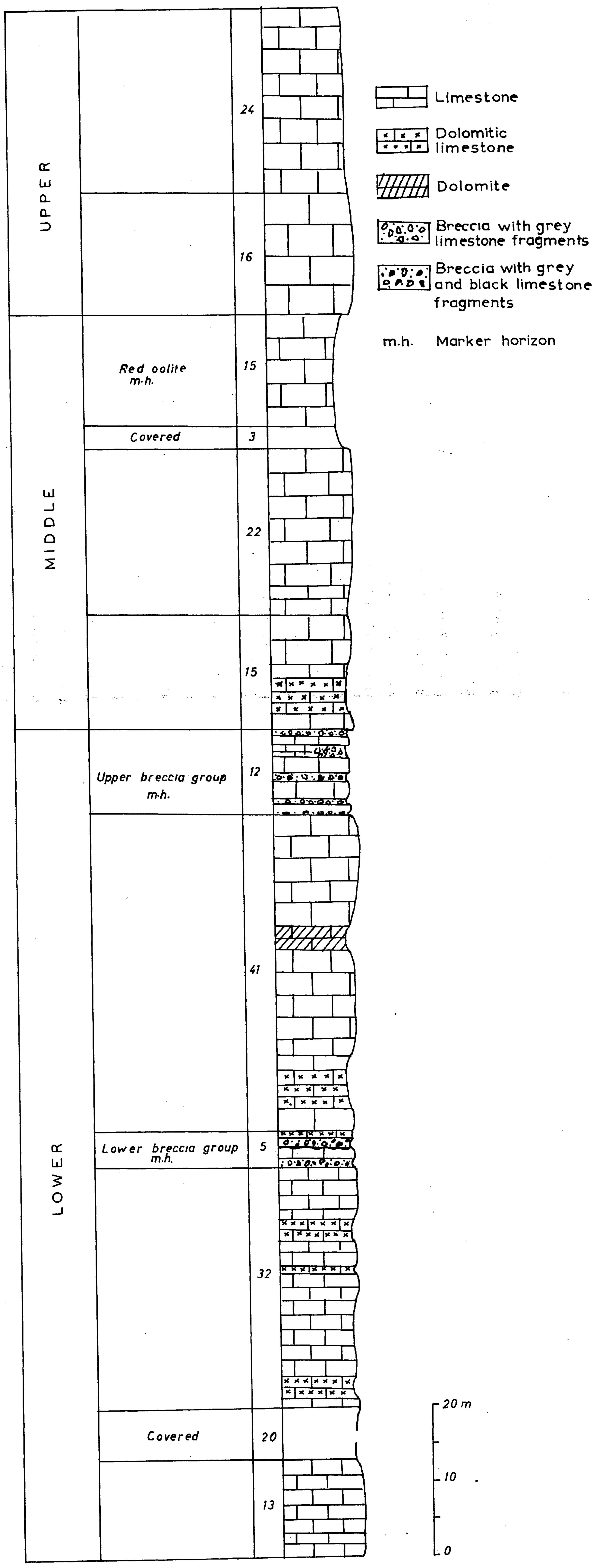


FIG. 9.—*Vertical section of the Parves Beds at la Balme gorge.*

lithologies alternate in a rhythmic manner. The full significance of this cyclic sedimentation can only be appreciated when a laboratory study is made of specimens. They are therefore discussed in part III of this thesis. In the field it is possible to sub-divide this unit into two main lithological groups (Fig. 9). The upper group is characterised by the presence of breccias and very thin marls, which are absent in the lower part of the formation. In la Balme, the breccias occur at two levels (Fig. 9), separated by a relatively thick succession of calcilutites, pellet limestones and dolomites.

The limestones, and more commonly the dolomites, are often laminated. These laminae, which are only a few millimetres thick, weather dark brown and are easily observable in the field. Stylolites parallel to the stratification are abundent. They are often arranged in groups of five or more especially near the bedding planes. In some beds stylolites merge into each other producing in places intercrossing networks which are roughly parallel to the stratification.

The breccias consist of pale grey or blackish fragments embedded in a marly matrix. The pale grey pebbles are fragments of fine grained lithographic limestones or calcilutites which in the field can be matched with the interbedded limestones of the Lower Parves. The black framents are similar in texture to the pale grey pebbles, but their source rock is unknown. The marly matrix is often light green in colour, and is invariably dolomitic in the lower group of breccias at la Balme. The matrix of the upper group is, however, free from dolomite. In some breccias the pebbles or granules of calcilutite are embedded in a groundmass consisting mainly of pellets of fine-grained calcite.

The limestone fragments in the breccias range in size from 1 mm. to 10 cms. They are often poorly sorted and angular. In the field they are seen as two different types. Firstly there are horizons or lenses of mainly fine-grained breccias consisting mainly of granules ranging in size from 1 to 4 mm. These can easily be distinguished from coarse-grained breccias which consist mainly of limestone pebbles and cobbles. The fine-grained breccias are usually better cemented than the latter type. It is probably more significant to differentiate breccias which

FIG. 10. Breccia in the Lower Parves Beds, filling a channel into the underlying limestone, La Balme gorge.

consist solely of pale grey fragments from breccias which include pale grey, dark grey and blackish limestone fragments.

Most breccias thin out to nothing in a distance of a few metres. They frequently pass laterally into marly horizons with which they are usually interbedded. The surface on which they rest is irregular and often channelled (Fig. 10). The overlying strata are usually undisturbed and in the upper group of breccias a thin marl often caps the brecciated horizon.

Except for few horizons which are rich in gastropods, fossils are relatively rare in the Lower Parves Beds. Fossils indentified in thin sections include:

Actinoporella podolica Alth

Clypeina jurassica Favre

Clypeina parvula Carozzi

Clavator reidi Graves

Clavator grovesis Harris

The Lower Parves Beds show some significant lateral variations, even within the limit of the area studied by the author. Some 44 metres of these beds are exposed north west of Bourdeau. This succession belongs to the uppermost breccia-bearing part of the Lower Parves. The breccias which are believed to correlate with upper breccias group in la Balme extend through a thickness of 16 metres and comprise 11 horizons of breccias, compared with 6 horizons extending through a thickness of 3.5 metres at la Balme. Immediately to the west of Ontex some 62 metres of Lower Parves are exposed. At this locality, as well as at other localities in the northern part of Charvaz ridge, breccias were only observed at the top of the Lower Parves succession, and it appears that the lower group of breccias occurring at la Balme is non-existent in the rest of the area.

Middle Parves Beds This division is fully exposed in la Balme gorge (Fig. 80). Here and indeed, throughout the area, two lithological sub-divisions are recognisable. The upper group measuring 15 metres at la Balme gorge (Fig. 9) has a very distinctive lithology and is the only reliable marker horizon in the Parves. The upper breccias in the Lower Parves might also serve as a marker horizon, but these are usually poorly exposed.

The Middle Parves Beds begin with brown calcarenites. These are more or less pellet limestones at la Balme gorge but bioclastic in the neighbourhood of Bourdeau. They are followed (Fig. 9) by brown or brownish grey dolomitic limestones. The latter, unlike those of the Lower Parves are thick or very thick-bedded; the beds range from 65 to 240 cm. in thickness. These are followed by some 22 metres of pale grey calcilutites and as frequently seen in the Lower Parves, they consist of an alternation of very thick with thin or medium-bedded limestones. The average thickness, is however, much higher than in comparable formations in the Lower Parves.

The upper lithological sub-division is more argillaceous and is interbedded with subordinate shales. The limestones are oolitic, dark grey or blackish with a distinctive reddish weathering. This group is relatively rich in macrofauna, especially lamellibranchs and brachiopods, compared with other parts of the Parves Beds. Some lignite was noted in la Balme gorge, while in the north, west of Sindon, black pyritised nodules occur in the same group. The fauna includes:

Acicularia sp.

Salpingoporella sp.

Pfenderina aff. neocomiensis (Pfender).

Upper Parves Beds This division consists of fine-grained and coarse pellet limestones, becoming slightly bioclastic towards the top. The lower part consists of very thick-bedded limestones ranging from 2.5 to 4.5 metres. The rest of the formation shows relatively uniform bedding thicknesses which range from 0.5 to 2.0 metres. The top of the Parves Beds is marked by oyster-covered surfaces which occur throughout the area and mark the close of yet another phase of carbonate sedimentation.

The Bourdeau Beds

The shaly and argillaceous nature of the lower part of this formation makes it relatively less resistent to weathering and hence poorly exposed throughout the area. West of Bourdeau, however, these beds are well exposed in an artificial cutting along the zig-zag road which leads to the Col du Chat. This is undoubtedly the most complete section in the region and has been chosen as a type locality.

In general terms the Bourdeau Beds consist of argillaceous calcarenites or marls interbedded with clean-washed calcarenites. Their largest outcrop extends from the type locality northwards to Conjux, forming a cultivated valley sub-parallel to the western flank of Lac du Bourget. Another discontinuous outcrop extends from the Tunnel du Chat to the east of Jongieux. In this outcrop the succession is incomplete since it is repeatedly cut out by faulting. A reasonably exposed outcrop extends along the greater part of the Montagne de Lierre. In the south-west of the area the Lower Bourdeau Beds outcropping near Yenne disappear under the Molasse when traced southwards

In the type locality the Bourdeau Beds are divisible into a lower and an upper lithological group. Rhythmic sedimentation is the most significant feature of this formation and the cycles are easily observable in the field. Details of the lithology are given below.

The Lower Bourdeau Beds. This sub-division consists of three cycles each of which comprise three units:

c. Grey nodular calcarenite

b. Grey shales and argillaceous calcarenites.

a. Coarse, current-bedded calcarenite.

The three cylces: abc, abc, abc extend over a thickness of 85 metres. The following succession was recorded in the type section; thicknesses are given in Fig. 11.

CYCLE I

1. Reddish brown, coarse-grained calcarenites with terebratulids and oysters.

2. Current-bedded calcarenites.

3. Grey shales.

4. Glauconitic limestones with a surface covered with oysters.

5. Grey shales.

6. Grey, nodular calcarenites alternating with shales (Limestone/shale ratio is 4 to 1); with cherts.

CYCLE II

7. Coarse, current-bedded calcarenites.

8. Covered with vegetation.

FIG. 12A. Nodular limestone in the Lower Bourdeau Beds, north-west of Bourdeau.

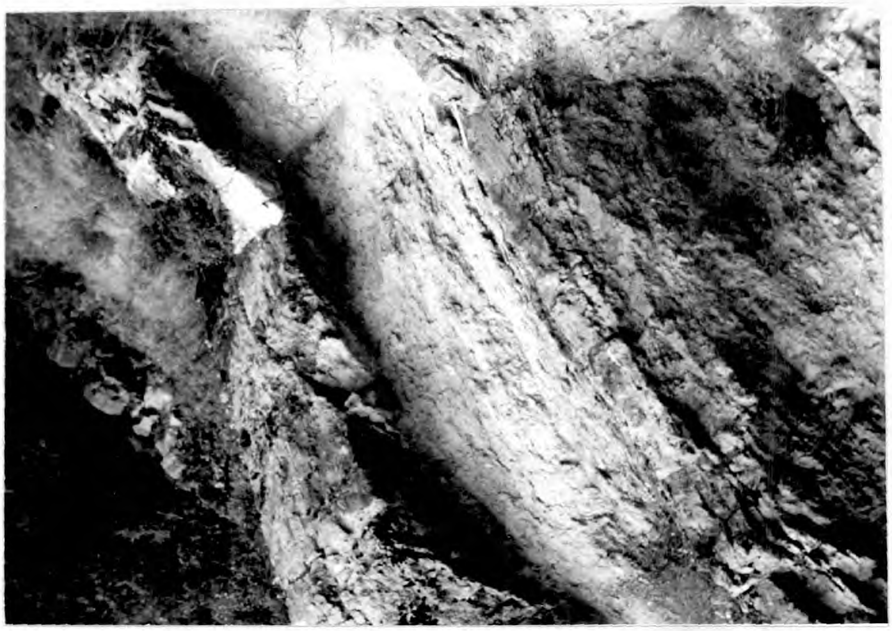


FIG. 12B. Limestone and shale alternation, in the Lower Bourdeau Beds, north-west of Bourdeau.

9. Grey, nodular calcarenites, with shales between the argillaceous nodules.

CYCLE III

10. Coarse glauconitic current-bed ed calcarenites with shaley interbeds.

11. Grey shales.

12. Grey argillaceous calcarenite.

13. Grey shales with a hard band with pholadomyas.

14. Thick-bedded glauconitic calcarenites with an oyster covered surface, and burrows.

15. Exposure covered with vegetation.

16. Grey glauconitic calcarenites.

17. Exposure covered with vegetation.

18. Grey nodular calcarenites.

The nodular limestones consist of closely spaced spheroidal or lensoid nodules, (Fig. 12). The short diameters average 15 cms. while the long diameters range from 30 to 50 cms. These nodules are often flattened parallel to the stratification. In Cycle I, the cores of these nodules are silicified, but cherts is absent from the nodular limestones of Cycles II and III. The nodules are usually embedded in shaly and argillaceous matrix to which they are very loosely attached. Relatively small nodules often bridge the "pore space" between the relatively large nodules. In spite of their nodular character these limestones exhibit the clearest joint surfaces in the area. All calcarenits which form unit (a) of the cycle are current-bedded whilst some of the calcarenites are in units b or c. The cross-lamination of the current-bedded limestones are commonly truncated at the top by concave or flat bedding surfaces.

Upper Bourdeau Beds. These beds show similar rhythmic sedimentation but the nodular limestones typical of the Lower Bourdeau Beds are completely absent from this formation. The cycles therefore include only two units, i.e. a and b. Also, the cyclic unit b, which consists of shales or marls, and limestones, is very thin compared with that of Lower Bourdeau Beds, and thus in general the latter consist predominently of shales and argillaceous limestones with subordinate amounts of coarse clean-washed calcarenites

(42 to 1). The Upper Bourdèau Beds, on the other hand consist predominently of coarse current bedded calcarenites (Fig. 13) with subordinate amount of shales or argillaceous limestones (93 to 1). The succession of the Upper Bourdeau Beds consists of the following lithological groups (Fig. 11).

CYCLE IV

19. Medium grained, known glauconitic calcarenites.

20. Covered with vegetation.

21. Medium calcarenites with cherts parallel to the stratification.

22. Medium, yellowish brown current-bedded calcarenites.

23. Argillaceous calcarenites alternating with their marls (Limestone/marl ratio is 6.4 to 1).

CYCLE V

24. Brown medium calcarenites, current-bedded.

25. Argillaceous calcarenites alternating with marls (Limestone/marl ratio is 6 to 1).

CYCLE VI

26. Brown, glauconitic, current-bedded calcarenites, medium-grained.

FIG. 13. Current-bedding in the Upper Bourdeau calcarenites, west of Conjux.

27. Reddish brown glauconite rich calcarenites.

28. Oölitic, current-bedded calcarenites.

29. Coarse bioclostic calcarenites.

30. Oolitic current-bedded calcarenites.

31. Bioclostic calcarenites with oysters scattered at random.

32. Coarse Oolitic, current-bedded calcarenites.

33. Fine argillaceous calcarenite alternating with shales, with ferruginous oyster-covered surfaces, and burrows at the top.

In the Bourdeau Beds, fossils occur mainly in the shales and in the argillaceous limestones of the Lower division. These include:

Lamellaerhynchia hauteriviensis Burri
Trigonia cf. *J. carinata*
Exogyra sp.
Pholadomya sp.

It is virtually impossible to trace the Lower Bourdeau Beds laterally because of the rarity of adequate exposures. The Upper Bourdeau Beds are, however, better exposed and have been recorded at several localities. East of Chevelu, along a newly constructed road, the Chambotte Limestone, together with about 30 metres of Upper Bourdeau Beds are well exposed. The latter are coarsely Oolitic at the top and relatively finer grained and glauconite-rich at the base, but while the Oolitic facies measures 16 metres west of Bourdeau they are only 5 metres in this locality which is only 2 kms. from Bourdeau. Further north, west of Billieme, about 44 metres are exposed in a more-or-less continuous section. The Oolitic facies is completely absent from this locality. The Upper Bourdeau Beds consists of coarse echinoderm calcarenites. The lower beds are extremely rich in glauconite which in certain instances form laminated beds produced by the concentration of this mineral along certain horizons. Almost due north of Bourdeau immediately to the south of Billion about 32 metres were recorded between the uppermost nodular limestone of the Lower Bourdeau Beds and the Chambotte Limestone. The basal beds of the latter are extremely rich in oysters. An Oolitic facies measuring about 2 to 3 metres in thickness occurs almost at the middle

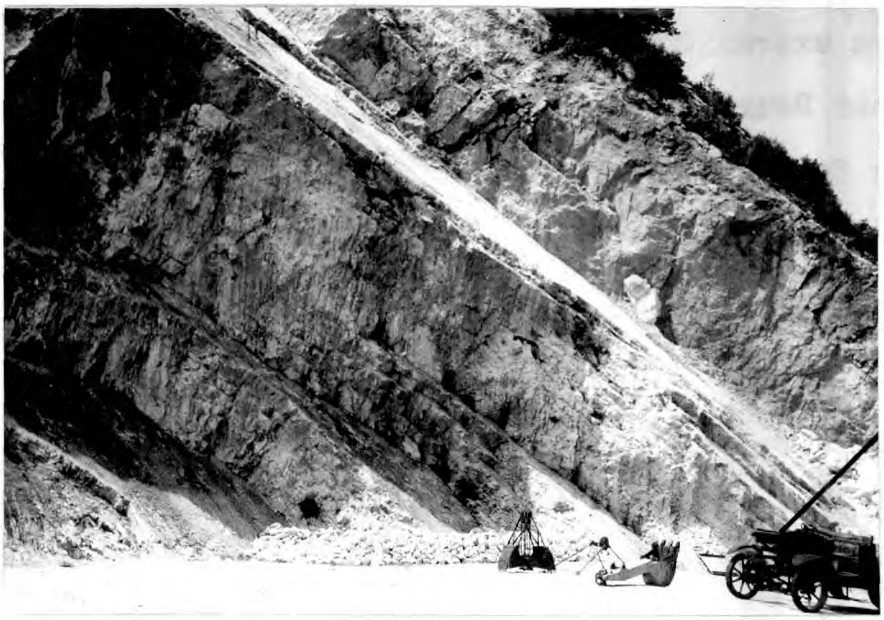


FIG. 14. The Chambotte Limestone at Vions.

of this formation and separates nudium glauconitic calcarenites at the base from coarse to very coarse grained calcarenites at the top which is almost free from glauconite. In the northern extremity of the Montagne de Charvaz, west of Conjux the Upper Bourdeau Beds measures about 36 metres. The Oolitic facies is completely absent at the latter locality.

To summarise, apart from a considerable variation in thickness, the Upper Bourdeau Beds show different detrital facies. The Oolitic group is of limited areal distribution and probably occurs at more than one level. Cyclic sedimentation and the presence of glauconitic-rich group at the base followed by a relatively coarse-grained, virtually glauconite free group at the top are persistant features throughout the area.

The Chambotte Limestone

This is the last of the Mesozoic formations preserved in this part of the Jura (Fig. 14). It reaches its best development in the Chambotte ridge on the western flank of Lac du Bourget, where it forms some dazzling white cliffs above the gentler slopes of the Bourdeau Beds. The village of La Chambotte lies on the summit of the ridge which extends in a north-south direction east of Lac du Bourget. In the area mapped, this formation forms the dip slopes which are steeply inclined towards the lake, under which most of the succession disappears. A more complete succession exists in the western part of the Lierre mountain, and perhaps the most accessible and well exposed section lies just north of the Tunnel du Chat. Lithologically the white colour is very distinctive, especially since it contrasts with the underlying highly ferruginous limestones of the Upper Bourdeau Beds.

East of Chevelu some 77 metres are exposed. Here, the succession consists of very thick-bedded calcilutites interbedded with pellet and bioclastic calcarenites. Some of the pellet calcarenites are very coarse grained and these are better termed calcirudites.

Immediately to the west of Billieme, much of the formation is hidden under the Molasse. Some 31 metres of the Chabotte Limestone are exposed. The succession at this locality is similar to that of Chevelu. The highest exposed beds at the latter locality, and indeed in the whole of the area studied by the author, are remarkably pure limestones. They show no indication of the marked palaeogeographical changes which must have preceded the deposition of the Molasse. Unless later beds are hidden under the Molasse (which is doubtful since the pre-Molasse surface is exposed immediately to the north of the Chevelu outcrop) it appears that the highest part of the Mesozoic succession have been removed by late Cretaceous or early Tertiary erosion.

CHAPTER 4

GEOLOGICAL STRUCTURE

In the area between Lac du Bourget and the Rhone, the Mesozoic rocks outcrop in two essentially north south mountain ridges; (i) the ridge of the Parves mountain in the west and (ii) the ridge of the Charvaz mountain in the east. (Fig. 2). These ridges are separated by the Yenne Molasse Basin, an area of low undulating country. A subsidiary north-south ridge of Mesozoic rocks, the Lierre ridge occurs within the area of the Molasse. These three ridges are generally referred to by Margerie (1936) and other authors as anticlinal ridges. Each of these ridges will be described in turn.

(1) The Parves Mountain Ridge

The ridge of the Parves Mountain is a part of a long ridge extending from near Virieu - le - Grand in the north some 30 kms south towards Pressins. Only that part of the ridge between la Balme gorge and the village of Traize lies within the area mapped. Here the beds dip eastwards at between 10° and 15° but the dip steepends to about 30° along the eastern side of the ridge where Mesozoic rocks pass beneath the Molasse and recent alluvium of the Rhone. In the area mapped the Molasse lies unconformably on the Bourdeau Beds but immediately to the south it oversteps onto the Parves Beds.

The west side of the ridge forms an impossing escarpment some 400 metres high. This escarpment is offset to the west on the north side of la Balme gorge as if by an east-west fault, but no evidence can be found of faulting along the line of the gorge. Riche (1909, 1910) recorded a strike fault which he traced along the escarpment of the Parves mountain north of la Balme; and he postulated that this extends southwards across the area described in this thesis but that there it was hidden beneath scree. Gidon (1951) denied the existence of this fault. The present author found that in many places along this escarpment, the lower part of the face is locally plastered with a reddish clayey veneer, which could possibly be remnants of a fault gorge. Hollande (1892) interpreted the structure of the Parves mountain north of La Balme as an overfold, ("genou anticlinal") overturned to the west but there is no evidence of this structure in the area mapped.

(2) The Lierre Mountain Ridge

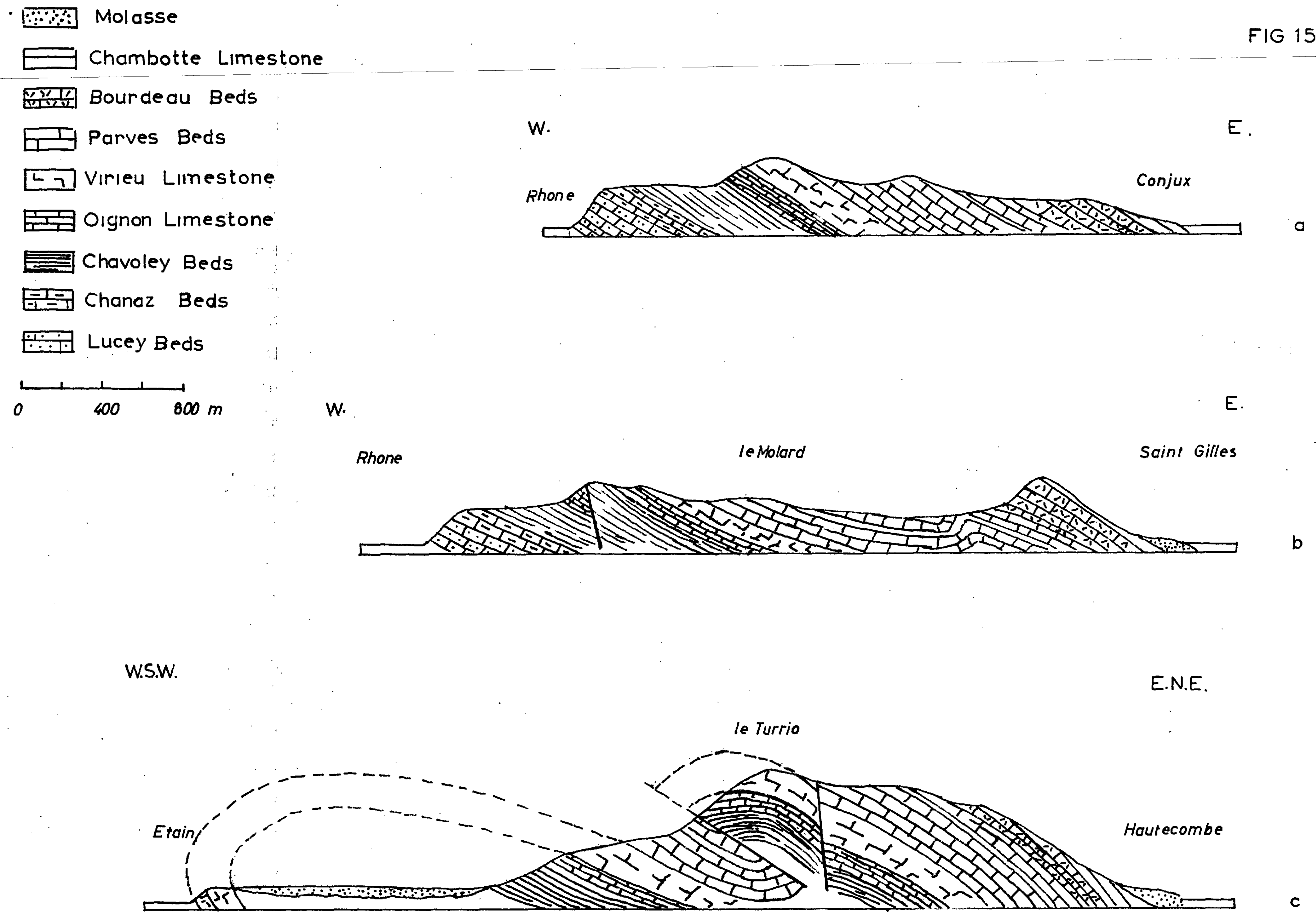
At the southern end of the ridge the outcrops of the various beds tend to be sigmoidal, swinging from south-east near the Chevelu Lakes in the extreme south, to approximately east-west and then to north-north-west along the middle part of the ridge (see map). Along this central part of the ridge the beds dip to the west, but the dip steepens as the beds are traced northwards, becoming vertical near le Grand and overturned and dipping to the east along the northern part of the ridge.

The Lierre ridge would therefore appear to represent the western limits of an overfold which plunges gently towards the south or south-south-east. This interpretation is in agreement with that of Gidon (1951). However, Gidon, postulated a strike fault in the north along the western side of the ridge but hidden beneath the Molasse. The present author can find no evidence of this fault, but there is an oblique fault trending north-west south-east which crosses the ridge near le Petit causing a sinistral displacement of the outcrop. The swing of the outcrops at the south end of the Lierre ridge is probably the expression of minor flexures on the normal limb of the major structure.

(3) The Charvaz Mountain Ridge

The ridge of the Charvaz mountain extends from the northern end of Lac du Bourget southwards along the western side of the lake and beyond. Some 16 kms. of the northern part of the length of this ridge lies within the area surveyed. Generally throughout the area, the beds dip to the east, but there are local important exceptions which will be discussed later. The width of the ridge varies from 4 kms. near Saint Gilles to 1.8 kms. near Bourdeau. These variations in the width are largely due to changes in dip. In the north, where the ridge is widest, the dip averages about 30° to the east but towards the south, in the narrowest part, the dip increases to between 50° and 60° east, locally reaching 80°.

Near the village of Quinfieux the regional dip of the ridge is interrupted by a minor asymmetrical flexure with



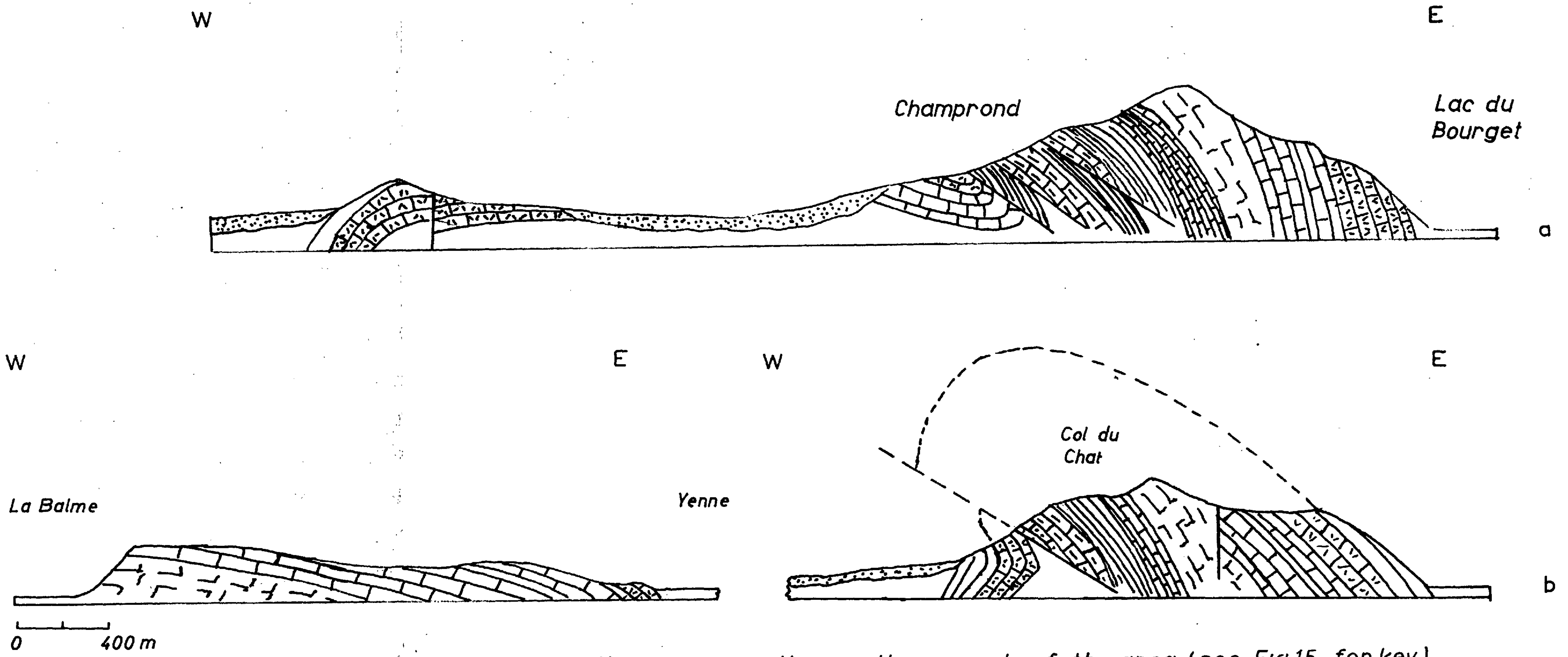
Sections across the northern part of the area.

its steep limb dipping at 81° to the west (Fig. 15b). This flexure pitches and ies out to the north.

A major thrust can be mapped along the ridge from the southern boundary northwards to beyond Ontex. In the south it outcrops close to the western side of the ridge, but towards the north it runs in towards the central part of the ridge. Along its length the thrust can be seen to cut across various members of the stratigraphical succession, both above and below the thrust plane. Its greatest effect can be seen near the Col du Chat where it brings Lucey beds against Bourdeau Beds, having cut out the greater part of the stratigraphical succession. (See Figs. 15c, 16a & b). North-west of the Lacs de Chevelu, the thrust passes into a complex thrust zone (Fig. 16a).

Above the western entrance to the Tunnel du Chat, the Bourdeau Beds and the Chambotte beds, which underlie the thrust, are overturned and show a reversed dip of 70° to the east, but at the entrance of the tunnel (i.e. a short distance to the west) the dip becomes normal but to the west. The author's interpretation of this structure is shown in Fig. 16b.

FIG.16.



Sections across the southern part of the area (see Fig 15 for key)

The Odgnon beds in the Col du Chat and northwards along their outcrop to the west of the le Chavre are characterised by zig zag folds with amplitudes varying up to 5 metres (Fig. 17). The Oignon beds consist of alternation of thin limestones and shales and are among the least competent beds in the succession. The zig zag folds are believed to have resulted from compression operating on this incompetent formation.

The structural interpretation of the Charvaz ridge by the author differs in several respects from those of Gidon and Aymé (1951). Gidon postulated an asymmetrical anticline followed towards the west by a syncline cut out at the base of the escarpment by a reversed fault. The present author finds no evidence to support this. Instead he found the easterly dipping Vivieu Limestone to be followed westwards by zig zag folds in the Oignon beds which overlie the thrust fault previously described (Fig. 15c). The latter fault has in fact resulted in the repetition of a part of the stratigraphical succession. Gidon envisaged another anticlinal structure under the scree of the Mouthoux hill, but the writer, further finds no evidence in support of this structure.

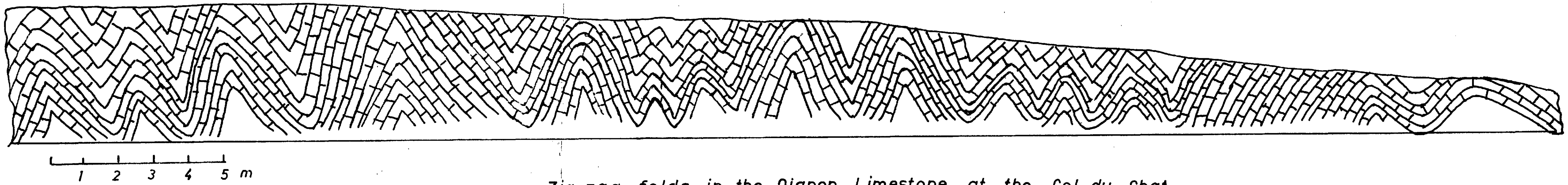
The Charvaz ridge is crossed by a number of east-west dip faults and by north-west/south-east oblique faults. The majority of these faults have only resulted in a slight displacement of outcrops.

Interpretation of the Structure

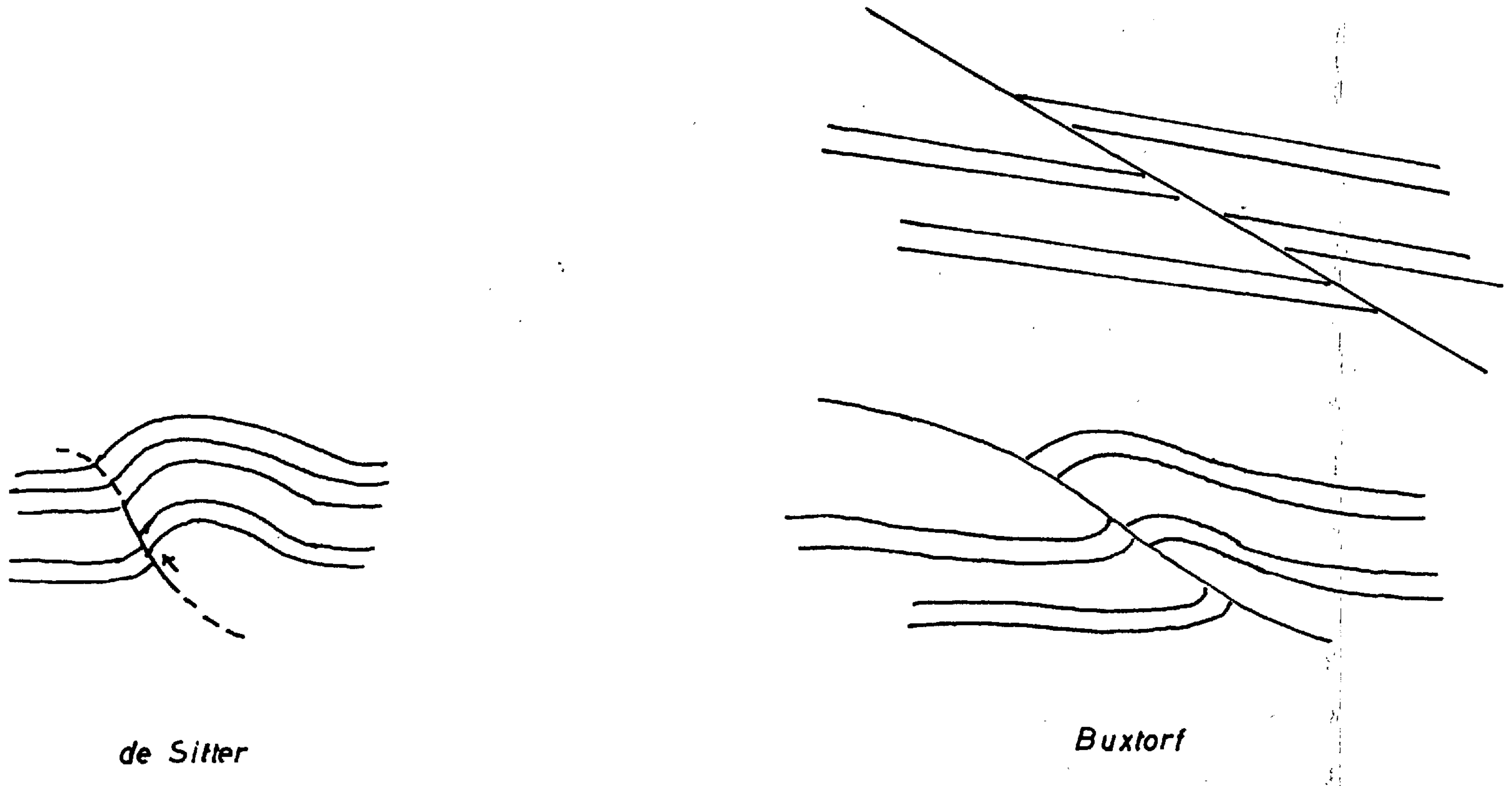
It has been stated earlier that the Lierre ridge appears to represent the western limb of an overfold. Both the Charvaz and the Parves ridge, however, show a predominence of eastern dips. Only in two localities viz. the Chevelu region and the Quinfieux region, are westerly dipping strata encountered, but these extend only for relatively short distances. It is therefore important to enquire, as to whether true anticlinal structures do in fact exist in these ridges. The Parves ridge needs to be traced further along its length before sufficient evidence can be obtained to solve this problem. The evidence presented above for the Charvaz ridge is capable of at least two interpretations.

(i) A thrust fault could have developed in easterly dipping strata at one stage of the Jura folding. This faulting might have been accompanied by local tilting of

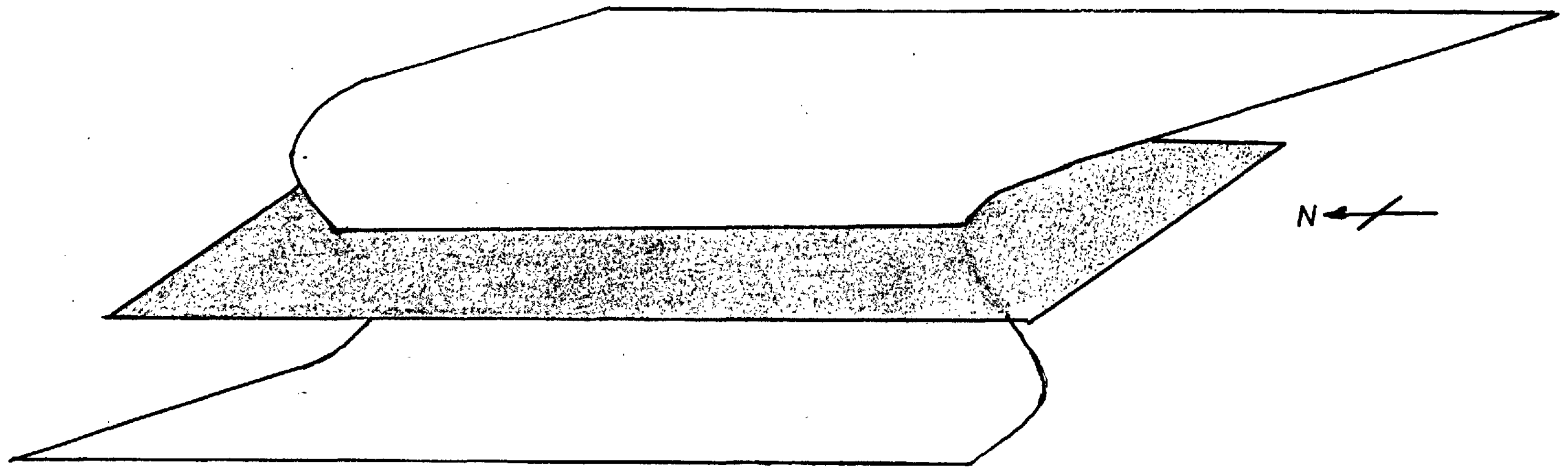
FIG.17.



Zig-zag folds in the Oignon Limestone at the Col du Chat.



Origin of thrust faulting according to Buxtorf and de Sitter.
(after de Sitter)



Schematic representation of the Lierre overfold the strata towards the west or even the overturning of beds observed in some localities. This is indeed the concept of Buxtrof (1916) based on the study of the tectonics of the Jura Mountains (Fig. 17).

(ii) The Charvaz ridge could also be regarded as representing a thrust-faulted anticline developed along lines envisaged by de Sitter (1956). The latter (p. 240 - 41) maintained that a thrust fault should develop in the inner layers of an asymmetrical anticline because of the lack of space in that part of the fold. De Sitter further states "laterally the slip along the thrust diminishes and finally disappears into a simple steep flank, or splits up into tear-faults which cross the anticline diagonally. The Jura Mountains, for instance, show many examples of transition of a thrust-faulted anticline into an asymmetric one". The asymmetrical flexure of the Quinfieux region could thus be the lateral equivalent of the thrust-fault of the Charvaz ridge. As stated earlier, the ridges in the area mapped are conventionally referred to as anticlinal ridges by Révil (1911 - 1913), Hollande (1898) and several other workers. Most of these authors have reached this conclusion by tracing the ridges for the greater part of their length.

Assuming this interpretation to be the correct one other facts do fit into the structural pattern. The Chambotte Limestone, which is the highest of the competant formations, shows tension gashes which are left unfilled with calcite. It was only possible to observe these gashes on bedding surfaces, west of the Col du Chat where two sets were observed. Their intersections with the bedding planes make an angle with the strike of 25° and 75° respectively. The latter set of tension gashes are shorter and more closely spaced. Below the Virieu Limestone the zig zag folds of the Oignon beds are believed to have resulted from compression. The anticlinal flexure observed in the Quinfieux regions plunges gently northwards. Assuming this plunge to be representative of the whole Charvaz "anticline", the thrust zone observed in the Chevelu region would then be structurally lower in the fold and this would further explain the development of several thrust faults under a stronger force of compression.

Slickensiding along bedding planes is rather rare in the area. This is probably because marly partings occur in almost every competent formation. In la Balme gorge, for instance, marls in the Lower Parves Beds have often been squeezed out into "pockets" and can be seen to thicken and thin out or even disappear in one exposure. These marls must have played an important role in lubricating bedding plane slip.

Stylolites parallel to the bedding are common throughout the Mesozoic succession. It has been observed, however, that where the beds show a steepening of dip, as for instance in la Balme gorge near Yenne, stylolites normal to bedding become dominant. These are generally rare in gently dipping strata. Part of the stress in the folding may therefore have been relieved along such stylolites.

The Jura folding is generally regarded as a text-book example of "Abcherung" or "décollement" structure. This concept of Buntorf implies that the Mesozoic sedimentary cover has been detached from the basement and glided on the anhydrite layers of the Trias. According to Lees (1952) the anhydrite group measures 460 feet near Basel while in the French Jura 400 feet of salt deposits have been recorded. While the basic concept of "décollement" has not since been challenged, the exact role of the basement

FIG. 17A. Zig-zag folds in the Oignon Limestone at the Col du Chat.

in the folding has been the subject of much controversy. Buxtorf (1916) maintained that a tangental pressure from the alpine front transmitted through the sedimentary cover led to a sliding across an undisturbed basement. Aubert (1945) and Lees (1952), however, underlined the active role of the basement in the folding and maintained that the Jura folds are the surface expression of deep-seated thrust anticlines. Gignoux (1950) envisaged the swelling up of the basement along certain zones to be the cause of the folding, a concept shared by Gidon and other geologists from the Grenoble school working in the Chambéry region. It would be premature to express opinions on such general theories from the mapping of a relatively small area.

The Age of the Folding

Throughout the deposition of the Mesozoic rocks there is little evidence of tectonic movements. In the Upper Jurassic sediments of Purbeckian age limestone breccias occur resting on eroded and channelled surfaces. These are often associated with fresh water fossils which indicate a short period of emergence at the end of the Jurassic.

From the study of the Purbeckian over large areas of the French and the Swiss Jura Carozzi (1948) and Donze (1951) concluded that the fresh water facies of this stage form elongated elliptical outcrops related to present day anticlines and synclines. This would suggest that embryonic folding has already commenced towards the close of the Jurassic. In the Bourdeau region a conglomerate occurs at the base of the Molasse. This has been studied by Gidon (unpublished Ms.) who showed that when the formation is traced upwards the pebbles and cobbles suggest derivation from progressively older formations, thus indicating the progressive uncovering of emerging massifs in Neogene times. The Molasse in the Yenne basin is in general gently tilted. The pre-Molasse surfaces exposed on the southern flank of the Mouthoux hill show Molasse sediments filling channels and pockets in Lower Cretaceous limestones, obviously indicating emergence and exposure of limestone surfaces to atmospheric weathering prior to the deposition of the Molasse. It is impossible to determine whether the absence of Cretaceous rock younger than the Chambotte Limestone is due to non-deposition or pre-Molasse erosion, without a regional study of the Molasse. The movements of uplift initiated in the Upper Jurassic must have been amplified prior to the deposition of the Molasse and continued during its deposition. This continuity of tectonism until a relatively recent epoch has been stressed by Revil (1910). Gidon (unpublished Ms.) states that in the Chambéry region the Pontian remained horizontal and thence concluded that the folding of the Jura chain in this region is of late Vindobian age. The only locality where intense movements have been observed is at the Tunnel du Chat where fracture cleavage and drag folds are developed in the Molasse. The drag folds are indicative of a shear couple acting in a plane sub-parallel with the thrust zone of the Charvaz anticline which is only a few metres to the east. It is inferred that movements along tectonic lines continued for some time after the deposition of the Molasse and in the thrust zones they were relatively more intense than in the rest of the Molasse basin.

CHAPTER 5

PART II PETROLOGY

INTRODUCTION

1. General

The Mesozoic rocks of the area show a wide variety of types ranging from limestones through dolomitic limestones to dolomites and from limestones through siliceous limestones to cherts. As stated earlier, it was decided that a detailed study should be made of two formations, the Parves Beds and the Bourdeau Beds. The Parves Beds were chosen because they have been extensively dolomitised and some specimens showed unusual textures which required more detailed examination. It was subsequently found that these textures had resulted from dedolomitisation. The Bourdeau Beds show six cycles of sedimentation, and it was felt that this formation would be a convenient one in which a regional study of facies changes could be made.

In this part of the thesis, a general account is given of the petrography of the Mesozoic rocks occurring in the area. Although they are mineralogically simple, consisting of calcite, dolomite and various forms of cryptocrystalline and microcrystalline silica, a wide range of rock types is developed. It is possible that certain of the dolomites and cherts are primary deposits; however there is considerable evidence which suggests that the majority of the dolomites and the siliceaous limestones are the result of post-depositional dolomitization and silicification. It is therefore necessary first of all to give a petrological account of the various types of calcitic limestones. In this account the variations in depositional composition and texture are described, together with the diagenetic modifications in so far as these result from the post-depositional introduction and redistribution of calcite. The post-depositional changes involving the formation of dolomite and chert are described in later chapters.

Apart from the local occurrence of organic structures, i.e. bioherms, the majority of the Jura limestones can be sub-divided on the basis of grain size into 'calcirudites' 'calcarenites' and 'calcilutites', using the nomenclature of Grabau (1904). In this thesis the grade limits chosen are approximately the same as those used by Wentworth (1922). The calcilutites have been divided into two groups; the coarse-grained calcilutites or 'calcite siltstones', and the fine grained calcilutites or 'calcite mudstones'. The accepted boundary of 2 microns between silt and clay grades is a natural one when applied to terrigenous materials, because it separates materials which are essentially primary detrital mineral grains from those which are essentially the insoluble decomposition products of weathering i.e. the clay minerals. However this boundary is not a suitable one when applied to the fine-grained limestones, because of the practical difficulty, if not impossibility, of measurement in thin section. It was therefore decided not to define the boundary between calcitic silt and calcitic mud precisely, but to differentiate them on the basis of whether or not, in thin section, the individual grains could be clearly resolved under the normal high power of the microscope (i.e. about 280).

The calcarenites, in common with their terrigenous analogues, may be either clean-washed, or have a fine-grained matrix. In the calcarenites this matrix may be either calcite mud or calcite silt; and it would appear possible that every gradation between such a calcarenite and a calcite mudstone or a calcite siltstone can occur. Calcilutites and calcarenites are common rock types in the area. Calcirudites, are rare, but where they occur they are important because they provide 'marker horizons' in the field. However time did not allow for a laboratory study to be made of these rocks.

2. Methods of Laboratory Study

Before discussing the various rock types in detail, the methods and techniques which have been used in the laboratory will be briefly outlined:

1. Polished surfaces of the rocks were etched with cold dilute hydrochloric acid and studied under the binocular mircroscope. By this method, the presence of dolomite or chert is readily determined; and the relative proportion and distribution of these minerals assessed.

2. Thin sections were made of some 280 specimens. As a routine procedure a small area of each thin section was etched with very dilute hydrochloric acid before the cover glass was mounted.

3. In those specimens where the textural relationships between dolomite and calcite were complex or obscure, the calcite was differentially stained with silver chromate; using the method described by Lemberg (1892). This method of differential staining was applied in some instances to polished surfaces to etched polished surfaces*, and more often to thin sections.

4. Particle size measurements were made on thin sections by the standard method of comparison circles.

5. Modal analyses were made using a point counting stage.

6. Chemical analysis were made of some 70 samples. The lime and magnesia content were determined by titrating with versine, using the standard analytical procedure. The total iron content was determined colorimetrically, and colorimetric method was also employed for determining manganese.

*It was found that differential staining of polished surfaces gives better results if these surfaces were etched with dilute hydrochloric acid before the staining test is carried out.

7. The insoluble residues of some 130 specimens were determined by dissolving 20 gms of a sample in dilute (10%) hydrochloric acid. The sand fraction was separated from the silt and clay by decantation, and was studied under the binocular microscope.

CHAPTER 6

CALCILUTITES

The calcilutites have been defined in the preceeding chapter as those limestones in which the individual calcite grains are less than 0.06 mm. in equivalent diameter. These rocks may be further sub-divided into fine-grained calcilutites or calcite mudstones and coarse-grained calcilutites or calcite siltstones. Calcilutites are common in the Parves Beds and also occur, but less extensively in the Chambotte Limestone. Argillaceous calcilutites or marls, occur in the Chanaz, Oignon and the Chavoley Beds (but time did not allow these rocks to be studied).

The calcilutites of the Lower Parves Beds are inter-bedded with pellet calcarenites, but rarely associated with bioclastic calcarenites. Whereas microfossils are virtually absent from the calcilutites, the associated calcarenites are relatively rich in microfossils. No calcilutites have been observed in association with the bioclastic calcarenites of the Lucey and Bourdeau Beds. The absence of calcilutites from the latter formations may be due in part to the difference in the skeletal components of the Parves Beds on the one hand, and the Lucey and the Bourdeau Beds on the other; the Parves Beds contain essentially calcareous algae and subordinate amounts of foraminifera and probably molluscs. The fauna of the Lucey and the Bourdeau Beds on the other hand consist mainly of echinoderms with subordinate proportions of bryozoa, brachiopods and molluscs. Calcilutites of the Parves Beds are for the most part fine-grained i.e. calcite mudstones. In the field many of the beds show bedding laminations and they have clearly been formed by the accumulation of discrete particles. In thin sections they appear cryptocrystalline under crossed nicols, but this is probably the aggregate effect of the several grains which are superimposed and overlap one another within the thickness of the thin section.

In any one specimen the texture is essentially uniform and there is little variation from specimen to specimen. The calcite mudstones show little direct evidence of the origin of the calcite which make these rocks. The following possibilities must be considered:

(a) That the calcite is skeletal in origin

(b) That the calcite is a by-product of organic activity

(c) That the calcite is inorganic in origin.

(a) Skeletal origin of calcilutite.

A fine-grained calcite mud or calcite silt could be produced by the desintegration of the calcareous skeletal structures of organisms. The skeletal structures of the corals and the calcareous algae consist of very fine-grained calcite and could be broken down to form a calcite mud, and similarly the polycrstalline shells of such organisms as brachiopods and lamellibranchs could break down to produce calcite silt. Ultramicroscopic organisms, particularly coccoliths could have also contributed to the formation of the calcilutites. Illing (1954) suggested that the disintegration of skeletal structures could occur in an anaerobic environment. In the Lower Parves Beds, where relatively thin beds of calcite mudstone occur, the calcilutite could have originated in this way. Dr. J. Taylor (personal communication) has been able to bring about the disintegration of the shells of various modern lamellibranch by prolonged treatment with hydrogen peroxide (i.e. in an oxadising environment). The virtual complete absence of fossil fragments in these beds suggests either (a) that the disintegration of fossil fragments must have been complete or (b) that they were deposited in an environment which was unfavourable for the growth of organisms. In the latter case the fine-grained calcite would have been derived mechanically from environments where conditions were more favourable for them to flourish. The uniform texture of the calcite mudstones of the Parves Beds suggests that if the calcite had originated in this way, then it was probably derived essentially from one type of organism only. Although it is possible that some of the thin beds of calcilutite and the matrix of some of the calcarenites may have been formed in this way, it seems unlikely that such an origin could be postulated for the relatively thick beds of calcilutites which occur in the Middle Parves and in the Chambotte Limestone.

(b) Calcite as a by-product of organic activity

Calcite can be precipitated from solution as a by-product of the vital activities of two groups of organisms, viz. the aquatic algae and certain bacteria.

The aquatic algae obtain the carbon dioxide they require for photosynthesis by removing carbon dioxide from solution in the surrounding water. In so doing they may cause the precipitation of calcium carbonte. It is possible that in shallow waters, where the bottom is covered with a dense mat of algae, such a process might operate, i.e. that a physio-chemical sub-environment could develop within the algae mat.

Although the activities of certain groups of bacteria can cause the precipitation of calcium carbonate it is difficult to imagine that thick beds and successions of such beds could have been formed in this way.

(c) Calcite of inorganic origin.

Illing (1954) showed that extensive inorganic precipitation of calcium carbonate is taking place in the Bahama Bank at the present day. This appears to result in part from the loss in carbon dioxide due to decreasing pressure in sea waters rising from the deeper regions, of the Atlantic, and in part from evaporation which must take place extensively in the shallows of the banks. That some of the rocks at least may be in the nature of evaporites is suggested by one of the specimens collected by the late S. Taha. The thin section of this rock shows square shaped areas of coarse-grained calcite, and it is possible that these may be salt pseudomorphs. It is significant that the specimen was collected from the Parves Beds, which are believed to span the Portlandian-Purbeckian boundary.

The calcium carbonate of these rocks may have been deposited as aragonite or calcite, but there is no evidence which makes it possible to determine the original nature of the carbonate. The equigranular texture of the rocks could have been produced from either aragonite or calcite. If it had been deposited as aragonite mud, the aragonite would have inverted to calcite, producing a granular texture. If deposited as minute calcite crystals, these could have been cemented by secondary enlargement to form an equigranular mosaic.

CHAPTER 7

CALCARENITES

The calcarenites are those limestones in which the particle size of the depositional components lies within the sand range as defined by Wentworth (1922) i.e. 2 mm. to 0.06 mm. Glauconite occurs in some of these rocks and some carry various proportions (up to 40%) of terriginous materials. Such a high proportion of terregenous detritus is, however, uncommoh.

Deposition Components

A wide variety of calcareous depositional components may be found within these rocks and may be sub-divided in the following way:

1. Skeletal components
   - (a) Polycrystalline skeletal fragments
   - (b) Bioclastic mosaic pseudomorphs (i.e. pseudomorphs of calcite after aragonitic shell fragments).

(c) monocrystalline skeletal framents
(i.e. echinoderm fragments).

2. Non-skeletal components
(a) Ooliths
(b) Pellets

3. Terrigenous and other components
(a) Quartz sand grains
(b) Glauconite

4. Microcrystalline and/or cryptocrystalline matrix.

1. Skeletal components

The organic components of calcarenites consist essentially of fragments of the calcareous skeletal structures of organisms. For petrographic purposes there bioclastic components are sub-divided on the basis of the texture of the shell fragments

(a) Polycrystalline skeletal fragments. Fragments of all calcareous skeletons except those of echinoderms and those creatures which secrete aragonitic structures are included within this group. The group is therefore a very broad one. In theory it should be possible to assign any particular fragment to its particular biological group. In practice, however, this is very difficult, because in rock slices the cross-sections across skeletal fragments show random orientations and it requires specialist knowledge and experience to make a complete assessment of all the types in any one specimen. The majority of the specimens studied showed a heterogeneous mixture of fragments and these are described simply as "bioclastic calcarenites". In certain instances, however, the fragments of a particular organism becomes dominant and the specimens are named accordingly, e.g. a "bryrzoan calcarenite", but these are relatively rare.

(b) Bioclastic mosaic pseudomorphs. The term "bioclastic mosaic pseudomorph" is used to describe bioclastic fragments in which the calcite mosaic is not the mosaic of an organic structure. The outlines are commonly concave-convex and are clearly those of shell fragments. These are being interpreted as calcite pseudomorphs often aragonitic shell fragments (Fig. 22). These calcite mosaics may have been formed in either of two ways; (a) by the inversion of aragonite to calcite; or (b) by the solution of aragonite and the subsequent infilling of the cavity with calcite. The inversion of aragonite to calcite involves an increase in volume (in the order of 6 - 10%) and it is possible that such an expansion would cause defommation of the outline. There is little evidence from thin sections, however, to suggest that this has occurred in the Jura limestones. Many of the mosaic pseudomorphs show the features of a drusy mosaic (Bathurst 1958) which suggests that the mosaic resulted from the infilling of a cavity.

(c) Monocrystalline skeletal fragments. The echinoderms stand apart from all other organisms in that the individual segments of the skeleton are single crystals of calcite in life, and are preserved as such in the fossil. Consequently fragments of echinoderms are readily differentiated from other bioclastic debris. From a purely palaeontological point of view, the differentiation of skeletal material into polycrystalline and monocrystalline fragments, is arbitrary and unnatural. However, from a petrological stand-point the distinction is an important and natural one. Sorby (1908) was perhaps the first to appreciate this. The plates, spines and ossicles of echinoderms have in life complex pattern of canals. Sorby found that the pore spaces of the spine of *Echinus* amounted to 51% of its volume, and that the specific gravity of the spine when full of water was 1.83. The effective weight of an echinoderm in sea water would therefore be less than half of that of a solid shell of the same bulk (specific gravity 2.7 - 2.8). This is a profound difference, and quite clearly echinoderm fragments may be winnowed out from other skeletal debris and transported by gentle currents which would hardly disturb the denser fragments. "We can thus easily understand why they so often occur almost or quite free from other material" (Sorby 1908, p. 189). These observations of Sorby are amply confirmed in the limestones of the Jura. Many of the bioclastic calcarenites are essentially pure concentration of the fragmented remains of this one group of organisms. Where echinoderms and other shell debris occur mixed in the one rock, the echinoderm fragments are characteristically coarsergrained than the other shell fragments; (see Fig. 26.).

2. <u>Non-skeletal components</u>

(a) <u>Ooliths.</u> Calcite Ooliths occur in some of the calcarenites of the Bourdeau Beds, and the Parves Beds. Both ooliths and superficial ooliths (Illing 1954) occur. These ooliths may have been deposited as aragonite or as calcite. It would be expected that the increase in volume occurring as a result of the inversion of aragonite to calcite would be apparent in those ooliths which were deposited as of aragonite. The outer layers of some of the ooliths show a form of exfoliation (Fig. 10). This exfoliation occurs outside a layer which has a coarse-grained crystalline mosaic the other layers of the oolith consist of very fine-grained calcite. It is possible that these crystalline layers were originally composed of aragonite and that the exfoliation of the outer layers results from the increase in volume accompanying the inversion.

(b) Pellets. Many limestones contain pellets of calcite; these vary considerably in size and in their general form and make-up. Some consist entirely of cryptocrystalline or microcrystalline calcite. Others show a mixture of cryptocrystalline and relatively coarse-grained calcite, and some contain microfossils or fragments of fossils. For convenience, all those compound fragments which are not entirely skeletal in origin are classed as "pellets". From a practical point of view it was found useful to differentiate two main types of pellets; these are (a) bahamiths and (b) composite grains.

The term "bahamite" was introduced by Beales (1958) to describe limestones comparable with those forming on the main part of the Bahama Bank. Illing (1959) used the term "bahamith" for the individual calcilutite grains or pellets which constitute the main part of the rock "bahamite". The term bahamith is used in this thesis to describe those pellets which are essentially cryptocrystalline. Some of them may have a compound texture, but the constituents all consist of cryptocrystalline calcite. The term "composite grain" is applied to those pellets which are not uniform in composition and texture but which contain skeletal fragments.

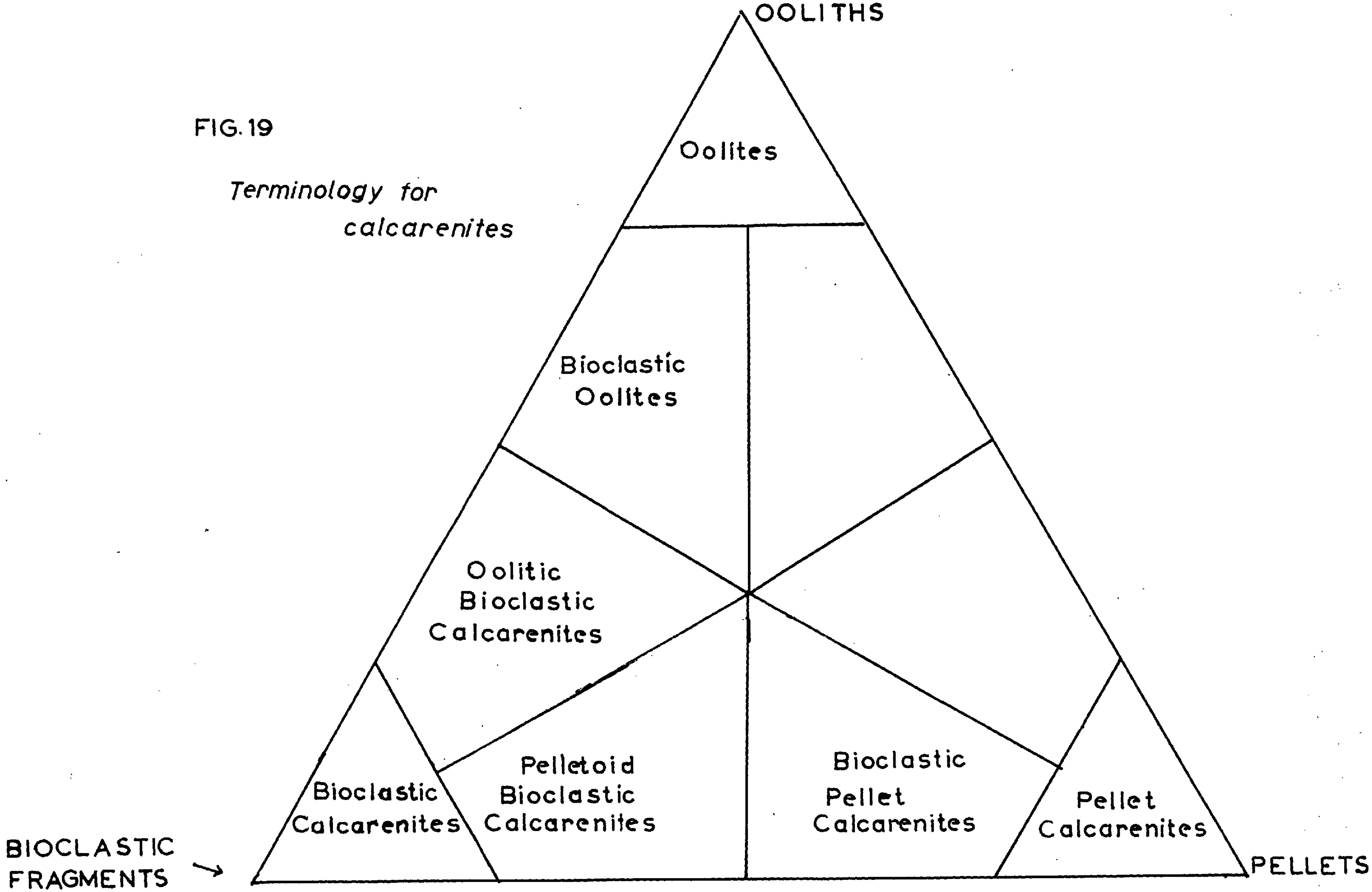
Bahamiths occur mainly in the calcarenites of the Parves Beds and in the Viriou and the Chambotte limestones, while composite grains are more frequently found in the calcarenites of the Chanaz and the Lucey Beds.

Particles described as pellets may have originated in a variety of ways. Certain ovoid cryptocrystalline pellets which range in size from 0.06 mm to 0.25 mm. may be faecal in origin. Such an origin is probable for the pellets in the fine-grained calcarenites of the Lucey Beds and the Chanaz Beds (Fig. 23). Some pellets show a pellicle of microcrystalline or fibrous calcite which may be algal encrustation; indeed others may be in the nature of algal balls.

Some workers have pointed out that certain pellets may be fragments of pre-existing limestones, but it is doubtful that this mode of origin would apply to the majority of those occurring in the rocks described, because the composition of most composite grains is similar to that of the rock in which they occur; for example, in oolites most composite grains contin ooliths and in bioclastic calcarenites they contain skeletal fragments similar to those constituting the main part of the rock (Fig. 21). These, therefore, may have originated in either of two ways (a) they may be the products of contemporaneous erosion within the general environment of deposition; or, (b) they may be accretionary in origin. The former mode of origin was envisaged by Folk (1959) for the majority of pellets or "intraclasts", while the latter was suggested by Illing (1954) for some

FIG. 19

Terminology for calcarenites



of the pellets or "grapestones" etc. which occur on the Bahama Banks. There is the further complication that in certain instances the structures of some skeletal fragments may be obliterated by recrystallization in the manner described by Illing (1954). In such cases they are undistinguishable from pellets. This is significant because some "pellets" in the calcarenites from the area studied contain faint, probably, skeletal structures.

Nomenclature of Calcarenites

All the various components described above occur in the calcarenites of the Jura, and in many of the rocks they are mixed in various proportions. The nomenclature necessarily becomes complex. However, it was decided to use a system based on a triangular diagram, using the three components: skeletal fragments, ooliths and pellets (see Fig. 19). Many of the rocks in these various groups occur either clean washed or with a calcilutite groundmass. Some specimens have been found in which the sand-size components are scattered or 'Float' in a calcilutite groundmass which makes up the bulk of the rock, and there are gradations between some of the calcarenites into the calcilutites.

The problem of devising a satisfactory, but generally acceptable system of nomenclature becomes increasingly difficult, for example, when applied to rocks in which the various types of bioclastic fragments (polycrystalline and monocrystalline skeletal fragments) and pellets (bahamiths and composite grains) are mixed. In the Jura rocks, however, it is not necessary to propose a comprehensive system covering all the possible arrangements and relative proportions of components, because there are clearly certain preferred compositions. Figure 19 shows the range of composition of the calcarenites from the area studied.

The following are the main rock types:

1. Bioclastic calcarenites
2. Pelletoid bioclastic calcarenites
3. Bioclastic pellet calcarenites
4. Pellet calcarenites (bahamites only)
5. Oolites and oolitic calcarenites.

These main groups of calcarenites and their textural variants are briefly described below.

1. Bioclastic calcarenites

The bioclastic group of calcarenites of the Jura

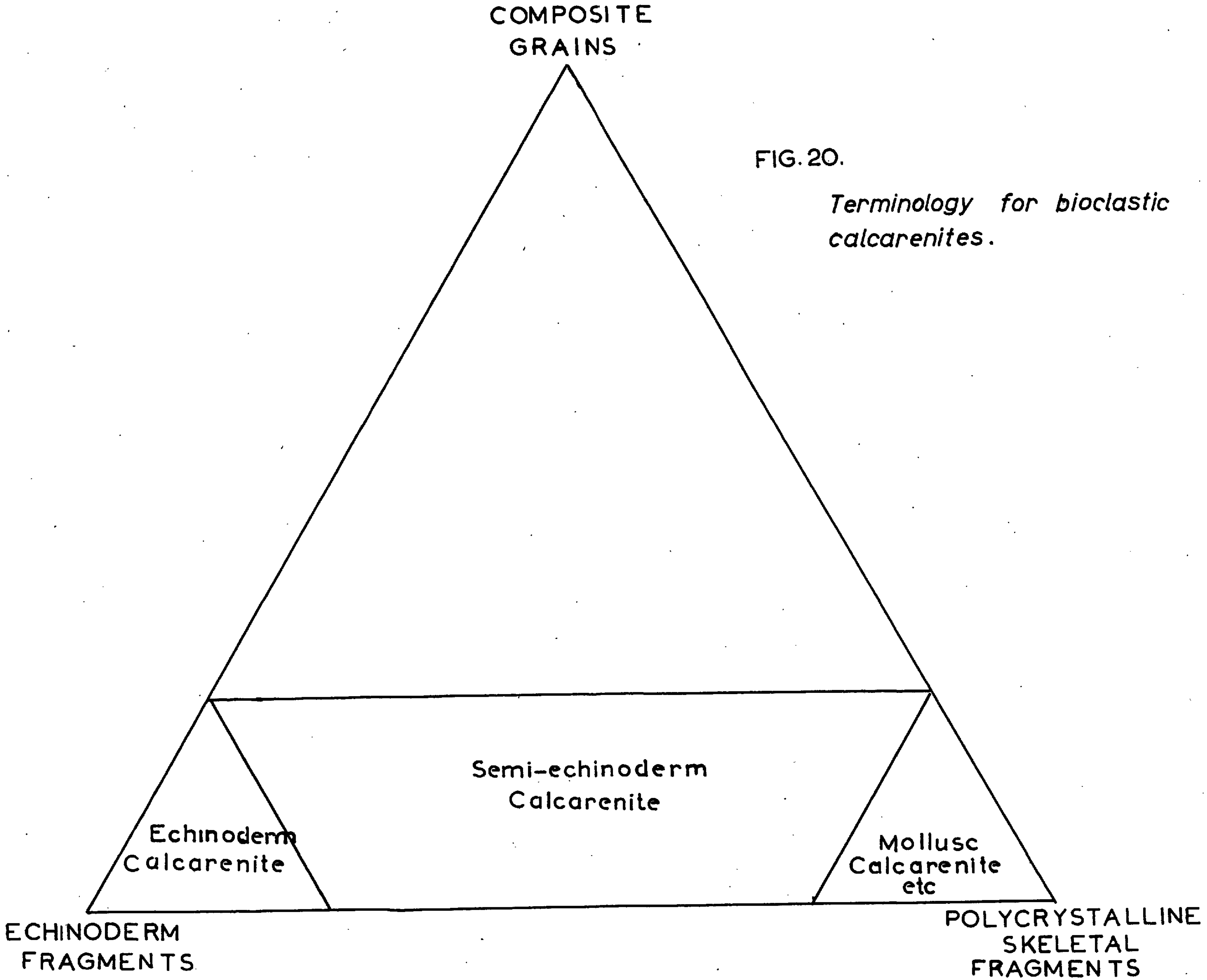


FIG. 20.

Terminology for bioclastic calcarenites.

includes all varieties of calcarenites which consist essentially of skeletal fragments and which may contain up to 25% of composite grains (Fig. 20). The two bioclastic end members are echinodermal calcarenites and calcarenites consisting essentially of polycrystalline skeletal fragments and bioclastic mosaic pseudomorphs. The latter rocks are termed "mollusc calcarenites" "brachiopod calcarenites" etc. according to the dominant polycrystalline skeletal element. As stated earlier, rocks consisting predominantly of echinoderm fragments are by far the most common.

These two varieties of bioclastic calcarenites show contrasting textures, because the elongate, slightly convex fragments of brachiopod and mollusc values usually show an orientation parallel to the bedding, thus contrasting with the more or less equigranular texture of the echinoderm calcarenites (Fig. 35).

Some specimens collected by S. Taha from the Lucey Beds in the adjacent area consist essentially of brachiopod and mollusc debris. In the area studied, the Lucey Beds, however, consist mainly of echinoderm calcarenites.

In some of the bioclastic calcarenites, echinoderm

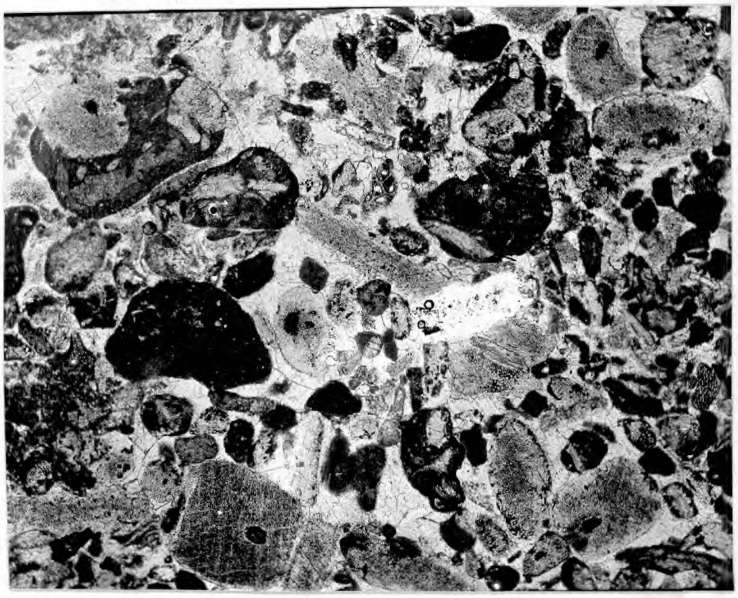


FIG. 21. Semi-echinoderm calcarenite, showing composite grains, echinoderm fragments and other skeletal debris, cemented by sparry calcite. Lucey Beds south of Chanaz (x15).

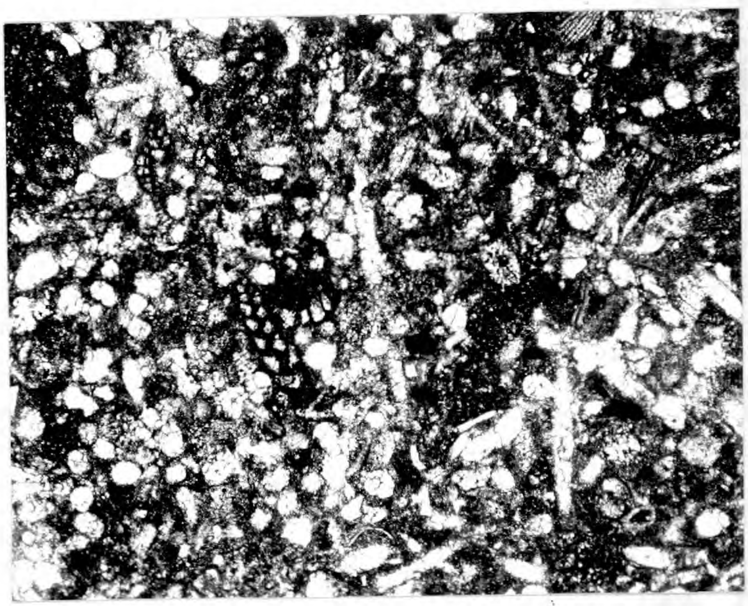


FIG. 22. Calcilutitic bioclastic calcarenite, consisting mainly of mosaic pseudomorphs and microcrystalline groundmass. Lower Bourdeau Beds north-west of Bourdeau (x30).

fragments are mixed with a wide variety of other skeletal debris and often with some composite grains (Fig. 21). Although these echinoderm fragments do not make up the bulk of the rock, they are the most important single component and such calcarenites can be appropriately termed "semi-echinoderm calcarenites".

The clean-washed bioclastic calcarenites and those with a cryptocrystalline or microcrystalline matrix occur extensively in the Lucey, Chanaz and Bourdeau Beds. The matrix of the "calcilutitic calcarenites" is commonly of a heterogeneous nature and its texture and composition suggest that it is in part at least bioclastic in origin. While there appears to be a tendency in the clean-washed bioclastic calcarenites towards the segregation and concentration of certain types of organisms (e.g. echinoderm fragments) no such tendency has been observed in the calcilutitic calcarenites, what is more, their skeletal fragments show little evidence of abrasion. A typical feature of many 'calcilutitic bioclastic calcarenites' is the presence of a heterogeneous mixture of skeletal debris. In some rocks belonging to this category, however, mosaic

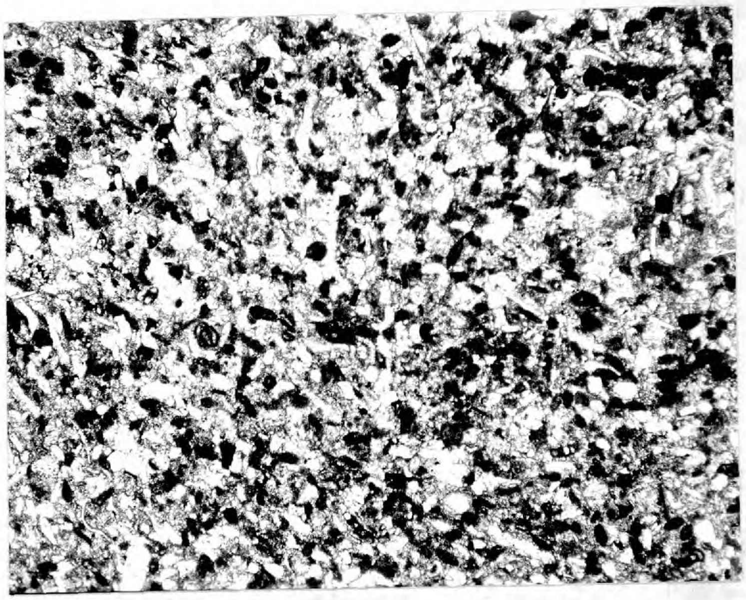


FIG. 23. Fine-grained bioclastic calcarenite, consisting of echinoderm fragments, polycrystalline skeletal fragments and pellets. The groundmass is microcrystalline. Lower Chanaz Beds, south of Chanaz (x30)

pseudomorphs become an important ingredient (Fig. 22). This is probably due to their deposition in a quieter-water environment. In the finer-grained bioclastic calcarenites (Fig. 23) the organic debris is usually mixed with a variable proportion of pellets, these range in size from 0.06 to 0.2 mm. and could be faecal in origin.

In the field the clean-washed calcarenites often exhibit current bedding (Fig. 4) but the author has not observed this in the calcilutitic calcarenites.

(2,3) Pelletoid bioclastic calcarenites and bioclastic pellet calcarenites

In some calcarenites the bioclastic skeletal fragments are mixed with various proportions of pellets (Fig. 24). In these rocks the pellets are predominantly cryptocrystalline (i.e. bahamiths) and therefore the two main rock types are termed "bahamitic bioclastic calcarenites" and "bioclastic bahamites" according to the relative proportions of bahamiths and bioclastic skeletal fragments.

Variation in the nature of the skeletal components allows for the differentiation of two textural variants. In one, the skeletal debris consist essentially of

FIG. 24. Bioclastic bahamite, showing bahamiths and echinoderm fragments, cemented by secondary overgrowth. Upper Bourdeau Beds Conjux (x20)

echinoderm fragments. Rocks consisting mainly of these and bahamiths present a characteristic texture (Fig. 24) and are usually cemented by overgrowth. The second variant contains a mixture of skeletal debris which usually includes polyzoa, molluscs and brachiopods (Fig. 34). The coarse-grained members of the bahamitic bioclastic calcarenites and the bioclastic bahamites are common in the Bourdeau Beds, and in the field they are usually cross-bedded. The fine-grained members are important in the Lucey and Chanaz Beds. In the field they rarely show current-bedding, but occasional beds show gently inclined cross-laminations.

4. Bahamites

The bahamites are those rocks which consist essentially of bahamiths. Pure bahamites are not uncommon, but usually they contain up to 20% of skeletal debris and composite grains (Fig. 24a). In some fragments of calcareous algae and foraminifera predominate but these rarely form more than 15% of the rocks. In others bioclastic mosaic pseudomorphs are the chief skeletal components. Bahamites are usually clean-washed, but examples of bahamites with a calcilutitic groundmass occur. These however are rare and have only been found at the transition where clean washed bahamites pass up into calcilutites.

Bahamites constitute a considerable part of the Parves Beds, and they also occur in the Virieu and Chambotte Limestones. In the latter formations some of the bahamites are extremely coarse-grained. The majority of them, however, lie within the grade limits of calcarenites. In the field the author has not observed cross-bedding in bahamites. They are usually interbedded with calcilutites.

5. Oolites and oolitic calcarenites

Rocks consisting essentially of ooliths are not rare in the Mesozoic succession of the area. In these oolites, the ooliths are mixed with minor proportions of bahamiths. Most of these bahamiths, however, are spherical in shape, and could have had essentially the same mode of origin as the associated ooliths. In this case the lack of concentric and radial structure, as seen under the microscope, could be attributed to their homogenous composition; these spherical bahamiths could originally have had a monomineralic

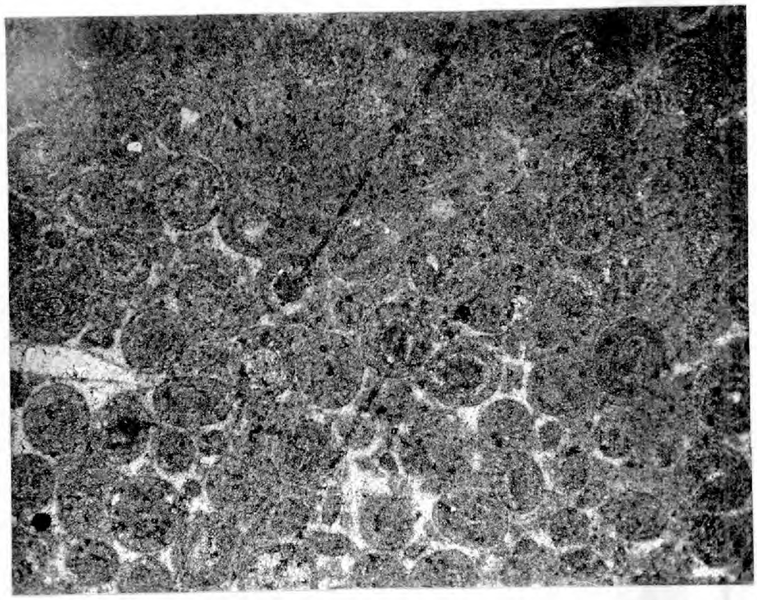


FIG. 25. Junction between an oolite with calcilutitic groundmass and one with a microcrystalline but sparry calcite cement. Lower Parves Beds, La Balme (x25)

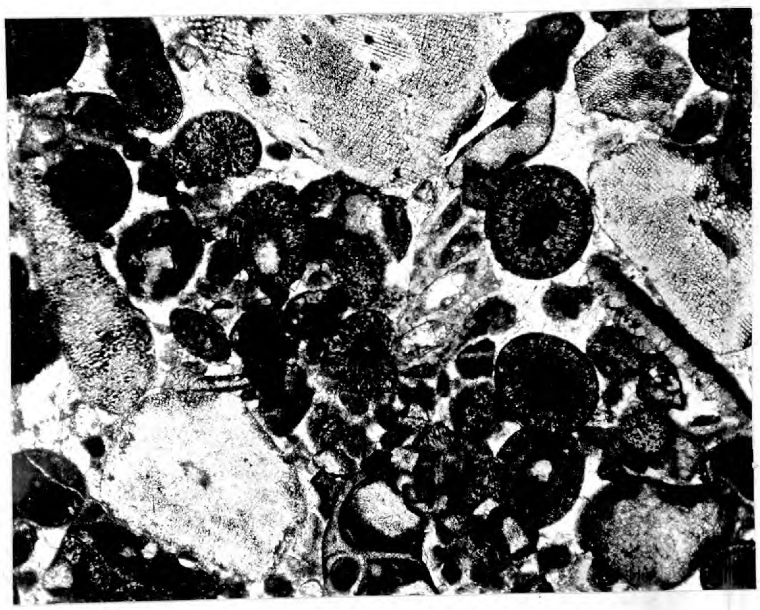


FIG. 26. Oolite calcarenite, showing ooliths, pellets and silicified echinoderm fragments, cemented by sparry calcite. Upper Bourdeau Beds, near Bourdeau (x25)

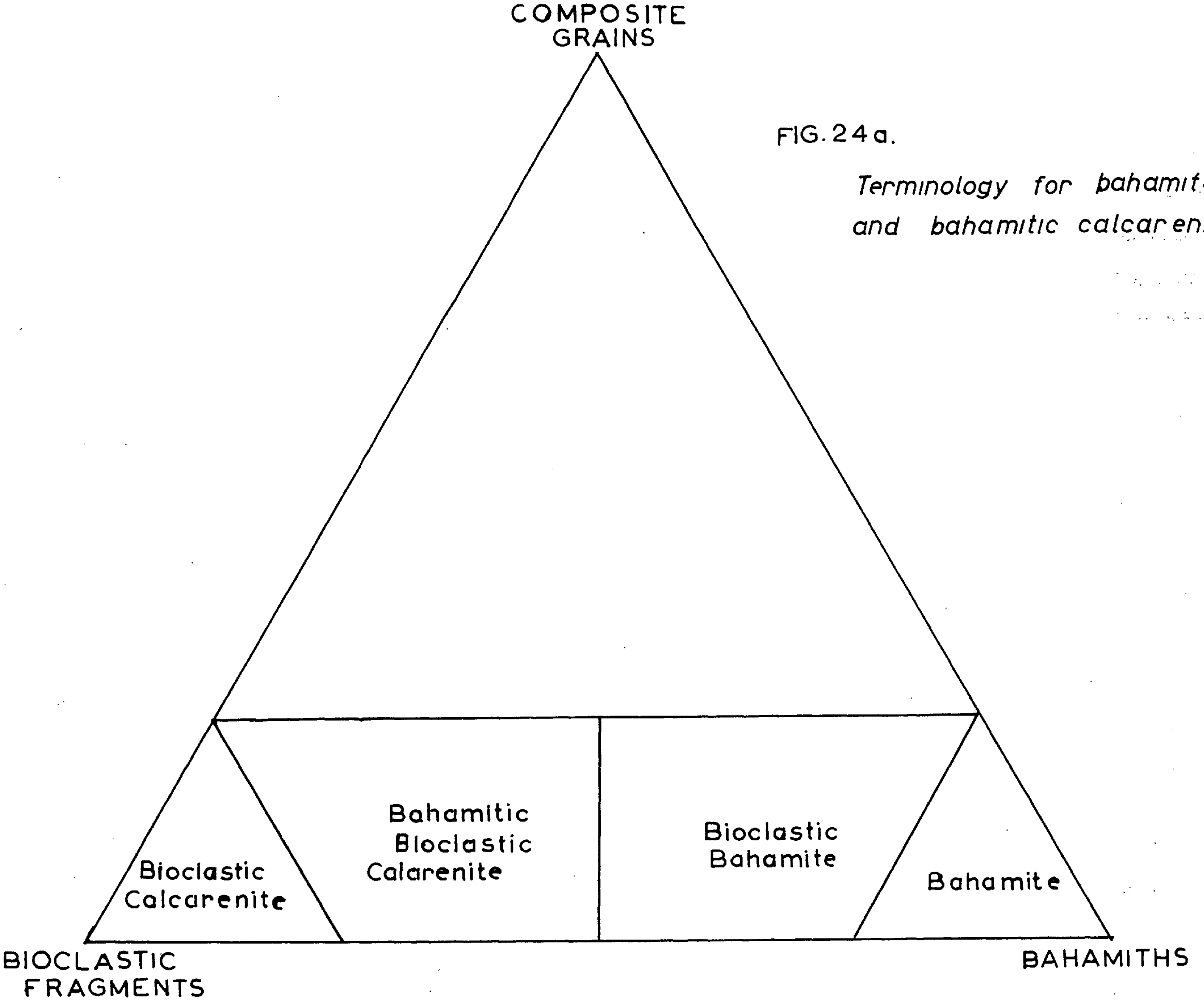


FIG. 24a.

Terminology for bahamites and bahamitic calcarenites.

composition, i.e. either aragonite or calcite. However, for practical purposes the spherical cryptocrystalline pellets are counted as bahamiths. Oolites occur either clean-washed or with a calcilutitic groundmass (Fig. 25), but the latter variety of oolite is comparatively rare, and as in the bahamites, they appear to be transitional between the clean-washed oolites and the calcilutites.

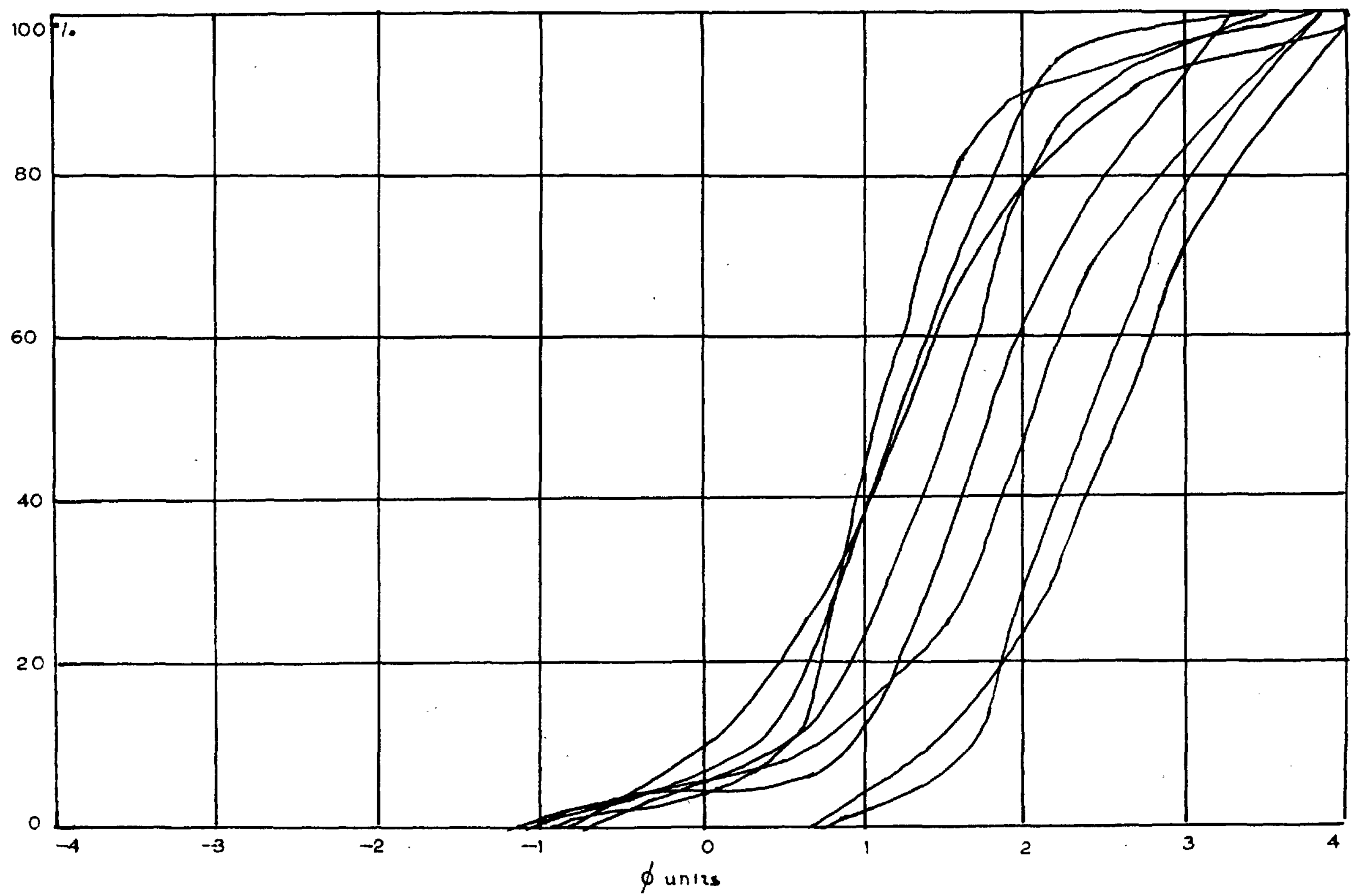
Oolitic calcarenites are not uncommon. These are usually mixed with skeletal debris (e.g. in the Upper Bourdeau Beds), but the ooliths commonly have nuclei of cryptocrystalline pellets (Fig. 26). This would suggest that they may have originated in an essentially bahamitic environment, and have been transported and later deposited with bioclastic debris. Indeed, this phenomenon is rather common in the calcarenites from the southern Jura; minor amounts of ooliths are found in a wide variety of calcarenites, and probably the most prominant of these is the distinctive marker horizon of the Middle Parves Beds (Chapter 3). At this horizon, pyritised ooliths are found "floating" in a microcrystalline groundmass; pyrite is usually concentrated towards the periphery of the ooliths. This rock clearly suggests that the ooliths might have originated in an oxidising environment, and have later been transported and deposited in a probably reducing environment.

Many skeletal fragments in bioclastic calcarenites, exhibit a pellicle of cryptocrystalline calcite which often shows a concentric structure. Such particles are termed by Illing (1954) "superficial ooliths". Although in some rocks the majority of skeletal fragments have acquired an oolitic coating, the latter usually constitutes a minor proportion of the rock, and such rocks are not considered as oolites.

In the field, oolites and oolitic calcarenites are usually current-bedded. They appear to be of limited areal and vertical distribution. This has been demonstrated in the oolitic calcarenites of the Bourdeau Beds (Chapter 3), what is more, although the writer has not observed oolites in the Virieu and the Lucey Beds, some excellent examples from these formations have been collected by S. Taha from the adjacent area in the departement of Ain.

<u>Grain-size Analysis</u>

Grain-size analyses were made of 14 thin sections of



FIG·27a—*Grain size frequency distributions for the Upper Bourdeau calcarenites north-west of Bourdeau.*

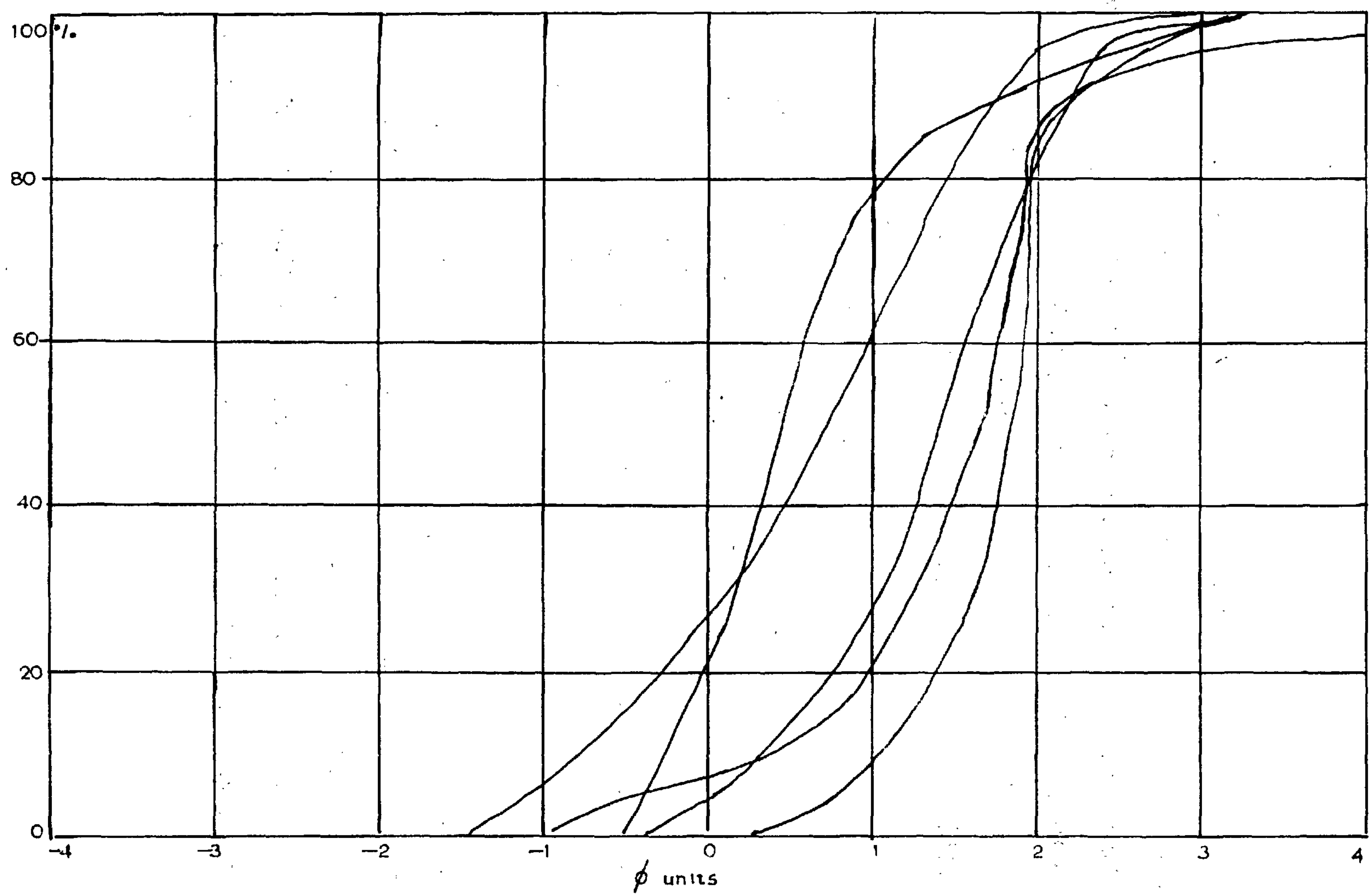


FIG. 27 b.— *Grain size frequency distributions for the Upper Bourdeau calcarenites near Conjux.*

calcarenites collected from the Upper Bourdeau Beds in the neighbourhood of both Bourdeau and Conjux. These analyses were made using the method of comparison circles. In each thin section up to 300 grains were measured.

Several authors have attempted to establish a correlation between the results of thin section particle-size analysis and sieve analysis. Correction factors were determined analytically by Krumbein (1935) and Packman (1955), and experimentally by Friedman (1958). Friedman, pointed out that the actual measure adopted (i.e. whether the short or the long axes of the grains were measured) may introduce an error of greater magnitude than the theoretical correction factor. What is more, Dr. J.C. Taylor (personal communication) using the method of comparison circles to estimate the size of each grain of a sandstone on the basis of equal areas, found that the values for the mean diameter obtained from thin section study agreed, for all practical purposes, with the true mean size of the loose grains. On these grounds, the author has therefore applied no theoretical corrections to the results. What is more, the shape factor in calcarenites is so variable that theoretical corrections

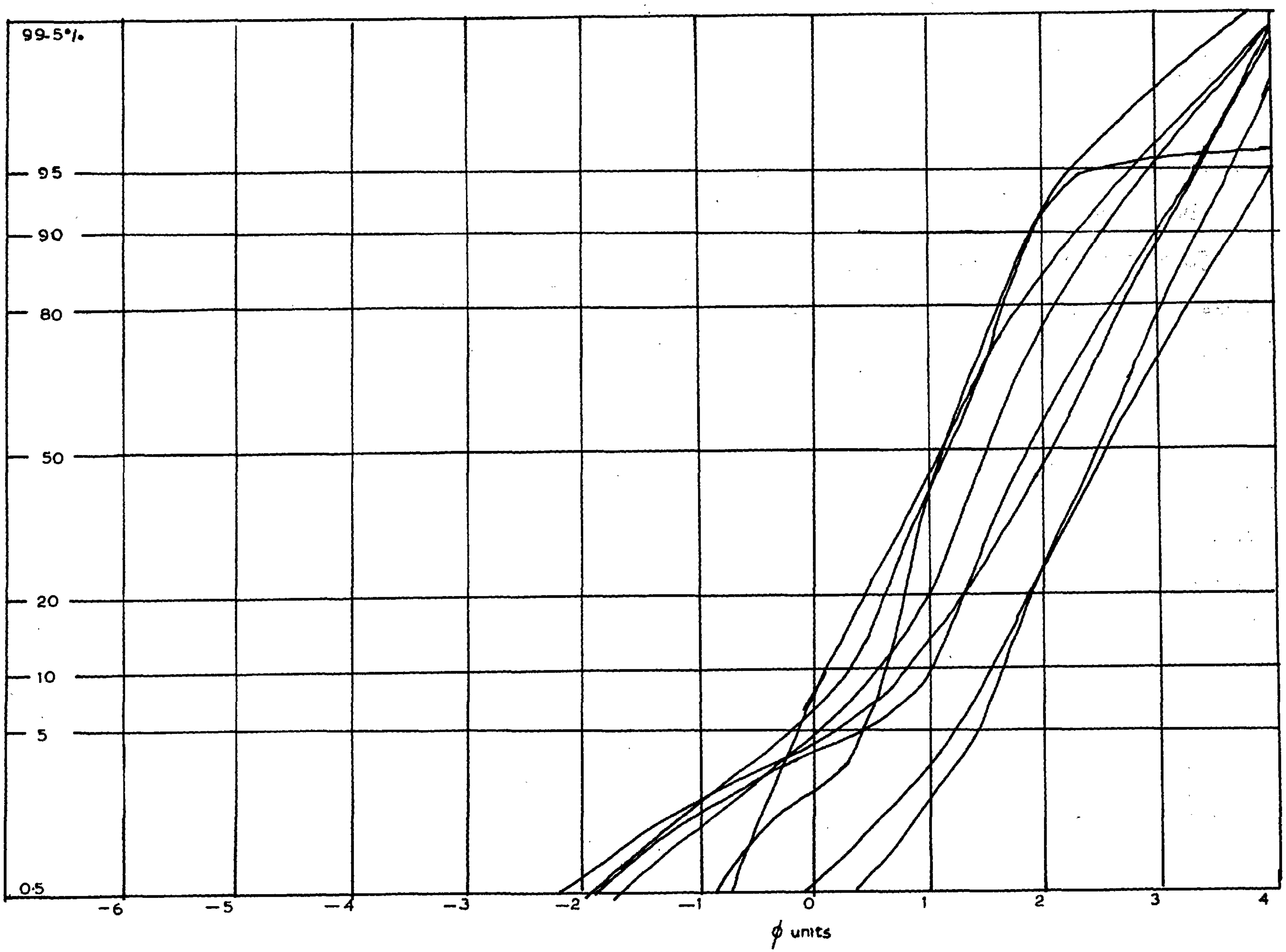


FIG. 28a.– *Grain size frequency distributions of the Upper Bourdeau calarenites north west of Bourdeau.*

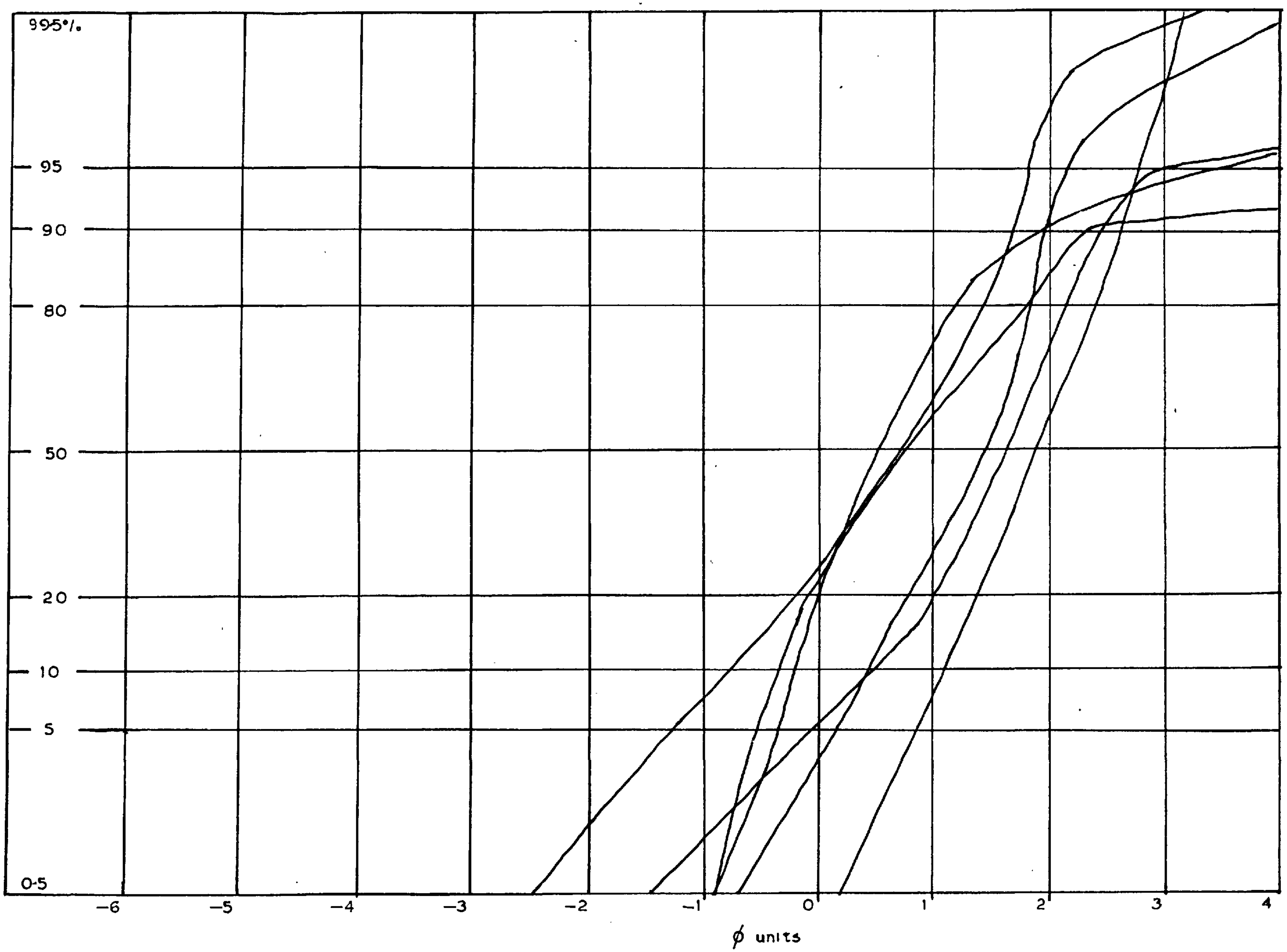
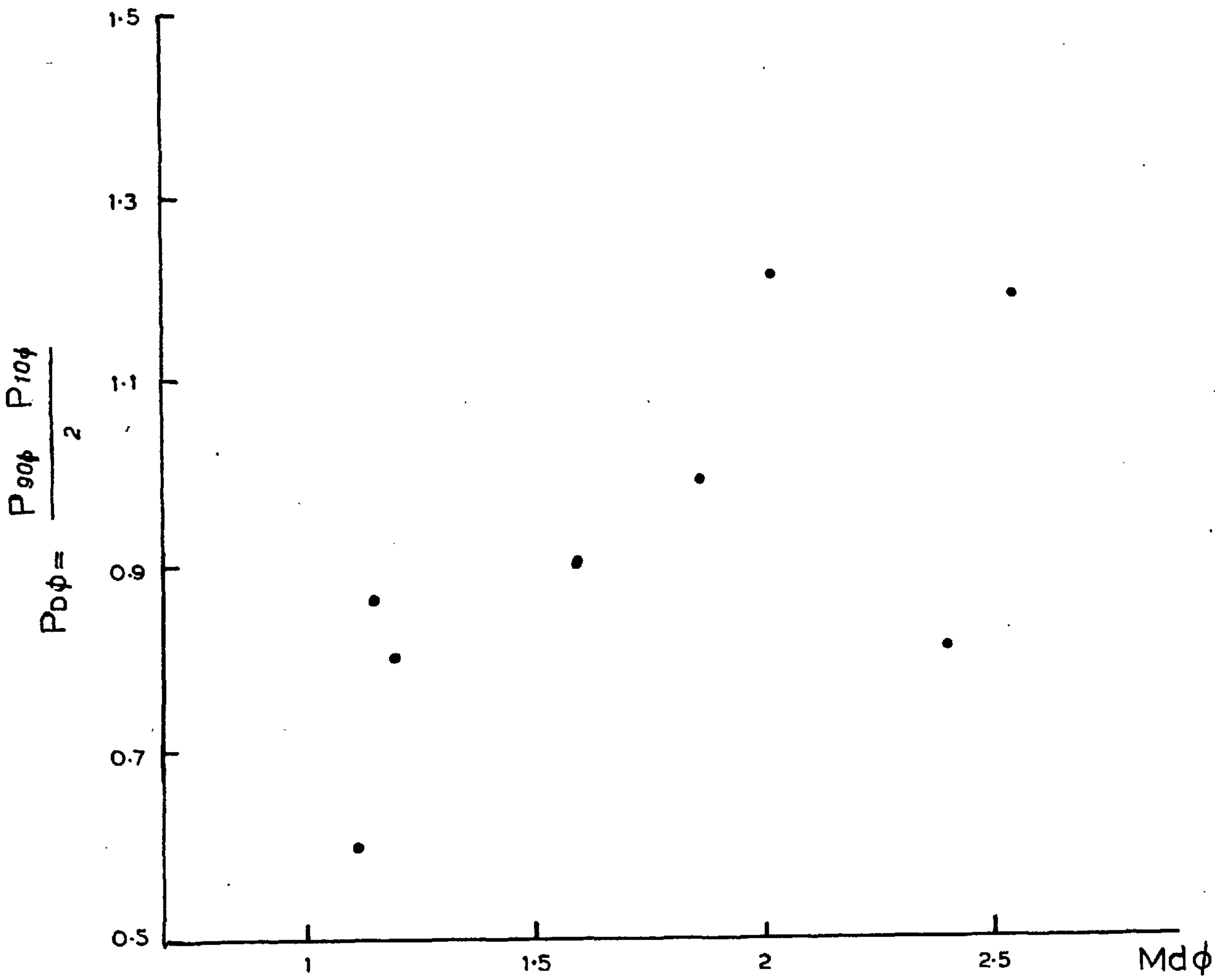


FIG. 28b.—*Grain size frequency distributions for the Upper Bourdeau calcarenites near Conjux.*

based essentially on spherical and ellipsoidal grains are of little validity.

The cummulitive curves of these samples (Fig. 27) show a grain size distribution similar to those of the calcareous sands of the Bahama Bank (Illing 1954). Probability curves of the majority of the distributions plot as straight lines (Fig. 28). This suggests that the grain size distributions are log normal. P D Ø (phi percentile deviation) ranges from 0.6 to 1.3 (table 6) indicating that they are reasonably well sorted sediments. A plot of P D Ø against M d Ø (phi median diameter), although scattered, suggests a general improgement in sorting with decrease in median diameter for the conjux specimens (Fig. 29), while the plot of specimens from Bourdeau suggests general improvement of sorting with increase in median diameter. These results would suggest that calcarenites with median diameters between 1.9 and 1.1 phi (i.e. between 0.27 and 0.46 mm.) are best sorted and that sorting becomes poorer in coarser and finer-grained calcarenites. This compares with similar relationship in sandstones and sands in which case the best sorted sediment has a median diameter about 2.5 phi (0.18 mm.). However, the higher value for the median diameter in calcarenites may be



FIG·29b.—*Showing improvement of sorting with increase in median diameter for specimens from near Bourdeau.*

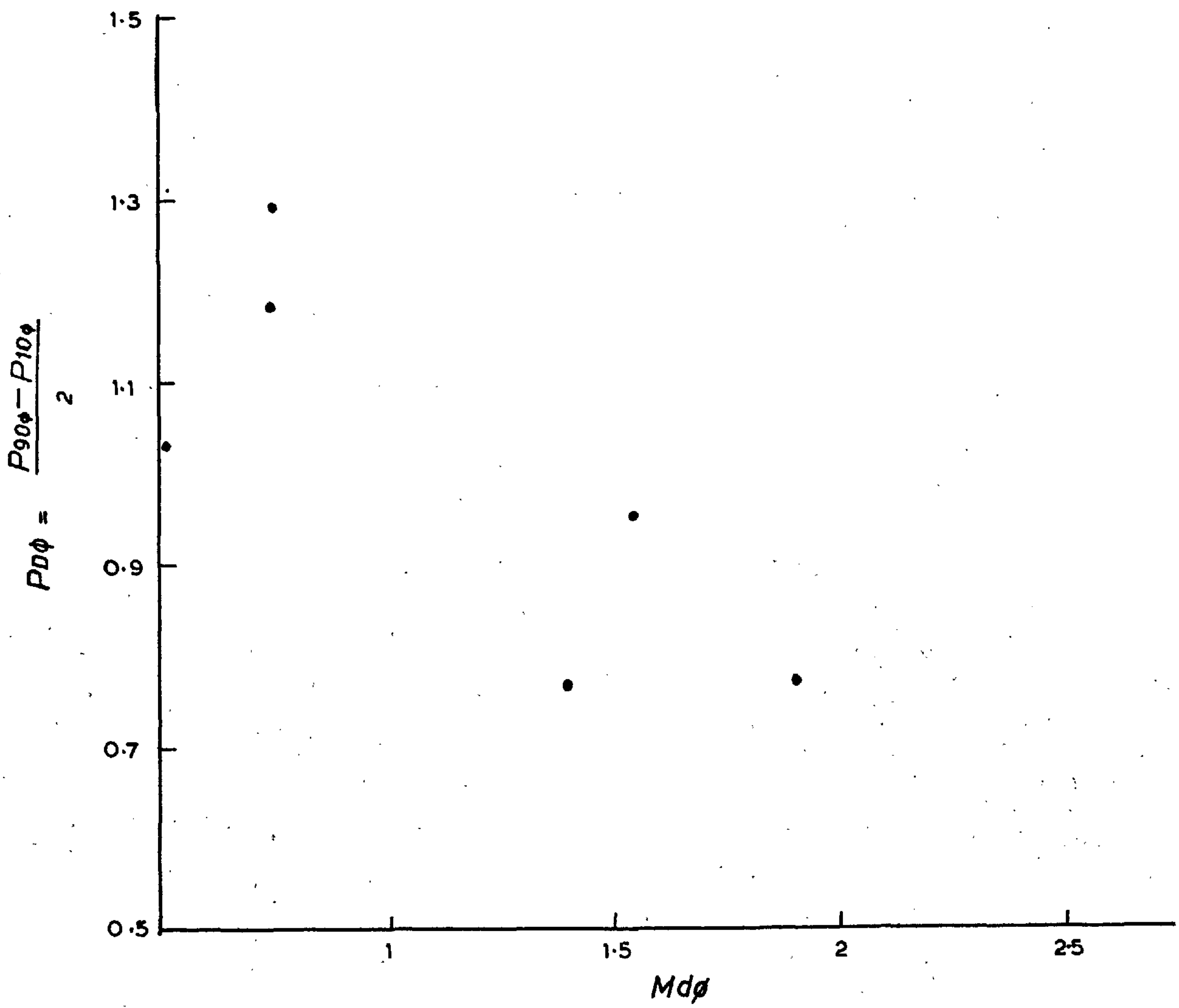


FIG. 29a.— *Showing improvement of sorting with decrease in median diameter for specimens from Conjux.*

due to differences in density compared to the siliceous sediment.

CHAPTER 8

DIAGENESIS I. DIAGENETIC CHANGES INVOLVING THE INTRODUCTION AND REDISTRIBUTION OF CALCITE

General

Attempts have been made to distinguish between "early diagenesis" and "late digenesis" according to whether diagenetic changes take place on the sea floor or after the sediment has been removed from direct contact with sea water. Such a distinction can be applied in the study of recent carbonate dedimentation (Ginsberg 1957) but is difficult to apply in the study of fossil sediments, because the time at which diagenetic reactions have taken place cannot always be demonstrated. It is possible, however, to distinguish modifications which are due to "mechanical" processes from others which are due to processes essentially "physico-chemical" in nature.

Modifications due to mechanical processes

In some instances, modifications which are essentially

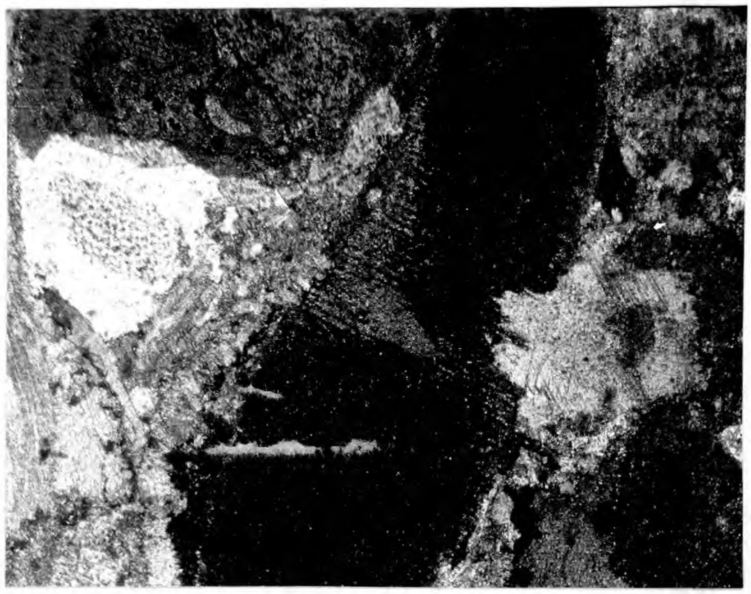


FIG. 30. Two interpenetrating echinoderm fragments, Lucey Beds, south of Chanaz (x 25).

mechanical have caused no observable solution of calcite, whilst in others solutions and probably redeposition of calcite has taken place. The results of point-counting analysis of some of the bioclastic bahamites show that many of the values which represent the volume of pore-space unoccupied by detrital grains, are notably below the figures calculated and experimentally determined by Sorby (1908). For example, some of the values are 13% and 15% compared with about 26% calculated by Sorby for the tightest possible packing. The texture of these rocks suggest that the bahamiths have been mechanically deformed and have coalesced so as to considerably reduce the inter-granular pore spaces. S. Taha had observed similar mechanical deformations between ooliths. More commonly, however, pressure-solution has resulted in the formation of microstylolitic boundaries, particularly among ooliths (Fig. 26). When such an effect was noted between echinoderm fragments, in some instances one of the fragments appears to have penetrated into theother (Fig. 30). This suggests some differential solubility, probably related to the crystallographic orientation of the monocrystalline fragments. In order to check these observations some experiments were conducted with calcite rhombohedra, in which these were partially dissolved in very dilute hydrochloric acid. The rhombohedra showed maximum solubility along the c-crystallographic axes.

Physico-Chemical Diagnectic Modifications

1. Cementation. Cementation includes all the diagenetic processes which bring about the lithification of the depositional components. Cementation textures may be expected to have some relationship to the texture of the depositional components. Where only one textural type of depositional component occurs, the cementation texture may be simple, but where the depositional components are heterogeneous, a complex cementation texture may be expected to occur. These possible relationships are discussed below Towards the latter part of the research it was found that the calcite of the cement is not always of the same composition. This was determined by treatment of the thin sections with a solution of potassium ferricyanide in 1% hydrochloric acid. The iron-rich calcite stained blue, whereas the iron free calcite remained unstained. Thus on the basis of the textural relationships of the iron-rich and

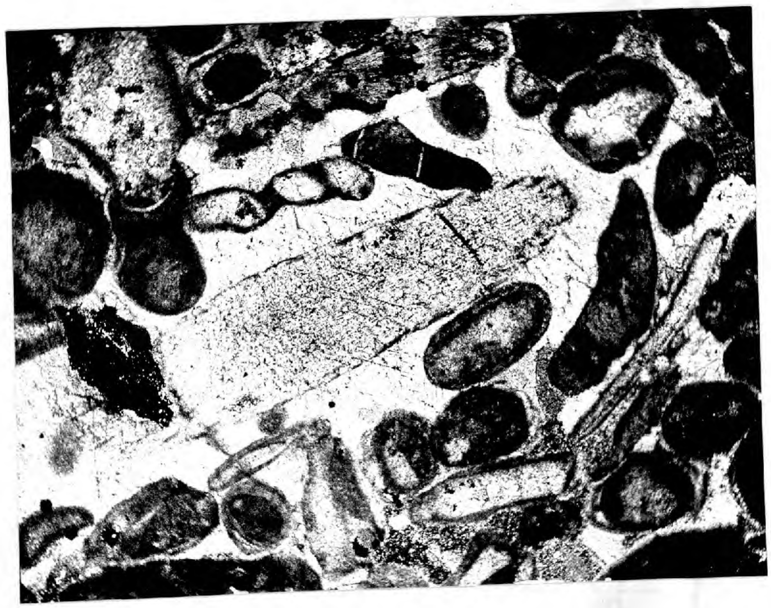


FIG. 31. Secondary overgrowth enclosing bahamiths.
Upper Bourdeau Bed near Conjux (x35).

the iron-free calcite it becomes possible to identify a cementation sequence.

(i) Cementation around echinoderm fragments.

(a) Secondary overgrowth into voids. This is a well known phenomenon, and involves the infilling of the echinoderm canals and external overgrowth into the pore spaces. This secondary growth is all in lattice continuity with the calcite of the organic fragments. In some specimens overgrowth is so extreme that it poikilitically encloses other (non-echinoderm) components (Fig. 31). Thin sections treated with potassium ferricyanide showed that, in some instances, the secondary overgrowth was iron-rich and in others iron-free. Where the overgrowth was iron-rich the echinoderm fragments took on a patchy blue stain. This patchiness is probably the expression of iron-rich calcite filling the pores of the iron-free calcite of the echinoderm fragment.

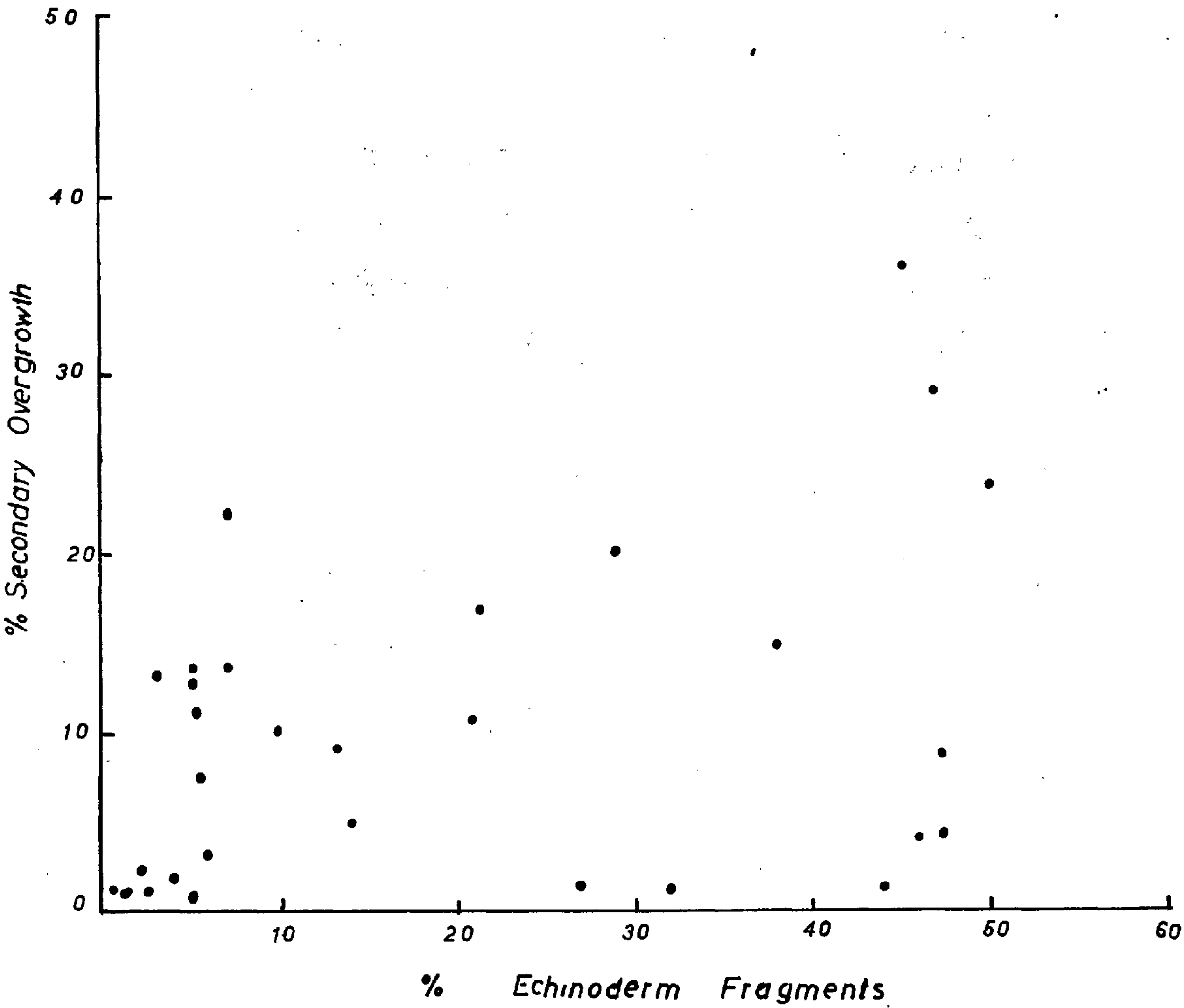
In many of the specimens, the calcite of the secondary overgrowths showed minute blebs, which although apparently carbonate, failed to go into extinction with the rest of the crystal. These blebs give the crystal the general appearance of a 'microperthite', and it is possible that they are an ex-solution phenomenon. S. Taha had noted a similar phenomenon, and what is more, whenever the orientation of an echinoderm of fragment and its overgrowth was such that an optical figure could be obtained, the calcite was always slightly biaxial. Although the optic axial angle was always small, the isogyres always parted completely.

It was observed, however, that in those clean-washed calcarenites in which the echinoderm fragments have acquired a pellicle of cryptocrystalline calcite, overgrowth is virtually non-existent (Fig. 35). This pellicle must have prevented free communication between the cementing solutions and the echinoderm fragments. In those rocks in which the pellicles were relatively thin, only some echinoderm fragments showed secondary overgrowth.

(b) Overgrowth replacing calcilutite groundmass and bahamiths. In some calcilutitic calcarenites, echinoderms show overgrowths which clearly must have formed by the replacement of the depositional matrix in the insterstices. Bathurst's "syntaxial rim" bounderies (1958), between the calcite mudstaone groundmass, is irregular but smooth in outline. In any one section, however, there are usually a few overgrowths which show an acute saw-toothed boundary with the matrix or replaced bahamith along one edge.

In all instances where this saw-toothed boundary is seen, the form of the teeth is always the same and clearly they must be acute cones. The fact that these cones are only seen in a limited number of overgrowths in any one section, suggests that they are perhaps developed only in certain crystallographic directions. No detailed statistical study was made to determine this, but in all those examples studied the cones only occurred on those overgrowths where the c-crystallographic axes of the crystal was in or near the plane of the thin section, and in the general direction of the cones.

(c) Volume of overgrowth. The point-counting of echinoderm calcarenites has shown that=whenever microcrystalline calcite is an important constituent of the groundmass, the volume of overgrowth is low. On the other hand, in clean-washed calcarenites secondary overgrowth provides the



FIG·33-Plot showing the absence of good correlation between the volumetric percentage of secondary overgrowth and the percentage of echinoderm fragments.

major part of the cement. These observations suggest that rim-cementation is affected mainly by overgrowth into voids, and that in these limestones the replacement of microcrystalline calcite in the groundmass is quantitatively unimportant. Thus it would appear that the relative volume of overgrowth in echinoderm calcarenites is essentially determined by the amount of pore-space available during cementation. A plot of the overgrowth against echinoderm fragments in any one thin section, shows a wide scatter of points (Fig. 33), and this would suggest that the relative volume of overgrowth is not simply related to the abundence of echinoderm fragments in the rocks. It appears that it is essentially determined by two factors (a) by the volume of available pore space and (b) by the extent to which the echinoderms were sealed by a pellicle of cryptocrystalline calcite. The former partly depends on the original porosity of the rock and in part on the amount of depositional microcrystalline matrix.

(ii) <u>Cementation around polycrystalline fragments</u>

Polycrystalline fragments (i.e. pellets and skeletal

FIG. 34A. Groundmass of prismatic calcite crystals of normal to the margins of the interstices, with granular calcite mosaics in the centre. The detrital components include recrystallised pellets and skeletal debris. Upper Bourdeau Beds near Conjux (x25).

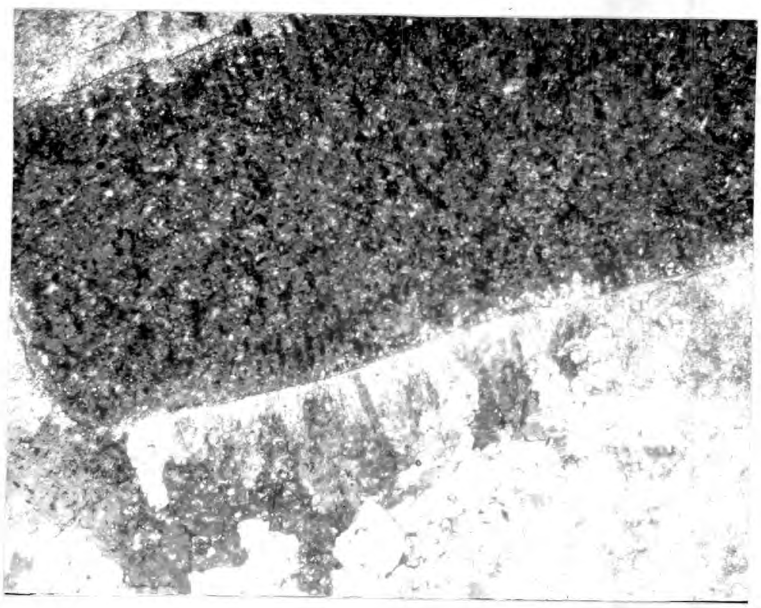


Fig. 34B. Prismatic calcite developed between secondary overgrowth and echinoderm fragment (x120) fragments) are usually cemented with a mosaic of granular calcite. The crystals of the granular calcite mosaic are always relatively fine-grained around the margins of the pore spaces and increase in size towards the centre (Fig.3[illegible]a). Two types of mosaics may be distinguished on the basis of the orientation of the calcite crystals lining the walls of the pore-spaces. In one type the lining crystals are orientated with their c-axes perpendicular to the surfaces of the detrital grains (i.e. the walls of the pore-space); in the other type, no preferred orientation is observable. In the former, the crystals are susually prismatic and a textural discontinuity exists between the prismatic lining and the mosaic at the centre of the pore-spaces.

Since the cementation of the monocrystalline skeletal fragments is usually achieved by the secondary overgrowth of these fragments, it is logical to presume that the cementation of polycrystalline fragments is also accomplished by the outgrowth of calcite crystals at the surface of the depositional components. In some specimens it was observed that many of the crystals in some biocalstic mosaic pseudomorphs are in optical continuity with crystals in the granular cement. However, if such a mode of origin did apply for the

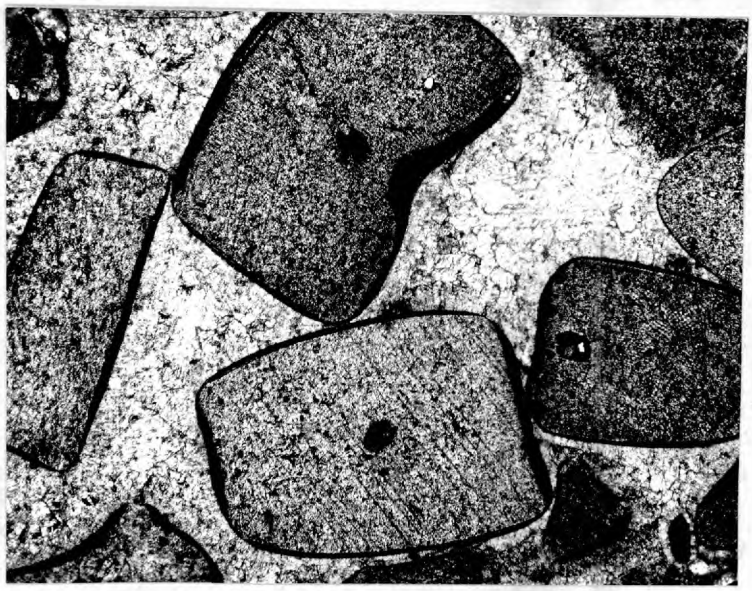


FIG. 35. Echinoderm calcarenite, cemented with a granular mosaic of calcite. The echinoderm fragments show a pellicle of cryptocrystalline calcite and no secondary overgrowths (x15).

cementation of the majority of polycrystalline fragments, the resulting granular mosaics in calcarenites consisting of a mixture of these components should exhibit a heterogeneous and a complex texture in any one specimen. What is more, the skeletal fragments which, for instance, consist of fibrous and prismatic calcite should be cemented with calcite of similar nature. No such relationships have been observed in the specimens studied. In fact, the majority of thin sections showed essentially a homogeneous and normally onetype of cementation texture (except for rim-growth). This would therefore suggest that cementation in the majority of calcarenites consisting of polycrystalline fragments has been achieved by deposition of calcite on free surfaces not in optical continuity with the fragments. Such a process may be due in a part to the presence of a pellicle of cryptocrystalline calcite on these fragments. As stated earlier such a pellicle has been observed in some bioclastic calcarenites, and in these it has inhibited overgrowth, even of echinoderm fragments (Fig. 35). It is possible that such a pellicle is usually deposited during the first phase of cementation, but rarely attains sufficient thickness to become noticeable under the petrological microscope. The exceptionally porous structure of echinoderm fragments would leave sufficient pore spaces so that in the second phase of cementation there would be free communication with the cementing fluids. In normal circumstances, therefore, only these fragments become cemented by overgrowth.

Deposition on free surfaces should give rise to a drusy type of mosaic (Bathurst 1958). Such a mosaic has been observed in coarse-grained calcarenites and also in the infillings of large polycrystalline skeletal fragments. In medium and fine-grained calcarenites, however, the drusy texture is not apparent. Bathurst (1958) emphasised the continuous nature of the process which leads to the formation of a drusy texture characterised by a gradual increase in the size of the crystals towards the centre of the cavities. Although such a textural continuity may be observed at times, there is some evidence which suggests that a dis-continuity exists between the calcite forming the lining of the cavities and that which occupies the centre. The evidence includes the following:

(i) In the first type of granular cementation described above, coarse crystals often extend across a considerable number of crystals lining the cavity. Indeed, in some bahamites, one

large crystal may occupy the whole pore space.
(ii) In the second type described above, the prismatic layer near the margins bears no textural relationship to the mosaic at the centre.

These observations are further supported by differential staining with potassium ferricyanide which showed that the fine-grained calcite in the lining of the pore spaces is iron-rich while that in the centre is iron-free.

CHAPTER 9

DIAGENESIS II. SILICIFICATION

1. General Statement

In the Jura rocks, cherts and siliceous limestones occur in the calcarenites of the Lucey, Chanaz and Bourdeau Beds. The sole occurrence of cherts in calcilutites is a local development in the Lower Virieu Limestone at la Balme. In the Lucey and Chanaz Beds there are alternations of bioclastic calcarenites and cherty calcarenites, but in the Bourdeau Beds silicification is less extensive. Partial silicification of the skeletal fragments is a common feature of echinoderm and semi-echinoderm calcarenites. In the cherty horizons, however, silicification has extended into the groundmass. There are also echinoderm calcarenites which are cemented essentially by granular quartz mosaics, but these appear to be only locally developed.

Silica occurs in the siliceous calcarenites in two forms, but opal was also found in some of the calcarenites studied by S. Taha from the Lucey Beds of the adjacent area.

The chalcedony shows either fibrous, spherulitic or granular aggregates. The distinction between granular chalcedony and very fine-grained quartz mosaic is made on the basis of the anomalous optical properties of chalcedony as opposed to quartz. This is believed to be an expression of a disordered rather than an ordered lattice.

2. Selective silicification of detrital components.

There is evidence which suggests that where partial silicification of a rock has taken place, the silicification is selective. The evidence which supports the suggestion is as follows:

(i) In almost all the specimens where extensive silicification of the skeletal fragments has occurred, the non-skeletal grains in the rock are unaffected.

(ii) No examples of silicification of bahamites have been found.

(iii) Composite grains also show selective silicifications as illustrated in figure 36. The large polycrystalline skeletal fragment consisting of fibrous calcite has been extensively replaced by chalcedony and quartz; while the cryptocrystalline calcite pellets near the periphery are unaffected by silicification.

The tendency to selective silicification is well seen in the Upper Bourdeau calcarenites. Those from the neighbourhood of Bourdeau are silicified whereas those from near Conjux are unaffected. These two groups represent the skeletal and non-skeletal facies of the Upper Bourdeau Beds respectively.

3. Silicification of monocrystalline skeletal fragments

Silicified echinoderm fragments show fibrous, spherulitic and granular chalcedony as well as quartz mosaics. In some rocks the chalcedony occurs only as an 'infilling' of the canals of the fragments; which suggests that in these examples the chalcedony may have been a collaidal precipitate. The majority of the rocks, however, show clear evidence of replacement.

Some echinoderm fragments are partially or completely replaced by chacedony; these fragments commonly exhibit fractures arranged almost at right angles to their length. In this type of replacement, the areas of chalcedony are virtually free from inclusions.

Another type of replacement of echinoderm fragments can be seen, in which these fragments are replaced by quartz mosaics. In these two main types of silica replacement, silicification is confined, in the majority of examples examined to echinoderm fragments only; the secondary overgrowths are rarely affected. This suggests that in these rocks silicification took place before cementation. Numerous examples have been found in which only the outer zones of the echinoderm fragments are silicified with the central parts unaffected. This indicates that silicification has proceeded from the margins inwards. However, examples do occur in which the chalcedony occurs as apparently random patches within the fragments. It is possible that these patches represent tongues of chalcedony which have grown in from the margins of the fragments, and this apparent randomness is due to the orientation of the thin section.

4. <u>Silicification of polycrystalline skeletal fragments</u>.

The majority of silicified or partially silicified

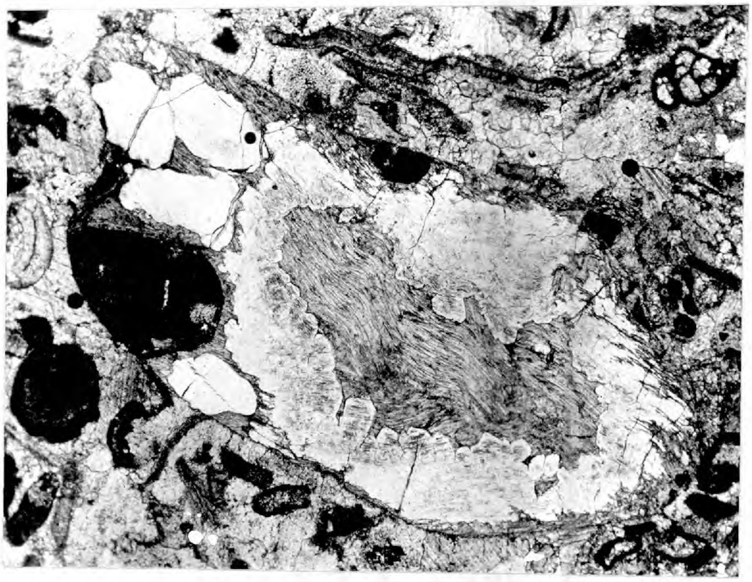


FIG. 36. Selective silicification of a composite grain. The skeletal fragment consisting of fibrous calcite has been replaced by Chalcedony (clear) and quartz (showing relics of fibrous calcite), while the fine-grained calcite near the periphery is unsilicified (x30).

polycrystalline skeletal fragments are those which consist of fibrous calcite. This does not imply that fibrous skeletal material is selectively silicified rathern than prismatic and other skeletal structures, since the first type are the most abundent. Where extensive replacement by chalcedony has taken place, the chalcedony shows fractures similar to those occurring in silicified echinoderm fragments (see fig. 36). Where replacement by quartz has occurred, ghosts of the skeletal structure may often be seen in the form of inclusions of calcite within the quartz (Fig. 36). Where corals have been silicified, the cavities within the structure are unaffected and are commonly filled with sparry calcite.

5. Quartz-cemented echinoderm-calcarenites.

In all partially silicified rocks, with the exception of those to be described in this section, it is always the skeletal fragments which have been replaced, and the rocks are cemented by calcite. However, in what are probably the Lucey Beds near St. Germain, S. Taha found echinoderm calcarenites in which the skeletal fragments are cemented

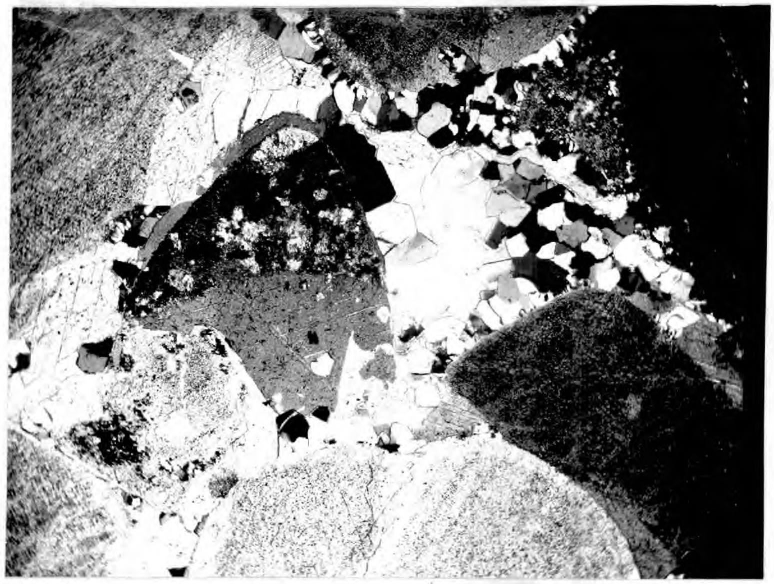


FIG. 37A. Quartz cemented echinoderm calcarenite. Echinoderm fragments are partially silicified. The rock is cemented by a granular quartz mosaic and by secondary overgrowths on the echinoderm fragments, St. Germain (x30).

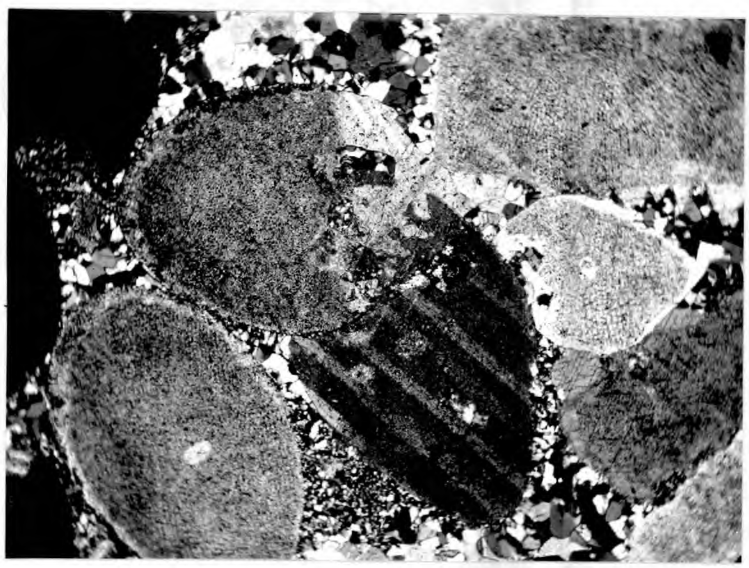


FIG. 37B. Pressure-solution contacts between secondary overgrowths (x30).

dominantly by a granular quartz mosaic with accessory secondary overgrowths of calcite. (see Fig. 37a and 37b). The texture of this rock is very complex. Some of the echinoderm fragments are partially silicified, either being replaced by granular chacedony or by a quartz mosaic which extends inwards from their margins. The quartz replacement mosaics show ghosts of the canals of the original skeletal structure. The secondary overgrowths of the calcite, however, are not affected, and it would appear that this first phase of silicification preceeded cementation. Secondary overgrowths of calcite only occupy a relatively small part of the original pore spaces, the remainder being filled by the granular quartz mosaic. One unusual feature of this rock is that not only do the echinoderm fragments show microstylolitic contacts, but the mutual boundaries between some of the secondary overgrowths are microstylolitic also. Such pressure - solution contacts could not have developed once the rock was completely cemented, and this suggest that the first phase of cementation consisted of only a limited development of secondary calcite cement. This must have been early, because it preceeded or was contemporaneous with, compaction.

The granular quartz mosaic shows the characteristic texture of a drusy mosaic, and would therefore appear to be the final infilling of the pore spaces. There is no conclusive evidence to suggest that the granular quartz mosaic of the cement is a replacement of an earlier calcite cement.

6. Completely silicified calcarenites (cherts)

In the rocks described in this section silicification has proceeded largely to completion; not only the skeletal components but the groundmass also has been replaced by one or more forms of silica.

In thin section, the outer zones of the 'chert' nodules show relics of fine-grained calcite and of skeletal fragments. The original detrital nature of these rocks is often shown by ghosts of skeletal fragments now outlined by ferric oxide or 'clayey' and other opaque matter. Many of the specimens studied come from the Lucey Beds and appear to have consisted originally of echinoderm fragments.

In the cores of the chert nodules, calcite is rare. The detrital texture of the original limestone can still be seen in the form of ferric oxide ghosts. Chalcedony, which forms the main part of the core, occurs as microcrystalline aggregates, but is spherulitic in places. Pseudomorphs after polycrystalline shell fragments usually consist of chalcedony arranged in fibres at right angles to the length of the fragments. Detrital quartz and dolomite are common in these cherts, and calcite after dolomite has been observed in a few of them. There is a decrease in the amount of opaque 'clayey' matter from the outer zones towards the core of many of the chert nodules.

General Conclusions

(i) All the specimens of chert studied have clearly arignated by replacement. The detrital nature of the original calcarenite is recognisable even in the central part of the chert nodules.

(ii) The occurrence of cherty groups of sediments interbedded with non-cherty groups, and the localisation of the majority of cherts in fine-grained calcarenites, suggests that certain primary characteritics of the sediments controlled the processes of silicification.

(iii) There appear to be four possible phases of silicification in the Jura rocks:

(a) Pre-cementation. This is clearly demonstrated by the presence of partially silicified echinoderm fragments with their overgrowths unaffected.

(b) During cementation. There is only one example in which silica has been introduced during cementation. This phase resulted in the filling of pore-spaces in echinoderm calcarenites, and it appears to have been accompanied by a little replacement.

(c) Post-cementation. The majority of the cherts studied formed after the limestones had been cemented.

(d) Post-jointing. In the Middle Lucey Beds, cherts occur at right angles to the stratification and sub-parallel to well developed vertical joints. These must have originated after the formation of these joints.

(iv) Chalcedony, quartz and opal, that order of abundence, occur in the siliceous limestones. Quartz forms microcrystalline mosaics or coarser mosaics which may be clear or may be full of inclusions.

(v) Silicification of the sand-size components appears to be selective; skeletal fragments are more susceptible to replacement by silica than non-skeletal grains. What may be of great significance, is that in all the specimens studied which show partial silificiation, the mosaic pseudomorphs are never replaced. On the other hand, in the completely silicified calcarenites, i.e. cherts, if mosaic pseudomorphs did occur they were replaced. It is believed that the mosaic pseudomorphs are calcite after aragonite skeletal structures. This suggests that, while the replacement of calcite by silica takes place with relative ease, the replaement of the orthorhombic dimorph cannot readily be achieved in the sedimentary realm.

(vi) Although this chapter was mainly concerned with the replacement of calcite by silica, evidence for the reverse process i.e. the replacement of quartz by calcite is not lacking. In the arenaceous limestones many of the detrital quartz grains show corroded and irregular margins against the calcite of the cement. A few shows several small quartz grains in optical continuity which are clearly parts of one larger quartz grain. The replacement of calcite by silica and of silica by calcite could be a matter of relative solution and precipitation. Correns (1950) pointed out that in acid solutions calcite is soluble, whereas in alkaline solutions silica is relatively soluble while calcite is insoluble. Thus it is possible that silicification may have resulted from the post-deposional change in PH of the connate waters. In the case of pre-cementation selective silicification, it is possible that the bacterial decomposition of protoplasmic matter within the skeletal structure, e.g. within the canals of echinoderm fragments, may have produced organic acids. However, extensive silicification to produce cherts is more difficult to exaplain, as is later mobilisation of silica to produce the cherts which occur filling joints. What is more, there is little evidence as to the possible source of the silica.

CHAPTER 10

DIAGENESIS III. DOLOMITIZATION

General

The mineral dolomite occurs throughout the Mesozoic succession in the Jura. However, it is only in the Virieu Limestone and in the Parves Beds that it becomes a significant component of the limestones. In the Virieu Limestone dolomite rock forms irregular masses (up to 10 metres in length). In the Parves Beds dolomites and dolomitic limestones occur only in the Lower and Middle divisions. They often form banded rocks and are interbedded with calcilutites and bahamites (Fig. 55). Both in the Virieu Limestone and in the Parves Beds, significant amounts of the mineral dolomite occur mainly in the calcilutites. Examples of dolomitic calcarenites, with dolomite as a major constituent, have been found, but these are rare.

While cherts occur extensively in the coarse-grained limestones (i.e. calcarenites) the mineral dolomite in these rocks is only an accessory. On the other hand, where dolomite forms the major part of the rock, cherts and even accessory authigenic quartz or chalcedony are virtually non-existent.

Megascopic characters of dolomitic limestones and dolomites

In the field two main types of dolomites and dolomitic limestones can be distinguished:

1. Those showing a homogeneous texture. These can usually be distinguished from normal limestones by their brownish colour and roughness to the touch. They have a fine- or coarse-grained granular appearance depending on the particle size of the dolomite.

2. Those with a heterogeneous appearance. These can be divided into two sub-types.

(i) Mottled limestones: These show patches of reddish brown dolomite and light grey limestone. Examination of polished surfaces etched with dilute hydrochloric acid shows that some of the dolomite boundaries are sharp while others are irregular. A zone of ferric oxide (0.5 to 1 mm. wide) usually marks the boundary. Some dolomite rhombs are scattered in the limestone and some calcite also occurs in the dolomite patches.

(ii) Banded dolomites and dolomitic limestones: In these the dolomite-rich bands are stained with iron oxides and hence are easily distinguished from the limestone bands. In most of these banded dolomites, the bands are usually about 1 cm. thick. Each band, however, can be seen to consist of a number of thinner dolomite-rich and dolomite-poor laminae (about 0.5 to 1 mm. thick). Some of the bands are wavy and in some cases the crests are truncated. In others the bands are more irregular; they converge and coalesce, superficially resembling augen-structures. Where stylolites occur in the limestones interbedded with these dolomites, they often behave in a similar manner. The banding and lamination of the dolomitic limestones and dolomites is always parallel or sub-parallel with the stratification. It is of interest to note that banded dolomitic limestones and dolomites occur in well-bedded successions, while the mottled limestones occur in massive formations.

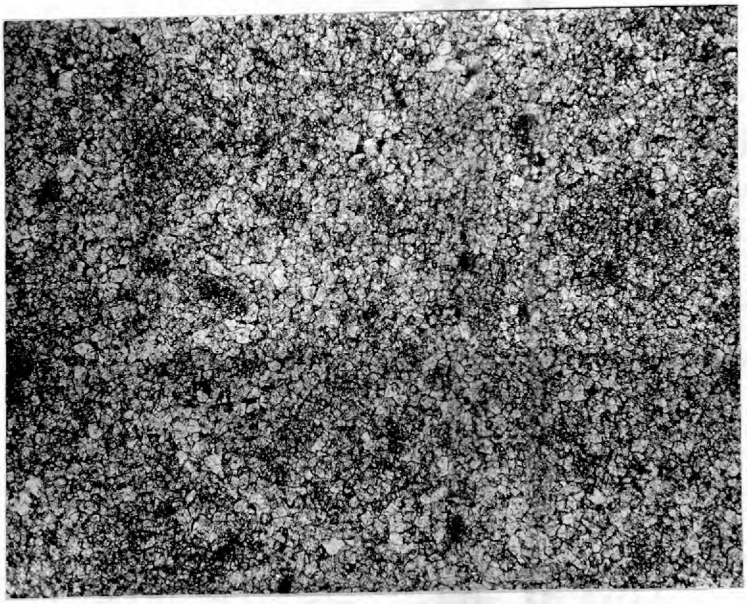


FIG.38. Fine-grained dolomite with interstitial microcrystalline calcite, Lower Parves Beds at La Balme gorge (x25)

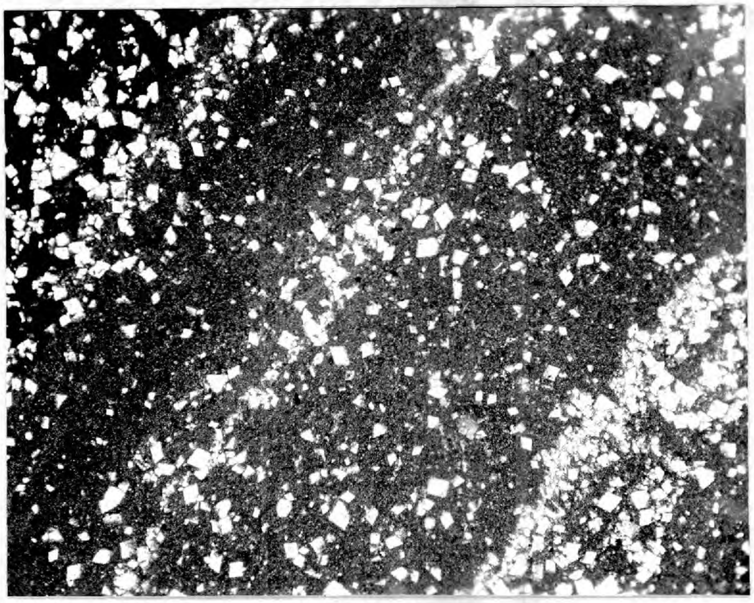


FIG. 39. Banded dolomitic calcilutite. The Upper left hand corner shows differential staining by silver chromate. Lower Parves Beds at la Balme gorge (x25)

Microscopic features of dolomitic limestones and dolomites

The mineral dolomite occurs in all the various types of calcarenites and calcilutites in varying proportions; these rocks are classed as dolomitic limestones. The dolomites consist almost exclusively of the mineral dolomite. The following rocks types can be differentiated:

1. Dolomitic limestones.

(i) Dolomitic calcarenites. In these rocks rhombs of dolomite occur scattered at random, and replace both the detrital components and the groundmass. The majority of calcarenites contain less than 5% dolomite. The occasional presence of greater amounts of dolomite in some specimens, together with relics of skeletal material, suggests that some dolomites have been formed by the complete dolomitisation of calcarenites.

(ii) Dolomitic calcilutites. These rocks consist of a groundmass of cryptocrystalline calcite in which rhombs of dolomite are distributed at random or are concentrated in bands (Fig. 39). In any one specimen, the rhombs are usually of the same order of size, but in different specimens, they vary from microcrystalline to coarse-grained.

2. Dolomites.

These rocks consist essentially of the mineral dolomite with or without accessory calcite. Those with calcite can be sub-divided into four types:

(i) Dolomites with intestitial microcrystalline calcite. These patches of microcrystalline calcite, see figure 38, appear to be relics of the earlier limestone, i.e. calcilutite.

(ii) Dolomites with interstitial sparry calcite. Many of the insterstices between the dolomite rhombs are filled with single crystals of calcite. It is difficult to determine whether this insterstitial calcite is primary or secondary in origin.

(iii) Dolomites in which the dolomite rhombs are poikilitically enclosed by a coarser-grained mosaic of calcite. In the majority of these rocks the dolomite is fine- or very fine-grained.

(iv) Dolomite with relics of skeletal material. These dolomites have obviously resulted from the replacement of detrital limestones.

Chemical analysis and insoluble residues of dolomites and dolomitic limestones

About 40 specimens from the Virieu Limestone and the Parves Beds of La Balme were analysed for magnesia and lime. These specimens included dolomites, dolomitic limestones and dolomite-free limestones. The insoluble residues of these specimens were obtained by treatment with hydrochloric acid. The results are summarised in Table 2 and Fig. 55.

The results of chemical analysis have been compared with the thin sections of the samples analysed, and a visual estimate of the amount of dolomite in these thin sections was made. Limestone, completely free from dolomite (Table 2) show a magnesian content ranging from 0.2% to 2.6% and these correspond to the magnesian limestones of Cayeux (1955). Two specimens with 1.65% and 2.5% of magnesia respectively contain a few scattered rhombs of dolomite. Eight specimens contain between 3% and 10% of magnesia, while the remaining specimens carry between 11.6% and 19.8%. Thin section examination of the specimens analysed indicates that when the dolomite rhombs are scattered throughout the limestone and the grains are not frequently touching, the magnesia content is up to 14.6%. When the number of contacts become considerable and anhedral grains of dolomite rather than rhombs become abundant, the magnesia content of the rock exceeds 16.2%, (i.e. the rock contain over 75% of dolomite). The results of chemical analysis of dolomites and dolomitic limestones from the south of France also indicate that carbonate sediments with dolomite greater than 75% are far more abundant than dolomitic limestones containing dolomite between 10% and 75% (Charpal and others 1959. Fig. 39). Although the limit between "calcitic dolomites" and "dolomites" suggested by Cayeux (1955) and other workers is 90%, it appears that 75% is a more natural one.

The insoluble residues of the specimens analysed consist mainly of 'clayey' matter. The sand fraction is insignificant and rarely exceeds 0.01% of a rock. When the polished surfaces of some of the banded dolomitic limestones were treated with an alchoholic solution of safranine, the dolomite-rich bands stained pink while the limestone bands remained practically unstained. The dyes are absorbed by the clay minerals which can be seen to be concentrated in the dolomitic bands. Further, it will be seen from figure 55, that the magnesia content of many of the specimens shows a close correlation with the proportion of insoluble residues. This figure also shows that the dolomites and dolomitic limestones of the Lower Parves Beds generally contain higher amounts of insoluble residues than the interbedded unaltered calcilutites and bahamites.

The origin of dolomitic limestones and dolomites

The textural relations between the dolomite and calcite in the calcarenites leaves no doubt that in these rocks the dolomite is diagenetic in origin and has replaced calcite. In the calcilutites, however, some of the fine-grained dolomitic limestones and dolomites could be interpreted as "primary dolomites". This has been suggested for similar rocks occurring to the south of the area by Charpal and others (1959). Alderman and Skinner (1957) have shown that, in the South-East province of South Australia, dolomite is being precipitated at the present day in a shallow inlet of the sea in conditions of high pH. In the Lower Parves Beds, fresh water horizons occur interbedded with marine horizons, and it is po sible that similar shllow lagoonal environments existed in which the physico-chemical conditions were favourable for the precipitation of dolomite. Such a primary mode of origin however, could only apply to some of the dolomite which occur in the Lower Parves Beds, because there are some rocks at this level which show evidence of a replacement origin.

In some of the bahamites, which are interbedded with the dolomitic calcilutites and dolomites of the Parves Beds, bbth the detrital components and the groundmass have been partially replaced by dolomite. Further, in many of the dolomitic calcilutites, dolomite occurs within stylolites or is concentrated in the microcrystalline calcite immediately above and below these stylolites. This evidence would suggest that a late diagenetic phase of dolomitisation has occurred. This has probably taken place after cementation. Some specimens of dolomite from the Parves Beds show secondary overgrowths of dolomite around dolomite rhombs, and in others, small rhombs of dolomite are enclosed within larger ones. This suggests the presence of, at least, two generations of dolomite.

Since much of the dolomite in the Mesozoic succession is of replacement origin, it is important to enquire whether selective dolomitization has taken place: i.e. whether certain types of sediment are more prone to dolomitization, and whether or not any one type of carbonate sediment contains components which are more susceptable to dolomitization than others. Fairbridge (1957) observed that the majority of dolomitized limestones were originally fine-grained, and suggested that fineness of grain is a primary feature for most sediments destined to become dolomite. It would be true to say that in the Jura the majority of dolomites are associated with fine-grained limestones, but dolomitized calcarenites do occur. Prominent among these latter are dolomitised pisolites occurring at the top of the Oignon Limestone in the west of Bugey, and dolomitised bahamites which occur in the Virieu Limestone and in the Parves Beds. In these calcarenites, however, the detrital components are essentially fine-grained. The heterogeneous textures of these calcarenites permits further observations regarding selective dolomitization to be made. Firstly it appears that the groundmass is more susceptible to dolomitization than the detrital components. In the dolomitized pisolite, for instance, the majority of the pisoliths have escaped dolomitization while the groundmass is almost completely dolomitized. Secondly, in bioclastic pellet calcarenites, microcrystalline pellets are more susceptible to dolomitization than the skeletal debris. The author has rarely seen dolomite rhombs enclosed within echinoderm fragments or within polycrystalline skeletal components. It is also evident in some of the dolomitic calcilutites that coarse-grained calcite is less favoured by dolomitisation than fine-grained calcite. In these, patches of sparry calcite occur, and the dolomite rhombs embedded in the cryptocrystalline groundmass only penetrate into the margins of the areas of the coarser-grained calcite. Examples of cavities containing internal sediment and drusy mosaics have been observed, and in these the layers of fine-grained internal sediment at the base of the cavities have been dolomitized while the drusy mosaic at the top is free from dolomite.

Dolomitization also appears to be selectively associated with certain sedimentary structures. The association of dolomite with stylolites has already been mentioned, and the dolomitization may be related to the ease of permeability along the stylolites. The tendency for the dolomites of the Parves Beds to be banded, might at first sight be interpreted as resulting from the selective dolomitisation of the relatively more permeable bands and laminae, but it is the clay-rich bands, mentioned earlier, which are dolomitized.

The possible sources of the magnesium required to produce dolomite are the following:

(a) sea water

(b) connate waters

(c) magnesian calcite

(d) magnesium absorbed in clay minerals.

There is no evidence to suggest that the magneium has been introduced into the Jura limestones by metasomatic or other processes.

If, as is considered possible, some of the fine-grained dolomites are primary, they would have derived their magnesium from the sea water. The majority of the dolomites and dolomitic limestones, which are clearly the result of post-depositional replacement, would have been removed from direct contact with sea water, and an internal source would appear to be more probable. The original concentration of magnesium in connate waters can only have been very small, and it is considered that magnesian calcite of organic origin was the most likely source.

It has long been known that the skeletons of certain modern organisms, which include corals, echinoderms and calcareous algae, contain significant proportions (i.e. 10 to 15%) of magnesium carbonate in the lattice. There is some evidence which indicates that redistribution of magnesium in the sediments takes place during diagenesis. Clarke and Wheeler (1922), who investigated the chemical composition of fossil crinoids from Lower Silurian to Eocene in age, pointed out that their magnesium content is considerably lower than is that of modern crinoids. Vinogradov (1953) suggested that this may be due to the removal of magnesium carbonate from the skeletons of crinoidea during "metamorphism". Graf and Goldsmith (1955) suggested that high-magnesian calcite is unstable under normal conditions, and that in the course of time the magnesium is released. It would pass into the intrastratal solutions and be available to promote dolomitization.

CHAPTER 11

DIAGENESIS IV DEDOLOMITISATION

1. Introduction

The term "dedolomitisation" was introduced by Von Morlot (1848) in the course of a discussion of the processes of dolomitisation. He suggested that dolomitisation, of a limestone, could result from the introduction of magnesium sulphate solutions according to the equation

$$2\ Ca\ Co_3 + Mg\ \ So_4 \qquad Ca\ Co_3\ MgCo_3 + Ca\ So_4$$

This reaction is a reversible one, and it is possible that calcium sulphate solutions might cause the replacement of dolomite by calcite. Von Morlot, however, knew of no examples of rocks which had been affected in this way.

J.H. Teall (1903) used the term to describe the metamorphic transformation of dolomite, but such a process was not implied by Von Morlot when he first coined the word. Apart from a general statement by Gilbert (1954), there does not appear to be any reference in Western European or

North American geological literature, to rocks in which dolomite has been replaced by calcite, but such rocks have been described by Russian geologists. The recent translation of Strakhov's textbook into French gives the only convenient petrographic account of these rocks, with photographs of some of the replacement textures.

Amongst the Jura rocks, numerous specimens were found which showed textures which could only reasonably be interpreted as having been produced by the replacement or partial replacement of dolomite by calcite. It was not until the author has found a transition, within one bed, of the Upper Virieu Limestone from dolomite into a limestone after a dolomite that the ultimate proof that the rocks had been dedolomitised was obtained. In the following section an account will be given of the known distribution of dedolomitised rocks in the Jura, and this will be followed by a description of the transition in the Virieu Limestone of la Balme gorge before the various types of replacement textures are discussed. A paper on these rocks by D.J. Shearman, S. Taha and the present writer (1960) has been read to the Geologists' Association and should be published shortly in their proceedings.

2. The Distribution of Dedolomitised Rocks in the Southern Jura.

Dedolomitised carbonate rocks occur in the Upper Virieu Limestone, the Parves Beds and in the Bourdeau Beds. Below the Virieu Limestone, although accessory dolomite does occur, no replacement of dolomite by calcite has been observed. Dedolomitised rocks have been found in the Virieu Limestone and the Bourdeau Beds near Chanaz, at the northern extremity of the area. At this locality no dolomite masses have been found in the Upper Virieu Limestone, but five out of six specimens collected from this formation showed complete replacement of dolomite by calcite. At la Balme gorge, the vertical extent of dedolomitisation in the Lower Parves Beds is shown in figure 55. In the beds underlying the Lower Breccia group, about 75% of the dolomite and dolomitic limestones have been dedolomitised. At Rossillion, S. Taha recorded similar extensive dedolomitisation at this level. However, both at la Balme gorge and at Rossillion dedolomitisation is less extensive in the highest parts of the Lower Parves Beds (i.e. the limestones with breccias) than below. In these upper beds only 7% of the dolomitised rocks have been dedolomitised.

Specimens collected by students of Imperial College from the Upper Virieu limestone and the Lower Parves Beds of an area covering much of Bugey showed numerous examples of dedolomitised rocks. Thus it would appear that there has been extensive dedolomitisation in the Virieu Limestone and in the Lower Parves Beds over an area extending from Lac du Bourget in the east to and beyond Rossillion and Premeyzel in the west (Fig. 2). An interesting example of dedolomitised oolitic limestone was also found by Mr. J. Murray of Imperial College in the Kimmeridgian of the Swiss Jura at Ostseite. More work is needed, however, before the regional extent of dedolomitisation is known.

3. The Transition from Dolomite into Limestone after Dolomite at La Balme

Within the Upper Virieu Limestone of la Balme gorge there are large irregular masses of dolomite up to 10 metres in lateral extent. The dolomites are granular, coarse-grained rocks, and pass into fine-grained limestones. The transitions are marked by zones of ferric oxide staining; the staining is strongest against the dolomite and fades off into the limestone. In the field it was thought that

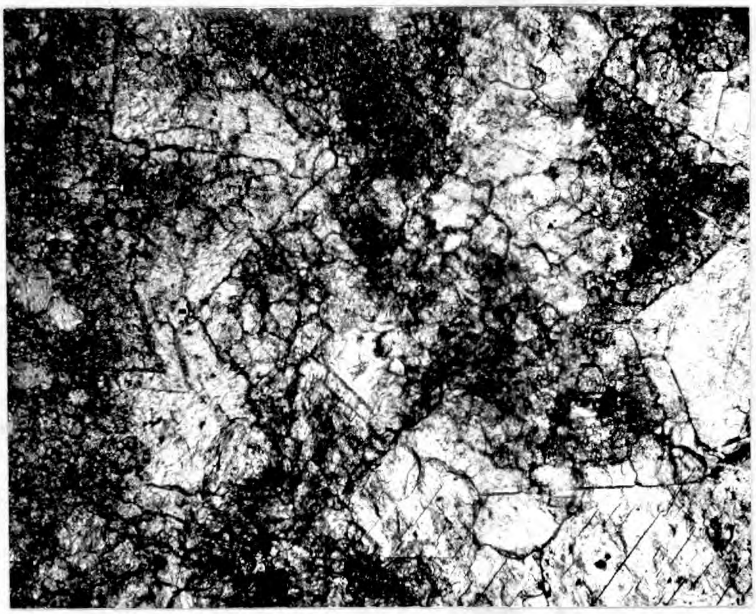
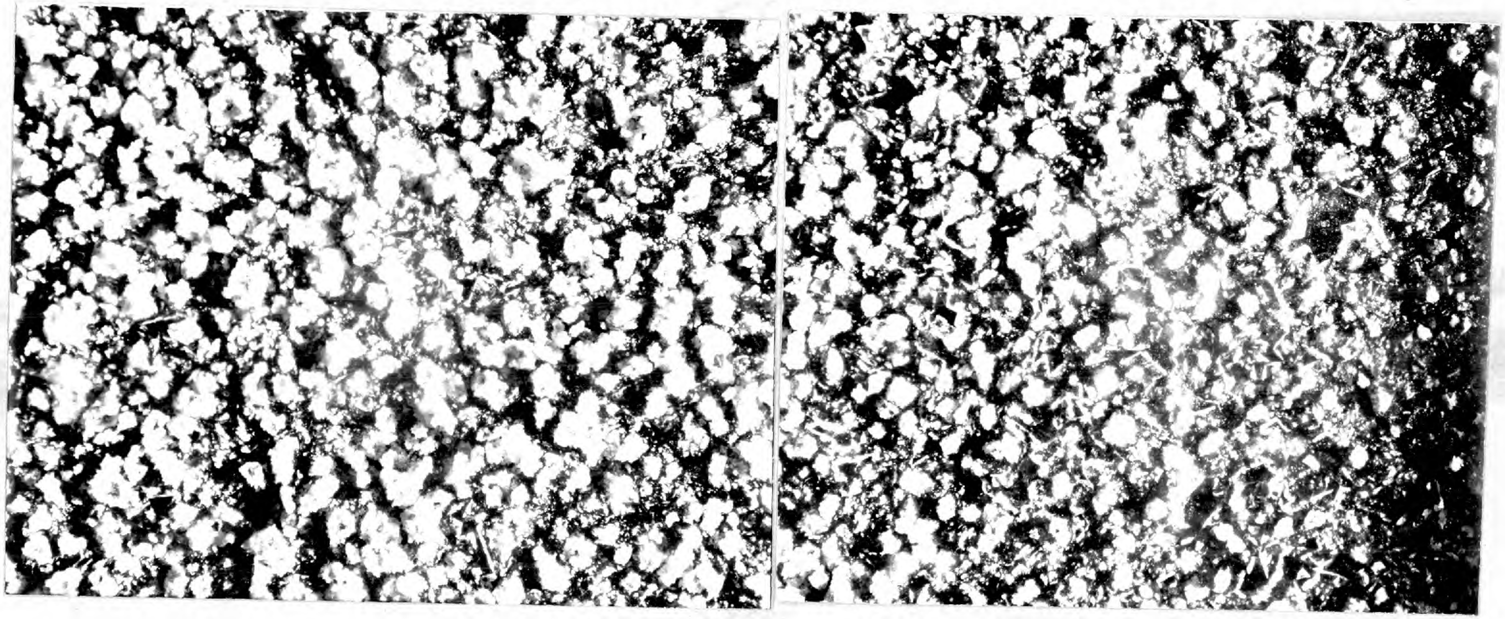


FIG. 41A. Composite calcite rhombs with a micro-crystalline core surrounded by coarser-grained calcite. Upper Virieu Limestone. La Balme gorge (x120).

FIG. 41B. Rhombs of dolomite. The rock was treated with hydrochloric acid which dissolved the interstitial coarse-grained calcite. Upper Virieu Limestone, La Balme gorge (x100).

the transitions were those resulting from dolomitisation, and specimens were collected across two of them in the hope that the study of these might shed some light on the nature of the process of dolomitisation. In the laboratory it was found that these transitions were not from limestone into dolomite resulting from dolomitisation, but from dolomite into limestone resulting from dedolomitisation. One of these transitions will be discussed in detail.

The transition zone between the dolomite and limestone is narrow (about 4 cm.) and three specimens were collected, one from the zone of transition and one each from the limestone and dolomite on either side. In thin section the textures of the limestone and dolomite are superficially similar (see figures 41A and B) both consist of mosaics of mutually interfering rhombs with coarse-grained crystals of calcite filling the insterstices between the rhombs. In the dolomite rock, the rhombs are rhombs of dolomite, but in the limestone the rock is entirely calcite, and each of the rhombs is made up of a fine-grained mosaic of calcite crystals. These rhombs are clearly pseudomorphs of calcite after dolomite. Across the transition the dolomite



a b

FIG. 42. Acid etched polished surface of a transition between dolomite and limestone. Upper Virieu Limestone, La Balme gorge (x20).

a. dolomite side of transition
b. limestone side of transition.

crystals are progressively replaced by calcite and the complete change from one rock type to the other takes place within a distance of approximately one centimetre. Figures 42A and 42B are photographs of an acid-etched polished surface of the transition zone. On the dolomite side of the transition (Fig. 42A) only the cores of the rhombs have been replaced by calcite, whereas towards the limestone side of the transition (Fig. 42B) the calcite cores have increased in size, so that only the outer zones of many of the dolomite rhombs remain. There can be no doubt that this transition is one of dedolomitisation, because the dolomite passes laterally into a limestone which shows the ghost texture of dolomite.

4. Partially Dedolomitised Rocks

Carbonate rocks in which dedolomitisation has not proceeded to completion were differentially stained with silver chromate to distinguish the replacement calcite from the relic dolomite. Several examples have been found in which dolomite rhombs show cores of fine-grained calcite

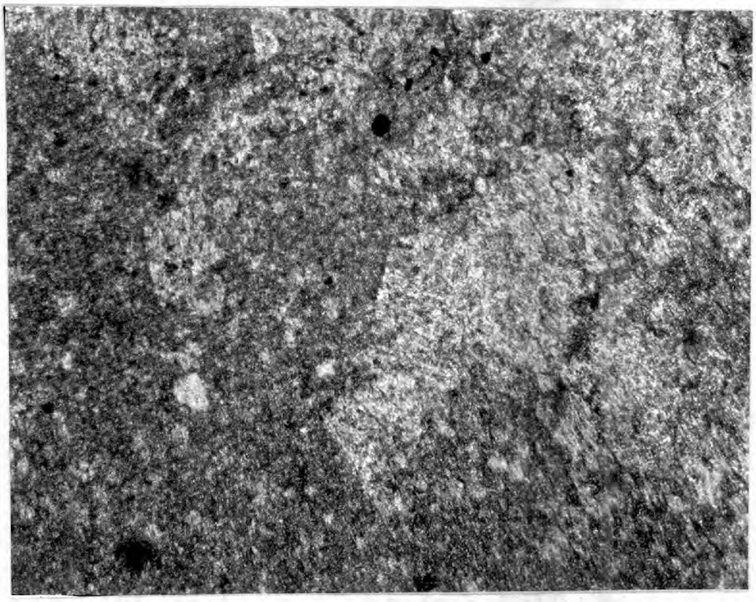


FIG. 43A. A junction between calcilutite and dolomite. The dolomite rhombs show grains of fine-grained calcite randomly scattered. Upper Virieu Limestone, La Balme gorge (x50).

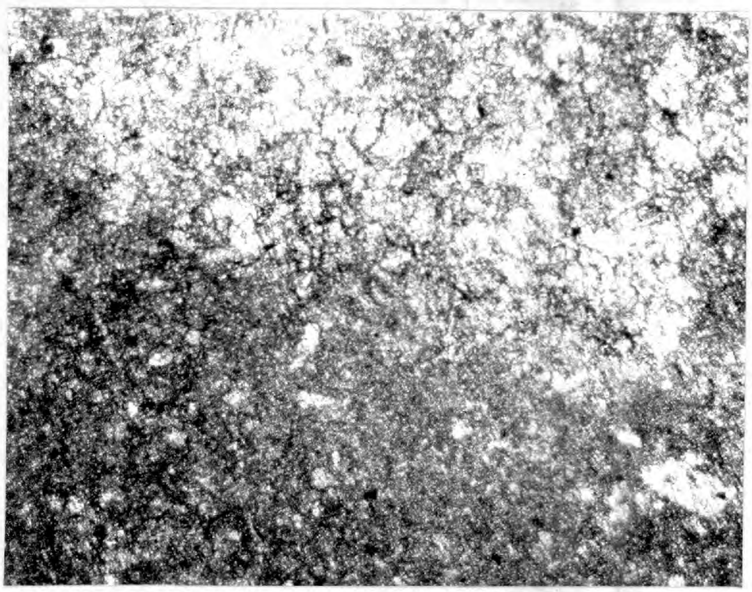


FIG. 43B. Junction between calcilutite and limestone after dolomite. The former dolomite grains now show a core of microcrystalline calcite surrounded by coarser-grained calcite. Upper Virieu Limestone la Balme gorge (x50).

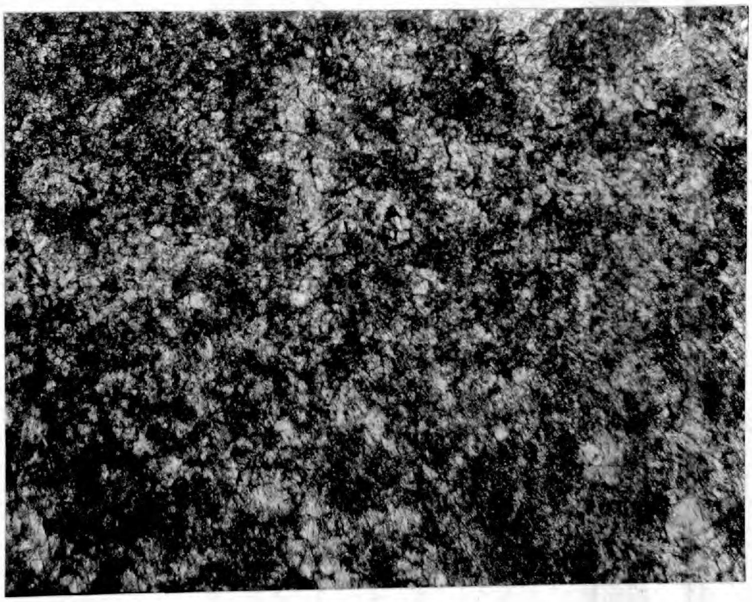


FIG. 44. Fully dedolomitised rock. The dolomite rhombs and grains ahve been replaced by microcrystalline calcite in the core and coarser-grained calcite towards the periphery. Upper Virieu Limestone at la Balme gorge (x25).

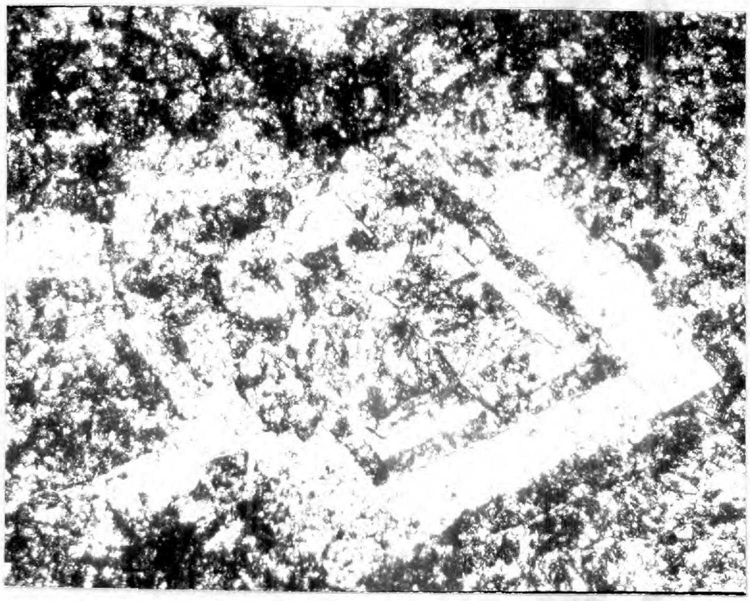


FIG. 45. Rhombs of dolomite, partially replaced by microcrystalline calcite (stained with silver chromate) in the core, and along certain rhombic zones. Upper Virieu Limestone, La Balme gorge (x120).

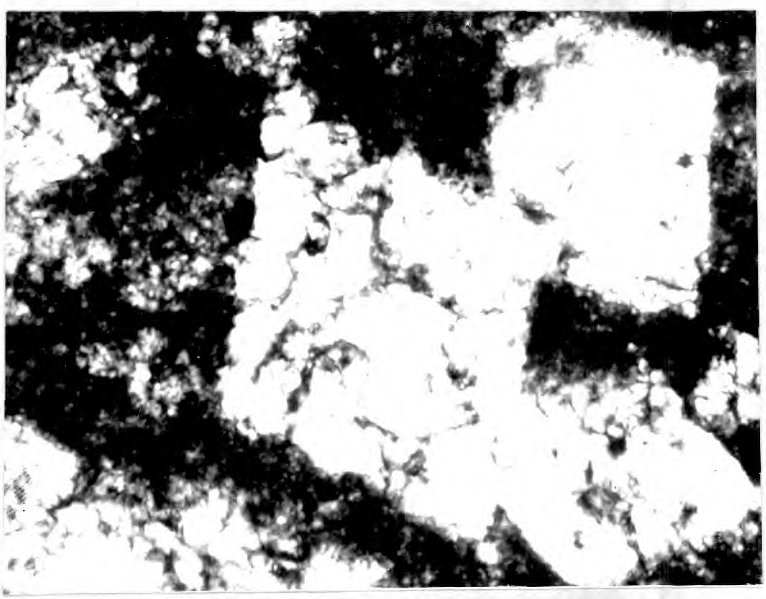


FIG. 46. Composite calcite rhombs (x1200)

(Fig. 48). A further stage in this style of replacement is illustrated in Fig. 47. In this specimen only the obtuse and acute angles of the outer zones of the rhombs have esacped replacement. In this mode of replacement, dedolomitisation appears to have proceeded from the centre of the dolomite rhombs outwards, ie. centrifugally. This is typical of dolomitic calcilutites. However, in some rocks corroded grains of dolomite have been observed, and in these the majority of the rhombohedral faces have been destroyed. In these rocks dedolomitisation must have proceeded inwards, i.e. centripetally. This has been observed when the relict dolomite is poikilitically enclosed by larger crystals of calcite. Khvorova (1958), described calcite poikilitically enclosing rhombs of dolomite which are not corroded, but which show cores of microcrystalline calcite.

In some rocks replacement of dolomite by calcite has taken place along particular zones (Fig. 45). These rocks show zones of dolomite of uniform width alternating with zones of microcrystalline calcite. In other specimens, however, dedolomitisation has taken place apparently at

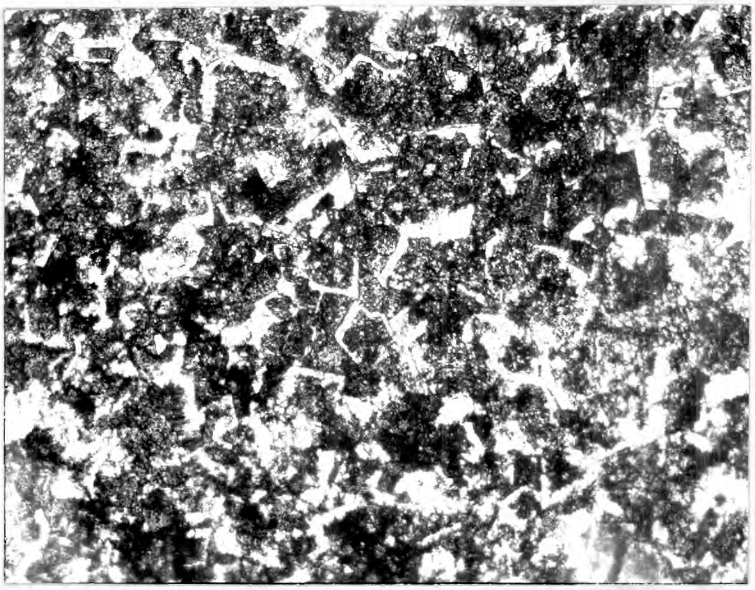


FIG. 47. Partially dedolomitised rock, showing relics of dolomite rhombs. The calcite has been stained with silver chromate. Lower Parves Beds, Rossillion (x25).

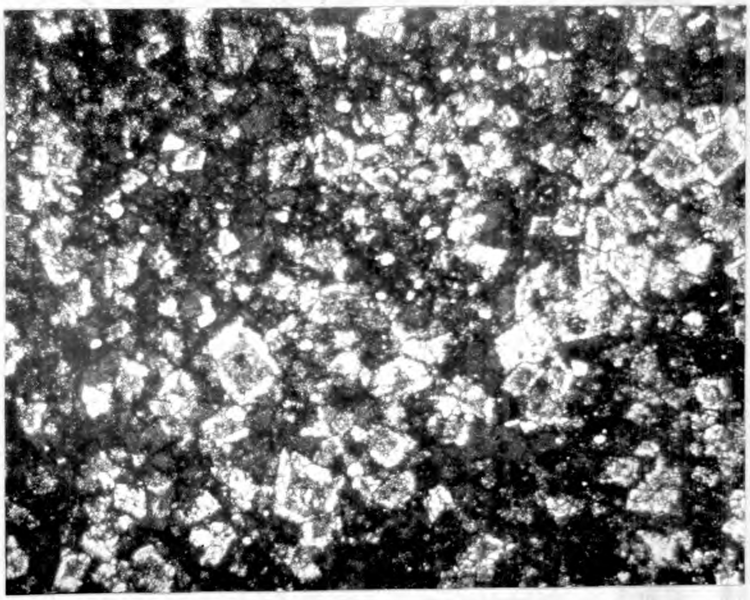


FIG. 48. Partially dedolomitised rhombs, showing cores of microcrystalline calcite. The calcite has been stained with silver chromate. Lower Parves Beds, La Balme gorge (x25).

random. In these, irregular inclusions, of calcite are scattered throughout the rhombs and the rhomb boundaries show a considerable amount of corrosion.

It would appear, therefore, that dedolomitisation may take place either centripetally, centrifugally, along certain selected zones or even apparently at random.

5. Fully Dedolomitised Carbonate Rocks

Fully dedolomitised rocks can be subdivided into two main groups on the basis of the texture of the calcite replacement mosaic:

(i) Dedolomitised rocks in which the dolomite has been replaced by a finer-grained calcite mosaic and

(ii) Dedolomitised rocks in which the dolomite has been replaced by a coarser grained calcite mosaic.

Each of these groups will be described in turn.

(i) Dedolomitised rocks in which the dolomite has been replaced by a finer-grained mosaic of calcite.

The dolomite in this group is usually replaced by a

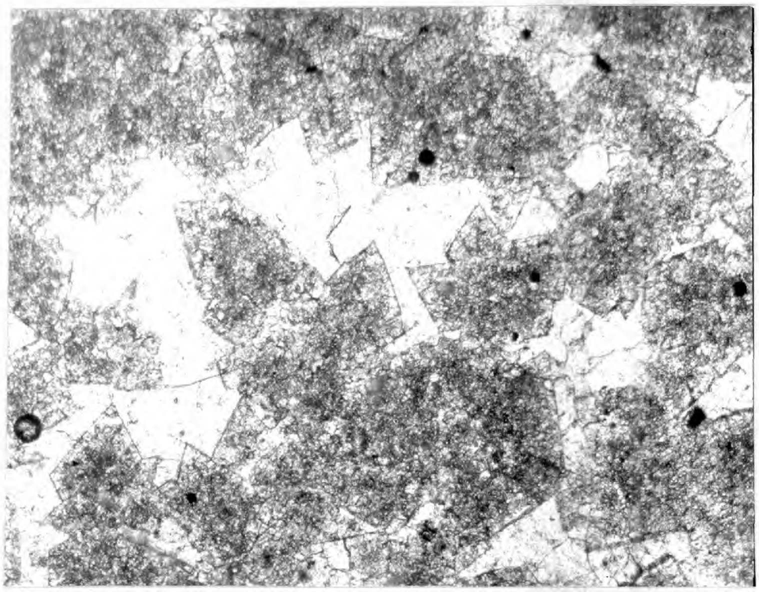


FIG. 49. Fully dedolomitised rock, consisting of microcrystalline replacement calcite and coarse-grained sparry calite. Upper Virieu Limestone, Chanaz (x40).

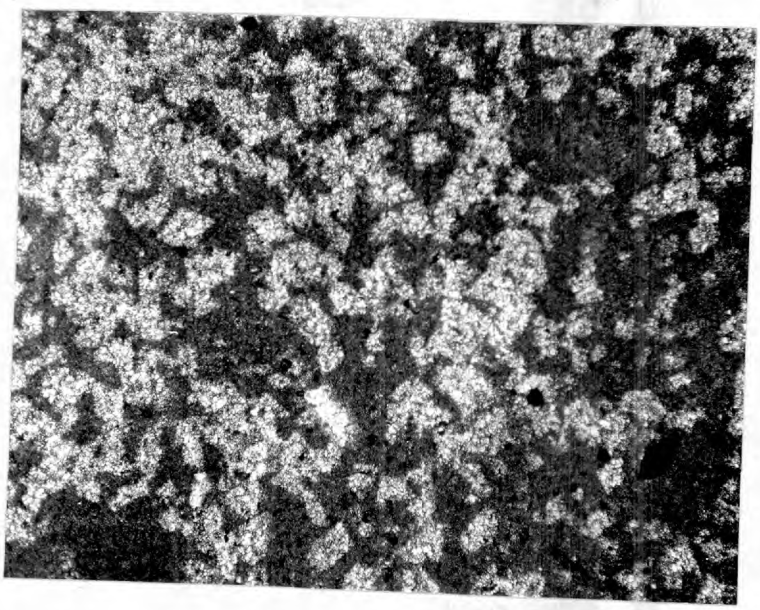


FIG. 50. Fully dedolomitised rock, consisting of rhombs of microcrystalline calcite and a cryptocrystalline calcite groundmass. la Balme gorge (x30)

granular mosaic of microcrystalline calcite (see Fig. 50) which can be clearly differentiated from the cryptocrystalline goundmass. In those dolomitised calcilutites in which the distribution of dolomite was patchy, with the dolomite crystals aggregated into a system of clots and stringers, dedolomitisation produced a rock with a texture which superficially resembles structure grumeleuse.

Several examples of dedolomitised dolomitic calcarenites have been found. The original sediments includes both bahamites and bioclastic bahamites. It has been stated in the previous chapter that dolomitisation appears to be a selective process, and that in dolomitised calcarenites dolomite rhombs occur mainly in the groundmass or replace bahamiths. In those rocks in which the rhombs are embedded in a groundmass which consists of relatively coarse-grained sparry calcite, the rhombs have been replaced by calcite of similar particle size and texture to that of the surrounding groundmass. In specimens in which the groundmass is essentially cryptocrystalline calcite, the replacement calcite is microcrystalline, i.e. slightly coarser-grained. Furthermore, some specimens have been found in which all these features are displayed in a single rhomb. In these specimens, ghosts rhombs cut across bahamiths, sparry calcite and secondary overgrowths on echinoderm fragments. Any one of these rhombs is seen to consist of three types of calcite mosaic. That part of a rhomb which cuts across bahamiths is essentially microcrystalline. That part which is surrounded by sparry calcite of the cement shows a coarse-grained calcite mosaic, and the remaining part of the rhomb is in optical continuity with the secondary overgrowth. These observations suggest that dedolomitisation tends to regenerate the pre-dolomitisation texture of the limestone.

Where dolomites have been replaced by calcite two textural types have been observed. In one, the dolomite has been replaced by an essentially equigranular calcite mosaic. In the other, the individual rhombs show a core of microcrystalline calcite surrounded by a rhombic zone of coarser-grained calcite (see Fig. 41A).

Dedolomitised carbonate sediments in which the original rock consisted of a mutually interferring grains of dolomite show relatively more complex textures. However, if the grains in these rocks are replaced by microcrystalline calcite surrounded by a zone of coarser-grained calcite, the ghost structure of the original dolomite can be detected (Fig. 44). These rocks usually show occasional ghost rhombs.

Examples of "mottled limestones" have been found in which the dolomite has been partially replaced by calcite. Fig. 43A is a photograph of a part of a mottled limestone and illustrates the junction between dolomite and calcilutite. Some specimens collected from the same mass of mottled limestone are megascopically identical with that described above, but in thin section they are seen to consist entirely of calcite. Fig. 43A illustrates the junction between a calcilutite and a limestone after dolomite of one of these specimens. The replacement textures in this rock and that illustrated in Fig. 44 may superficially resemble that of a grain-growth mosaic (Bathurst 1958), the presence of occasional composite calcite rhombs and their comparison with the textures of dolomites collected from the unreplaced dolomite mass, however, leaves no doubt that they have resulted from dedolomitisation.

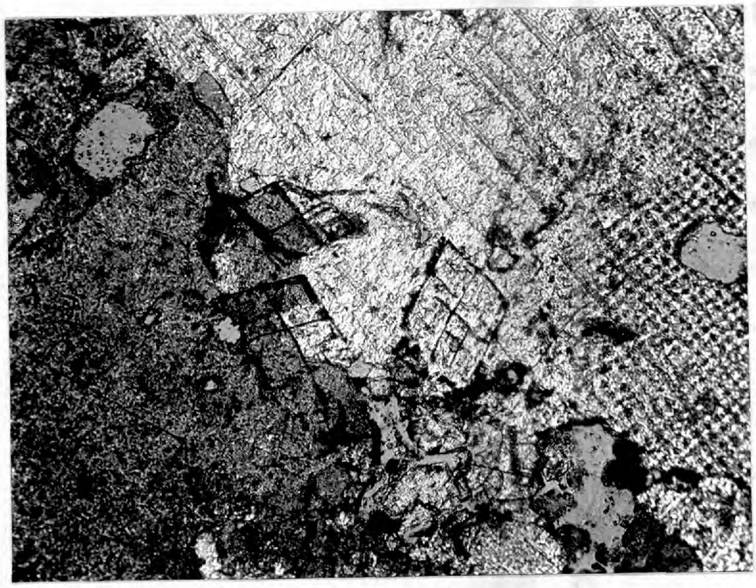


FIG. 51. Echinoderm calcarenite with rhombs in the secondary overgrowth shown up by ferric oxide staining. Lower Bourdeau Beds, near Bourdeau (x75).

(ii) <u>Dedolomitised rocks in which the dolomite has been replaced by coarser-grained calcite.</u>

This group can be conveniently subdivided into two main types. The one has resulted from the dedolomitisation of dolomitic limestones, and the other has resulted from the dedolomitisation of dolomites.

(a) Replacement of dolomitic limestones by calcite which is coarser-grained than the dolomite rhombs has been observed only in echinoderm calcarenites. In these, rhombic zones of ferric oxide occur within the calcite of the secondary overgrowth (Fig. 51). These ferric oxide zones resemble the zones which often occur within dolomite rhombs; they are interpreted as being ghosts of former dolomite crystals which have been replaced by calcite. Where these zones of ferric oxide occur within the calcite overgrowths on echinoderm debris, the calcite is crystallographically continuous across the overgrowth and the included rhomb. Locally, the rhombic zones lie across the boundary between two secondary overgrowths; the boundary passes unbroken across them. A thin section of this rock was treated with very dilute hydrochloric acid and potassium ferricyanide to test for the distribution of ferrous iron in the calcite. The calcite of each echinoderm fragment, the overgrowth on those fragments and the included rhombs, although all single crystals of calcite, stained differentially. The calcite of the echinoderm fragment took a faint irregular blue stain; the overgrowth stained strongly blue; but the calcite enclosed within the rhombic zones of ferric oxide remained unstained. What is more, outside the ferric oxide zones there remained a narrow rhombic zone of unstained calcite. This differentiation of iron-rich and iron-poor calcite helps to elucidate the diagenetic history of the rock. The first phase was the development of iron-rich overgrowths on and in lattice continuity with the calcite of the detrital echinoderm fragments. The rock was subsequently dolomitised, and scattered dolomite rhombs locally replaced the calcite of the overgrowths. Later, the process of dedolomitisation replaced the dolomite by an essentially iron free-calcite. The limits of the earlier dolomite rhombs are marked by the boundaries between the stained and unstained calcite, and the zones of ferric oxides represent

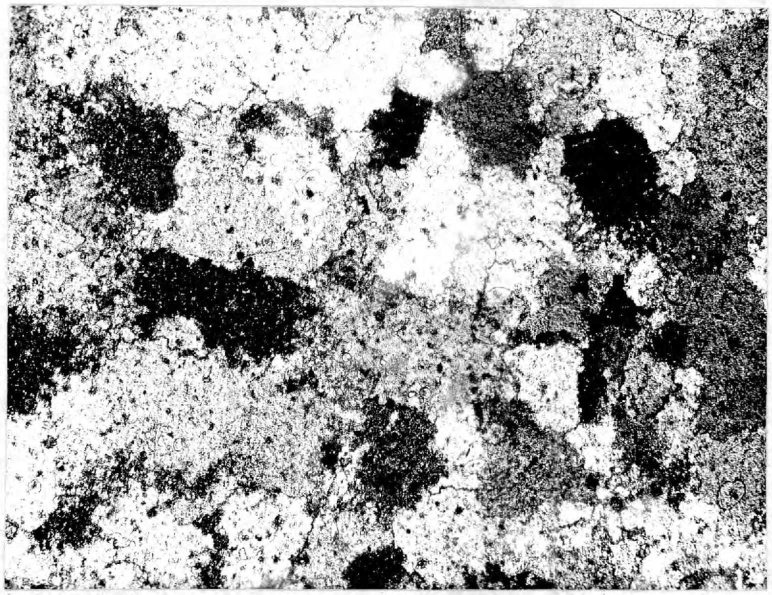


FIG. 52. Fully dedolomitised rock, consisting of a coarse-grained calcite mosaic which shows ghost texture of a finer-grained dolomite mosaic. Lower Parves Beds, Rossillion (x45)

zones within the original dolomite.

(b) True dolomites replaced by calcite also occur (see Fig. 52).

It has been mentioned in previous chapters that some rocks occur in which granular aggregates of dolomite crystals are poikilitically enclosed within larger crystals of calcite. In these rocks some grains of dolomite show sharp clear crystal boundaries, and the dolomite has not been modified in any way. However, several examples have been found in which the boundaries of the dolomite crystals are irregular in outline and are embayed by the enclosing calcite crystals in a manner suggesting replacement. If this process of replacement by poikilitic calcite were to go to completion, the resultant limestone would be an equigranual coarse-grained calcite rock. In such rocks the grain boundaries of the earlier dolomite mosaics are outlined by ferric oxide staining. In a variant of this type of dedolomitisation texture, the calcite crystals are optically clear and free from inclusions. The author interprets this limestone as a dedolomitised rock in which the outlines of the earlier dolomite grains boundaries are not preserved as a palimpsest texture. In both types, the grain boundaries are complex, and in thin section these rocks have the general features of metamorphosed limestone, and they appear strangely out of place in a normal sedimentary sequence.

6. The Origin of Dedolomitised Rocks

The author has already drawn attention to the fact that in many rocks, dedolomitisation tends to regenerate the pre-dolomitisation texture of the rock. It is possible that when a limestone is dolomitised, submicroscopic relics of the original calcite may remain unreplaced within the dolomite crystals. During dedolomitisation these inclusions would act as nuclei about which the replacement calcite would be orientated. The textures of many of the dedolomitised rocks can be explained on the basis of this suggestion. Thus in dolomitised calcilutites minute relics of calcite within the dolomite rhombs would show random orientations, so that on dedolomitisation these might give rise to microcrystalline calcite mosaics. In the calcarenites, when replacement by dolomite occurs in the overgrowth on an echinoderm fragment, the calcite relics which remain in the dolomite will all have the same lattice orientation. On dedolomitisation, these inclusions would therefore tend to regenerate a lattice in continuity with the secondary overgrowths.

It has already been mentioned, that Von Morlot (1848) suggested that dedolomitisation could be caused by calcium sulphate solutions..

Tatarski (1949), disucssing the occurrence of dedolomitised rocks in Russia, observed that dedolomitisation is always a near surface phenomonon, and that bore hole samples do not show evidence of dedolomitisation at depth. He believed that the process resulted from superficial gypsiferous solutions as suggested by Von Morlot. Khvorova (1958) attributed the dedolomitisation of the Carboniferous rocks of the Russian platform to the action of salts washed out from Lower Permian rocks.

If gypsiferous solutions were the cause of dedolomitisation in the Jura they could have been derived from any of three sources: (a) From above; during or after the deposition of the Tertiary sediments, (b) From within; from the Lower Parves Beds which show some evidence of the former existence of evaporites, or (c) From below: from the underlying evaporites of the Triassic sediments.

The possible existence of two generations of dolomite would suggest that the magnesium liberated during dedolomitisation may have caused a second phase of dolomitisation in the Jura.

Furthermore, the presence of extensively dedolomitised horizons, together with others which show little dedolomitisation, throughout a significant part of the Southern Jura, would suggest that other factors may have been important. However, further speculations on the possible mode of origin should be reserved until the field relations of these rocks are better known.

PART III

CHAPTER 12

SYSTEMATIC PETROGRAPHIC DESCRIPTIONS AND CONCLUSIONS

In this part of the thesis a brief general description will be given on each formation in the Mesozoic succession of the area. An attempt will be made to correlate the field and the petrographic evidence in order to deduce the possible depositional environment.

1. The Lucey Beds

(a) Petrography The Lower Lucey Beds consist essentially of bioclastic calcarenites. The major components include echinoderm fragments and polyzoa. Fragments of lamellibranchs and brachiopods are relatively less abundant. These bioclastic calcarenites are commonly cemented by overgrowth and/or with granular calcite mosaic. They range in grain size from medium to very coarse. Polymodal particle size distributions are not uncommon. The arenaceous layers in the Lower Lucey Beds are often laminated. This lamination is due to variation in the relative abundence of quartz grains in successive laminae.

The Middle Lucey Beds are mainly fine-grained bioclastic calcarenites. They consist essentially of two components, i.e. cryptocrystalline ovoid pellets and echinoderm fragments. These rocks are almost equigranular; the grain size of their components commonly ranges from 100 to 250 microns. They are usually cemented by overgrowth. The sandy partings in the Middle Lucey comprise up to 25% detrital quartz grains. These quartz grains, together with subordinate ammounts of felspar, are embedded in an calcareous groundmass strongly stained with limonite. The iron oxide stain makes the determination of the carbonate material rather difficult, if not impossible. The sand grains are subangular to sub-rounded and often contain numerous inclusions of apatite. The petrography of chert modules in the Middle Lucey has been already described in Chapter 9. The specimens studied suggest that at least some of the chert nodules have originated by the replacement of fine-grained bioclastic calcarenites.

The Upper Lucey calcarenites are petrographically similar to those of the Lower Lucey. Composite grains are, however, relatively more important while polyzoa are rather rare in these calcarenites.

(b) Depositional environment. The following criteria are important in connection with the depositional environment of the Lucey Beds:

1. In the field the Lower and Upper Lucey consist essentially of coarse-grained, current-bedded calcarenites, while the Middle Lucey comprise mainly fine-grained calcarenites with cherts.

2. Terrigenous matter occurs as arenaceous layers interbedded with the bioclastic calcarenites in the Lower and the basal part of the Middle Lucey Beds. They are virtually absent from the rest of the formation.

3. Further west in Bugey, a coralline facies occurs in the Lucey Beds. This facies thins out in an easterly direction, while the overlying cherty horizons appear to thicken in

the same direction. This facies is absent from the area studied and it has probably been replaced by the fine-grained calcarenites with cherts, which constitute the Middle Lucey Beds in this area.

4. Petrographically the sediments consist essentially of bioclastic clean-washed calcarenites in which echinoderm fragments predominate. At some horizons polycrystalline skeletal debris, especially that of polyzoa, become important.

5. The majority of cherts appear to be post-depositional, and have resulted from the replacement of the fine-grained bioclastic limestones.

6. The depositional components are well rounded and fairly well sorted.

It can be inferred from (1) and (4) that the Lucey Beds were deposited in a shallow water environment. This evidence further indicates strong current and wave action. During the deposition of the Lower Lucey and the basal part of the Middle Lucey Beds it appears that neighbouring land areas supplied greater amounts of sand than clay matter. During the deposition of the rest of the Lucey Beds, there must have been an appreciable decline in the supply of terrigenous matter.

In Lucey time a reef must have existed throughout most of Bugey. The fauna, which includes corals, presumably indicates warm clear waters. Reef corals usually flourish in waters less than 30 metres deep. Carozzi (1954) suggested a limit of 5 to 15 metres for the reef limestones of Grand-Saleve. Thus a tentative suggestion for the depth of water in the west of the area is from 15 to 20 metres. Between Lac du Bourget and the Rhone, fine-grained bioclastic sediments were probably deposited alongside the reef which formed further west. It is perhaps significant that current-bedding is virtually absent from these fine-grained calcarenites, although it is well developed throughout the rest of the formation. This would suggest that relatively quieter waters must have prevailed during the deposition of the Middle Lucey Beds, which could be related to the existence of a reef immediately to the west.

Although most of the cherts appear to be post-depositional, more extensive petrographic study is needed before it can be ascertained whether or not the beds in which replacement took place were originally rich in sponge spicules and other siliceous organisms. However, the arenaceous layers of the Lower and Middle Lucey Beds may be considered as a possible source of silica.

The depositional environment of the Upper Lucey Beds must have been similar to that of the Lower Lucey, but as stated earlier, relatively small amounts of terrigenous matter, especially sand, must have been supplied from neighbouring land areas.

2. <u>The Chanaz Beds</u>

(a) <u>Petrography</u>. The Chanaz Beds present a rather significant petrographic feature which distinguished them from the Lucey Beds i.e. the presence of a calcilutitic groundmass throughout the whole of this formation. In this feature they contrast with the clean-washed bioclastic calcarenites of the Lucey Beds. The presence of fine-grained shell fragments and the heterogenous character of this groundmass suggests that it has originated mainly by a mechanical, breakdown of the skeletal debris.

The Lower Chanaz Beds comprise essentially fine-grained calcarenites and marls. In the former, the sand-size components include pellets, ranging from 80 to 120 microns in size, and skeletal fragments. Among the skeletal debris only echinoderm fragments could be determined. The pellets and the skeletal fragments are embedded in a dark grey groundmass of microcrystalline or cryptocrystalline calcite. The dark grey colour of the groundmass is probably due to admixture with clay matter.

The Middle Chanaz Beds consist essentially of coarse-grained bioclastic calcarenites. The major components include polycrystalline skeletal fragments, particularly brachiopods, monocrystalline skeletal fragments and composite grains in that order of importance. These sand-size components are embedded in a dark cryptocrystalline matrix. The composite grains form a coarser fraction with particle sizes up to 2 mm. Unlike other calcareous grains they are heavily stained with limonite. These characters suggest that they have originated elsewhere in the basin of deposition. Unlike the coarse calcarenites of the Lucéy Beds, the skeletal fragments in the Middle Chanaz are subangular and commonly ill-sorted.

The Upper Chanaz Beds (C4, Fig. 3) consist of fine-grained calcarenites similar to those of the Lower Chanaz. They differ, however, in that pellets are subordinate to skeletal debris, and also in the presence of minor amounts of sponge spicules and pyrite. Both field and microscopic evidence suggests that the irregular chert nodules which occur in this division originated by replacement.

(b) Depositional environment. Evidence in connection with the depositional environment of the Chanaz Beds includes the following:

1. The passage from the current-bedded clean-washed calcarenites of the Upper Lucey to the fine-grained limestones and marls of the Lower Chanaz is rather abrupt.

2. The marly horizons which frequently occur in the Middle Chanaz Beds are extremely rich in well preserved fossils These include brachiopods, lamellibranchs, echinoids and ammonites. Among these fossils brachiopods commonly predominate.

3. The highest beds of the Upper Chanaz are highly ferruginous, and extremely rich in well-preserved ammonites and brachiopods.

4. Except for the coarse-grained calcarenites of the Middle Chanaz, the main part of this formation is fine-grained.

The sand-size components include ovoid pellets (probably faecal pellets) and skeletal debris. These components are invariably embedded in a calcilutitic groundmass. The skeletal fragments are commonly ill-sorted and have suffered little abrasion.

5. The terrigenous matter consists essentially of clay. In the calcarenites, the clay matter is probably admixed with the calcilutitic groundmass.

Points (1) and (4) indicate a sudden incurring of quiet water sedimentation which prevailed throughout the deposition of virtually the whole formation. At times (points 2 and 3) the amount of sediment accumulating must have been very small, thus reflecting the stability of the sea floor.

Recent work on present day carbonate sedimentation (Houbolt 1957, Illing 1954) shows that fine or coarse-grained carbonate sediment, with calcilutitic groundmass, usually accumulates in the quiet-water and sheltered areas of the shallow banks. Quiet-water sedimentation does not necessarily indicate a greater depth of water.

3. The Chavoley Beds

(a) Petrography. Time did not allow for a detailed laboratory study to be made of this formation. Thin sections of specimens collected at random suggest that the limestones consist essentially of cryptocrystalline, calcite mixed with various proportions of clay matter. Many specimens examined are speckled with iron oxide. The latter together with the terrigenous material are probably responsible for the brown colour observed in thin section.

(b) Depositional environment. The relevant evidence regarding the depositional environment of the Chavoley Beds is summarised below:

1. The Chavoley Beds consist essentially of alternations of marls and calcilutites, with marls predominating in the middle part of the formation.
2. The formation is relatively rich in well-preserved macrofossils. Among these, ammonites are the most abundent and appear to be concentrated in certain horizons.
3. Petrographically the formation appears to consist of

fine-grained calcilutites.

The evidence briefly outlined above suggests deposition in quiet-water environment. It is possible as suggested earlier for fine-grained carbonate sediments to accumulate in the sheltered quiet-water areas of shallow banks on which carbonate sedimentation is taking place. Such a mode of origin is probable in those instances where relatively thin calcilutites are interbedded with coarser grained carbonate sediments, and facies changes would be expected to occur over relatively short distances. However, for such a thick succession (about 200 metres) as the Chavoley Beds to be deposited in a shallow water environment it would require a delicate balance between subsidence and the rate of sediment accumulation. This formation shows fairly uniform lithologies in the area studied by the author and over much of Bugey. Other workers also recorded similar lithologies from adjacent parts of the southern Jura. It is therefore more probable that a slight deepening of the basin of sedimentation has taken place. This suggestion is further supported to some extent by the faunal assemblage. Assuming that the supply of terrigenous matter was constant, such a deepening might have been accompanied by a general decline in the deposition of carbonates and their replacement by marls.

4. <u>The Oignon Limestone</u>

(a) <u>Petrography.</u> As with the previous formation, no detailed laboratory studies were made of the limestones and thin marl partings of the Oignon Limestone. However, thin sections cut of some specimens from the limestones show an equigranular texture of cryptocrystalline calcite with occasional small cavities. Specimens collected from the pisolitic facies in the western extremity of Bugey near Luis, show pisoliths up to 2 cm in size. Many of these pisoliths are flattened and slightly concave-convex, and the majority have nuclei of polycrystalline skeletal fragments. It appears that the shape of many of the pisoliths has been partly determined by the shape of their nuclei. The flattened and slightly concave-convex pisoliths, for instance, often show concentric layers parallel to nuclei of concave-convex skeletal fragments. Some pisoliths have nuclei of optically clear calcite mosaics, comparable to the drusy mosaic described by

Bathurst (1958). Such pisoliths probably originally had nuclei of aragonitic skeletal fragments which were subsequently dissolved and the resultant cavities were subsequently filled with secondary calcite.

The groundmass of the pisolite has been extensively dolomitised. However, ghosts of skeletal fragments mainly those of brachiopods and molluscs, together with remnants of calcilute can still be recognised. It appears that the majority of the pisoliths have escaped dolomitisation.

<u>Depositional environment</u>. The following evidence is significant in connection with depositional environment of the Oignon Limestone:

1. The formation consists of a rhythmic alternation of shales and well-bedded calcilutites, except at the top where a pisolitic facies occurs.
2. The pisolite facies extends over much of Bugey, but thins out in a south-easterly direction and is absent from the area between Lac du Bourget and the Rhone.
3. Fossils are relatively rare, but when present they are usually well preserved.

4. The limestones consist essentially of fine-grained calcilutites.

The Oignon Limestone marks a phase of rhythmic sedimentation which becomes a dominent feature of many of the overlying formations. The relatively thin shales might represent the same length of time as the interbedded calcilutites but with impoverished carbonate deposition. Apart from a net increase in carbonate matter and a marked decrease in fauna, the sediments of the Oignon Limestone are essentially similar to those of the Chavoley Beds. The pisolite which occurs at the top of the Oignon Limestone over much of Bugey indicates that deposition above the wave base was probably re-established at the end of the Oignon times. South eastwards however, on approaching the sub-alpine domain, the deposition of fine-grained calcilutites must have continued since the pisolite is absent from the area between Lac du Bourget and the Rhone. Dreyfuss (1954) envisaged a reduced rate of subsidence in the whole of the Jura and the prevalence of water depths of 60 to 70 metres during the deposition of this formation.

5. The Virieu Limestone

(a) Petrography. The Lower Virieu Limestone, which is seen in the field to consist essentially of calcilutite, has not been studied in thin section. Specimens collected by S. Taha from the neighbourhood of Virieu-le-Grand comprise mainly fine-grained calcilutite with various proportions of skeletal debris. The basal part comprises medium-grained dolomites which have been extensively dedolomitised. Dolomitisation and subsequent replacement by calcite has destroyed most of the depositional characters of the basal part of the Upper Virieu. Those parts which escaped dolomitisation consist essentially of calcilutite with some scattered skeletal fragments. The petrography of the dolomites has been described earlier (see Chapter 10).

The higher parts of the Upper Virieu Limestone consist predominantly of calcilutites with considerable proportions of bioclastic mosaic pseudomorphs. These probably represent what were originally aragonitic lamellibranchs and coral fragments. Other components which form minor constituents are calcareous algae, brachiopods and echinoderm fragments. Most specimens from the Upper Virieu contain some scattered composite rhombs of calcite mosaic. Pellet calcarenites, mainly bahamites occur especially near the top of the Upper Virieu. These bahamites are commonly cemented with granular mosaics. Some consist of pellets embedded in a predominantly calcilutitic groundmass.

(b) Depositional environment. The field and laboratory evidence which is important in connection with conditions of deposition of the Virieu Limestone can be summarised as follows:

1. Except for some 40 metres at the base, the Virieu Limestone is essentially massive and frequently unstratified.
2. The formation is richly fossiliferous. The fossils include calcareous algae, lamellibranchs and corals. The latter appear to be often in the position of growth.
3. Some intraformational conglomerates or breccias occur locally (e.g. at Chanaz).
4. The Virieu Limestone shows a considerable variation in thickness, even within the limits of the area studied by the author.
5. Petrographically, the formation consist essentially of calcilutite mixed with various proportions of skeletal

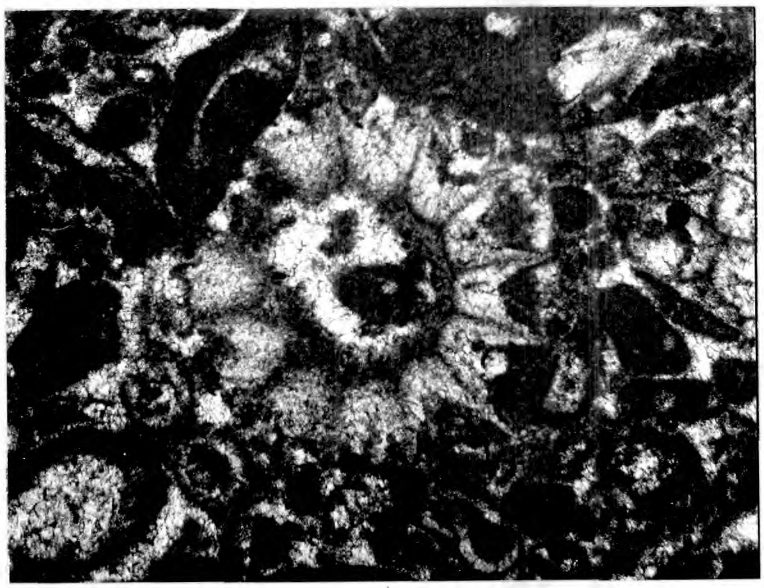


FIG. 53. Clypeina jurassica Favre. Lower Parves Beds, La Balme gorge (x50)

debris, and some subordinate bahamites occur, especially near the top. These limestones have been dolomitised to various degrees and in part subsequently dedolomitised.

It has already been pointed out that, towards the west of the area, a shallow-water environment was re-established over much of Bugey at the end of the Oignon times. The breccias observed locally at the base of the Virieu Limestone reflect the instability of the sea floor at the beginning of Virieu times. During the deposition of the Virieu Limestone both field and laboratory evidence suggests that a shallow-water environment was re-established over much of the southern Jura. However, corals and dasyclad algae became abundant only in the Upper Virieu Limestone. This would suggest that the shallowing of the sea floor must have been a gradual and progressive process. The corals and dasyclad algae indicate clear and presumably warm shallow waters, and the presence of some clean-washed bahamites would suggest that relatively strong current action must have prevailed at times. At Nantua, Riche (1893) estimated a depth of water of 70 to 160 metres for this formation. The base of modern reefs ranges from about 7 to 18 metres whilst at Bikini atoll corals rapidly disappear below a depth of 82 metres.

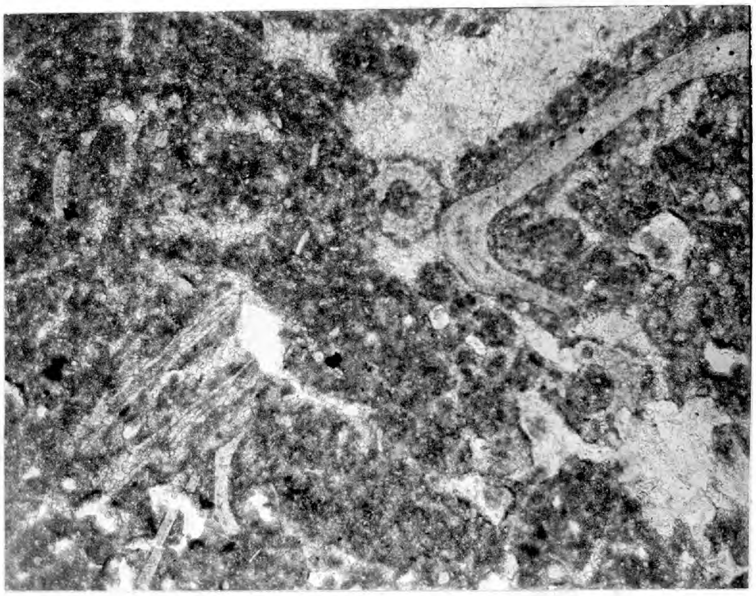


FIG. 54. *Clavator reidi* Groves. Lower Parves Beds (Upper division), La Balme gorge (x45).

Dasyclad algae exist today in depths of water between 30 and 60 metres. It would appear therefore that a maximum depth of 60 metres, and probably much shallower at times must have prevailed throughout much of Viriou times.

6(A) The Lower Parves Beds

In this section, the field evidence concerning the Lower Parves Beds at la Balme gorge, has been combined with the petrographic studies to give a somewhat detailed succession of this division. It was only after the latter study was carried out in the laboratory, that the field succession became intelligible. For this reason the latter was excluded from Chapter (3) on the Mesozoic succession.

The reappearence of stratification is taken as marking the base of the Lower Parves Beds. However, some 30 metres of the basal beds, although stratified, are poorly exposed, and these have been excluded from the table given on page These beds appear to consist mainly of pale grey calcilutites.

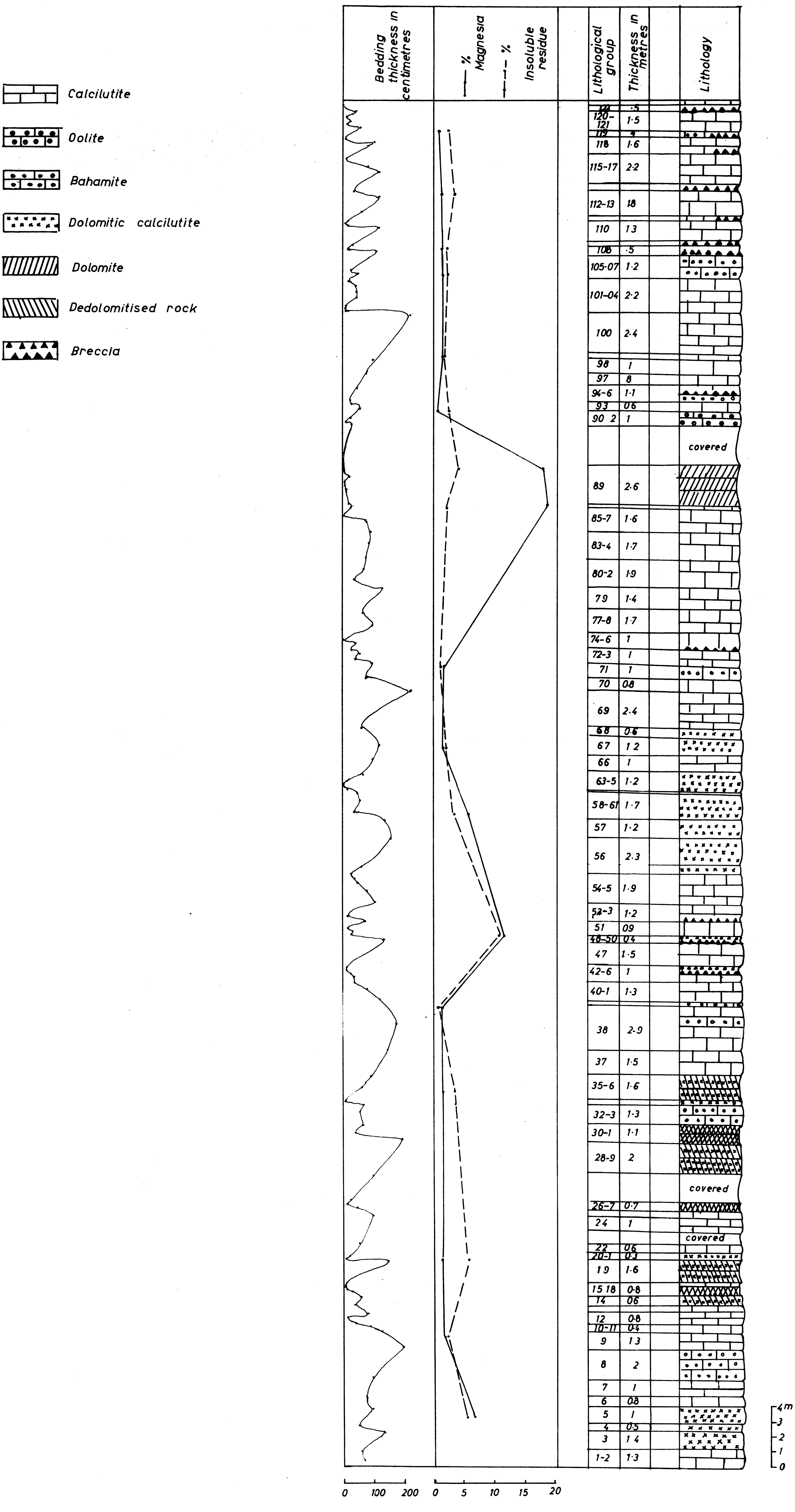


FIG.55. VERTICAL VARIATIONS IN LITHOLOGY AND COMPOSITION IN THE LOWER PARVES BEDS.

TABLE 3.

The Succession of the Lower Parves Beds (Fig. 55)

1,2.	Pale grey calcilutite.
3.	Laminated dolomitic calcilutite; alternation of laminae rich and poor in dolomite.
4.	Calcitic dolomite.
5.	Laminated dolomitic calcilutite.
6,7.	Pale grey calcilutite, with stylolites which merge into one another.
8.	Bahamite, cemented with sparry calcite; with *Acicularia* sp. and *Clypeina jurassia* Favre.
9,10.	Calcilutitic bahamite, with composite calcite rhombs associated with sstylolites, with textularids, miliolids, *Actinoporella podolica* Alth. and *Clypeina jurassica* Favre.
11-13.	Yellowish grey calcilutite.
14.	Pinkish grey dedolomitised dolomitic calcilutite; texture superficially resembling "texture grumeleuse" of Cayeux (1936).
15.	Reddish brown very fine-grained dolomite; replaced by coarser-grained calcite mosaic.

16. Reddish-brown microcrystalline dolomite replaced by coarser brained calcite, alternating with clay partings.

17,18. Yellowish grey calcilutite.

19. Brown dedolomitised dolomitic calcilutite.

20.21. Reddish-brown dolomitic calcilutite partially replaced by calcite.

22,23. Brown calcilutite.

24,25. Whitish-grey calcilutite.

26,27. Pinkish-grey dedolomitised dolomite.

28,29. Whitish-grey dedolomitised dolomitic bahamite, with *Acicularia* sp., milliolids, textularids, and *Clavator grovesi* Harris.

30.31. Brown dedolomitised dolomite.

32,33. Light grey bahamite.

34. Pale brown dolomitic calcilutite with zoned dolomite rhombs.

35,36. Dedolomitised dolomitic calcilutite with stylolites and marly partings.

37. Pale grey calcilutite.

38. Pale grey calcilutite with some calcilutitic pellet calcarenites.

39. Coarse-grained bahamite with small gastropods.

40,41. Brown dolomitic calcilutite.

42. Pale grey calcilutite.

43. Breccia, with pale grey fragments of calcilutite and a dolomitic matrix.

44. Brown dolomitic calcilutite.

45. Breccia, with pale grey and blackish fragments of calcilutite, passing laterally into marl.

46,47 Pale grey calcilutite.

48. Breccia, with light grey and dark grey calcilutitic fragments and a dolomitic matrix; resting on an eroded surface.

49. Laminated dolomitic calcilutite.

50. Breccia, with light grey fragments of calcilutite passing laterally into marl.

51. Laminated dolomitic calcilutite.

52. Breccia, with light grey and blackish calcilutitic fragments and a dolomitic matrix.

53-55. Pale grey calcilutite with stylolites.

56-61 Dolomitic calcilutite with Clypeina parvula Cavoozzi.

62. Pale grey calcilutite.

63-65. Laminated dolomitic calcilutite.

66. Pale grey calcilutite.

67. Dolomitic calcilutite with miliolid and Clavator sp.

68. Brown dolomitic calcilutite.

69. Pale grey calcilutite with miliolids and Clavator sp.

70. Pale grey calcilutite with stylolites.

71. White calcilutite, bahamitic at the top and with Clypeina jurassica Favre, Actinoporella podolica Alth. and Clavator reidi Groves.

72,73. Pale grey calcilutite.

74. Pale-grey calcilutite with fine-grained breccia at the base.

75-79 Pale grey calcilutite.

80-87. Whitish grey calcilutite with stylolites near the top and bottom of each bed.

88. Pale grey calcilutitic bahamite, with miliolids and Actinoporella podolica Alth.

89. Brown fine-grained laminated dolomites.

90-92 Pale grey oolite, with Clypeina parvula Cavozzi.

93. Brownish-grey argillaceous calcilutite.

94. Fine-grained bahamite.

95. Brecciated limestone.

96-100 Pale grey calcilutite.

101-104 Pale grey calcilutite interbedded with marls and calcilutitic pellet calcarenite, with miliolids and *Actinoporella podolica* Alth.

105,106. Pale grey bahamite.

107 Breccia, with light grey and blackish fragments of calcilutite, with *Clavator reidi* Groves

108,109. Breccia, with pale grey and dark grey calcilutitic pebbles, resting on an eroded and channelled surface.

110-111 Brown calcilutite, brecciated in parts.

112,113 Dark grey calcilutite with stylolites.

114. Breccia, with light grey fragments of calcilutite, overlain by a shaly bed.

115-117. Pale grey calcilutite.

118. Argillaceous calcilutite, brecciated in parts.

119. Bahamite, partly brecciated, with miliolids, textularids, *Acicularia* sp. *Clypeina* sp. and *Actinoporella poddica* Alth.

120. Pale grey calcilutite.

122 Breccia, with pale grey gragments, resting on an eroded surface and overlain by shale.

123. Pale grey calcilutite.

As stated in Chapter (3), two lithological groups could be recognised; (i) a lower division without breccias and (ii) an upper division with breccias. Each of these will be described in turn.

(i) Lower Division. The succession in this sub-division is presented in table (3) and figure 55. An inspection of the table shows that certain lithological groups are often repeated in an orderly manner. The main rock types that occur in the succession can be grouped as follows:

a. Dolomite or dedolomitised dolomite.

b. Dolomitic calcilutite or its dedolomitised equivalents.

c. Calcilutite or calcilutitic bahamite.

d. Bahamite.

Beds 1 to 27 show the following sequence: cb, cd, cba, cb, ca. With the exception of one bed therefore (no. 8), the succession consists up to this level of a rhythmic alternation of calcilutite and dolomitic calcilutite or dolomite. Higher up in the succession (beds 30 to 31) the sequence; a, dbc, db show that at these levels the clean-washed bahamites become important.

(ii) Upper division. In addition to the rock types a, b, c, d breccias occur in this sub-division. This additional type can be referred to "e". The succession begins with the sequences (beds 42 to 52) ce, be, ce, be, bc; which is essentially an alternation of breccias with calcilutites. This is followed by the sequence cb, cb, cb, bc, (beds 53 to 70). The highest breccia beds (Fig. 55) are preceded by the sequence cd, ce, cd, cd (beds 71 to 94) which appart from a local brecciation is characterised by the occurrence of clean-washed bahamites. This can be compared with the sequence which preceded the first group of breccias. Thus it appears that bahamites become important just before the appearance of breccias in the succession. The highest sequence ecd, ec, ec, ec, edc, ec; differs only from the breccia sequence above in the absence of dolomitic limestones.

The significance of these rhythmic alternation become clearer when the rock types are related to some variable which can be determined, in the limestones. The insoluble residues, for instance, are useful for this purpose. Inspection of table (2) and figure (55) would suggest that dolomitic and dedolomitised carbonate rocks carry a relatively higher amount of insoluble residues than dolomite-free limestones. Favre and Richard (1927) pointed out that dolomites which occur in this formation are generally richer in detrital quartz than the dolomitic limestones. Thus it appears that the sequence a b c d indicates a gradual impoverishment in the amount of terriginous matter.

Depositional environment. Rhythmic fluctuations in the amount of terrigenous material must have taken place during the deposition of the basal part of the Lower Parves Beds. Such fluctuations could be due to periodic changes in carbonate deposition. The frequent occurrence of fresh water fossils, however, especially towards the top of the Lower Parves Beds suggests that vertical oscillations of the sea floor, and probably some corresponding movements of neighbouring land areas were responsible for these fluctuations. This is similar to the conclusion reached by Favre and Richard (1927) after a consideration of various lines of evidence regarding the origin of breccias which occur in the upper part of the succession.

One of the major difficulties regarding the origin of the breccias occurring in the Lower Parves Beds is the presence in them of blackish fragments of limestones which cannot be matched with any of the known limestones of the Mesozoic succession. To account for these fragments Carrozzi (1948) postulated emergent islands, covered with lucustrine sapropels, in the Swiss Jura during the Purbeckian times. Donze (1958) pointed out that the black colouration of these fragments is due to the presence in them of hydrocarbons.

The beds underlying some of the breccias in the Lower Parves Beds of la Balme gorge show black mottling without being brecciated. This would suggest that some of the Lower Parves carbonate sediments might have been blackened prior to their brecciation. It is possible that reducing conditions, which could have prevailed in parts of the lagoons which must have existed at times, inhibited the oxidation of organic matter.

Two of the most significant features of the Lower Parves breccias at la Balme are their deposition on eroded and channelled surfaces (Fig. 10), and their frequent passage into normal limestones or marls. Some of the channels filled with breccias cut through several beds of limestones. The recession of the sea and the extreme shallowing of the sea floor would bring the sediments under the influence of current and wave action as suggested by Favre and Richard (1927). This might have resulted first in the erosion and channelling of the depositional surfaces. Later submergence and lowering of base level might have led to the infilling of these channels with breccias.

The period of emergence observed towards the end of Lower Parves times marks the close of a major cycle of sedimentation. The cycle began with the shallow and current-swept environment of Lucey times. A slight deepening of the sea floor may have been initiated in the Chanaz times and must have reached its maximum during the deposition of the Chavoley Beds. A shallowing of the sea floor during Oignon times led up to the re-establishment of Shallow-water sedimentation during the deposition of the Virieu Limestone. This shallow-water environment persisted throughout the Lower Parves times and ended with a period of emergence at the close of Jurassic sedimentation.

B. The Middle and Upper Parves Beds

(a) Petrography. It is possible to recognise two lithological sub-divisions in the Middle Parves Beds (Chapter 3). The lower sub-division begins with a pellet calcarenite consisting of bahamiths and minor amounts (10%) of skeletal fragments. The latter include Foraminifera, echinoderms and lamellibranchs. The overlying limestones are dolomitic. The basal part of these beds (Fig. 9) contain up to 50% of dolomite. Relics of skeletal fragments are found scattered throughout the rock. Higher up the skeletal fragments become rare and the sediments pass into a dolomitic calcilutite. The overlying strata consist essentially of calcilutites with a minor proportion of foraminifera (2-3%).

The upper sub-division of the Middle Parves Beds (Fig. 9) consist of limestones characterised by the presence of ooliths. These ooliths commonly "float" in a heterogenous groundmass of microcrystalline calcite. They contain grains of pyrite especially towards the periphery. Pyrite is also present as irregular patches in the groundmass of these limestones. Other components include fragments of brachiopods, echinoderms and lamellibranchs. These skeletal fragments are commonly ill-sorted and sub-angular. No thin sections have been cut of the Upper Parves Beds.

(b) Depositional envirnoment. The basal part of the Middle Parves Beds mark the return of marine conditions after a relatively short period of fresh water conditions at the close of the Jurassic (Revil 1911). These beds consist mainly of clean-washed calcarenites, indicating the existence of currents sufficiently strong to winnow away the finer grained calcite.

The ooliths, in the upper sub-division of the Middle Parves Beds, may have originated elsewhere in the general environment of deposition, since the texture of the limestones which contain these ooliths indicates an almost complete absence of wave and current action. In these ooliths most of the pyrite grains are concentrated towards the periphery. It is possible therefore that the ooliths originated in oxygenated and agitated waters, and were later pyritised. Although the presence of pyrite does not necessarily indicate the presence of reducing conditions above the water-sediment interface, (Martin 1958), it suggests that the raw material from which it later formed was present in the sediment.

The Upper Parves Beds mark a return to a rough-water environment. Sedimentation must have kept pace with subsidence because it appears that some 40 metres of sediment accumulated mainly above wave base. Towards the top echinoderms become important, and the frequence of oyster-covered surfaces indicate the occurrence of several halts in sedimentation. The highest surface in the Parves Beds is bored and with this non-sequence the essentially bahamite type of carbonate sedimentation comes to an end.

7. The Bourdeau Beds

(a) Petrography. The Bourdeau Beds consist essentially of biocalstic calcarenites and marls. The former can be divided into calcilutitic calcarenites and clean-washed calcarenites according to whether or not they were deposited with a groundmass of calcilutite. These correspond to phases a, b and c, respectively, of the cycles already recognised in the field (Chapter 3). Besides these rhythmic alte nations, which expresses

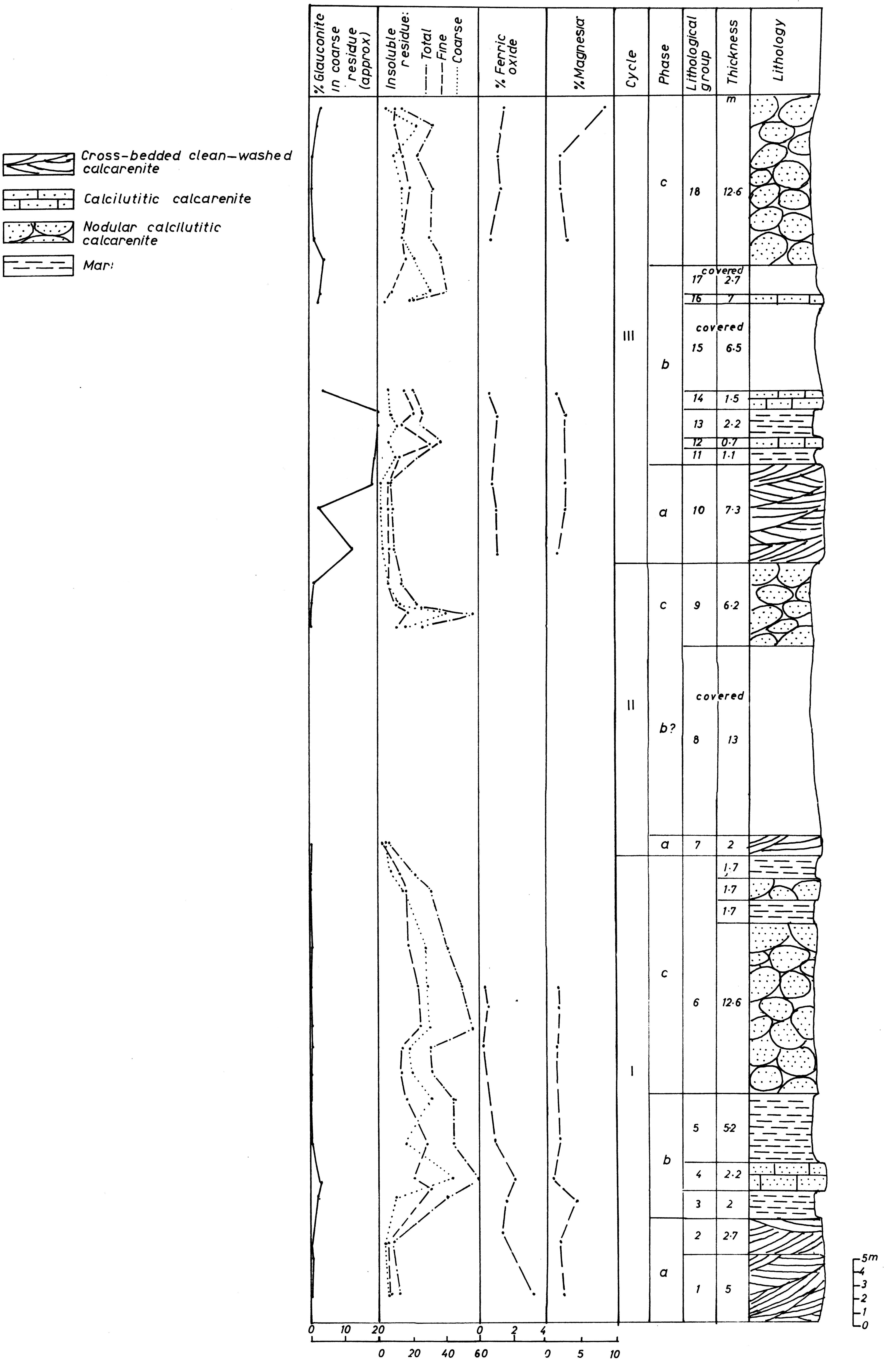


FIG. 56. *VERTICAL VARIATION IN LITHOLOGY AND COMPOSITION IN THE LOWER BOURDEAU BEDS.*

themselves petrographically by the presence or absence of a groundmass of calcilutite, thin section studies, aided by modal analyses of the various components, have shown that some significant vertical and later variations exist in the Bourdeau Beds. Most of these variations are unrecognisable in the field. In the Lower Bourdeau, however, except for some minor variations, the composition and texture of each phase is essentially similar.

The current-bedded calcarenites, (phase 'a' of each cycle) consist essentially of coarse-grained bioclastic calcarenites. The skeletal fragments consist largely of echinoderms and subordinate polycrystalline shell fragments. These calcarenites are cemented mainly by overgrowth. In the clean-washed calcarenites of cycle III, glauconite is an important accessory (Fig. 56).

Phase 'b' of each cycle includes both shales and limestones. The shales consist of about 50% carbonate matter, probably in the form of microcrystalline calcite. The limestones of cycle I consist almost exclusively of echinoderm fragments, while in cycle III, bioclastic mosaic pseudomorphs are the dominant sand-size componnnt. The skeletal fragments

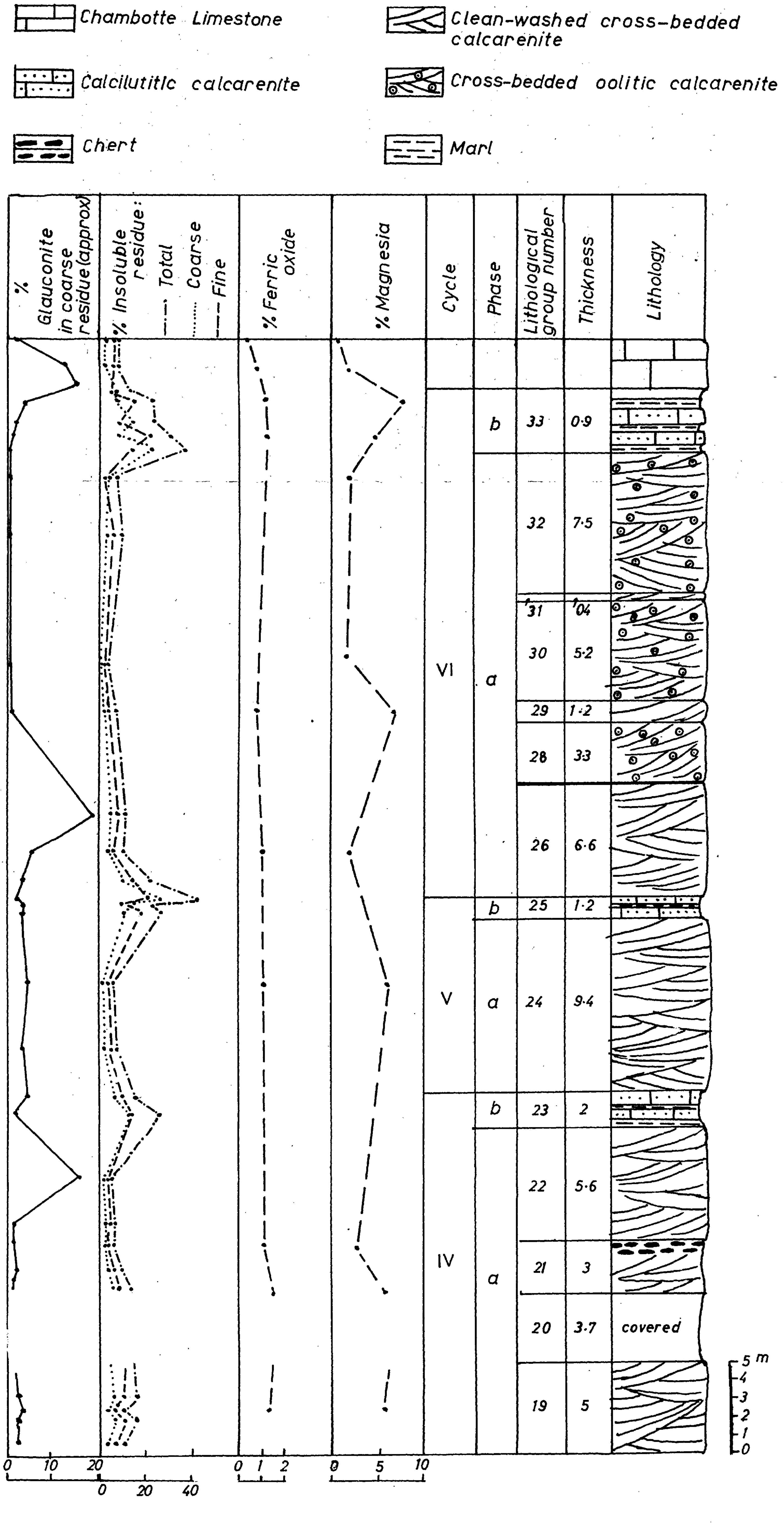


FIG 57 VERTICAL VARIATIONS IN LITHOLOLOGY AND COMPOSITION IN THE UPPER BOURDEAU BEDS.

are commonly sub-angular and ill-sorted. They are usually embedded in a dark grey microcrystalline groundmass. Minor constituents include composite calcite rhombs, detrital quartz grains and glauconite.

The nodular limestones (phase 'c' of each cycle) comprise two major sand-size components, i.e. echinoderm fragments and bioclastic mosaic pseudomorphs (Fig. 22). The latter (which are typical of this group) are circular in cross-section. Their longitudinal and oblique sections together with their circular cross-sections suggest an originally cylindrical shaped organic fragment. The groundmass in these limestones consists mainly of fine-grained microcrystalline calcite mixed with some fine-grained skeletal debris which gives it a heterogenous appearance. In some specimens, the calcilutitic groundmass may form the major part of the rock, in which case the sand-size components are no longer in contact. Minor constituents in the nodular limestones include dolomite, calcite after dolomite, detrital quartz and glauconite.

In the calcarenites of the Upper Bourdeau Beds two additional components make their appearance i.e. ooliths and

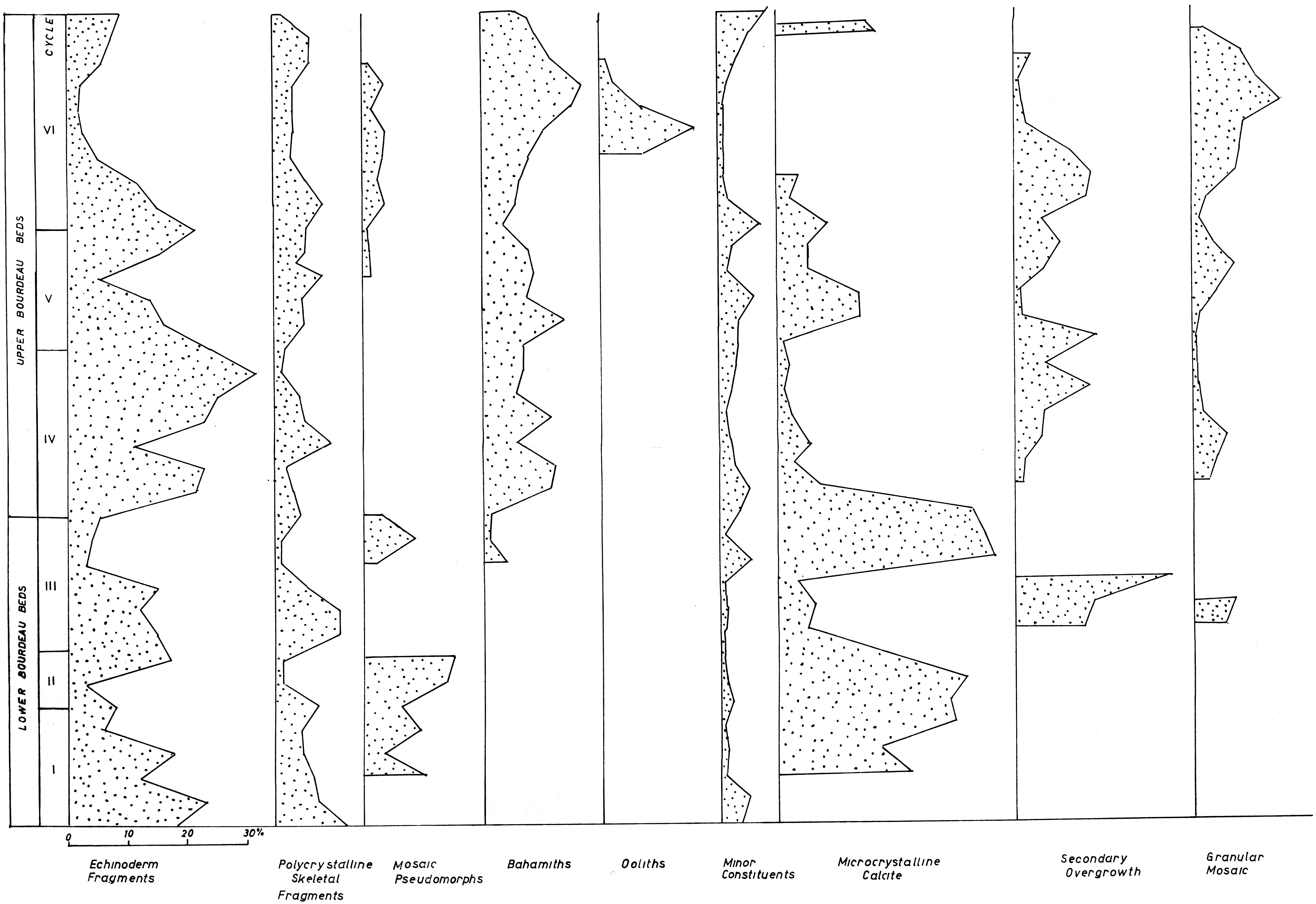


FIG. 58. — COMPOSITION OF THE BOURDEAU BEDS NORTH-WEST OF BOURDEAU.

pellets (Fig. 58 and 60). These, however, are subordinate to echinoderm fragments at the base of this division, but towards the top they become the dominant components. The major components are usually well-sorted and in the clean-washed calcarenites (phase 'a'), they are cemented by optically clear calcite either as overgrowths or echinoderm fragments or as granular mosaics of calcite. In the argillaceous calcarenites (phase 'b') the pellets and echinoderm fragments are embedded in a groundmass of microcrystalline calcite. These are commonly rich in dolomite or calcite after dolomite.

To summarise, the Lower Bourdeau Beds are almost exclusively skeletal, while the Upper Bourdeau Beds consist of a mixed bahamite and skeletal facies at the base. Towards the top bahamiths and ooliths occur in sufficient abundance to form an essentially non-skeletal facies. Thus it appears that physio-chemical precipitation of carbonate matter became relatively important towards the top of the formation.

The skeletal fragments also show some variation in their vertical distribution. These are best demonstrated

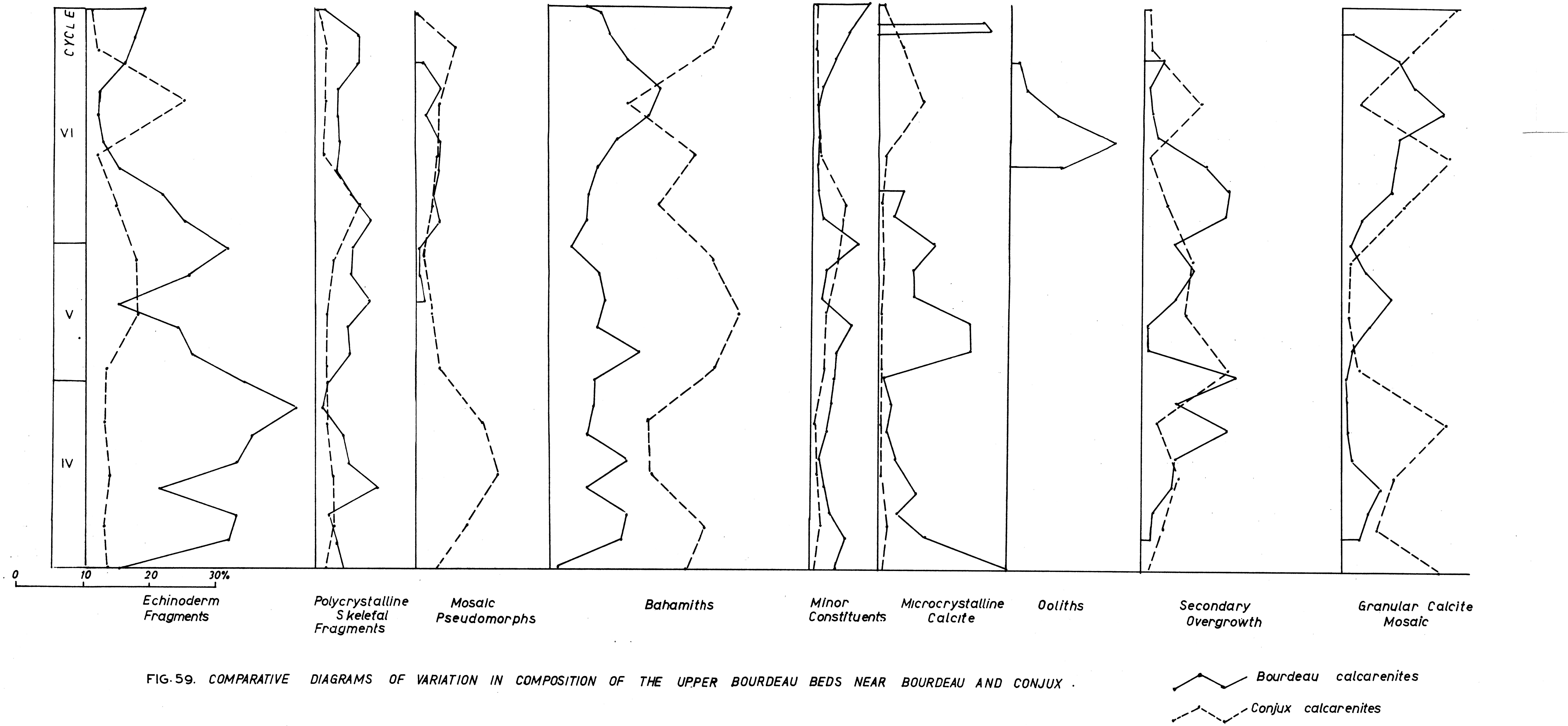


FIG. 59. COMPARATIVE DIAGRAMS OF VARIATION IN COMPOSITION OF THE UPPER BOURDEAU BEDS NEAR BOURDEAU AND CONJUX.

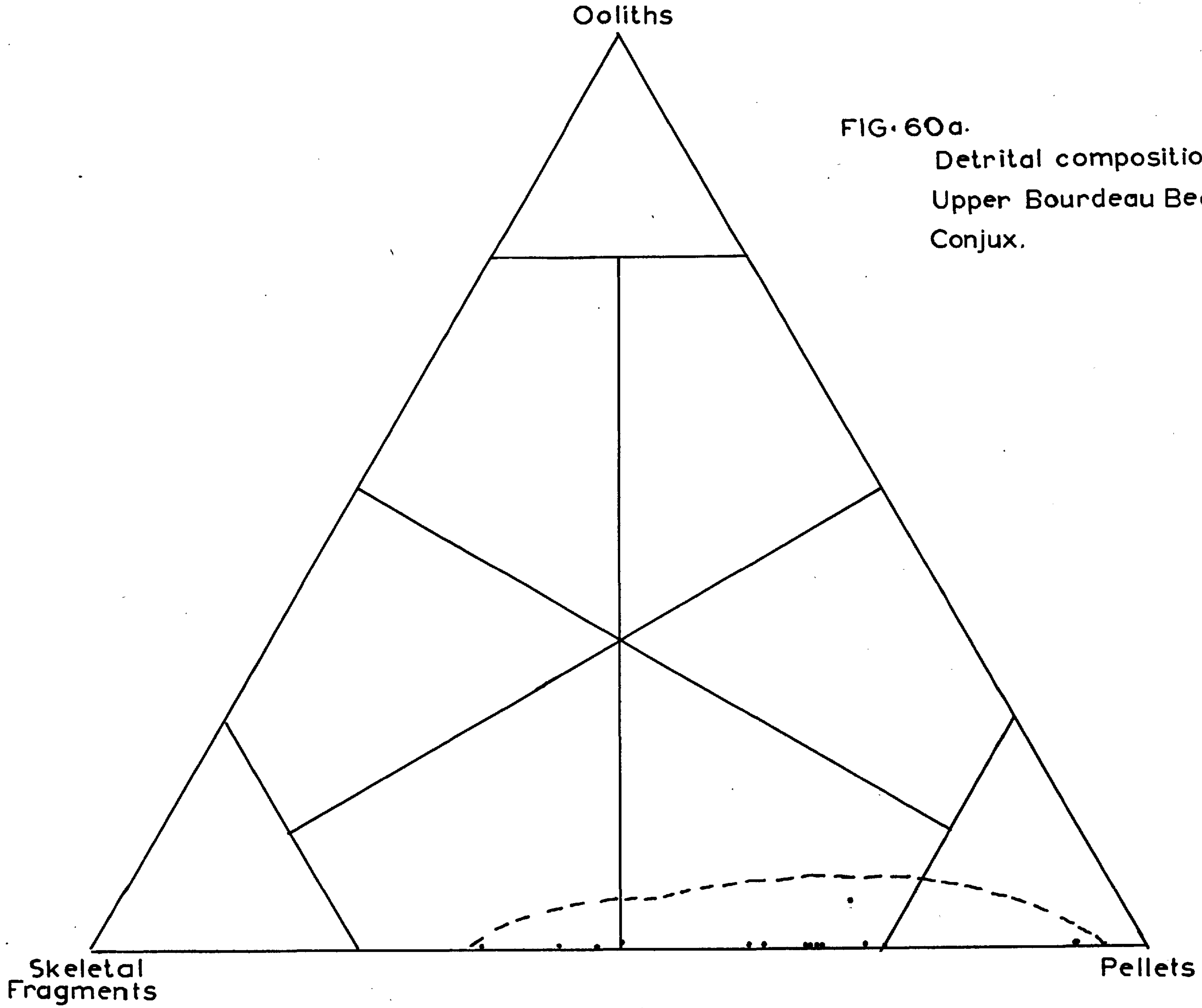


FIG. 60a.
Detrital composition of the Upper Bourdeau Beds at Conjux.

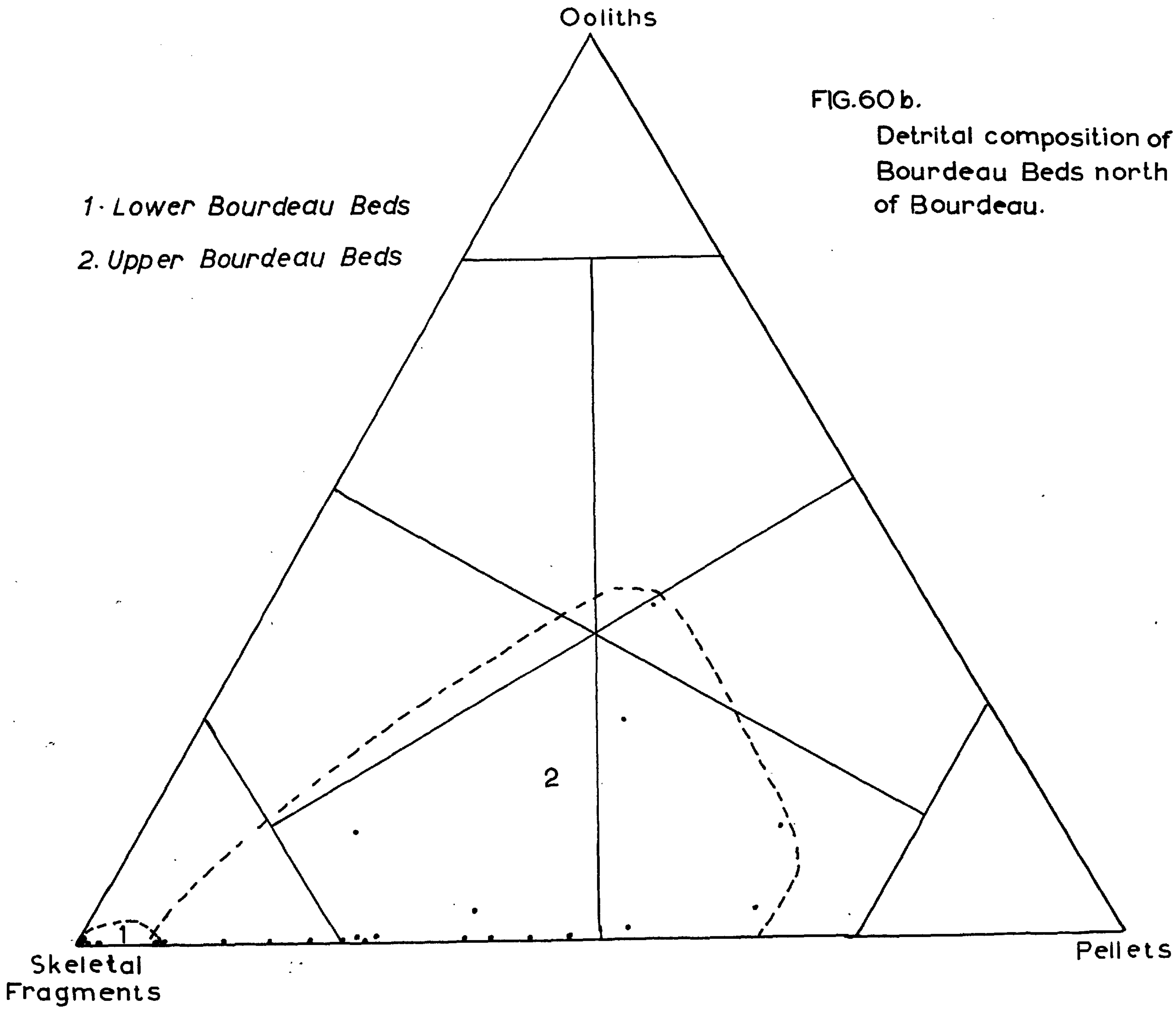


FIG.60 b.
Detrital composition of the Bourdeau Beds north west of Bourdeau.

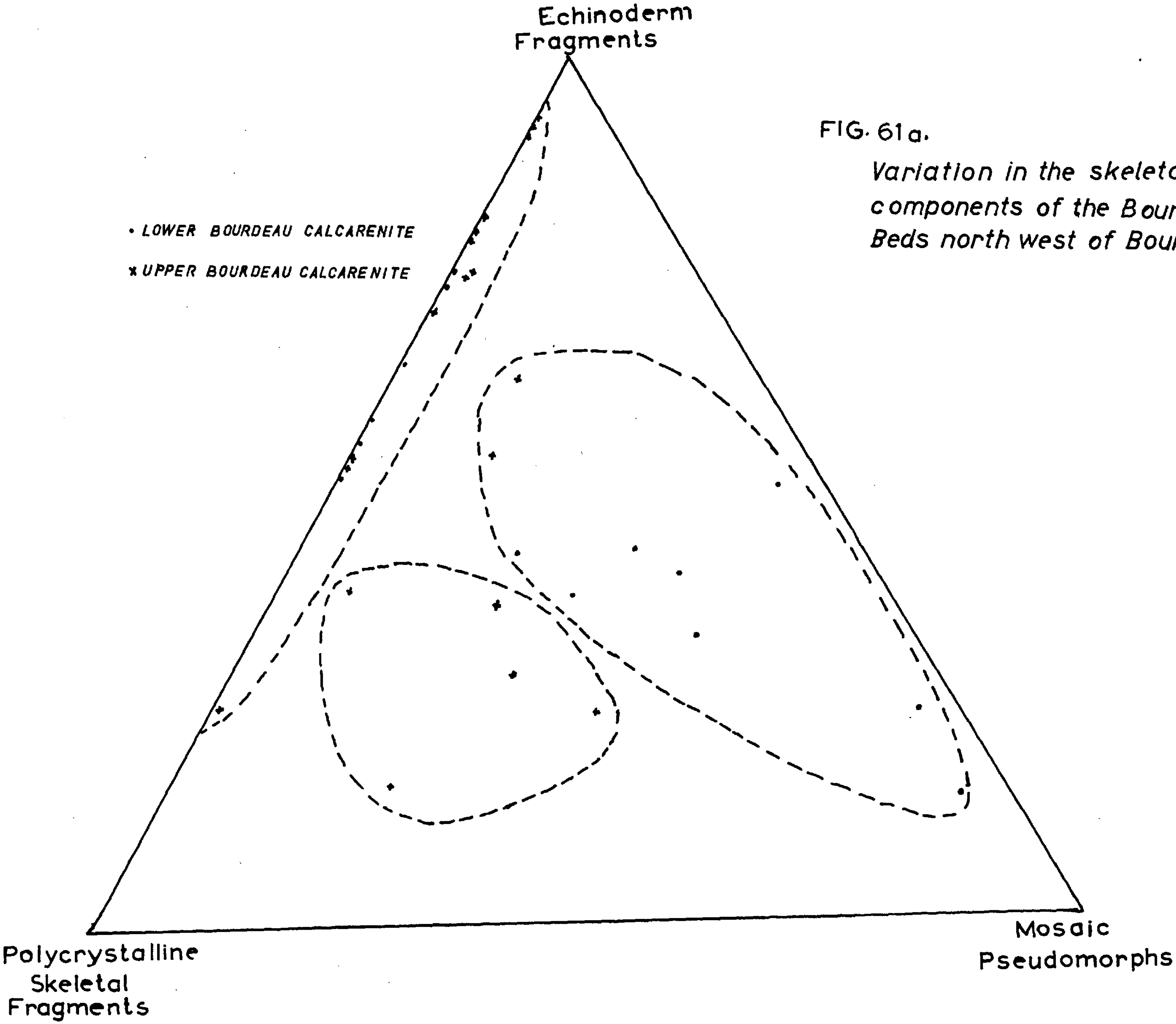


FIG. 61a.

Variation in the skeletal components of the Bourdeau Beds north west of Bourdeau.

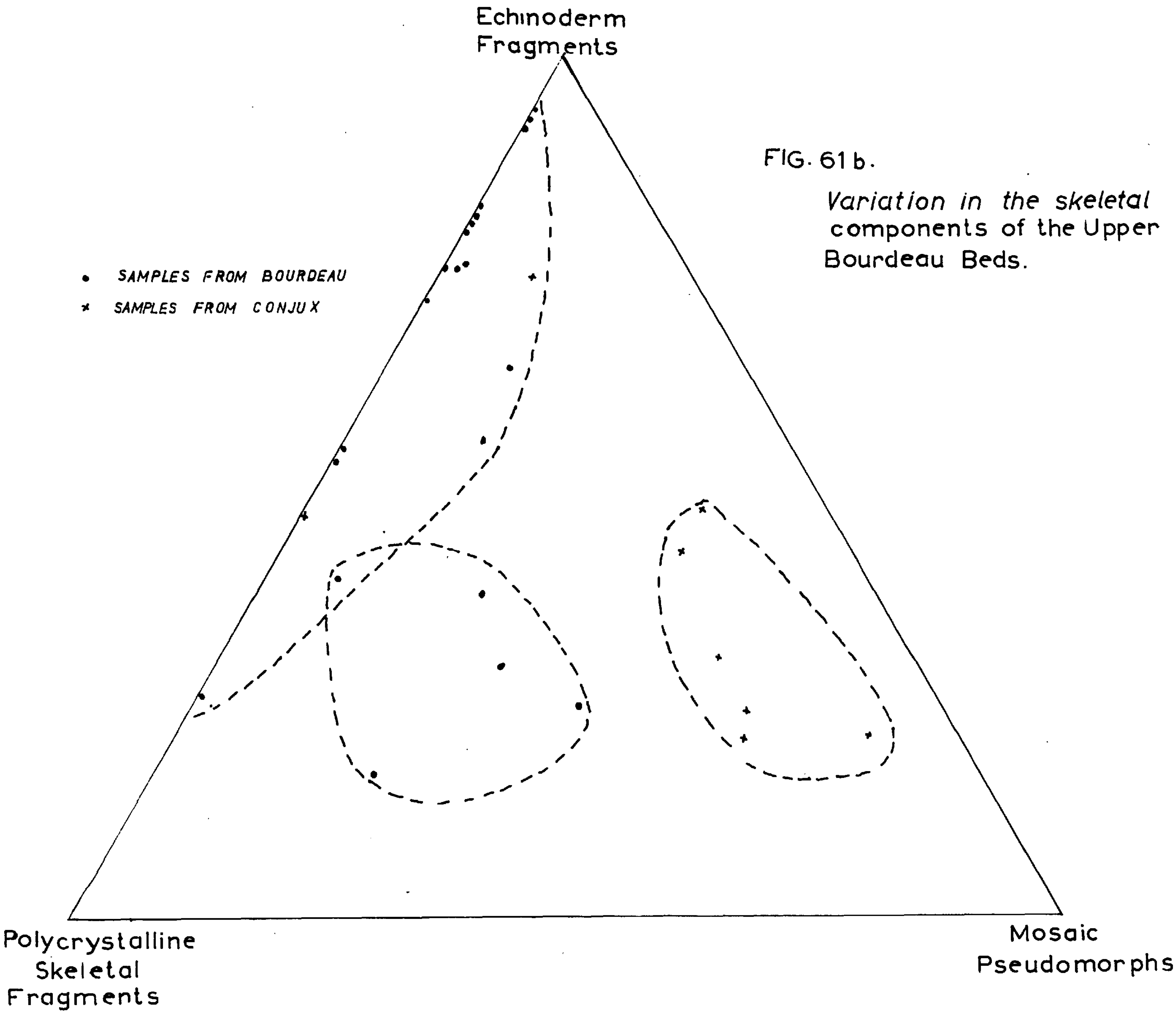


FIG. 61 b.

Variation in the skeletal components of the Upper Bourdeau Beds.

by plotting the three main variables (i.e. echinoderm fragments, bioclastic mosaic pseudomorphs and polycrystalline skeletal fragments) on triangular diagrams (Fig. 61a & b). These diagrams clearly show that the Lower Bourdeau Beds fall into two main groups. One group consists of two main components i.e. echinoderm fragments and polycrystalline skeletal fragments while in the other, these two components are mixed in various proportions with mosaic pseudomorphs. The two groups occur in the clean-washed and calcilutitic calcarenites respectively. The relatively high proportions of bioclastic mosaic pseudomorphs in the latter can be attributed to their preservation in comparatively quiet-water environment.

Figure 59 demonstrates the existence of some lateral variation in the clean-washed calcarenites of the Upper Bourdeau Beds. At the northern extremity of the Charvaz ridge, at Conjux, this division consists almost entirely of bahamiths. In spite of this probable passage into a bahamite facies, there is little apparent variation in the composition of the skeletal components.

(b) Insoluble residues. The study of the insoluble residues further confirms the field and the petrographic evidence regarding the rhythmic pattern of sedimentation in the Bourdeau Beds (Fig. 56-7). Carbonate-rich groups alternate with others which may contain up to 55% of terrigenous matter. The sand fraction (Figs. 56, 57), of the insoluble residues does not always represent only detrital material. Glauconite and chalcedony do in certain rocks form over 90% of the coarse fraction. The detrital quartz is usually fine-grained and sub-angular to sub-rounded. Chalcedony forms relatively large whitish grains, while glauconite occurs in two varieties; in one variety it forms dark green spheroidal grains, while the other variety is light green. The latter displays an intricate network of micro-columns and appears to be an infilling of the canals of echinoderm plates or spines. Authigenic silica appears to be associated with the coarse-grained clean-washed calcarenites in many of which it forms up to 90% of the insoluble residue. In the calcilutitic calcarenites, authigenic silica rarely exceeds 5% of the residue. Glauconite on the other hand, occurs in a variety of rock types in the Bourdeau Beds, in cycle III, for instance, it occurs in the clean-washed calcarenites, in the calcilutitic calcarenites and in the shales. In the Upper Bourdeau Beds the coarse-grained calcarenites at the top of this division are virtually free from glauconite while the finer-grained calcarenites at the base are relatively glauconite-rich. This distribution of glauconite in the Upper Bourdeau Beds (Fig. 57) persists throughout the area studied in spite of the facies variation described above.

(c) Chemical analysis. Some 38 samples from the Bourdeau Beds were analysed for magnesium oxide, calcium oxide and total iron content (ferrous and ferric iron) (Figures 56, 57 and Table 4). From these samples ten were analysed for manganese. Only traces (about 0.03%) were present in the different types of limestones and showed little variation.

The magneium oxides content ranges from 1.2% to about 7%. The relatively high magnesian content in some calcilutitic calcarenites can be related to the presence of dolomite. The magnesian content depends partly on the composition and relative abundance of the skeletal fragments. Bøggild (1930) and Vinogradov (1953) pointed out that two groups of calcitic skeletons can be recognised;

in one group, which includes brachiopods and molluscs the skeletons contain only up to 2% of magnesium carbonate, while in the other group, which includes echinoderm fragments and polyzoa, the skeletons contain 10% or more of magnesium carbonate. This would suggest that variation observed in the modal analysis of the skeletal fragments and also that between the skeletal fragments, bahamiths and ooliths should correspond to the variation in the magnesian content of these specimens. Comparison of the results of chemical and modal analysis shows that no such simple relationship exists. The complexity of factors on which the magnesian content depends readily explains this lack of correlation. Among other things, the magnesian content depends on the amount of glauconite present, and probably also on the amount of clay matter. Further diagenetic changes such as dolomitisation and dedolomitisation introduce further complications.

The $^{Ca}/_{mg}$ ratios (Table 4) range from 5 to 40% and it appears that lower ratios are particularly confined to the calcilutitic calcarenites. However, no such low $^{Ca}/_{mg}$ ratios have been recorded from the Upper Bourdeau calcarenites at Conjux. This, of course, could be the result of insufficient sampling. It appears, however, that the use of $^{Ca}/_{mg}$ ratios for correlation of carbonate rocks as has been suggested by Chillinger (1953) is unreliable when applied to calcarenites with a variable composition and a complex diagenitic history.

The total iron content is relatively high throughout the Bourdeau Beds (Figs. 56, 57 and Table 4). This iron enrichment is reflected in the field in the typical reddish brown colour of these limestones. Some of the iron is related to the presence of glauconite. According to Pettijohn (1956) glauconite is roughly half silica, one quarter iron oxide, one tenth alumina and magnesia and one fifth potash and water.

(d) Depositional environment. The most important evidence concerning the environment of deposition of the Bourdeau Beds can be summarised as follows:

1. The Bourdeau Beds consist of rhythmic alternations of current-bedded clean-washed calcarenites, shales and calcilutitic calcarenites.

2. In the Lower Bourdeau Beds shales and calcilutitic

calcarenites predominate while in the Upper Bourdeau Beds this relationship is reversed.

3. Oyster-covered surfaces often occur in the calcilutitic calcarenites of the majority of the cycles.

4. In thin section, the clean washed calcarenites are seen to be well sorted while the calcilutitic calcarenites are rather ill-sorted and contain sub-angular skeletal debris.

5. The Lower Bourdeau Beds are essentially bioclastic while the Upper Bourdeau Beds near Bourdeau show a gradational passage from a bioclastic to an oolitic and bahamitic facies, and the whole division appears to pass in the north into a bahamite facies.

6. The insoluble residues and to some extent the chemical analysis confirm the rhythmic pattern of sedimentation.

Deposition in Bourdeau times must have commenced in a shallow-water current-swept environment (Points 1and 4). This, however, appears to have lasted for a relatively short period of time, and must have been followed by a quiet-water environment of relatively long duration (Point 2). A quiet-water environment could have been achieved by the establishment of a barrier on neighbouring areas of the sea floor. This is, however, unlikely, since it would be difficult to envisage the establishment of such a hypothetical barrier and its removal at least six times during the deposition of the Bourdeau Beds. It is more probable that a periodic subsidence of the sea floor lowered the sediments repeatedly below wave-base. The sediment deposited in quiet-water environment is typified by an increase in the proportions of terrigenous material, especially clays. This could have been achieved in at least two ways. Either the supply of terrigenous material increased, probably indicating some positive movements in neighbouring land areas, or the rate of deposition of carbonate matter has declined during this period. The frequent occurrence of oyster-covered surfaces (Point 3) suggests a slow rate of sediment accumulation. This could have resulted from a decline in the deposition of carbonate matter in slightly deeper waters. This alternation of turbulent and quiet-water environments, must have been repeated three times during the Lower Bourdeau times.

In Upper Bourdeau times, bioclastic sedimentation must have gradually given way to a more physico-chemical type of sedimentation (Point 5). Subsidence must have kept pace with sediment accumulation over a relatively long period of time, thus retaining deposition above wave base. The presence of oyster-covered surfaces suggest that a slower rate of sedimentation existed also during the deposition of the Upper Bourdeau Beds. At least, two facies must have existed in the shallows of the Upper Bourdeau seas. These are a bahamite, and a mixed, bahamite oolitic and skeletal facies. This shallow-water sedimentation resembles in many respects recent carbonate deposition described by Illing (1954) and others on the Bahama Banks. That of the Lower Bourdeau Beds can be even more closely compared with the recent carbonate deposition described by Houbolt (1957) in the Persian Gulf.

8. The Chambotte Limestone

(a) Petrography. The Chambotte Limestone consists essentially of pellet calcarenites and calcilutites, with occasional calcirudites. The calcilutites consist of cryptocrystalline calcite with variable proportions of skeletal fragments. These consist mainly of Foraminifera and lamellibranchs. The calcarenites and calcirudites consist chiefly of pellets of cryptocrystalline calcite, i.e. bahamiths, but they also contain subordinate amounts of composite grains. The latter usually contain fragments of molluscs and Foraminifera. Most of the coarse-grained limestones are cemented with optically clear calcite showing a drusy texture.

(b) Depositional environment. Shallow-water sedimentation which prevailed during the Upper Bourdeau times must have continued during the deposition of much of the Chambotte Limestone. The depositional environment, however, must have differed in many respects from that of the Bourdeau Beds. The echinoderm skeletal fragments which predominate in the sediment of the Bourdeau Beds are virtually absent from the Chambotte limestones. Instead, fragments of what presumably were originally aragonitic skeletons, and foraminifera become important. The calcarenite facies in the Chambotte Limestone are essentially bahamitic, and are comparable with those which formed in the shallow seas of the Parves and the Virieu Limestone. Carbonate sedimentation, as inferred from the exposed part of the Mesozoic succession, therefore ends, as it began, with a shallow-water, current-swept environment.

APPENDIX

TABLE 2

Insoluble Residues, Magnesia and Lime content of Limestones, Dolomitic Limestones and Dolomites from the Virieu Limestone and the Parves Beds at la Balme gorge.

Specimen no.	Location*	%MgO	%CaO	% Insoluble Residue
117	26.5	2.22	55.15	-
118	28.9	1.1	54.0	-
119	30.3	17.8	34.2	-
120	31.0	7.6	46.0	-
121	31.5	7.5	45.6	-
134	38**	6.62	46.68	5.4
136	43.2	1.8	54.82	2.1
139	46.4	1.65	51.32	-
141	48.3	1.35	49.7	5.7
145	57.7	1.73	53.62	3.4
147	62.2	1.77	55.09	1.0
148	63.7	.40	54.8	-
151	67.4	11.62	38.22	10.8
152	67.8	3.05	48.5	9.7
155	74.8	10.08	42.32	-
156	75.3	5.87	48.81	4.2
158	79.9	1.65	54.55	2.0
161	85.8	1.58	55.2	1.1
164	93.8	1.59	54.82	-
168	100.6	18.42	35.58	2.0
169	101.5	19.8	30.8	16.2
170	102.0	17.59	33.52	4.0
171	106.2	0.72	54.35	2.5
174	110.0	1.33	55.4	1.7
176	114.8	1.29	55.07	2.1

*Distance in metres above the base of the Virieu Limestone.

**From this specimen onwards distances are measured upwards from the base of the Parves Beds.

TABLE 2 Contd.

Specimen no.	Location	%MgO	%CaO	% Insoluble Residue
177	116.4	1.18	54.85	2.2
178	117.0	2.31	53.16	
181	123.8	0.9	56.5	2.0
184	129.0	2.05	45.76	5.2
185	130.8	3.42	49.16	4.8
186	134.6	9.97	41.65	2.4
189	141.4	0.86	53.86	1.2
190	148.3	0.74	54.91	0.7
191	157.4	1.15	54.58	0.8
192	158.6	0.45	54.53	-

Lime, magnesia and ferric oxide content of limestones from the Bourdeau Beds (a) north-west of Bourdeau and (b) west of Conjux.

TABLE 4

a

Specimen no.	Location*	%CaO	%MgO	CaO/MgO	%Fe_2O_3
16	0.8	37.5	7.3	5.1	1.13
18	2.5	35.4	4.4	8.0	1.32
57/219	3.8	50.8	1.5	36.3	-
57/217	14.2	52.2	1.2	43.5	-
57/216	17.3	51.0	6.4	8.0	0.62
57/213	23.3	51.7	1.9	27.2	0.96
57/211	29.2	52.0	5.6	9.3	0.85
57/208	43.7	51.4	2.7	19.0	1.01
57/207	47.2	46.9	6.6	7.1	1.47
57/204	52.3	50.3	5.3	9.5	1.18
57/201	56.1	46.5	8.4	5.54	1.41
42	59.3	44.1	1.8	24.5	1.08
43	61.1	37.5	1.9	19.7	1.45
44	65.2	38.1	2.4	15.9	0.58
48	77.8	44.6	1.6	27.7	0.66
50	79.4	40.3	2.5	16.1	1.03
55	84.0	51.3	2.2	23.3	0.83
59	87.0	51.8	2.5	20.7	0.97
60	90.0	50.7	1.2	42.3	1.25
71	119.8	41.8	1.5	27.9	0.27
73	122.4	36.7	1.7	21.6	0.47
76	128.0	34.8	1.2	29.0	0.26
78	134.6	29.5	1.9	15.5	0.83
79	137.9	19.8	1.0	19.8	2.11
80	138.1	28.0	4.1	6.8	1.7
82	141.0	49.5	2.0	24.8	1.51
83	143	47.3	2.3	20.5	3.2

*Distance in metres from top of the formation.

TABLE 4 Contd.

Specimen no.	Location	%CaO	%MgO	CaO/MgO	%Fe_2O_3
		b.			
X 111	.6	55.6	3.6	15.4	0.07
110	3.6	57.7	1.6	36.0	0.08
106	11.6	55.0	1.9	28.9	0.23
105	13.7	54.5	2.0	37.8	0.39
103	15.8	53.8	2.8	19.2	0.65
101	16.8	54.7	1.9	28.8	0.40
100	20.9	55.1	1.9	29.0	0.12

TABLE 5

Insoluble residues of specimens from the Bourdeau Beds northwest of Bourdeau.

Specimen no.	Location*	%Coarse Residue	%Fine Residue	%Total
16	.8	6.66	14.11	20.7
17	2.2	14.4	8.3	22.7
18	2.5	7.3	22.5	29.8
19	3.2	21.0	14.6	35.6
57/219	3.8	4.1	2.8	6.9
57/217	14.2	1.3	1.7	2.6
57/216	17.3	2.3	3.5	5.8
57/213	23.3	3.0	3.8	6.8
21	26.2	26.4	20.8	42.2
23	26.4	14.3	8.2	23.1
22	27.0	18.2	17.3	35.5
25	34.5	1.5	4.6	6.1
26	36.6	5.6	9.6	15.2
27	36.8	13.1	12.4	25.5
28	40.2	1.2	3.4	4.6
29	42.3	2.5	3.8	6.3
32	44.8	3.2	5.9	9.1
33	45.4	6.0	7.5	13.5
36	51.8	6.0	10.3	16.3
37	52.8	2.9	6.5	9.4
38	54.0	3.4	6.3	9.7
41	57.4	22.6	9.4	32.0
42	59.3	7.2	12.8	20.6
43	61.1	13.9	17.9	31.8
44	65.2	14.6	14.4	29.0
46	70.4	31.9	8.1	40.0
47	70.8	17.7	2.8	20.5
48	77.8	14.8	15.3	20.1

*Distance from top of the formation

TABLE 5 Contd.

Specimen no.	Location	%Coarse Residue	%Fine Residue	%Total
50	79.4	6.3	19.3	25.6
51	80.2	10.9	14.0	24.9
52	81.4	6.3	30.2	36.5
53	82.4	10.5	12.4	22.9
55	84.0	1.3	6.0	7.3
56	84.4	15.9	26.0	41.9
59	87.0	1.0	4.8	5.8
60	90.0	2.6	6.3	8.9
61	93.2	6.6	6.7	13.3
63	95.1	39.[illegible]	17.3	57.0
66	111.4	2.2	4.2	6.4
67	114.6	12.2	9.7	21.9
69	116.6	15.0	17.5	32.5
70	119.2	24.4	17.4	41.8
72	120.3	28.0	22.9	50.9
74	123.6	31.1	25.3	56.4
75	125.8	18.3	13.1	31.4
76.	128.0	19.4	13.1	32.5
78	134.6	16.6	28.6	45.2
79	137.5	45.9	19.5	65.4
80	138.1	10.0	31.4	41.4
82	141.0	4.2	5.3	9.5
83	143.2	6.3	6.3	12.6

TABLE 6

(i) Results of grain size analysis of samples from the Upper Bourdeau Beds west of Conjux

Specimen no.	XIII	X109	X106	X103	X100	X98
Location						
Diameter ø						
> -1.81	1.8	-	-	-	-	-
-1.8 to -1.3	3.0	-	-	-	0.2	0.5
-1.3 to -0.88	6.5	-	0.2	-	0.4	0.6
-0.88 to -0.63	2.7	-	4.5	-	1.5	1.6
-0.63 to -0.38	5.5	-	7.2	1.5	3.8	1.6
-0.38 to -0.17	5.5	-	7.2	1.5	9.1	2.7
-0.17 to 0.15	6.4	0.6	9.0	4.4	14.2	0.5
0.15 -0.38	5.1	0.6	6.3	2.9	12.1	3.2
0.38 -0.66	9.1	0.6	12.6	7.3	18.9	3.2
0.66 -0.86	8.2	4.0	5.4	2.9	14.4	5.8
0.86 - 1.1	16.0	3.5	-	17.0	7.6	10.0
1.1 - 1.35	6.4	7.5	15.3	5.8	3.8	6.4
1.35 - 1.61	10.0	18.8	5.4	23.0	1.5	11.1
1.61 - 1.86	8.2	19.5	8.1	8.7	30.0	20.2
1.86 - 2.0	4.6	35.9	9.9	20.1	1.8	23.7
2.0 - 2.4	0.6	5.4	0.1	1.5	1.5	0.6
2.4 - 2.9	-	6.3	0.1	1.5	1.5	0.6
2.9 - 3.9	-	2.3	0.1	1.5	1.0	4.6
< 3.9	0.5	-	8.5	0.4	4.0	3.0
Mdø	0.75	1.9	0.73	1.4	0.5	1.56
Pdø	1.3	0.78	1.2	0.77	1.03	0.96

TABLE 6 Contd.

(ii) Results of grain-size analysis of samples from the Upper Bourdeau Beds north-west of Bourdeau.

Specimen no.	57/219	57/217	57/215	57/213	57/211
Location*	3.8	14.2	16.8	23.3	29.3
Diameter Ø					
>1.8 Ø	-	0.5	-	0.3	0.6
-1.8 to -1.3	-	0.7	-	0.6	0.6
-1.3 to -0.88	-	.3	0.3	0.9	0.5
-0.88 to -0.63	0.4	0.9	0.3	0.6	0.5
-0.63 to -0.38	1.6	0.8	1.0	0.3	1.0
-0.38 to -0.17	4.0	2.7	0.3	0.6	-
-0.17 to -0.15	4.8	3.0	0.6	2.9	-
0.15 to +0.38	6.4	2.0	2.0	0.6	-
0.38 - 0.66	9.2	9.4	5.3	3.5	1.5
0.66 - 0.86	12.3	10.0	17.5	5.9	1.5
0.86 - 1.1	15.1	18.7	25.4	8.2	5.9
1.1 - 1.35	10.7	12.7	14.7	11.2	12.6
1.35 - 1.61	8.7	12.8	14.5	13.5	12.7
1.61 - 1.86	8.3	11.9	7.6	21.7	13.7
1.86 - 2.0	7.9	9.3	4.8	16.5	21.8
2.0 - 2.4	1.6	-	0.3	3.3	2.0
2.4 - 2.9	2.8	0.3	0.6	4.7	14.2
2.9 - 3.9	4.0	3.3	0.3	4.3	10.2
<3.9	2.0	0.6	4.4	0.3	0.6
MdØ	1.05	1.2	1.12	1.6	1.85
PDØ	1.1	0.8	0.6	0.9	1.0

*Distance in metres from top of the division.

TABLE 6 Contd.

(ii) Contd.

Specimen no.	57/207	57/204	57/201
Location	47.2	52.3	56.1
Diameter m.m.			
2	-	1.4	-
2 - 1.4	-	1.4	-
1.4 - 1.0	-	3.1	-
1 - 0.84	-	0.9	-
0.84 - 0.68	-	1.9	-
0.68 - 0.62	0.4	1.4	0.1
0.62 - 0.57	0.7	1	1.3
0.57 - .51	2.4	3.2	1.0
0.51 - .46	-	1.0	0.6
.46 - 0.40	3.2	5.8	0.9
0.40 - 0.35	3.1	6.5	3.2
0.35 - 0.31	7.3	10.5	6.4
0.31 - 0.24	10.8	13.6	14.4
0.24 - 0.2	16.7	17.3	18.5
0.2 - .14	21.6	11.0	28.1
0.14 - 0.08	27.0	18.4	4.4
0.08 - 0.04	6.3	1.4	20.5
.04	0.5	0.2	0.3
MdØ	2.6	2.02	2.43
PDØ	1.09	1.21	0.85

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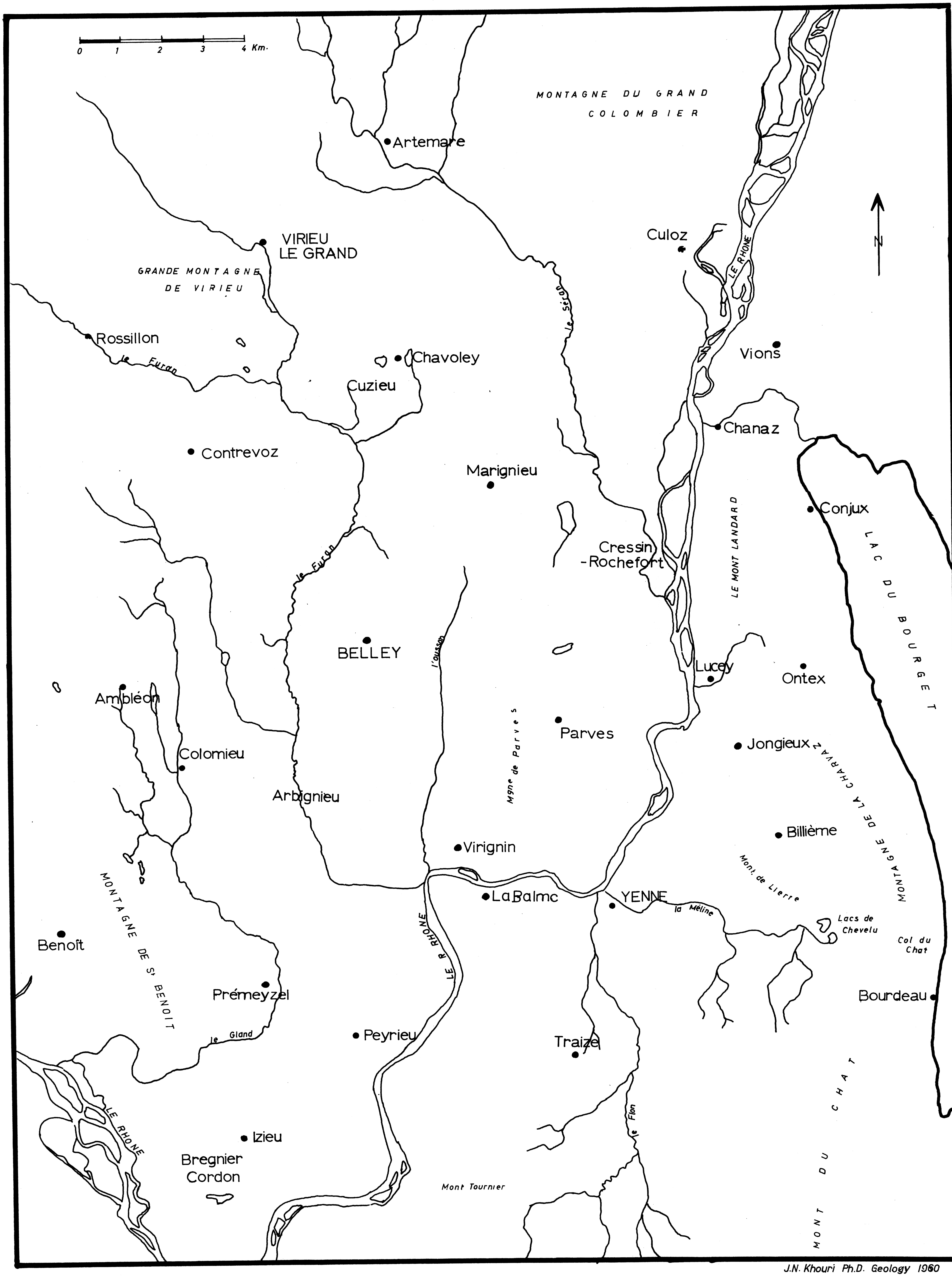

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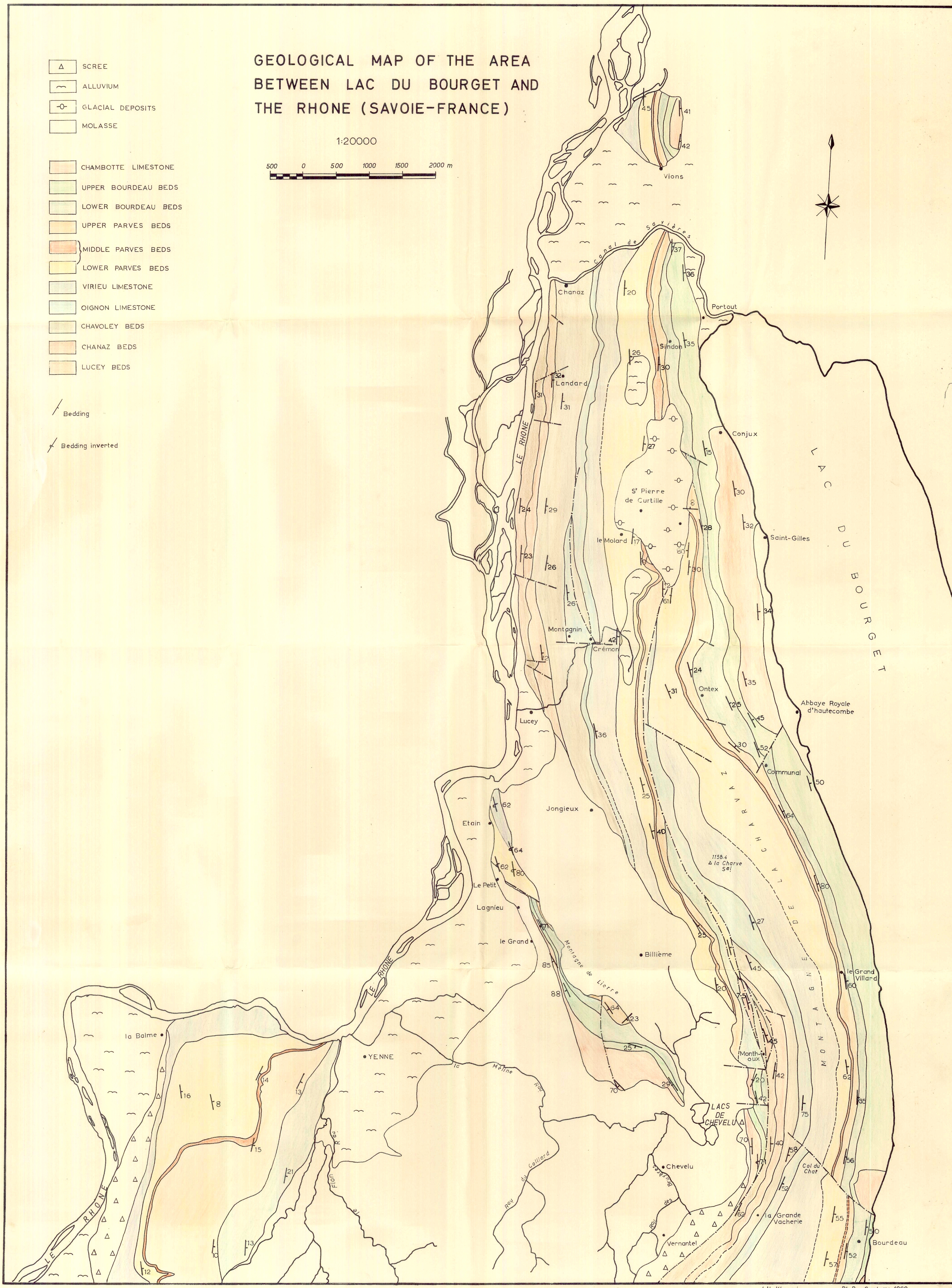
FIG. 2. LOCALITY MAP.



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