THE GEOLOGY OF THE FRENCH JURA MOUNTAINS WEST OF BELLEY (AIN).

by

B.D.Evamy, B.A., F.G.S.

Thesis submitted for the Degree of Doctor of Philosophy in the Faculty of Science of the University of London.

September, 1963

ABSTRACT

The geology of the French Jura, west of Belley, is described. The area of detailed investigation, which incorporates approximately 130 sq.km., was mapped on a scale of 1/20,000.

Principal contributions to previous work were descriptions of the Middle Jurassic stratigraphy of the region by Riche (1893) and Pelletier (1960). The region was mapped only once prior to the present study, and this on a scale of 1/80,000 in the eighteen-nineties by the French Geological Survey.

Well-exposed Mesozoic limestones form a column, 1000m. thick, ranging in age from Bajocian to Aptian. Poorly-exposed Tertiary molasse is also found. The petrography of the lithostratigraphical units mapped, is described. Faunas and floras collected provided data for subsequent biostratigraphical interpretation, usually indicating both the age and palaeo-environment of the fossil sediments.

Two main cycles of sedimentation were recognised in the Mesozoic, with the recurrence of coral reefs, delicate bathymetric indicators, at three principal horizons (Bajocian, Kimmeridgian/Portlandian and Aptian).

The area consists of a broad "box-type" anticline bordered in the west by a zone of strike faults and in the east by the molasse-bearing Belley syncline. A relationship exists between bedding thickness and style of deformation so

that disharmonic folding characterizes the region. The development of the geomorphology of the southern Jura is discussed in relation to geological structure.

Specific problems in limestone petrology were investigated. A staining technique was developed to detect variations in ferrous-iron content within dolomite and calcite whilst simultaneously differentiating these two minerals. Pyrite oxidation was shown to yield a reagent capable of causing replacement of dolomite by calcite. The history of the development of overgrowths around echinoderm fragments has been elucidated by employing staining techniques.

ACKNOWLEDGEMENTS

The work described in this thesis was carried out while the writer was a member of the Department of Geology of Imperial College of Science & Technology, University of London. The author was able to devote himself to full time research due to the financial backing of a Research Student-ship awarded by the Shell International Petroleum Company, to which Company he is deeply indebted. The writer also acknowledges with thanks the receipt of part of a Foundation Scholarship, awarded in 1959, by Trinity College, Dublin.

The author wishes to thank his supervisor, Dr.D.V.Ager, for his advice and assistance, especially in problems concerning stratigraphy and palaeo-ecology, both in the field and in the laboratory. He is furthermore grateful to Dr.Ager for his unflagging interest in all aspects of the work, and for critically reading the manuscript of the thesis. Special thanks are also due to Mr.D.J.Shearman for introducing the writer to the fascinating study of limestone petrology, and for his constructive criticism over many parts of the thesis manuscript. Mr.Shearman's dynamic enthusiasm and encouragement, in particular over problems concerning diagenesis, will be especially remembered by the author. The writer would like to record his thanks to Mr.A.E.Gunther who visited him in the field on two occasions.

The author wishes to thank Dr.J.C.M.Taylor for sharing his wealth of information on laboratory techniques and for making available, at various times, his comprehensive

knowledge of the literature on sedimentary petrology. The author has had many interesting discussions on limestone petrology with Mr.R.G.C.Bathurst and Mr.R.W.Macqueen, both of whom have also critically read parts of the manuscript of this thesis. The writer is grateful to Dr.G.Evans, Mr.D.J.J.Kinsman, and Mr.D.J.Shearman for many stimulating discussions on the Recent carbonate sediments of the Abu Dhabi area of the Persian Gulf. These discussions have assisted the author's interpretation of the depositional environment of several of the fossil carbonate sequences studied by him.

Fauna and flora collected by the author have been identified by Dr.C.G.Adams, Dr.D.V.Ager, Dr.J.H.Callomon, Dr.R.Casey, Dr.L.R.Cox, Professor D.T.Donovan, Mr.G.F.Elliott, Dr.M.P.Kerney, Dr.R.P.S.Jefferies, Dr.R.V.Melville, Mr.N.F.Morris, Dr.J.W.Murray and Dr.H.Dighton Thomas, to all of whom he is greatly indebted.

Thanks are due to Mr.E.Hill and his staff for making most of the thin sections used in the present study, to Mr.J.A.Gee for his expert assistance in the preparation of the photomicrographs which illustrate this thesis, and to Miss Mary Pugh for her help with some of the diagrams.

The author wishes to thank Professor Moret of Grenoble University for allowing him to work in the region, and to Dr.P.Gidon of Chambéry for discussing some aspects of the regional geology. The author is particularly grateful to Mons.G.Lienhardt of the Bureau de Recherches Géologiques et Minières at Lons-le-Saunier (Jura), for conducting him over the

Ledonian Jura, and for showing him the cores from the deep borings put down in The Vignoble. Mons. Lienhardt also demonstrated convincingly to the author that in this region the contact between the Mesozoic and Palaeozoic rocks is one of décollement.

Finally, the author wishes to thank the people of the southern Jura, and especially the villagers of Virieu- le Grand and Ambléon for receiving him and his wife into their community during the course of field work.

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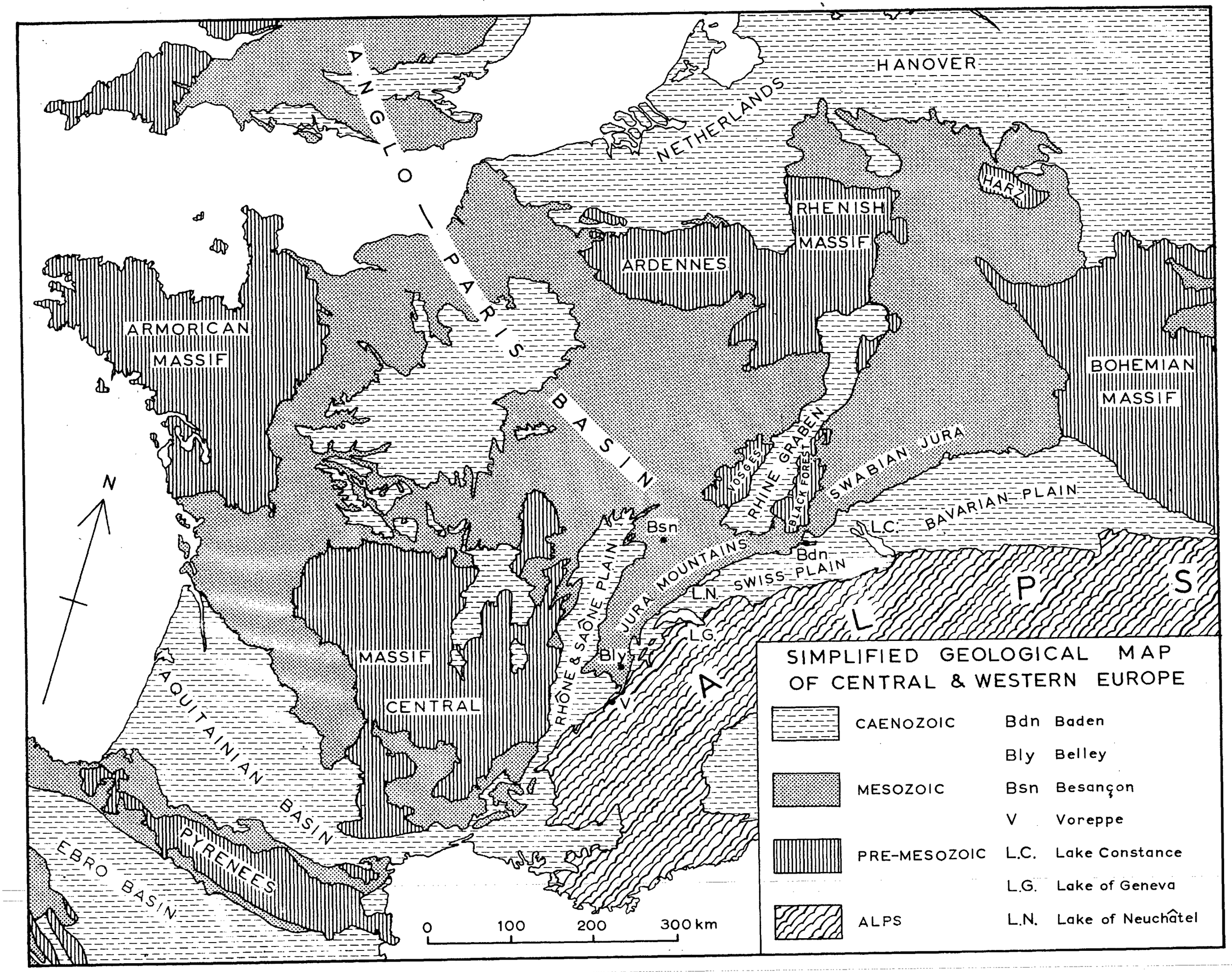
F R O N T I S P I E C E

Lac d'Armaille and the
Cliffs of Innimont, part
of the area west of Belley,
from the painting by
Marguerite de Montfalcon

PART I.

INTRODUCTION & REVIEW OF PREVIOUS WORK.


ANGLO-PARIS BASIN
HANOVER
NETHERLANDS
RHENISH MASSIF
HARZ
ARDENNES
ARMORICAN MASSIF
BOHEMIAN MASSIF
VOSGES
RHINE GRABEN
BLACK FOREST
SWABIAN JURA
BAVARIAN PLAIN
L.C.
Bsn
Bdn
JURA MOUNTAINS
SWISS PLAIN
L.N.
L.G.
Bly
V
RHÔNE & SAÔNE PLAIN
MASSIF CENTRAL
AQUITAINIAN BASIN
PYRENEES
EBRO BASIN
ALPS
N
0 100 200 300 km
SIMPLIFIED GEOLOGICAL MAP OF CENTRAL & WESTERN EUROPE
CAENOZOIC
MESOZOIC
PRE-MESOZOIC
ALPS
Bdn Baden
Bly Belley
Bsn Besançon
V Voreppe
L.C. Lake Constance
L.G. Lake of Geneva
L.N. Lake of Neuchâtel

CHAPTER 1.

INTRODUCTION.

A. THE JURA.

(i) General.

The Jura Mountains were mentioned in the writings of Caesar, Strabo, Pliny and Ptolemy. The word "Jura" is derived from the names which these writers assigned to the Range. These names were Joux, Jorat, Jorasse and Juriens, all of which aptly mean "forest", since the limestone hills of the Jura are characteristically thickly wooded. The Jura Mountains have subsequently given their name to the Jurassic System of rocks, which are so well exposed in the Range.

The Jura Mountains form an arc of ridges in eastern France and western Switzerland. The rocks exposed in the Range are dominantly calcareous and have facies typical of shelf seas. Structurally the Jura are set over the north-west foreland of the Alps. The crescent forming the Jura (fig.1.) is concavo-convex with the concave side facing the Alps. The arc extends from Voreppe, near Grenoble north-eastwards for 360 km. to Baden (between Basel and Zürich). The widest part of the Range, where it measures 60 km. across, is from lac de Neuchâtel to Besançon in the central region of the Jura. The transverse dimensions of the Range diminish from this zone north-eastwards towards Baden and southwards towards Voreppe. The width of the Range becomes less than 10 km. before these extremities are

FIG. 2

SOME TYPICAL FEATURES OF THE STRUCTURE & GEOMORPHOLOGY OF THE JURA MOUNTAINS

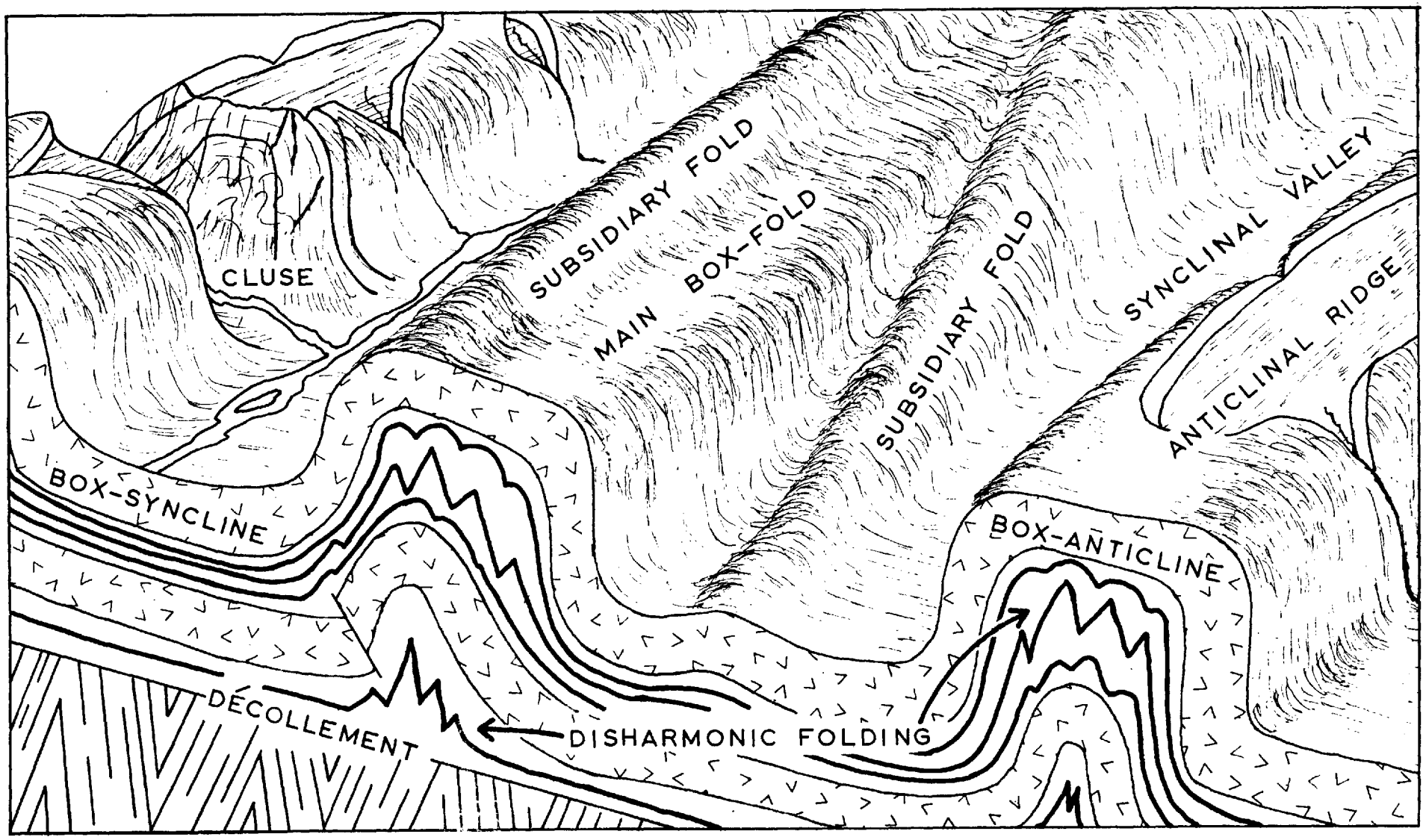
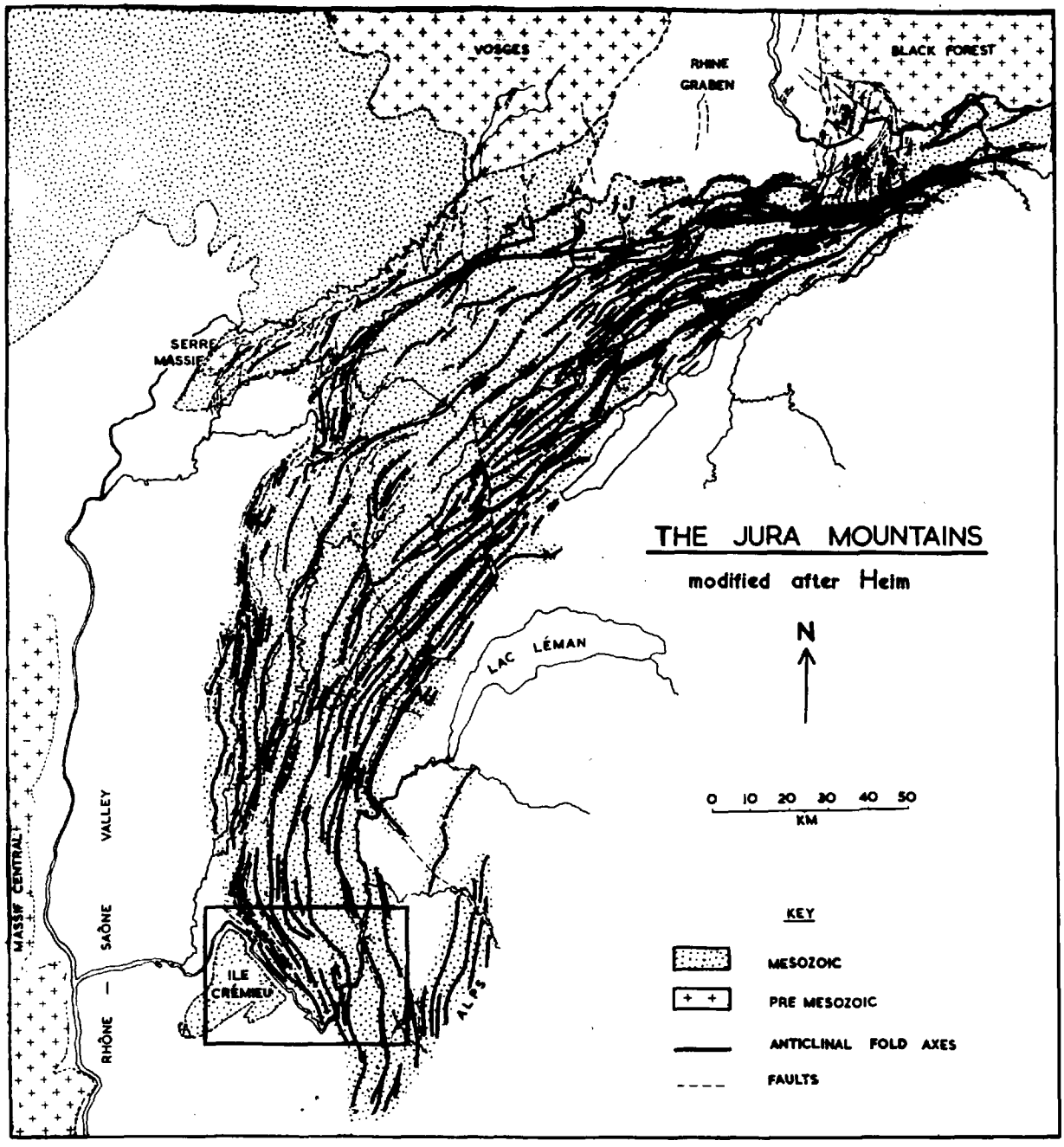


FIG. 3



RECTANGLE ENCLOSES AREA CONSIDERED IN GENERAL TERMS

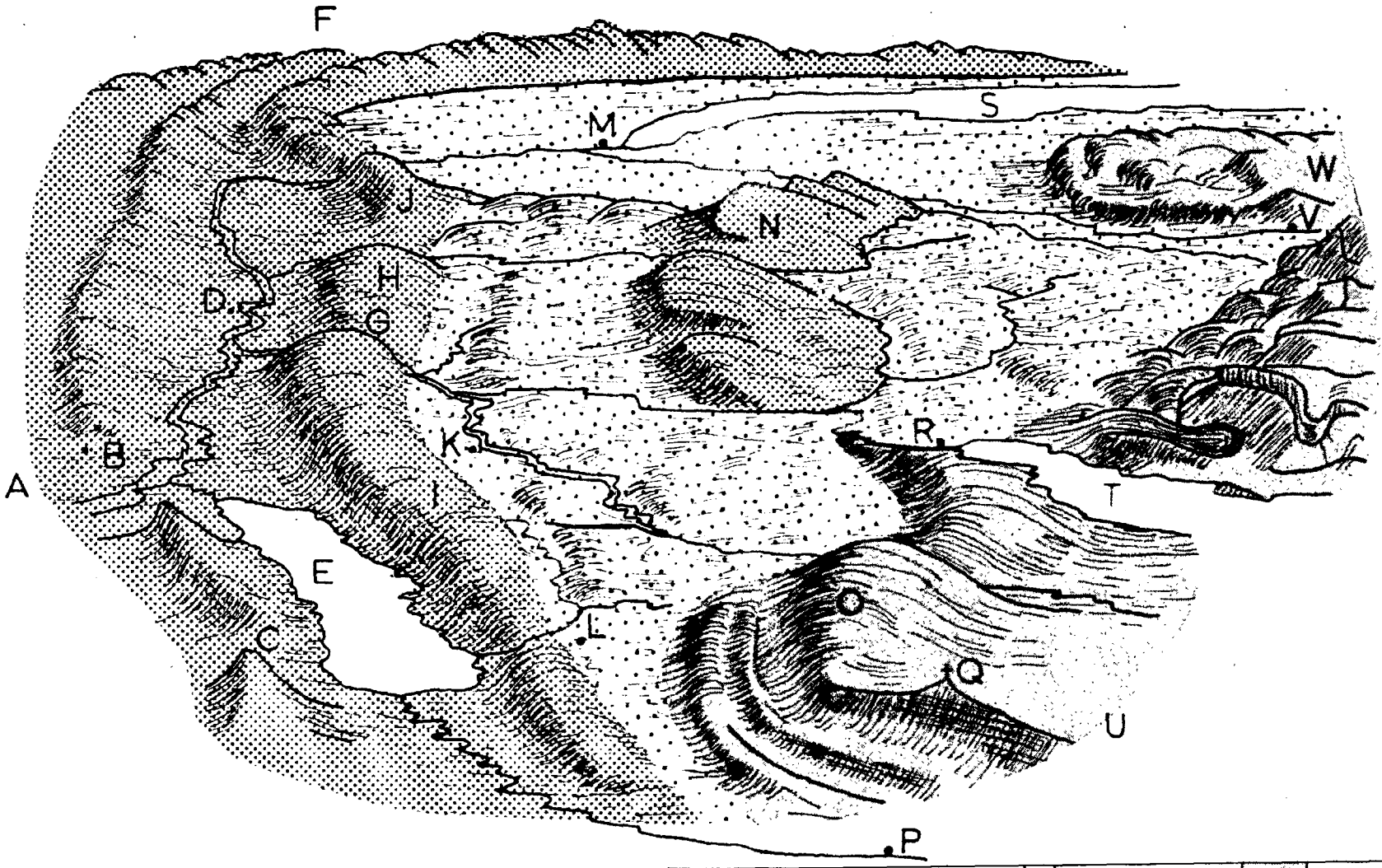
reached.

The Jura arc is made up of folded and faulted unmetamorphosed Mesozoic limestones and marls. Tertiary deposits, also folded, are often found in the synclinal areas. The massive limestone members of the Mesozoic succession are generally competent and control the form of the folds. These are usually the classical Jura "box-folds" with two axial planes (fig.2). The incompetent marls and thinly bedded limestones are typically contorted and moulded around the massive units. The competent units in a major anticline may display a different style of folding at various levels in the structure. Disharmonic folding of this type characterises the Jura. The same basic phenomenon, on a more drastic scale, is generally considered to have occurred between the Mesozoic blanket of the Jura and the Palaeozoic basement during the Alpine orogeny. The folded Mesozoic is thought to have become completely detached from the basement and to have slid bodily over a lubricant of Triassic evaporites.

The Jura anticlines, approximately 160 in number, vary from a few kilometres to 70km. in length. The tectonic trend is sub-parallel to the form of the Range as a whole (see fig.3). Faults and the axes of folds thus often have arcuate traces. In the centre of the Jura, where the Range is widest, approximately 20 anticlines are found. Towards the extremities of the Range the anticlines reduce in number, and at Baden and Voreppe they are represented by single anticlinal folds.

FIG. 4

THE DIVERGENCE OF THE JURA AND THE ALPS FROM CHAMBÉRY, after W.G.Collingwood(1884).



A	MARAIS de LAVOURS	E	LAC du BOURGET	I	CHAMBOTTE RIDGE	M	GENEVA	Q	DENT du NIVOLET	U	BAUGES MASSIF		THE ALPS
B	CULOZ	F	CENTRAL JURA	J	VUACHE	N	MONT SALÈVE	R	ANNECY	V	BONNEVILLE		SALEVE
C	COL du CHAT	G	VAL du FIER	K	RUMILLY	O	MONT REVARD	S	LAKE of GENEVA	W	PRÉ-ALPS		THE JURA
D	SEYSSEL	H	GROS FOUG	L	AIX-les-BAINS	P	CHAMBÉRY	T	LAC d'ANNECY		MOLASSE PLAIN of France & Switzerland		

The Jura Mountains diverge from the Subalpine ranges at Chambéry (fig.4) and expand northwards as a virgation. From Chambéry to their northern limit at Baden they are separated from the Alpine front to the south-east by the Franco-Swiss molasse plain.

Although structurally the arc of the Jura Mountains terminates at Baden, the shelf sea or "Jurassian" facies of the Mesozoic continues north-eastwards from Baden into the unfolded Swabian Jura (fig.1). This range, too, is separated from the Alps by Tertiary deposits, here in the Bavarian Plain.

The Jura Mountains afford a characteristic scenery (figs. 2 & 9). Typically, but not always, the anticlines are arch-like mountains, and the synclines are the principal valleys. Strike vales ("combes") occur where the softer geological formations have been eroded, while the strike ridges ("crêts") form over the resistant members of the succession. A "cluse" (fig.2) is a valley or gorge which cuts across the strike. The terms in inverted commas above were all introduced in 1832 by Thurmann, the pioneer of geomorphological studies in the Jura.

The presence of anticlinal ridges and synclinal valleys in the Jura indicates a youthful topography. The molasse deposits, now confined mainly to the synclines, may once have existed over the anticlines, but this remains uncertain.

The soil from the molasse is much thicker and more fertile than that afforded by the majority of the Mesozoic

Plate 2.

PLATE 2

A. The Mont & Dents du Chat, & the Yenne valley. (Savoie).

B. The Fier gorge through the Cres Foug-Chambotte ridge, viewed from the Grand Colombier. In the foreground, the Rhône valley syncline, & in the distance the Franco-Swiss Molasse Plain.

limestones exposed in the anticlines. Hence, while the anticlines are heavily forested with fir and boxwood, which only require thin soils, the synclines are either grass covered, or cultivated for growing grain and vines. Examples of this are shown in plate 2, which illustrates the marked and abrupt change in vegetation from the limestones of the anticlinal ridges to the molasse terrain of the synclinal valleys in the south-eastern Jura.

(ii) Divisions of the Jura.

While reading the geological literature on the Jura Mountains, one can easily become confused by the numerous names used for different parts of the Range. It therefore has been considered useful to outline the various criteria for dividing the Jura and to explain the rather complicated nomenclature for the Range.

The north-western or convex border of the Jura crescent is basically flat-lying country. From south to north (see fig.3) the north-western limit of the Jura fold belt overlooks the Ile de Crémieu (faulted plateau of Mesozoic rocks), the alluvial deposits of the Saône, and a northern faulted plateau. This latter plateau, known as the Tabular Jura ("Jura Tabulaire" or "Tafel-Jura"), separates the main arc of the Jura, known as the Folded Jura ("Jura Plissé" or "Kettenjura"), from the Vosges Massif, the Rhine Graben and the Black Forest Massif. The junction between the Folded and Tabular Jura takes the form of a low-angle thrust plane over which the Folded Jura has been moved. Occasional isolated

FIG. 5

DIVISIONS OF THE JURA MOUNTAINS

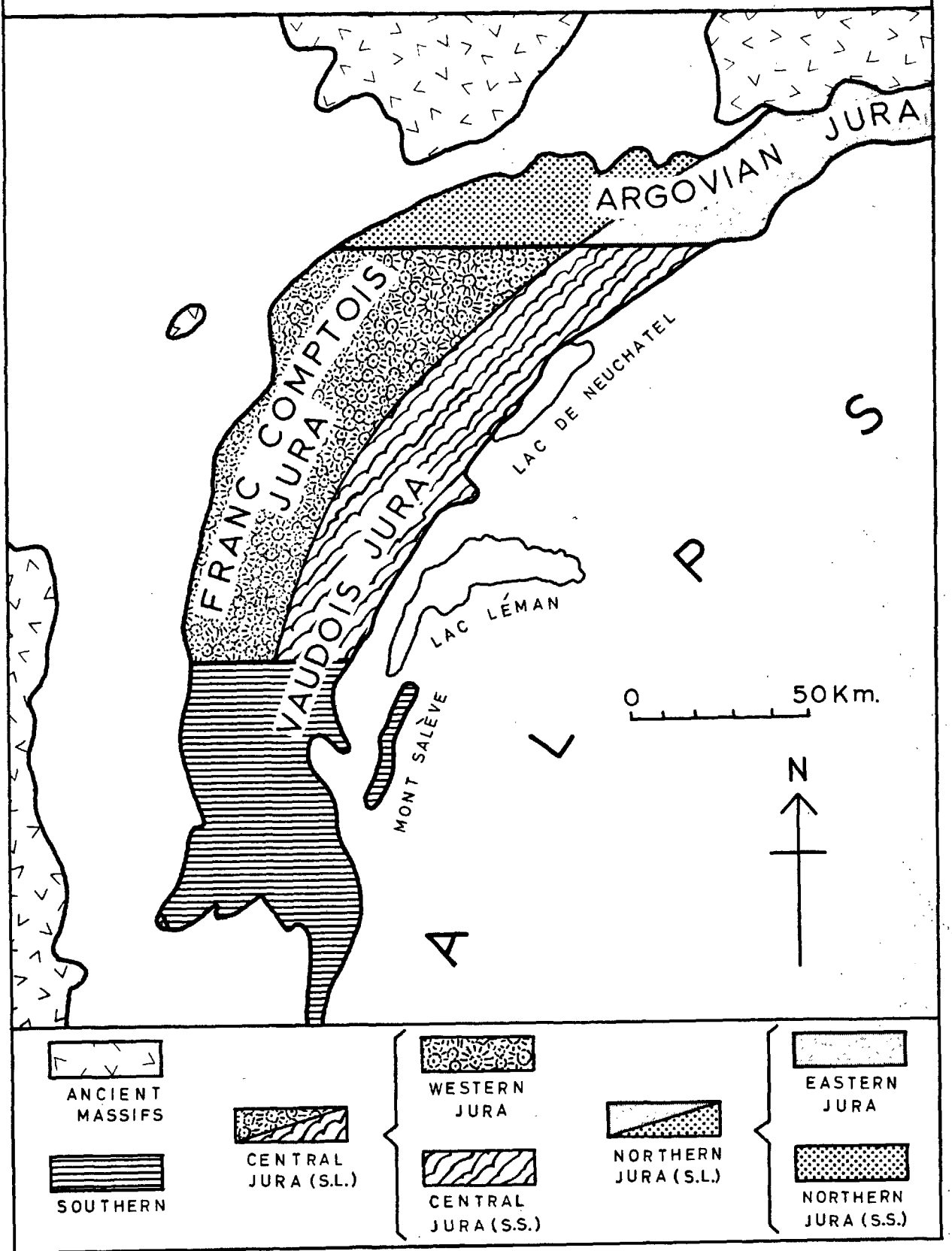
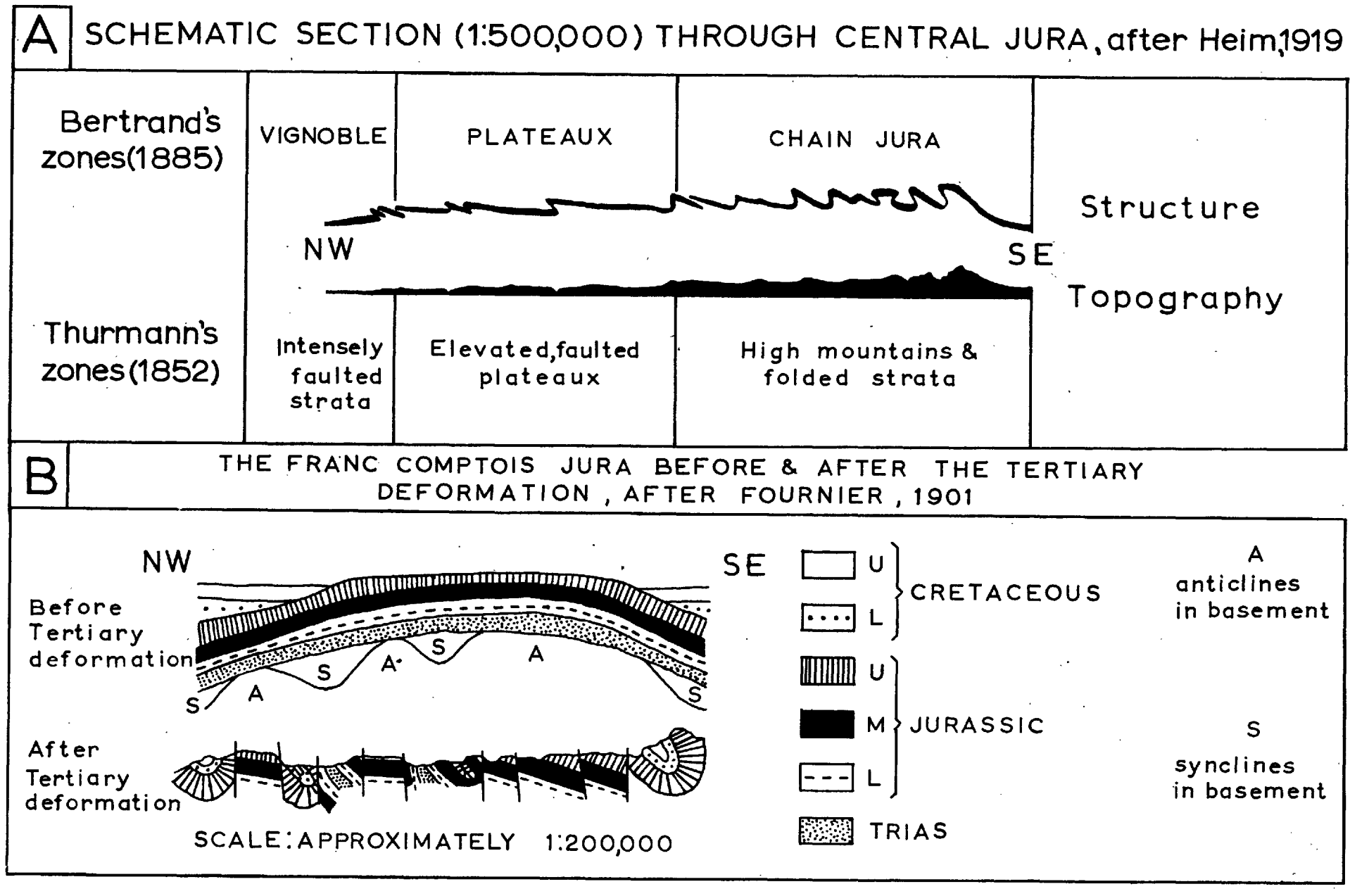


FIG. 6


A
SCHEMATIC SECTION (1:500,000) THROUGH CENTRAL JURA, after Heim, 1919
Bertrand's zones (1885)
VIGNOBLE
PLATEAUX
CHAIN JURA
Structure
NW
SE
Topography
Thurmann's zones (1852)
Intensely faulted strata
Elevated, faulted plateaux
High mountains & folded strata
B
THE FRANC COMPTOIS JURA BEFORE & AFTER THE TERTIARY DEFORMATION, AFTER FOURNIER, 1901
NW
SE
Before Tertiary deformation
After Tertiary deformation
A
S
SCALE: APPROXIMATELY 1:200,000
U
L
CRETACEOUS
U
M
L
JURASSIC
TRIAS
A anticlines in basement
S synclines in basement

klippen of the Folded Jura are found over the unfolded Jura tableland. The Tabular Jura is suspected to continue below the alluvium of the Saône, and to connect up with the unfolded Mesozoic strata of the Ile de Crémieu in the south. Meanwhile the Swabian Jura (fig.2) to the north-east of the Black Forest could be a continuation of the Tabular Jura in this direction.

In 1857 Marcou proposed a division of the Jura based on facies similarities between the rocks in the Range and those of the surrounding sedimentary basins. He attached approximately a third of the Jura to the facies of each of these basins. The division is rather imprecise but it is still employed by some present day geologists. The divisions (see fig.5) are as follows:

The facies of the Anglo-Paris Basin was related to the adjacent north-western part of the Jura, known as the Franc-Comptois Jura.

The facies of the German Basin was related to the adjacent north-eastern part of the Jura, known as the Argovian Jura.

The facies of the Mediterranean Basin was related to the adjacent southern part of the Jura, known as the Vaudois Jura.

Thurmann (1852) divided the Jura arc into three zones parallel to its length. These zones are best seen by examining a cross section through the central part of the Jura (fig.6A). Thurmann's zones were, from east to west:

The zone of high mountains and folded strata.

The zone of elevated relief and of unfolded but somewhat faulted strata, characteristically disposed in plateaux.

The zone of low altitude and of greatly faulted strata disposed, according to Thurmann, in numbrous plateaux.

In 1855 Marcel Bertrand elaborated somewhat on the individualities of Thurmann's zones (fig.6A). Bertrand's longitudinal zones of the Jura are those which are most commonly employed at the present day. From east to west these are:

The Chain Jura, a zone of folded strata with faulting associated with the folding. This division occupies the highest part of the range topographically and extends eastwards to the Franco-Swiss Plain.

The term "Chain Jura" is commonly, and incorrectly, used as a synonym of "Folded Jura". In fact the Chain Jura is the eastern-most zone of the Folded Jura.

The Plateaux, a zone of relatively unfolded strata cut up into three principal plateaux by major faults. The elevation of these plateaux increases from west to east. The southerly convergence of the major faults leads to the disappearance of the zone in this direction.

The term "Plateau Jura" is sometimes used as a synonym of "Tabular Jura". This leads to confusion since the Plateaux correctly form the middle longitudinal zone of the Central, Folded Jura. In contrast the Tabular Jura rim the convex side of the arc of the Folded Jura.

The Vignoble, a zone of greatly faulted Liassic and

Plates 3 & 4

PLATES 3 & 4

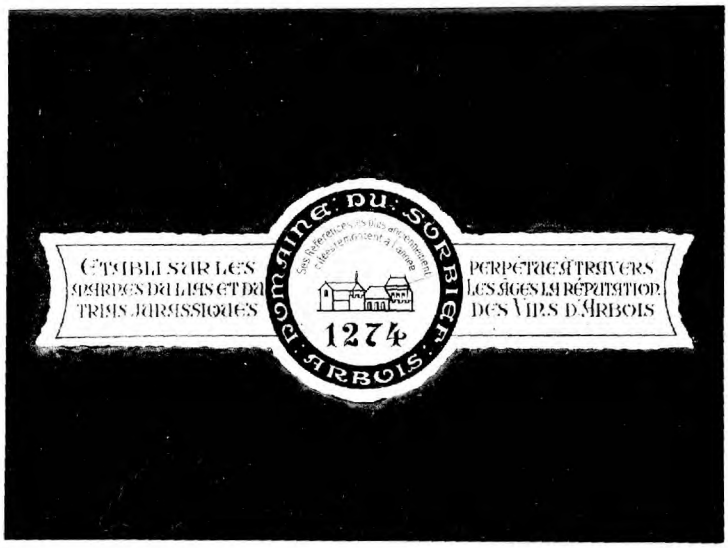


PLATE 3. Wine bottle label from Arbois (Jura). "Established on the Liassic & Triassic marls of the Jura".

PLATE 4. Typical Jura houses, Contrevoz, (Ain).

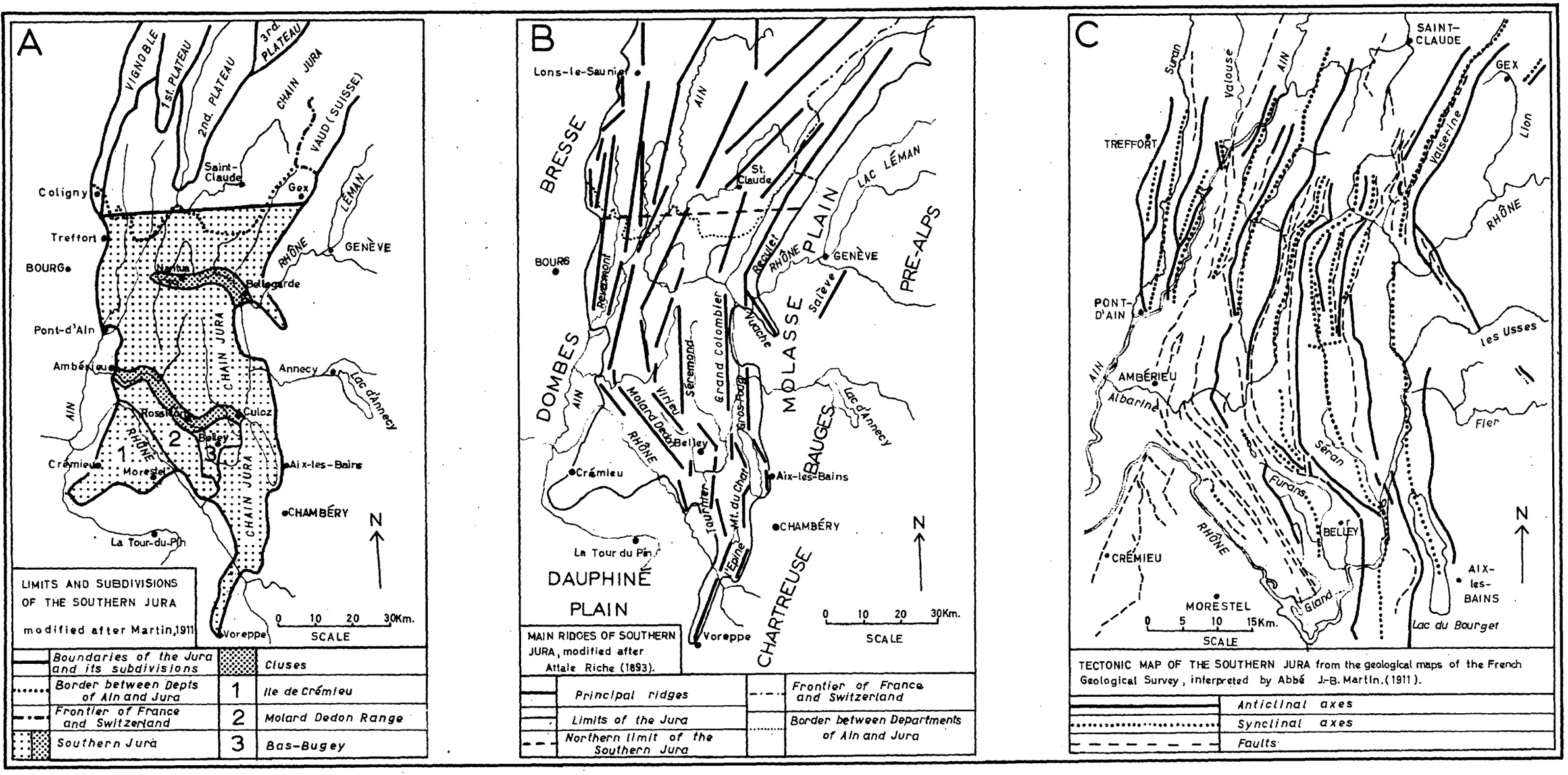
Triassic strata. Some shreds of Upper Jurassic rocks remain in this division due to the faulting (see fig.35).

The zones of the Plateaux and Vignoble are often classed under the single division of the "Ledonian Jura". This name is derived from the Latin, "Ledo Salinarius" for Lons-le-Saunier, the principal town in the neighbourhood.

The term "Vignoble" is not directly connected with the structure of the region, as are the terms "Plateaux" and "Chain" Jura. The name is, however, related to the geology. "Vignoble" means a large vineyard. The region of The Vignoble is cultivated, on account of its fertile soil, for the extensive vineyards of the "Côte du Jura" wines. The fertility of the soil is due to the outcrops of the Liassic and Triassic marls, which occur almost exclusively over The Vignoble, a fact which is acknowledged by the vine growers themselves, (see plate 3, of a wine bottle label from Arbois, Côte du Jura).

As well as distinguishing longitudinal zones in the Jura, Thurmann (1852) divided the Range transversally into four natural divisions separated by the deep gorges which cut across the structural trend of the Mountains. In 1887 Boyer simplified this scheme by having only three divisions, the limits of which did not, however, correspond to the positions of the deep transverse gorges. These were the Northern, Central and Southern Jura. Certain geologists now subdivide Boyer's Northern Jura into an eastern part, known as the

FIG. 7


A
VIGNOBLE
1st. PLATEAU
2nd. PLATEAU
3rd. PLATEAU
CHAIN JURA
VAUD (SUISSE)
Saint-Claude
Gex
LÉMAN
Coligny
Treffort
BOURG
Nantua
Bellegarde
RHÔNE
GENÈVE
Pont-d'Ain
Ambérieu
Annecy
Lac d'Annecy
AIN
Rossillon
Culoz
Belley
Crémieu
Morestel
Aix-les-Bains
CHAMBÉRY
La Tour-du-Pin
Voreppe
N
0 10 20 30Km.
SCALE
LIMITS AND SUBDIVISIONS OF THE SOUTHERN JURA
modified after Martin, 1911
Boundaries of the Jura and its subdivisions
Border between Depts of Ain and Jura
Frontier of France and Switzerland
Southern Jura
Cluses
1 Ile de Crémieu
2 Molard Dedon Range
3 Bas-Bugey
B
Lons-le-Saunier
BRESSE
AIN
St. Claude
LAC LÉMAN
PLAIN
PRE-ALPS
BOURG
Reyssouze
Seille
RHÔNE
GENÈVE
Salève
DOMBES
Grand Colombier
Fier
MOLASSE
Séremond
Virieu
Lac d'Annecy
Molard Dedon
Belley
Bas-Bugey
BAUGES
Crémieu
Aix-les-Bains
Tourbière
Mt. du Chat
CHAMBÉRY
La Tour du Pin
DAUPHINE PLAIN
Epine
CHARTREUSE
Voreppe
N
0 10 20 30Km.
SCALE
MAIN RIDGES OF SOUTHERN JURA, modified after Attale Riche (1893).
Principal ridges
Limits of the Jura
Northern limit of the Southern Jura
Frontier of France and Switzerland
Border between Departments of Ain and Jura
C
Suran
Valouse
AIN
SAINT-CLAUDE
GEX
Lion
Valserine
TREFFORT
RHÔNE
PONT-D'AIN
Les Usses
AIN
AMBÉRIEU
Albarine
Fier
Séran
Furans
RHÔNE
BELLEY
CRÉMIEU
AIX-les-BAINS
MORESTEL
Gland
Lac du Bourget
N
0 5 10 15Km.
SCALE
TECTONIC MAP OF THE SOUTHERN JURA from the geological maps of the French Geological Survey, interpreted by Abbé J.-B. Martin. (1911).
Anticlinal axes
Synclinal axes
Faults

Eastern Jura, and a western half termed the Northern Jura (sensu stricto). Similarly the Central Jura is often divided into a western zone, corresponding approximately to the Ledonian Jura, known as the Western Jura, and an eastern zone termed the Central Jura (sensu stricto). This terminology is summarised in fig.5.

B. THE SOUTHERN JURA.

The area studied by the present author lies in the Southern Jura, a region almost synonymous with the ancient province of Bugey. The limits of the Southern Jura are indicated in fig. 7 A & B. The northern boundary of the Southern Jura was arbitrarily fixed by Martin (1911). It corresponds to a line joining Gex in the east with the point between Treffort and Coligny in the west, where the zone of The Vignoble has its southern termination. The Southern Jura is divided basically into Haut - and Bas - Bugey. Many authors have taken the gorges of the cluse extending from Ambérieu via Rosillon to Culoz (fig. 7A & 8) to represent the demarcation line between the two regions. Such a division is independent of topography, since most of the western region south of the cluse is equally as high, or higher than the area north of the cluse. On this basis therefore, there would be an appreciable area of "haut" ground classified as "Bas" - Bugey. The present author refers to the area south of the Ambérieu-Culoz cluse as the "southern French Jura".

A more realistic division of Bugey on the basis of difference in altitude was made by Cholley (1931-1933). The

lowering of topography south of the cluse from Rosillon to Culoz was taken as the northern boundary of Bas-Bugey. The western limit followed the foot of the Molard Dedon, Tantainet and St.Benoît ridges (map 2). Cholley was rather vague about the southern and eastern limits of Bas-Bugey. The present author has adopted the basis of Cholley's division of Bugey but has defined more closely the southern and eastern limits to Bas-Bugey. These definitions are set out in full in chapter 16, which deals with the geomorphology of the region.

C. THE AREA WEST OF BELLEY (AIN).

(i) Limits of area mapped.

The area to the west of Belley, mapped by the present author (fig. 11) has boundaries, defined as follows: The northern limit coincides with the Amberieu-Culoz cluse over its stretch from la Burbanche to Pugieu (see map 1). The northern limit is also defined by the course of the river Furan which, from its source at la Burbanche flows down the cluse towards Pugieu. The eastern border of the region too is also fixed by the course of the Furan, which turns away southwards from cluse at Pugieu and, leaving Belley to the east, joins the Rhône east of Peyzieu. The southern border then follows the Rhône up to the valley of lac de Pluvis (see map 1). The overall western limit to the area basically follows the geological strike which is oriented approximately N.30°W. The author, however, has worked further to the west in certain places to elucidate specific problems of structure or facies.

The precise western limit (see map 1), runs from lac de Pluvis in the south, northwards to Crozet. The strike is then followed via Conzieu to Innimont. From here the western border resumes its northward trend up to la Burbanche. The environs of Cerin, west of Innimont, were also mapped, in order to determine the stratigraphical position of the interesting lithographic stone here which has, in the past, yielded an abundant vertebrate fauna.

(ii). Climate & human geography.

The area investigated experiences a cool-temperate climate. It is situated midway between the marine and continental sub-zones of this climate, as defined by Miller (1944). Snow falls during the winter months, especially over high ground. During other seasons precipitation typically takes the form of sporadic torrential downpours of rain, interspersed by fine hot spells. It is this alternation of rain and sun that gives the countryside its lush green and profuse vegetation.

Belley, the capital and religious centre of Bugey, has a population of about 6000 people. The majority of these farm the fertile lowlands of the molasse-bearing Belley syncline. Belley is famed for its Morocco leather and the local tanneries employ many of the inhabitants as well as a few of the people of the surrounding villages. The town is quite a good shopping centre.

The region as a whole is sparsely populated. Most villages have between 100 and 300 inhabitants, for example,

Prémeyzel with about 150. Somewhat larger villages are to be found in the cluse along which passes the "Route Nationale" from Lyon to Geneva and the main Paris to Geneva and Rome railway. Both Virieu-le-Grand and Culoz are villages in the cluse. They have a number of shops and populations approaching 1000 people. Virieu-le-Grand is especially important since its railway station serves the nearby capital, Belley. The village makes a conveniently accessible headquarters for visitors to the area.

The houses of Bas-Bugey have a characteristic and picturesque type of roof (plate 4). The angle of the roofs is made sufficiently steep so that during winter accumulated snow slides off before the burden can cause damage to the structure of the roof. The steepness of the roof, however, would prevent workers from carrying out repairs (replacing tiles etc.) and also from being able to deal with chimney fires from the top. Consequently several series of steps are built from flagstones over those parts of the roof supported by firm brick walls. This enables the roof to be climbed with ease.

Bugey is virtually unfrequented by tourists. The southern part, centred on Belley, is not even covered by the comprehensive Michelin guide of France. The area is, however, well known and loved by the people of Lyon who come regularly in spring to search for "escargot", and in summer to fish the rivers for trout and the lakes for carp, perch and pike. The truly delightful countryside is marred only by the intense

insect life, which is particularly vigorous near the marshes of the area and close to the cattle.

D. THE RESEARCH.

(i) Field & laboratory work.

The author spent a total of just over one year in the field during which time the area investigated was mapped on a scale of 1:20,000 (3.168 inches to the mile.)

Three weeks of the first season (1960) were spent examining stratigraphical successions in regions earlier mapped by members of Imperial College and comparing the stratigraphy of these successions with others exposed elsewhere in the Jura, for example in the environs of Nantua and St.Claude. This allowed the author to familiarise himself with certain of the lithological units mapped by his predecessors. The writer then spent six weeks studying a small central part of the area, investigated in detail. The selected terrain lay to the east of Ambléon and west of the Furan, (see map 1). The whole of the exposed stratigraphical column was sampled for subsequent laboratory study. The initial work in the laboratory was carried out during the winter season, 1960/61. As a result of an examination of thin sections and polished surfaces of the samples collected, it was realised that the coarser grained lithologies were more amenable to microscopic study than their finer grained counterparts, since the particles of the latter could rarely be resolved even when using a high power oil-immersion objective lens.

It was therefore decided to study in detail those coarse-grained rocks which offered the greatest variability in composition. The remainder of the succession was described in general terms from thin sections. Also during the 1960/61 winter season the criteria upon which the lithological mapping units had been earlier distinguished in the field were all tested in the laboratory. Most of these criteria were shown to be valid. Others were found to require certain modification.

The author spent the six months from March to August inclusive, in the field in 1961. The summer was poor and much torrential rain hindered field work. All the relatively low-lying ground in the area, as well as the high terrain of the Montagne d'Izieu (see map 2) was mapped during this period. In addition the small area mapped the previous summer was re-examined and checked in the light of the winter's laboratory study.

A microscope and apparatus for making thin sections were taken into the field in order to study specific problems in limestone petrology as these came to light in the field. Included in the laboratory apparatus were reagents to stain thin sections and polished surfaces. Since the summer was so poor the author accomplished an appreciable amount of laboratory work in the field. Many of the petrological problems, later given detailed study in the laboratory, were initially found during these preliminary intestigations in the field. In the winter season 1961/62, laboratory studies were made on specific petrological and petrographical problems.

Meanwhile the systematic thin section description of the formations mapped, was continued.

A third, and final field season began in May 1962 and lasted four months. The summer was extremely dry and conditions were ideal for field work. The mapping of the area was completed during this season, with the investigation of the high forested terrain of the Molard Dedon-Innimont ridge (map 2). In addition , the field problems opened up by the laboratory studies of the previous winter were investigated. On account of the beautiful weather experienced during the summer of 1962, the author spent the maximum possible time in the field. Laboratory apparatus brought to France was consequently, scarcely used.

The winter of 1962/63 was spent partly in writing up the results of the research and in the preparation of this thesis. Some laboratory work was, however, undertaken in order to complete the studies made during the previous winter.

(ii) <u>The themes of the research</u>.

(a) <u>General</u>.

The main contribution in this thesis is the geological map (map 1). The time spent in distinguishing and mapping the distributions of the various lithological units far outweighs that spent on any other single problem. Furthermore, the draughting of the map from field slips took longer than the drawing of any of the other illustrations in this thesis. Apart from this main contribution the results of the

investigations carried out by the author fall into four themes for this thesis, a section of which is devoted to each.

(b) Pre-Mesozoic & Mesozoic stratigraphy.

The exposed Mesozoic succession in the area extends from the Bajocian to the Aptian and includes three principal coral reef horizons. The rocks are all calcareous and nearly all limestones. At first, differences in lithology within the succession are difficult to recognise. However, as the rocks become more familiar during the course of study, they are seen to consist of almost every grade of sediment from conglomerate to clay. It is the presence of calcium carbonate, almost to the exclusion of other components in the Mesozoic rocks (a reflection of foreland sedimentation), which makes it initially difficult to identify the lithological sub-divisions present. Nevertheless, it was necessary to recognise these lithostratigraphical divisions of the succession before the mapping of the area could successfully commence. Hence the characteristics of as many distinctive lithologies as could be found were preliminarily noted for the purposes of this field mapping. The principal lithological units were named after type localities where they were considered to be best exposed in the region. During the course of mapping and subsequent laboratory work, more and more distinctive features of the lithological formations were found. In addition, the number of recognisable mapping units increased. At times, during the work of the present

TABLE I

TABLE I.

Mesozoic succession in the southern French Jura.[1]

Formation		Stage	Approximate thickness
"Gault"		Albian	?
Chambotte Limestone		Barremian(?)-Aptian	160m
Bourdeau Beds		Hauterivian-Barremian(?)	60-120m
Parves Beds	Upper	Valanginian	50m
	Middle	Berriasian	20m
	Lower	Portlandian s.l.[1] ("Purbeckian")	110m
Virieu Limestone	Upper = Massive	Kimmeridgian(?)[1]. Portlandian s.l.[1]	100-400m
	Lower = Bedded	Kimmeridgian[1]	70m
Oignon Beds		Lower Kimmeridgian	60m
Chavoley Beds		Middle Oxfordian-Lower Kimmeridgian	200m
Chanaz Beds	Upper & Middle	Bathonian-Callovian	50m
	Lower	Upper Bajocian	15m
Ambléon Limestone	Upper	Bajocian	40m
	Middle		95m
	Lower		80m
Cuzieu Beds	Upper = Flags	Aalenian[1]-Lower Bajocian(??)	100m
	Lower = Shales	Pliensbachian(?)-Toarcian	
Chazey-Bons Limestone		Sinemurian-Pliensbachian(?)	?

1. The stare usage is that recommended by the Luxemburg Jurassic Colloquium, 1962, as accepted by the British Mesozoic Committee (Ager,1963b).

TABLE II

TABLE II.

STRATIGRAPHICAL STAGES OF THE MESOZOIC SUCCESSION INVESTIGATED.

A. Cretaceous stages.

Neocomian (Wealden)	Albian, Aptian, Barremian	"Urgonian" reef facies
	Hauterivian, Valanginian, Berriasian	(Infra-Valanginian)

B. Jurassic stages.

	British Mesozoic Committee, Ager (1963b)	Arkell (1956)	French Authors
UPPER = MALM	Portlandian	Purbeckian, Portlandian	Portlandien: Purbeckien (Tithonien), Bononien
	Kimmeridgian	gravesiana, beckeri, tenuilobatum: Kimeridgian	Kimmeridgien: Bolonien, Virgulien, Ptérocerien; Séquanien = Astartien, Rauracien, Argovien, Oxfordien; Lusitanien
	Oxfordian	Oxfordian	
MIDDLE = DOGGER	Callovian	Callovian	Callovien
	Bathonian	Bathonian	Bathonien
	Bajocian, Aalenian	Bajocian	Bajocien, Aalénien
LOWER = LIAS	Toarcian	Toarcian	Toarcien
	Pliensbachian	Pliensbachian: Domerian, Carixian	Pliensbachien: Domérien, Carixien; Charmouthien
	Sinemurian	Sinemurian s.l.: Upper, Lower	Lotharingien; Sinémurien s.s.
	Hettangian	Hettangian	Hettangien
			Rhétien
TRIAS	Rhaetian	Rhaetian	
	Keuper	Keuper	Keuper

author and of other members of the team from Imperial College it became necessary to replace certain of the original type localities by better exposed sections elsewhere. In this way the nomenclature for the lithological formations developed and matured to that in present use, (Ager & Evamy, 1963). This is illustrated in Table I. Here, the names and thicknesses of the lithological units are presented in stratigraphical sequence.

Fossils collected from each lithostratigraphical unit by the author in the area west of Belley, and by other members of the team from Imperial College elsewhere in the southern French Jura provided data for subsequent biostratigraphical interpretation. The ammonite, brachiopod, and echinoid faunas yielded the principal evidence from which the sequence of stratigraphical stages was elucidated. This sequence is shown in Table I. in relation to the succession of lithostratigraphical units recognised in the field.

The names of the stages used for the Jurassic are those recently recommended by the Luxemburg Jurassic Colloquium (1962), as accepted by the British Mesozoic Committee (Ager 1963b). These stage names are related to those of Arkell (1956) in Table II.

French geologists who have worked in the region have made a practice of mapping stages directly. This rather subjective approach makes it difficult to distinguish observation from inference, and it is confusing often to find

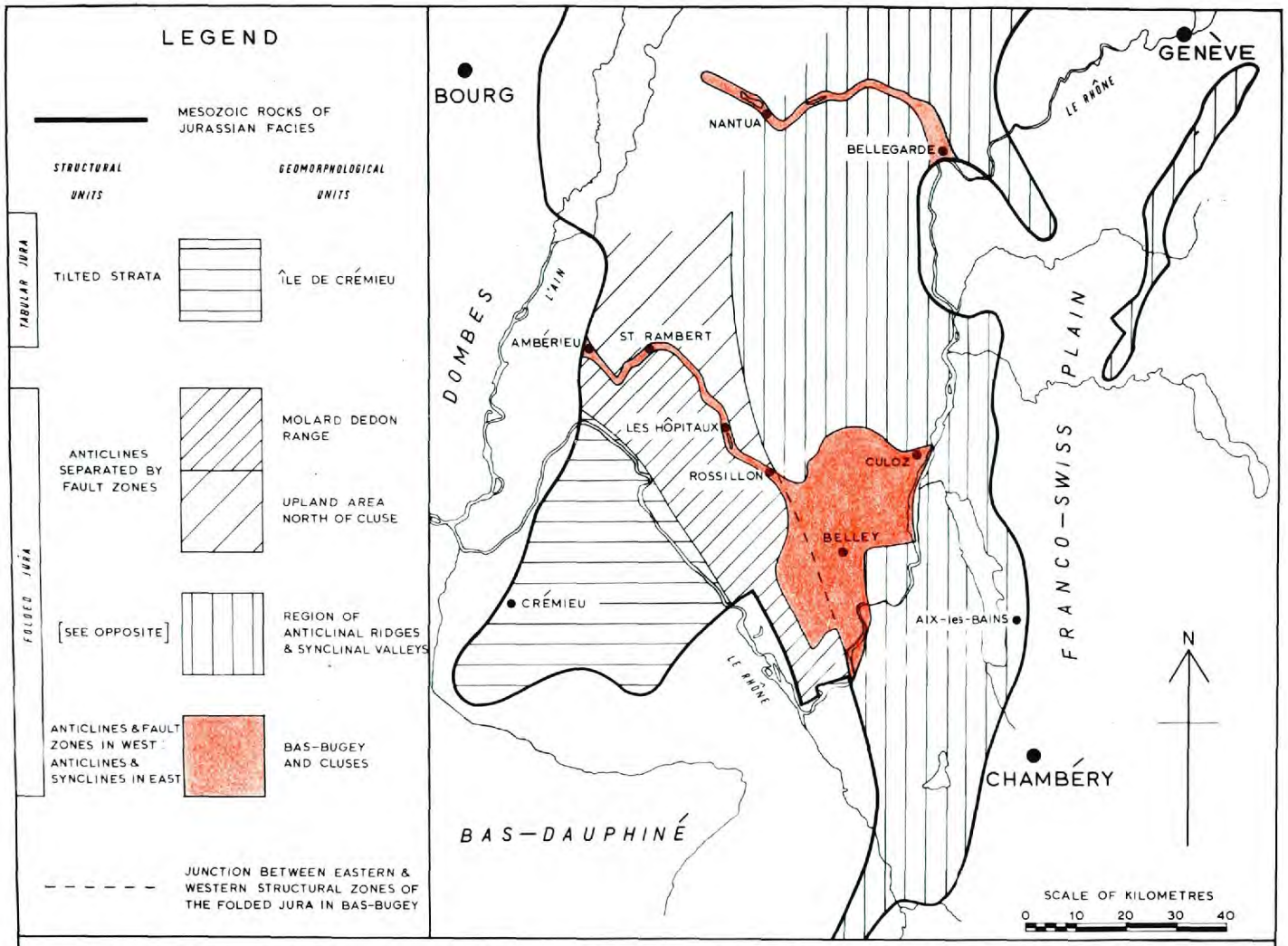
that the "Bajocien" of one author is the "Bathonien" of another Since the fossil faunas and floras upon which the limits of stages are defined are restricted in distribution, it must ultimately be the lithological unit which is mapped. It is highly unlikely that stage boundaries should correspond exactly to the limits of mapping units. The French stage names, shown for clarification against those recommended by the British Mesozoic Committee and those of Arkell (Table II), are only used in this thesis where reference is made to the work of French geologists. Then the names are enclosed in inverted commas.

The Mesozoic succession in the area mapped begins with the Bajocian. The Lias is only poorly seen in the southern French Jura. Liassic and Triassic rocks are best known from the exposures in The Vignoble, the westernmost zone of the Folded, Central Jura. The Bureau de Recherches Géologiques et Minières have put down numerous boreholes into this zone in a programme to explore the coal-bearing Stephanian Basin below Lons-le-Saunier. The cores from these boreholes, some of which have reached the crystalline basement, and the natural outcrops in The Vignoble make this zone a classic area for studying the late Palaeozoic and early Mesozoic stratigraphy of the Jura. For this reason the pre-Bajocian geological history of the region is summarised from publications by members of the B.R.G.M. at Lons-le-Saunier and from personal communication with these authors appertaining to the outcrops and deep cores of the Ledonian Jura.

In the area mapped the Bajocian consists of shallow-water bioclastic calcarenites (Cuzieu Flags and Lower Ambléon Limestone), a notable reef development (Middle Ambléon Limestone) and oolite (Upper Ambléon Limestone). This is followed by a highly fossiliferous calcarenite sequence in the Bathonian and Callovian (Chanaz Beds). After a discontinuity or condensed sequence covering the Lower Oxfordian, a deeper water facies (Chavoley Beds) prevails through the Upper Oxfordian into the Lower Kimmeridgian. This passes upwards into regularly bedded calcilutites with some bedded dolomite (Oignon Beds). A pisolite horizon heralds the return of shallower water conditions during the deposition of the Lower or "Bedded" Virieu Limestone and the cycle of sedimentation is completed by a massive reef limestone (Upper or "Massive" Virieu Limestone) of Upper Kimmeridgian and/Lower Portlandian age. Well-bedded lagoonal limestones (Lower Parves Beds) terminate the Jurassic succession in "Purbeckian" facies. The return of marine conditions with numerous halts and subsidiary cycles of sedimentation, occurs in the Lower Cretaceous.Neocomian shallow water calcarenites (Middle and Upper Parves Beds and Bourdeau Beds) are surmounted by a third reef development (Chambotte Limestone) in the Aptian.

The present author has made a special study of the lower exposed formations (Cuzieu Flags, Ambléon Limestone and Chanaz Beds). In this there has been little overlap with the earlier work of Khouri (1960), who analysed the Parves and Bourdeau Beds in detail. The succession from the

FIG.8



STRUCTURAL AND GEOMORPHOLOGICAL UNITS OF THE SOUTHERN FRENCH JURA

Chavoley Beds to the Chambotte Limestone has been described in general terms by the present author.

(c). Caenozoic stratigraphy.

Caenozoic deposits are widespread over the area mapped. They tend, however, to be poorly exposed due to thick soil cover. At the base of the molasse a conglomerate is found made up of limestone boulders and gravels of local origin. This is overlain by grey-green poorly cemented, cross-bedded, micaceous sandstones, probably of fluviatile origin. The Quaternary deposits consist of boulder clay, fluviatile gravel (made up of pebbles of metamorphic and igneous rock) and large erratic blocks of green schist. Whereas the boulder clay and fluviatile gravel tend to be concentrated over the low-lying terrain, the large erratic blocks are found over both high and low ground alike. In discussing the Caenozoic stratigraphy of the area some reference is made to the geomorphology, which developed during the Caenozoic. It must be stressed that the section on Caenozoic stratigraphy is not regarded as a main theme in this thesis.

(d). Geomorphology and Geological structure.

The southern French Jura, that is the area south of the Ambérieu-Culoz cluse, falls into four geomorphological units (figs. 7A & 8) which, taken from west to east, are as follows.

Ile de Crémieu, a plateau of faulted Mesozoic rocks, tilted gently to the south-east. This region is a southern outpost of the Tabular Jura.

Molard Dedon Range, an upland area made up of relatively unfaulted anticlines separated by zones carrying numerous strike faults. The Molard Dedon Range extends from the western scarp of the Folded Jura above the Rhône eastwards to the low ground below the Molard Dedon, Tantainet and St.Benoît ridges (see fig.8.& map 2). The Molard Dedon Range is a part of Haut-Bugey.

Bas-Bugey, a lowland area, centred on Belley, through which pass narrow fault zones, and broad anticlines and synclines.

Chain Jura, a zone of forested ridges exposing Mesozoic strata (generally disposed in anticlines) separated by fertile valleys (usually synclinal) often carrying molasse. This is the eastern-most zone of the Folded Jura, as defined by Bertrand (1885).

The anomalous lowland area of Bas-Bugey has a structure in the west resembling that of the Molard Dedon Range and in the east that of the Chain Jura. It is evident that the four geomorphological units of the southern French Jura fall into three structural zones. These are, from west to east, the Tabular Jura, the zone of anticlines separated by shatter zones, and the zone of anticlines separated by broad synclines. The structure and geomorphology of the southern French Jura has recently been described by Ager and Evamy (1963).

The area mapped in detail occupies a privileged position in that it straddles the western boundary of

Bas-Bugey (see map 2), lying in part in the high ground of the Molard Dedon range and in part over the low ground of western Bas-Bugey. Structurally too, the area lies in an important position spanning the boundary between the zone of anticlines separated by shatter zones and the zone of anticlines separated by broad synclines (see fig.8). Taken from west to east the main structures of the area mapped are as follows:

The Tantainet-St.Benoît anticline. This structure lies over heavily forested Mesozoic terrain, parts of which have been mapped by the author. The eastern flank of the anticline which in the south of the area rises steeply into Haut-Bugey, is generally taken as the western limit of the area mapped.

The Crapéou - Izieu fault zone. This is composed essentially of well-exposed Mesozoic strata involved in numerous strike faults. Rather poorly-exposed Tertiary deposits are also found in the fault zone. Part of the fault zone passes through Bas-Bugey. Most of it, however, is to be found in the Molard Dedon Range.

The Ordonnaz-Ambléon-Prémeyzel anticline. This structure forms the principal part of the area mapped. It is a typical "box-fold" in the south. Further north subsidiary anticlines arise on each flank of the main structure. This is illustrated diagrammatically in fig.2. The flat "box-roof" of the main structure becomes synclinally disposed between the two flanking anticlines (see map 2). In describing the

distribution of the various formations mapped it has been found convenient to give each element of the main structure an independent name (see map 2). The eastern subsidiary anticline has been termed the Molard Dedon-Colomieu anticline. This is separated from the main fold by the Arborias syncline. The main fold, from just north of Ambléon south-eastwards via Prémeyzel to the Rhône, has been referred to as the Ambléon-Prémeyzel fold. The syncline between the two subsidiary anticlines is known as the Innimont syncline and the western subsidiary anticline is the Innimont anticline. The central part of the Ordonnaz-Ambléon-Prémeyzel anticline passes through western Bas-Bugey. Both its northern and southern extremities, however, lie in the Molard Dedon Range.

Rosillon-Belley Syncline. Parts of this broad molasse-bearing syncline extend into the area mapped. The structure marks the beginning of the zone where broad synclines alternate with anticlines.

(e). Specific laboratory studies. Most of the work described in the final part of this thesis has involved the application of chemical staining techniques to the study of diagenesis in limestones.

CHAPTER 2.

REVIEW OF PREVIOUS WORK.

The history of research carried out on the Jura Range and specifically on the area considered in this thesis, may be conveniently divided into the following phases:

A. The phase of investigation executed prior to the formation of the Geological Society of France (1779-1830).

B. The phase of work accomplished after the inauguration of the Geological Society of France, but before the formal establishment of the French Geological Survey (1830-1874). This phase may be subdivided into the following periods.

(i) The period during which official topographical base maps were not yet available (1830-1860).

(ii) The period during which published topographical base maps became obtainable (1860-1874).

C. The phase of research effected after the establishment of the French Geological Survey (1874 to the present day). This phase may be subdivided into the following periods.

(i) The period of initial organisation in the French Geological Survey (1874-1897).

(ii) The period of the publication and first revision of the Chambéry sheet, 1:80,000 geological map (1897-1911).

(iii) The period of lull in geological research, but of significant advance in geomorphological study, (1911-1946).

(iv) The period of recent geological research in the Chambéry region (1946 to the present day).

A. INVESTIGATION CARRIED OUT BETWEEN 1779 & 1830.

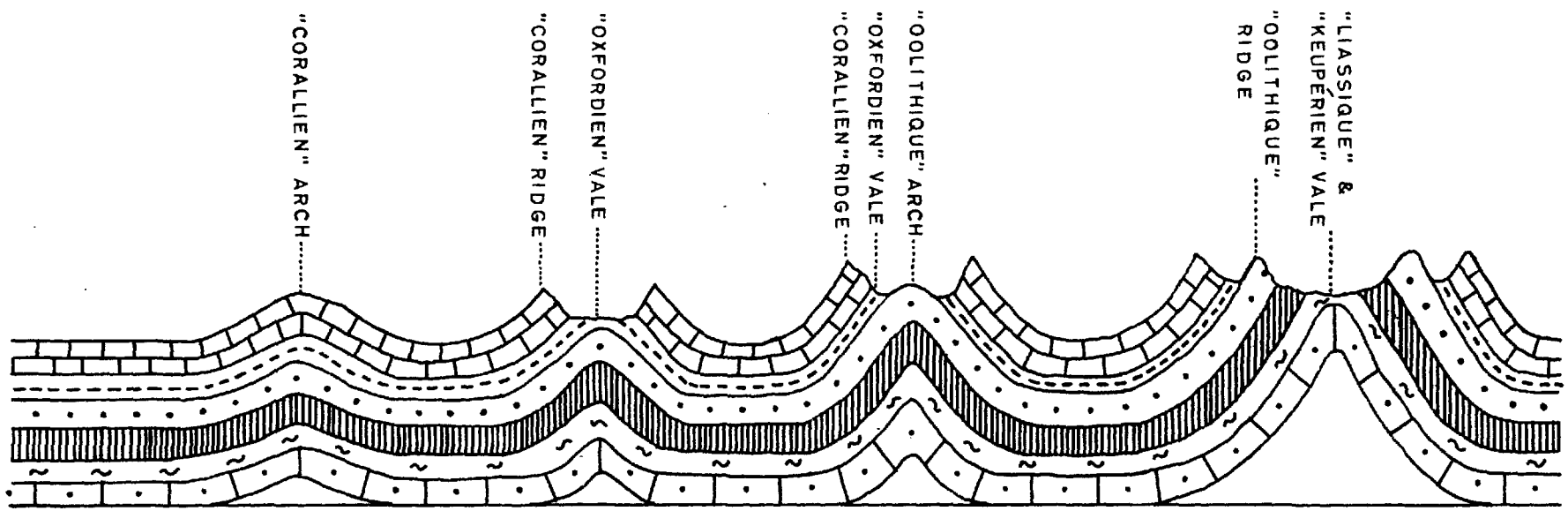
The Jura Mountains have attracted the interest of geologists since the latter half of the eighteenth century. References to the mineralogy of the rocks in the Jura, especially in the environs of Lons-le-Saunier, go back to the mid-seventeen hundreds. The first general account of the Range, however, appears to be that of the Benedict de Saussure (1779) who specially commented on the numerous subparallel ridges of these mountains.

Until 1830 (date of the inauguration of the French Geological Society) geologists tended only to recognise the more spectacular features of the geology of the Jura, for example, the steeply dipping beds, the folds and the faults beautifully exposed in some of the cluses which cut across the Range. Leopold de Buch was one of the principal contributors to the study of the Jura during this period. While de Buch (references in de Margerie, 1922) was engaged upon the geology of the Swiss Jura, Billiet (1823) was preparing the first accounts of the geology around Chambéry (Savoie). It was during this initial period of work on the Jura that the first reference appears in the geological literature, to the region of Bugey. This is Dupasquier's description (1825) of the mineralogy of the rocks near St.Rambert-en-Bugey, a a town in the cluse near Ambérieu.

Very little of the Mesozoic stratigraphy had been elucidated by 1830. This is understandable since, from Lias

FIG. 9

GEOMORPHOLOGY RELATED TO INTENSITY OF FOLDING & SUBSEQENT EROSION, AFTER THURMANN (1832).



"CORALLIEN"

"LIASSIQUE"

"OXFORDIEN"

"KEUPÉRIEN"

"OOLITHIQUE"

"CONCHYLIEN"

to Lower Cretaceous the stratigraphical succession in the Jura is composed essentially of limestone. It requires more than a cursory glance to familiarise oneself with the variations in lithology present, and to extract a diagnostic fauna. Due then to the absence of a dependable stratigraphy, correlations between successions some distance apart, were lacking. Thus the formulation of a regional tectonic analysis of the Range was impracticable at this stage.

B. INVESTIGATION CARRIED OUT BETWEEN 1830 & 1874.

(i) 1830-1860.

The first meeting of the French Geological Society took place on March 17th, 1830. The influence of the Society on research in the Jura was fundamental. Shortly after its inauguration J.Thurmann (1832) published the first of his classic works on the geomorphology of the Range. This began a new era in the history of geological investigation on the Jura. In his well-known "Essai sur les soulèvemens jurassiques du Porrentruy" (1832), Thurmann described the Jurassic stratigraphy of Porrentruy (north-west Switzerland, near Basel). He noted in particular the alternation of resistant limestones in the Middle Jurassic and the Kimmeridgian, with the soft calcareous marls in the Keuper, Lias, and Oxfordian. He then put forward his "théorie orographiques du soulèvemens jurassiques en quatres ordres" in which the strike valleys and ridges of the Jura were explained in terms of the degree of uplift by folding, and of subsequent erosion (see fig.9).

In 1835 Rozet, founder member of the French Geological Society, successfully applied Thurmann's ideas on geomorphology to the Southern Jura. Then came a flood of similar work by numerous geologists, all applying Thurmann's concepts to various parts of the Jura. Their accounts may be found in the early bulletins of the French Geological Society. This was clearly the age of Thurmann's "soulèvemens".

The accomplishments of Thurmann stimulated great interest in the stratigraphy of the Jura, as well as in its geomorphology. It was here that Gressly (1838-41) first introduced the concept of facies into geological terminology. One of the most fundamental discoveries of this time, however, was that of Lory who, in 1849, recognised a fresh water deposit between the Neocomian and Portlandian. This discovery began the long history of work which has led to the recognition of a highly complex lagoono-lacustrine "Purbeckian" facies in the Jura.

During this period the first geological map of France was published by order of the Ministry of Public Works. The geology on the map was explained by three accompanying volumes (1841, 1848 and 1873) written by Dufrénoy and de Beaumont, both mining engineers. The work to produce this map began in 1825, according to a notice put in the Annales des Mines of 1827. Field workers must have prepared their own topographical base maps for the survey. The first volume of explanation (1841) dealt with the Triassic and older rocks. The second volume (1848) dealt principally with the Jurassic,

though it contained no account of the Jura Mountains. The third and final volume (1873) described the Chalk, Tertiary and Recent sediments and the volcanic rocks of France. Thus a government organised geological survey began in France some 10 years before that in Britain. However, the official Geological Survey of France, also organised by the Ministry of Public Works, was not formally established until much later, in 1874.

The increased knowledge of the stratigraphy of the Jura, due to the work of Thurmann and his followers, allowed more reliable correlations to be made between stratigraphical successions some distance apart. Seigfried from Zürich, and Studer from Bern (1851-53) used this increased knowledge to draw up the first comprehensive structural analysis of the Swiss Jura.

Geological investigation in the Southern Jura was not intense during this period. Millet (1935) was the first to comment on the geology around Belley. He identified the three basic divisions of the Jurassic in the region and rightly stressed the dominance of the Malm. He correctly attributed the Gryphaea limestone of Chazey Bons (Sinemurian), in which he noted much lignite, to the Lias. However, he wrongly assigned the crinoidal calcarenites of Bas-Bugey (Ambléon Limestone, Bajocian), also to the Lias. He gave analyses of the Upper Oxfordian "chaux hydraulique" (cementstone) of the area. Millet realised that the Mesozoic

rocks of the Grand Colombier had been folded into an anticline separating the synclinal areas of Valromey and the Rhone Valley which, like the Belley syncline, contained Tertiary molasse.

More comprehensive studies upon the geology of Ain were carried out by Millet in 1839 and 1840. In 1839 he published a paper dealing exclusively with the Keuper of Ain which he divided into lower variegated marls and upper sandstones, possibly of the Infra-Lias. Millet listed the fauna and common minerals occurring in the Keuper. He discussed its economic geology and the fertility of its soil. In 1840 he read a paper along similar lines, this time specially treating the Lias of Ain, which he divided into lower Gryphaea limestone and upper belemnite marls (presumably the Cuzieu Shales). It was a pity that Millet terminated his work here, for accounts of all the exposed stages in the succession would have provided a valuable contribution at this time, to the knowledge of stratigraphy in the Southern Jura.

In August, 1844, the Geological Society of France organised their first "réunion extraordinaire à Chambéry". It was during this meeting that the first reported excursion to the now celebrated Col du Chat (fig.4.) was made.

This period of research in the Southern Jura was marked by the discovery of a lithographical stone at Cerin. In 1838 Drian, an engineer from Lyon, found fossil reptiles and fish as well as plant remains in this now famous Cerin

Stone. Jules Itier, who since 1821 had been describing similarly fossiliferous beds from elsewhere in the Bas-Bugey, attributed the Cerin Stone to the "Kimmeridgien". From 1840 to 1866 various French and German geologists proposed ages ranging from Oxfordian to Portlandian for these beds. However, first Lory (1866), and then Ebray (1874) later confirmed Itier's original opinion that the lithographic stone is of "Kimmeridgien" age.

In 1846, after making some preliminary descriptions of the fish he had found at Cerin, Drian communicated with Victor Thollière about his discoveries. Thiollière , an expert on vertebrates, then examined the vertebrate fauna as it issued from Cerin. He published numerous descriptions of the fish and other vertebrates (1848, 1850, 1852, 1854, 1858 & 1859).

(ii) <u>1860-1874.</u>

Official topographical maps of the Jura "à l'état major" 1:80,000) became available in 1860. This encouraged geologists to plot their field data directly onto accurate base maps. As a result of this, litho-stratigraphical studies began to appear in the geological literature. From 1862-1874 the Swiss Jura were subjected to an intensive field survey organised by La Société Helvetique des Sciences Naturelles. It was during this period that Moesch published his classic treatise (1867) on the stratigraphy of the Swiss Jura.

In France mining engineers who, as members of an "embryo" Geological Survey, had earlier produced the first

official geological map of France, prepared the first detailed (1:80,000) geological maps of the Jura. The geology of the area covered by the present Chambéry sheet, however, was not mapped at this time.

The reluctance of the geologists in the south to start mapping, was probably because their principal interest still lay in the magnificent vertebrate fauna issuing from the quarry of lithographic stone at Cerin.

In 1871 Falsan found the illustrations for Thiollière's second major work, which had remained uncompleted after the latter's death. The illustrations had been missing for about 10 years. As a consequence of this find Falsan and Dumortier decided to publish a posthumous memoir for Victor Thiollière on the fauna from Cerin. In this they were aided by Paul Gervais, one of Thiollière's students.

C. INVESTIGATION CARRIED OUT BETWEEN 1874 & THE PRESENT DAY.

(i) 1874-1897.

During this period two important general works on the Jura were completed. These were Maillard's thesis on the Purbeckian of the Swiss Jura (1884), and the first of de Loriol's fine monographs on the fauna of the Jura (1876-1898) Having, since 1825, proved itself more and more necessary in an unofficial capacity the French Geological Survey was formally inaugurated in 1874. It was not until 1889, however, that the first of its bulletins was published. According to de Margerie (1922), Douxami, Hollande and Riche mapped the area covered by the Chambéry sheet for the Survey. The

mapping commenced in 1884 and took approximately five years to complete. After this, there seems to have been a delay of nine years before the first references to the Chambéry region appeared in the Survey literature. These references took the form of reports, published in 1898, of field work carried out by Douxami, Hollande and Riche in the previous season ("Comptes rendus des collaborateurs pour la campagne de 1897").

Earlier on, in 1880 and 1884, D.Hollande described stratigraphical successions from the Jura folds in parts of Ain, and most of Savoie. He also made some tentative correlations between the "Purbeckien" of the Grand Colombier and the Montagne du Chat. In 1885 he reported on an alternation of marine and fresh-water bands in the "Purbeckien" of the Montagnes du Chat and d'Izieu. (The latter ridge is in the area mapped by the present author.)

In 1884 and 1885 the Geological Society of France held the second of its "réunions extraordinaires" in the Jura. Field trips were organised from Chambéry. Hollande and Pillet contributed to the meeting by leading excursions to la Balme gorge, Vions and Chanaz, (see map 3). Pillet (1885b) who reported on these visits dealt mainly with his prime interest, the "Purbeckien" macrofauna. The successions at la Balme gorge (through the Parves-Tournier ridge) and the Col du Chat soon became celebrated for their "Portlandien" and "Purbeckien" fauna. Meanwhile it came to be a matter of routine for geological excursions in the area to visit Chanaz, where a

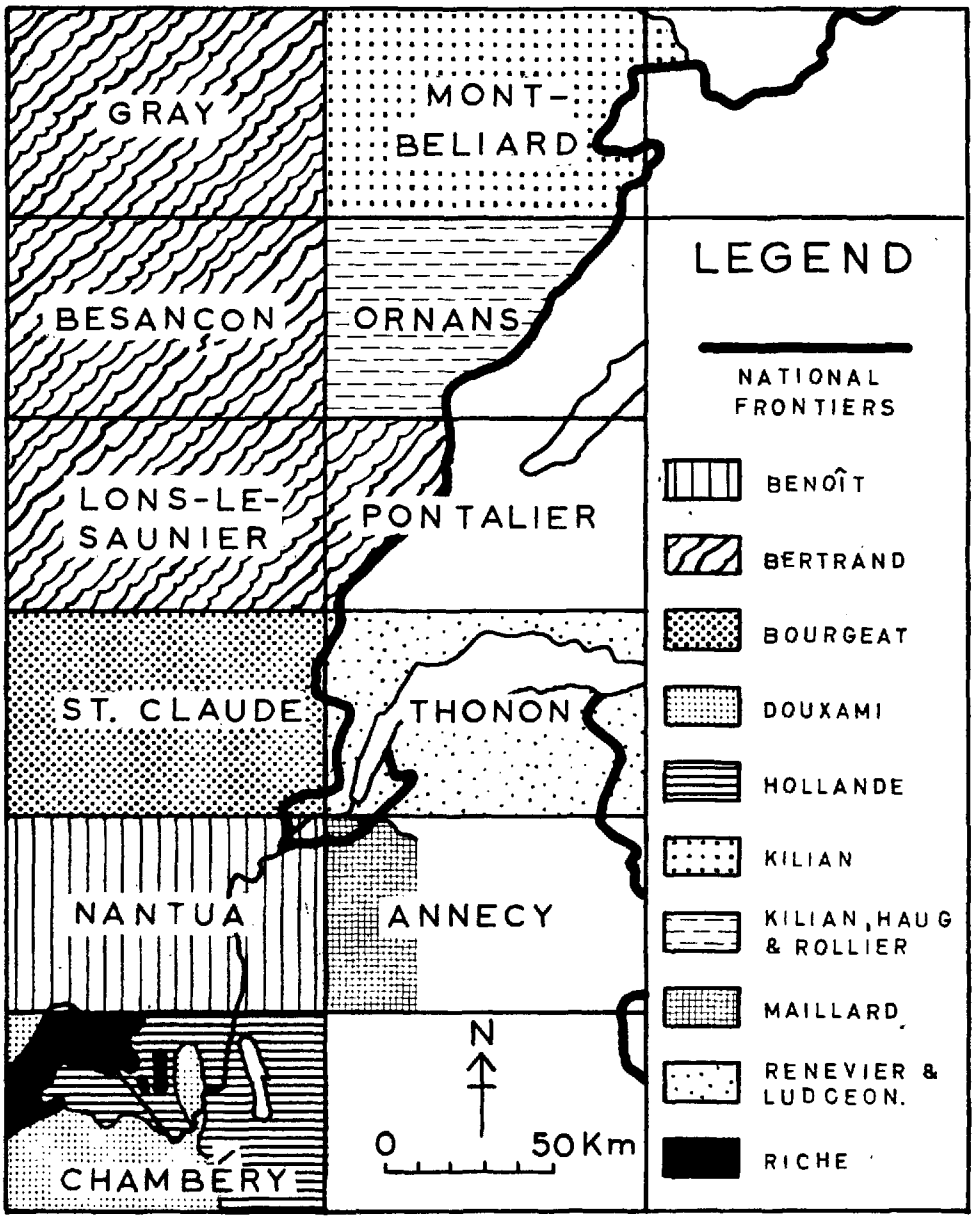
ferruginous oolite yielded an abundance of fine Callovian ammonites. Some of these were described in 1897 by Parona and Bonarelli.

Pillet (1885a) also gave an account of the Society's visit during the field meeting, to Lac d'Armaille, which lies in the area surveyed by the present author. The geologists present with Pillet recognised the calcareous oil shales with plant and fish remains which crop out in the Bedded Virieu Limestone near the lake. Pillet believed that the same facies existed at Cerin at the same stratigraphical level, namely the "Virgulien". Later, in 1892, Lortet described the reptilian fauna from the "Virgulien" of Cerin in an impressive memoir dedicated to Victor Thiollière, who had earlier figured the fossil fish from there. In 1889 and 1895 A.S.Woodward of the British Museum wrote notes on some of the fossil fish from the Cerin Stone.

During the period while the Geological Survey was becoming established, geologists such as Bourgeat, Riche and Douxami were preparing their doctorate theses. These workers were later to become field geologists for the Geological Survey. The areas for which they became responsible were clearly controlled by the subjects of their theses.

In 1888 Bourgeat presented his thesis, the now classic and much quoted study on reef development in the Southern Jura. In this region Bourgeat recognised reefs in the Bajocian and then again in the Upper Jurassic, and finally in the Urgonian. From his examinations of the

FIG. 10



AREAS MAPPED BY SURVEY GEOLOGISTS IN CENTRAL & SOUTHERN JURA

[after de Margerie, 1922]

stratigraphy across the Southern Jura he was led to believe that the Upper Jurassic reefs had developed at successively higher levels in the column from north-west to south-east, as if they had been migrating slowly towards the rim of the Subalpine or Dauphinois geosyncline. Bourgeat's hypothesis is discussed in the light of the work done by the present author in chapters 9 & 10 of this thesis.

Hollande's principal contribution, prior to the official mapping of the area by the Geological Survey, was published in the Survey bulletin for 1892. It was a short, but nevertheless searching study on the Nivolet-Revard anticline in the Bauges Range of the Subalps (map 3), and on the south-eastern Jura folds in the ridges of Gros Foug-Chambotte, Chat-Epine and Parves-Tournier. The paper includes a section across all the structures from Revard to the Parves Ridge, but no geological map. Hollande also compared lithologies and faunas between the Jura and Subalps. With his experience of the terrain in this region, Hollande was prepared for his later task of mapping the eastern part of the Chambéry sheet (see fig.10).

The doctorate thesis of Attale Riche (1893) dealt with the Bajocian to Oxfordian succession of the entire Southern Jura. This excellent work established the detailed stratigraphy of the stages concerned by a study of numerous road and stream sections. Mapping apparently did not form a part of his thesis work. Although Riche had sampled the same area as Bourgeat, the former paid more attention to the area

south of the Ambérieu-Culoz cluse. When the Geological Survey began mapping the Chambéry region, Riche was called upon to deal with the western part of this area, including part of the Ile de Crémieu and the Molard Dedon Range (fig.10).

The subject of H.Douxami's thesis, published in 1896, was the Tertiary of Dauphiné, Savoie and western Switzerland. This was one of the pioneer works on the molasse deposits in the region. He gave an account of the Tertiary of St.Martin-de Bavel, east of Virieu-le Grand, but no mention was made of the molasse of the Belley syncline in his thesis. Douxami later mapped the Tertiary and Quaternary deposits of the area covered by the Chambéry sheet for the Geological Survey (fig.10

(ii) <u>1897-1911</u>

At this stage in the history of research carried out on the Jura, de Loriol (1902-1904) published the second of his memoirs on the fauna from the Range. Meanwhile de Riaz (1895 & 1898) had published the first descriptions of the Callovian and Oxfordian ammonites from Trept in the Ile de Crémieu. This locality is now celebrated for its ammonite faunas.

During this period the most significant geological work done in the Chambéry region was that of the French Geological Survey. The chart, shown in fig.10, after de Margerie (1922), gives the names of the geologists responsible for the survey of the French Jura, as well as specifying the areas in which each was mapping. It can be seen that Bertrand dealt with more than three of the 1:80,000 sheets of the Jura.

Bourgeat and Benoît were each responsible for one sheet. In contrast, the Chambéry area claimed the interest of three research workers, H.Douxami, D.Hollande and A.Riche. The area studied in detail by the present author was originally mapped in part by Hollande and partly also by Riche. The ground is basically divided into a southern region surveyed by Hollande and a northern zone mapped by Riche. However, there are also two isolated patches of Riche's terrain entirely surrounded by that of Hollande. This arrangement led to many inconsistencies in the resulting geological map. The separation of Douxami's work on the Tertiary was more justified since the molasse is principally found in the synclinal zones of the area (map.3.) However, the present author has found molasse involved in fault zones along with the Mesozoic succession. Under these circumstances it is felt that only a geologist who has mapped the area as an entity, is in a position to appreciate its Tertiary geology fully.

The 1:80,000 geological map of the Chambéry area was published in 1901. It was accompanied by a pamphlet ("notice explicative") of about 3,500 words explaining the stratigraphy and structure of the area covered by the map. This "notice explicative" does not deal adequately with the work done by Douxami, Hollande and Riche. In 1922 the first volume was published of Emmanuel de Margerie's very comprehensive memoir on the French Survey's work on the Jura. This first volume consists almost entirely of bibliography. Yet, nowhere in it is there any record or reference to the detailed geological mapping that must have led to the publication.

of the Chambéry sheet, save for the 1901 pamphlet already mentioned. It was not until 1936, with the publication of de Margerie's second volume, that a detailed account of the geology of the area became available, despite the fact that the field work for the region had been carried out twenty years earlier.

De Margerie gave a comprehensive account of the geology covered by the Chambéry sheet. However, apart from the chart, shown in fig.10, and some references to authors in the margins of the text, one is left ignorant of the origin of much of his data. This would not be so important had the detailed research of Douxami, Hollande and Riche been published elsewhere and reference could be made to such work. Nor would de Margerie's omission to clarify sources of information matter if his chart (fig.10) could be relied upon implicitly. The field reports of Douxami, Hollande and Riche ("comptes rendus des collaborateurs") suggest that in fact the distribution of individual field work, as laid out in fig.10, is incorrect. Riche for example, did considerable work on Valromey, the Grand Colombier and the Parves ridge, which were allegedly in Hollande's territory. Hollande meanwhile reported on field work done by him on the molasse of Belley, Valromey etc., (Douxami's ground). His field reports also often deal with the Mesozoic geology of Riche's terrain. It appears that only Douxami occupied himself solely with the geology originally planned for him.

Since the original survey of the area covered by the

present author was made by Douxami, Hollande and Riche, it is interesting to estimate the extent of the work done in the area by each. This can be carried out by examining the major works by these authors on the region (see earlier), and the "comptes rendus" for the field season 1897-1911 when the Chambéry sheet was being prepared and in its first revision.

Hollande spent two out of the fourteen field seasons from 1897 to 1911 on the area considered in this thesis. In the "comptes rendus" of 1898 he noted the Izieu syncline with its Hauterivian deposits. He commented on the molasse near the Chateau d'Andert. Hollande correctly stated that the anticline at Prémeyzel continues northwards to Ambléon with a fault zone running along its western flank. In 1899 his field record gave localities where the principal stratigraphical stages are exposed in the area. In the same account he commented briefly on the structure of the Molard Dedon north-east of Innimont. In all the other years Hollande either made no field report, or dealt exclusively with the terrain east of Belley.

Riche studied the folds mapped by the present author during two out of the fourteen field seasons from 1897 to 1911. His reports are to be found in the "comptes rendus" of 1899 and 1910.

In 1898 (field report published in 1899) Riche probably accompanied Hollande during part of the field season, since both these workers commented in the same way on the

9

structure of the Molard Dedon north-east of Innimont. In addition, Riche correctly recognised the double fault zone running along the western flank of the Ambléon-Prémeyzel anticline as had already been noted by Hollande the year before.

During his work for the French Geological Survey in the period 1897-1911, Douxami spent two field seasons on the Belley syncline. The accounts of this field work appear in the "comptes rendus" for 1898 and 1899. In 1898 Douxami adequately described the molasse-bearing Belley syncline as a 300 metre plateau separated from the flanking anticlines in Mesozoic terrain by the rivers Furan and Ousson. He gave a cross-section to illustrate the Tertiary succession exposed near Magnieu on the north-eastern side of the syncline. As Douxami pointed out, the Tertiary of Belley is exposed mainly along the flanks of the syncline, and in some deeply cut river valleys where the extensive glacial deposits have been eroded away.

(iii) <u>1911-1946.</u>

Although geological investigation specific to the Chambéry region was slight during this period, many important general works on the Jura were published.

Detailed stratigraphical studies, especially on the "Portlandien" and "Purbeckien" of the Grand Salève were published in 1913 by Favre and Joukowsky, and on the section exposed at la Balme gorge in 1927 by Favre and Richard. Later the Callovian ammonite fauna from Chanaz was described by

Lemoine (1932) and Blondet (1935b). Blondet (1935a & c) also dealt with a similar fauna from Trept and Optevoz in the Ile de Crémieu.

The tectonics of the Jura received much attention at this time. Two main theories for the structural evolution of the Jura emerged. The first, due to A.Buxtorf (1916), proposed that tangential pressure from the Alps was transmitted through the Mesozoic strata of the Jura. The Anhydrite Group of the Middle Muschelkalk towards the base of the Mesozoic succession was thought to have acted as a lubricant between the Palæozoic basement and the main Mesozoic cover. The cover was believed to have become detached from the basement and to have glided over the Triassic anhydrite. This, the "abscherung" or "décollement" theory of Buxtorf, is accepted by most geologists today. Nevertheless certain workers also believed that folding in the Jura had commenced in as far back as Jurassic times. The pattern of sedimentation in Oxfordian to Kimmeridgian strata led D.Aubert (1945 and 1947) to suggest that the present day anticlines of the Jura had been subaqueous ridges in Jurassic times. He was apparently able to trace these sedimentation patterns back into the Lias. He even suggested that this embryonic Jura folding was a posthumous Hercynian deformation. A similar hypothesis had been proposed in 1901 by Fournier, who considered a part of the Franc Comptois Jura to have been folded into a broad anticlinal arch prior to the intense folding and faulting of the Tertiary (fig. 6B). The theory of embryonic Jura folding

was favoured by Revil (1911), but it was not until 1948, when Carozzi published his thesis, that this hypothesis was given further support based on patterns of sedimentation in the "Purbeckien" of Switzerland.

Two further important works on the structure of the Jura which emerged during this period are those of Heim (1919), dealing with the Swiss Jura, and of Collet (1927) treating the whole Jura Range in a more general way as part of a discussion on the structure of the Alps.

The period from 1911-1946 was characterised by a marked lull in geological investigation in the Chambéry region. The last contribution of any significance was Revil's thesis in two volumes (1911-1913) on the most easterly Jura folds and the Subalps of Savoie. After 1911 the field reports of Douxami, Hollande and Riche no longer dealt in any way with the Chambéry area. The early nineteen-twenties saw a new generation of geological survey workers commencing research in the Southern Jura. However, no member of this team ever revised the mapping carried out by Riche and Hollande in the area considered in the present thesis. In fact, during the period (1911-1946) the only other purely geological publication concerning the area mapped was by C.R.Eastman (1914). This took the form of a catalogue of the fossil fish from the Cerin lithographic stone on display in the Carnegie Museum, U.S.A.

The gap in geological research in the area concerned during the period covering the two world wars was bridged to

a certain extent by the work of two geographers, J.B.Martin (1911) and André Cholley 1931-1933.

Martin published his thesis in 1911. Its subject was the physical geography of Bugey. After outlining the stratigraphical column in the area from the crystalline basement (exposed in the south-west of the Ile de Crémieu,) to the Recent deposits, Martin summarised the tectonics of the region. He then discussed the influence of the geological structure and stratigraphy on the geomorphology. His treatment of the topographical evolution of the Molard Dedon Range and Bas-Bugey is not considered to be as valuable as his study on the history of the Ambérieu-Culoz cluse. This latter problem had clearly attracted Martin's interest. He himself concluded, like Depéret before him (1899), that an earlier Rhône had passed along the cluse from Culoz to Ambérieu. However, whereas Depéret had considered this to have occurred in Pliocene times, Martin believed that the Rhône had passed via the cluse later, during the last interglacial period. Gignoux (1914) also contributed to the study of the Quaternary geology of the area mapped. He favoured Martin's opinion on the age of the Rhône through the cluse. In 1931, 1932 and 1933 Cholley published papers, all dealing essentially with the same subject. He set out to show in these papers that the topography of the Southern Jura reflected the presence of Hercynian basement not far below the Mesozoic cover. As evidence, he quoted the "box-folds" in the northeastern Bugey. Here, he considered the anticlines to have cores of up-faulted basement, whilst

he believed the synclines in the Mesozoic to lie above down-faulted, graben-like structures within the basement. The western scarp of the Folded Jura, above the Ile de Crémieu and the Rhône, rises in a series of steps. This, according to Cholley, gives the Molard Dedon Range the appearance of an ancient faulted massif. The unfolded, but faulted Ile de Crémieu was thought by Cholley to be the surface expression of a block of basement, chopped up by more numerous faults than usual. In the opinion of the present author Cholley's hypothesis of horst and graben structures in the basement, is based on mere speculation. His idea could only be tested by deep borings which are lacking in the area considered. Where such borings have been put down "nearby" in the Jura, the evidence suggests that the basement is not involved in the Jura folds., (see fig. 35).

Cholley discussed one other problem in his contributions from 1931-1933. He set out to show that the surface of the Ile de Crémieu bears remnants of numerous erosion surfaces ranging from one of post-Cretaceous but pre-Aquitanian age to a more recent surface of Pliocene age. Cholley believed that pre-Pontian erosion surfaces over the Ile de Crémieu had been warped and faulted during Pontian earth-movements. He recognised the same situation in the more complex geomorphological unit of Bas-Bugey. Cholley's theory is given greater attention in chapter 16, which deals with the geomorphology of the area.

(iv) 1946 to the present day.

During the period 1946 to the present day a number of important general works on the Jura emerged. Introductions to the geology of the Jura were given by Gignoux (1950) in his "Géologie Stratigraphique", and by Arkell (1956) in his "Jurassic Geology of the World".

In 1954 Maurice Dreyfuss published a brilliant memoir on Upper Jurassic sedimentation in the Paris Basin, The Jura and the Subalps. He used his results to establish the palaeogeography of these areas throughout the Upper Jurassic.

Carozzi's thesis (1948) dealt with the Purbeckian of the Swiss Jura. The theories in this on embryonic folding in the Jura during "Purbeckien" times are considered again in chapter 10 . As a sequel to the work of Carozzi (1948), Donze's thesis (1958) concerned the passage beds from the Jurassic to Cretaceous in the French Jura, the Subalps, Provence and the Maritime Alps.

Returning more specifically to the Southern French Jura, Arkell (1946) made a revision of de Riaz's description of the Oxfordian ammonites of Trept (Ile de Crémieu). This was followed by similar work carried out from 1950-1954 by Marcel Pelletier and more recently (1958-the present) by Raymond Enay.

The publication in 1949 of de Saint-Seine's fine monograph on the fossil fish from Cerin, brought the history of work done on this notable exposure up to date. After

re-describing the vertebrates from Cerin, de Saint-Seine reserved a section of his monograph to a discussion on the palaeo-ecology of the Kimmeridgian fauna and flora of Bugey. He likened conditions in the Southern Jura then to the present day environment of the Australian Great Barrier Reef.

As a result of revisions given to the eastern part of the Chambéry sheet, principally by Gidon of the French Geological Survey, the second edition of the sheet was published in 1958. In this new edition, however, the cartographic interpretation of the geology west of Belley and south of the Ambérieu-Culoz cluse was reproduced almost exactly from the first edition of 1901. The only slight modifications to this western half of the sheet were those revisions recommended by Riche from field work carried out in 1910 (see earlier).

The French Geological Survey are at present engaged in revising the geology of the Chambéry sheet for the third edition. According to Gidon (personal communication) this sheet will be published on a scale of 1:50,000. In 1958 Gidon began mapping in the molasse terrain of the Subalps for his first contribution towards the new 1:50,000 edition. In a personal communication, Gidon informed the present author that Raymond Enay of the University of Lyon, had been officially appointed field geologist by the French Survey for the area west of Belley. However, since Gidon's 1958 account on the re-mapping of the Subalps on this scale, there has been no field report or other publication dealing with the Chambéry sheet in any of the Survey Bulletins.

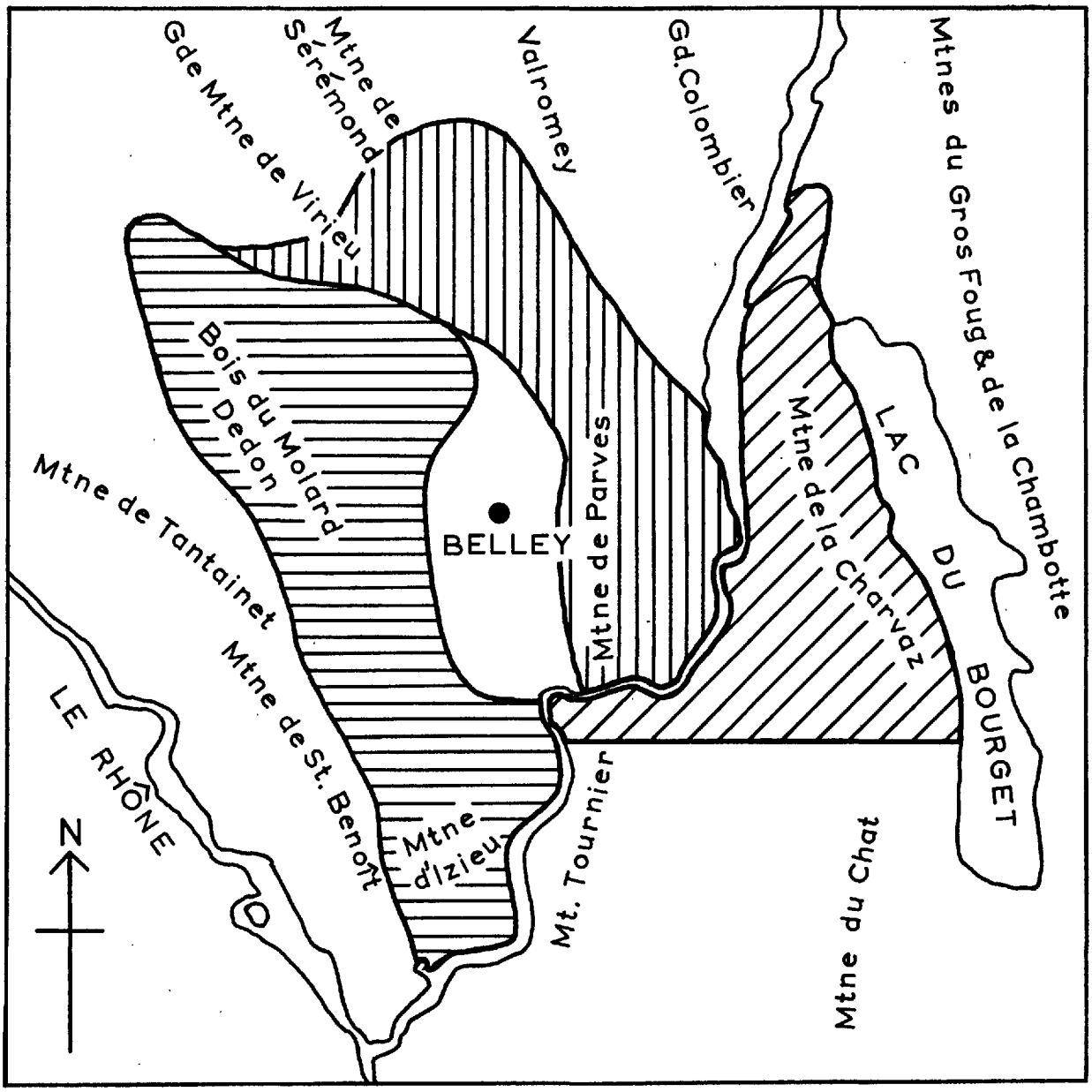
Marcel Pelletier published seven short papers, principally on the Middle Jurassic of the Southern Jura, in the four years from 1950 until his tragic death by drowning in 1954. During these years Pelletier had been accumulating material on the Middle Jurassic of Bugey for a doctorate thesis. In 1960 a posthumous memoir of Pelletier's research was presented by his supervisors, Thoral and Gauthier. Pelletier had worked the detailed Bajocian stratigraphy of the entire Southern Jura. It was a very similar study to that made in 1893 by Riche, involving no geological mapping, but only the examination of isolated sections. It may be considered as a revision of Riche's thesis work. Pelletier, however, did make some significant advances towards correlating the Bajocian successions throughout Bugey. He found that in certain localities the Bajocian bioclastic calcarenites and reef limestones contained ammonites. Their occurrence at this level in the region is known to be extremely rare. Pelletier found the corals of the Bajocian to undergo certain recognisable changes up the stratigraphical column. Certain varieties of coral appeared to be confined to given ammonite zones. He was therefore able to zone the Bajocian succession from the coral fauna alone.

After Pelletier's death, Enay undertook research on the geology of the Southern Jura. His publications, which began in 1958 have, to date, all been palaeontological.

Enay (personal communication) has been preparing a

FIG. 11

AREAS MAPPED BY GEOLOGISTS WORKING FOR Ph.D. DEGREES FROM IMPERIAL COLLEGE



doctorate thesis on the ammonites of the Southern Jura. This research does not combat with the theme of the present author's work (see Chapter 1).

In 1956 Dr. D.V.Ager of Imperial College, selected Bas-Bugey and the south-eastern Jura as a training ground for students who were prospective oil geologists. The area was chosen principally for two reasons. Firstly, the Jura Mountains have their structural setting in a foreland region where oil reservoirs are typically found. In addition to this, many of the limestones of the Jura are directly comparable to those carrying the bulk of the oil in the Middle East. Rocks of similar age and facies in the United Kingdom are poorly exposed and not greatly folded. Secondly, for research workers from London, the area offered a different language and unfamiliar customs, conditions likely to recur often in the life of an oil geologist.

In July and August 1956, three undergraduates, Messrs. S.Taha, F.Al Kasim and P.Whiddon, commenced the project by mapping small areas in the vicinity of Virieu-le Grand. A year later one of these, Taha, returned to prepare a Ph.D. thesis on a larger area taking in those regions already examined. Taha's terrain lay to the east of Belley and west of the Rhône (fig.11). It included the ridges of Virieu, Séréemond and Parves. At the same time J.N.Khouri, also from Imperial College, commenced research for a Ph.D. on the area west of the lac du Bourget and east of the Rhône (fig.11), taking in the Charvaz ridge and part of the Montagne du Chat.

Both workers spent the summers of 1957 and 1958 in the field. Taha, however, was prevented from writing up his valuable work due to his regrettable premature death early in 1959. Taha had been particularly interested in the process of dedolomitisation. In publishing on this subject in 1961 with the late S.Taha as co-author, Shearman and Khouri dedicated the paper to the memory of their friend, Said.

In the summer of 1958, while Khouri and Taha were still working in the Southern Jura, a group of four undergraduate students from Imperial College carried out their individual mapping in parts of the area considered in the present thesis. P.Emerson worked a northern district centred on Appregnin. Miss I.Dickinson mapped further south in the Ambléon region. J.W.Murray and Y.H.Stavrinou occupied themselves with the most southerly part, the Prémeyzel and Izieu regions respectively. At the same time Miss E.Bryant commenced a study on the brachiopod faunas of the region, and made extensive collections. Mr. D.J.Shearman came to the Jura in 1958 to supervise the sedimentological aspects of the research being carried out.

A full report on the history of the work done in the southern French Jura by members of Imperial College, together with accounts of the stratigraphy, structure and geomorphology of the region, has been given by Ager and Evamy (1963).

PART II.

PRE-MESOZOIC & MESOZOIC STRATIGRAPHY

CHAPTER 3.

PRE-BAJOCIAN STRATIGRAPHY.

A. THE BASEMENT & UPPER PALAEOZOIC.

The nearest surface exposure of the crystalline basement to the area mapped, occurs in the south-west corner of the Ile de Crémieu (fig.3). The outcrop is an isolated fragment of the Massif Central migmatite complex, and is here faulted against the Jurassic succession of the Crémieu plateau.

One of the best known parts of the basement below the Jura is that of the Ledonian district. Borehole evidence has shown it here to be essentially similar to the crystalline rocks exposed in the Massif Central. It is generally believed to consist of Palaeozoic and older rocks, which were folded and granitised during the Variscan orogeny. Subsidence of the basement later gave rise to tectonically controlled limnic coal basins which developed mainly during the Lower and Middle Stephanian. One of these, the Ledonian Basin, has been shown to exist below the Jura in the region of Lons-le-Saunier (Bonte et alia, 1953). The subsidence, which initiated the Ledonian Basin, is generally thought to have been caused by a late repercussion of the Asturian tectonism. Down-warping was evidently rapid for, according to Greber and Lienhardt (1960), the upper surface of the basement below the Ledonian Jura constitutes a buried landscape of irregular topography.

Above rocks of Middle Stephanian age, is an important erosion surface, unconformably overlain by an Upper

Permian (Saxonian) conglomerate (Bonte et alia, 1953). The folding and uplift, which preceded the development of this erosion surface was ascribed by Lienhardt (1960) to the Saalian disturbance. During this phase of tectonism the limnic coal basins were compressed into tight synclines (Gignoux, 1960). The Saalian earth-movements were the last major manifestation of the Variscan orogeny to affect the succession in the region of the Jura. The Saxonian sediments, deposited above the erosion surface on the Middle Stephanian, are not confined to the coal basins like the Lower and Middle Stephanian. Instead, they overlap extensively onto the adjacent parts of the crystalline basement (Gignoux, 1960). Hence after the Variscan orogeny, the area now occupied by the Jura Range was a continental region of high relief with subsiding intermontane coal basins. Erosion, apparently slowly reduced the elevated topography. This process was punctuated by repercussions of the Variscan disturbance, which rejuvenated the topography. Peneplaination, almost achieved in the Saxonian, was ultimately accomplished in the Lower Trias, after which an entirely new era of sedimentation commenced with the gradual return of marine conditions.

B. THE TRIAS.

(i) Description.

The only surface outcrops of Trias in the southern French Jura occur outside the area mapped in the west of the Molard Dedon Range (see map 3). They are limited in extent and involve only the uppermost Keuper, which is very poorly

exposed. The stratigraphy of the Triassic of the Jura Range is best known from the boreholes put down in the Ledonian Jura.

Following Ricour (1962), Bonte et alia (1953), and certain private communications from the B.R.G.M., the Trias here, of typical German facies, begins with 70 m. of variegated Bunter Sandstone, readily distinguished from the Permian sandstones below, which are much redder. The Muschelkalk (110m) has a thin dolomite at its base which contains Myophoria orbicularis Bronn. This horizon is considered by Ricour (1962) as a reliable marker for the basal Muschelkalk of German facies. The dolomite is followed by the Anhydrite Group (90m) which consists of an alternation of marl, anhydrite, and dolomite. The Anhydrite Group is overlain by crinoidal limestones and dolomites of the Upper Muschelkalk (40m). These pass upwards into black shales with associated dolomite and anhydrite of the Lettenkohle (30m). The Lower Keuper (average thickness 160m) consists almost wholly of rock salt and is very variable in thickness. The relatively thin Middle Keuper (25m) consists from the base upwards, of the "reed" sandstones (with Equisetites), red shale, and rubbly dolomite. The Upper Keuper (100m) may be studied from surface outcrops. It contains varying proportions of marl, dolomite and anhydrite. The Trias is terminated by the Rhaetian (25m). At the base of this stage occurs a carbonaceous sandstone with bone beds. The sandstone is cut by burrows, which sometimes penetrate the

the surface of the uppermost Keuper below. Black shales with Rhaetavicula contorta (Portlock) and some marl, complete the Rhaetian.

(ii) Summary of geological history:

The Bunter Sandstone is generally considered to be of aeolian origin, deposited in an arid desert environment. This facies extends all over the foreland zone to the Tethyan geosyncline. South-east of the autochthonous crystalline massifs of the Alps the entire Trias is marine, having been deposited in the Tethyan sea. In the Middle Triassic times the Muschelkalk sea transgressed across the Lower Triassic peneplain. The sea did not invade the higher ground of the Massif Central and the Ardennes. It was separated from the Tethyan sea by the then emergent barrier of the embryonic autochthonous crystalline massifs of the Alps. The principal connection with the Alpine sea lay to the east of the Bohemian Massif (Gignoux, 1960). Gignoux also proposed a southern connection through the region now occupied by the Southern Jura. This suggestion was based on evidence derived from a borehole put down in 1917 at Torcieu in the northern part of the Ambérieu-Culoz cluse. Certain crinoidal limestones from the cores of this borehole were attributed to the Upper Muschelkalk by Roman (1926). These, however, were indicated by Thoral and Ricour (1950) and Ricour (1962) to contain the foraminifera Cristellaria tricarinata var. polymorpha (Terquem) of Jurassic age. The presence of marine Muschelkalk at Torcieu thus became uncertain. Nevertheless a southern

connection between the Middle Triassic seas of the Jura and Provence was suggested by Ricour (1962) from the evidence of outcrops at Mt.Crussol, and boreholes put down in Bas-Dauphiné.

The fauna of the Muschelkalk, as to be expected for the deposits of an isolated sea, is lacking in variety. According to Gignoux (1960) it is an impoverished and selected Alpine fauna. The many evaporitic deposits in the Muschelkalk indicate that the climate at the time of deposition was both hot, and dry. In fact, the sea dried up completely before the deposition of the Keuper, and the Lettenkohle or uppermost Muschelkalk consists of an alternation of marine and and continental beds. French authors attribute the saliferous Keuper marl to a lagoonal environment, while the "reed" sandstones above are generally believed to be of fluviatile origin. The "reeds" themselves are thought to represent vegetated strips bordering rivers.

Apart from the transitory marine phase of the Muschelkalk, the Triassic sediments over the Jura to the end of the Keuper are all believed to have been continental, representing part of a vast desert region which had its south-eastern margin bordering on the Alpine geosynclinal sea. The Rhaetian marine transgression over this continent at the end of the Trias did not alter the basic character of these two contrasting sedimentary domains. During the Jurassic, sedimentation in the Alpine region took place in numerous troughs separated by tectonically unstable cordillera. In contrast the Jurassic limestones of the Jura, Swabia, and the Paris

basin

are all shallow-water deposits. The Vosges, Black Forest and Massif Central bordering the convex margin of the Jura, remained either above sea-level, or as platforms below shallow water during the Rhaetian. This situation later prevailed throughout the rest of the Mesozoic.

The Rhaetian marine transgression which is represented by numerous bone beds, did not immediately cover the worn-down Variscan continent in the Jura region. Continental marls in the Ledonian district are found separating the marine Lower Rhaetian from the poorly developed Hettangian.

C. THE LIAS.

(i) Description.

Outcrops of Lias in the southern French Jura are more numerous than those of the Keuper. Nevertheless the succession is poorly seen and rather incomplete due to faulting. The lithostratigraphical formations found to belong to the Lias in Bugey can be recognised in the better exposed Liassic successions of the Ledonian Jura.

Bonte et alia (1953) have briefly summarised the Liassic stratigraphy exposed in boreholes from the Ledonian Jura. Lefavrais (1961) made a detailed and more complete study of the whole Liassic succession in the region. According to this author, the "Hettangien" is rudimentary and consists of dolomites with marly intercalations. It also often occurs merely as a breccia. The "Hettangien" soon gives way to the characteristic blue Gryphaea limestone of the "Sinémurien" (25 m). Phosphate nodules appear in the upper part of this stage.

The blue limestone is resistant to weathering and generally provides an escarpment. The same facies in the Sinemurian crops out at the base of the exposed succession in the region studied by the team from Imperial College. Here, it is called the Chazey Bons Limestone after its type locality, north of Belley (see map 1). It is a well-bedded, rather coarse calcarenite yielding abundant Gryphaea arcuata (Lamarck) and other faunas reminiscent of English Blue Lias, including Paracoroniceras sp. and Calcirhynchia calcaria Buckman. These both indicate a Lower Sinemurian age. The Chazey Bons Limestone is poorly exposed, neither the base nor the summit of the formation being seen. It is not known if the phosphate nodules occur higher up within the same unit, as in the Central Jura.

In the Ledonian Jura the Upper "Sinémurien" (10m) consists of thinly-bedded limestone passing upwards into glauconitic "Carixien" limestones (2-3m), rich in ammonites and belemnites. The "Domérien", poorly fossiliferous throughout, begins with a micaceous marl with occasional Amaltheus margaritatus de Montfort (100m). This series is followed by a more resistant sequence of alternating limestone and marl (6m). The "Toarcien" (70m) consists, at the base, of carbonaceous shales rich in ammonites and Posidonomya's. This is followed by a blue marl characterised by "Turbo" subduplicatus D'Orbigny, passing upwards into nodular marls with belemnites.

Overlying the Chazey Bons Limestone of the southern

French Jura is a poorly exposed formation known as the Cuzieu Beds, sub-divided into Lower Cuzieu Shales and Upper Cuzieu Flags. Even at the type section (the western slopes of Donalèche Hill, near Cuzieu) where the beds are best exposed, only a few horizons of the Cuzieu Shales are seen. This Lower member appears to consist predominantly of shale, but a few limestone bands have been found, especially near the top. Lithologically the Cuzieu Shales resemble the "Toarcien" shales of the Ledonian Jura. It is hence significant that a ferruginous oolite in the shales has yielded the ammonite Frechiella sp. of Toarcian age. No evidence has been found of the Pliensbachian stage in either the Chazey Bons Limestone, or the Cuzieu Shales. It may even be faulted out or represented by a discontinuity. The Cuzieu Flags, which overlie the Shales, are the oldest beds seen at the surface in the area mapped by the present author. They are described in the following chapter (4).

(ii). Summary of geological history.

The Rhaetian and Hettangian constitute the "Infra-Lias" of early French authors. During these stages sedimentation was still rather variable, since marine conditions were not yet firmly established. From the Sinemurian, however, uniformity of environment became a characteristic of Liassic deposition over the entire shelf area north of Tethys. Lithologies of the same age from the Southern and Central Jura are directly comparable. Furthermore, close analogies may be

seen in the Liassic successions of the Jura and the Anglo-Paris basin.

The calcarenites of the Sinemurian are probably of shallow-water origin. However, deepening of the sea floor had progressed since the initial Rhaetian transgression. This first influenced the deposition of the relatively shallow-water Carixian glauconitic limestones, and then gave rise to the probably deeper water shales of the Domerian and Lower Toarcian. During the Upper Toarcian the sea is thought to have become shallower once again, leading up to the Bajocian wave-washed calcarenites and reef developments. By the commencement of the Bajocian, therefore, the Jura had seen one complete cycle of Mesozoic sedimentation.

CHAPTER 4.

THE CUZIEU FLAGS.

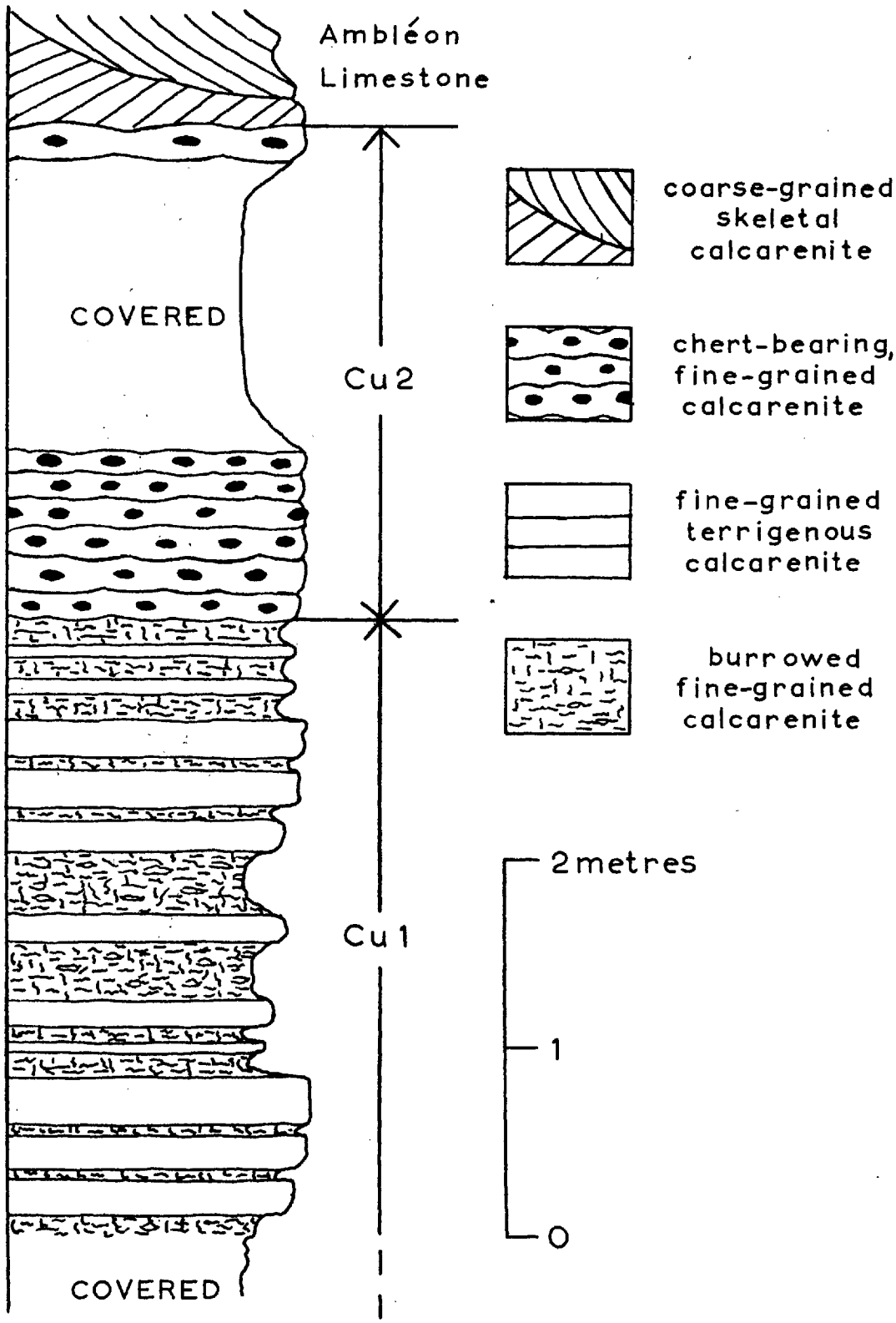
A. GENERAL.

The lowermost exposures of the Cuzieu Beds of Donalèche Hill (the type section) are extremely shaly, but further up the formation subordinate thinly-bedded limestone bands begin to occur sporadically within the shales. These limestone bands increase in abundance up the succession with respect to the shaly layers, until finally limestone is found to predominate over shale. Mica flakes can be seen glistening on the bedding plane surfaces between limestones. The Upper Cuzieu Beds have thus the appearance of a flagstone unit. The Cuzieu Beds have therefore been divided into a lower group termed the Cuzieu Shales, and an upper member known as the Cuzieu Flags. The poorly resistant Shales characteristically form fertile strike vales and the gentle grassy slopes leading up to the escarpments of the Cuzieu Flags and overlying Ambléon Limestone.

The Cuzieu Flags are found in three exposures of limited extent in the area studied in detail (see map 1). In only one of these is the contact with the overlying Ambléon Limestone seen. This occurs at the triangle of the roads about 4km. south-east of Ambléon (map 1) where the rivers Agnin and Gland join and flow southwards together. Before the confluence, the Agnin cuts across the strike of the Ambléon-Prémeyzel anticline. Although the river may once

FIG. 12

VERTICAL COLUMN OF THE CUZIEU FLAGS EXPOSED AT THE CONFLUENCE OF THE GLAND AND AGNIN



have had erosive power sufficient to cut such a path through the Mesozoic terrain, its surface waters now do not touch the folded limestone formations. Instead, the river flows over pre-existing alluvium, presumably its own. Fig.14 shows the disposition of the Mesozoic strata here. It can be seen that only a very small thickness (5½m.) of Cuzieu Flags is exposed. However, the complete section affords excellent exposure of the passage from the Flags into the overlying Ambléon Limestone.

B. PETROGRAPHY.

(i) Field study.

The Cuzieu Flags exposed at the confluence of the Glaud and Agnin consist of alternating tough limestones and less resistant shaly bands (fig.12). The former are generally about 20cm. thick. The shales may be up to 30 cm. thick, but most commonly occur as mere veneers separating the limestones. Both shales and limestones contain accessory muscovite.

The shaly layers are generally rather nodular. They are dark, and appear to contain much clay material and fine-grained calcite. The nodular appearance is due to the presence of irregular bands of partially silicified, fine-grained calcarenite. At the base of the exposed succession (Cuzieu Flags 1, or Cu 1 in fig.12) the limestones are well-bedded. These become more nodular higher up (Cu 2), where they too contain partially silicified calcarenite. Thin shaly layers between these chert-bearing limestones appear to

Plates 5 & 6.

PLATES 5 & 6

PLATE 5. Shales & nodular, silicified limestones of the Cuzieu Flags, (X ½). St.Bois, (Ain).

PLATE 6. Alternating laminations of detrital quartz & fine-grained skeletal debris. Pyritised Foraminifera appear dark. Plane polarised light, (X14). Cuzieu Flags at confluence of Gland & Agnin.

be bent around the silicified nodules (see plate 5). This suggests that a phase of silicification, strengthening the zones now occupied by the chert, took place prior to the compaction of the sediments.

The principal difference in composition between the shales and limestones of the Cuzieu Flags is that the shales contain most clay and calcilutite. Calcarenite, which occurs in both lithologies is consistently fine-grained. The first band of coarse bioclastic calcarenite represents the beginning of the overlying Ambléon Limestone.

The Cuzieu Flags appear to be the "marnes à Cancellophycus" of French authors. The name refers to the network of burrows, which ramify the shaly beds of the Cuzieu Flags. The more resistant limestones are only superficially burrowed over regions marginal to their bedding planes. These burrows, which are filled with fine-grained dark clay and calcilutite, are believed by French geologists to have been caused by the problematical fossil "Cancellophycus" scoparius (Thiollière). In the area studied the burrows attributed to "Cancellophycus" are not U-type habitation burrows but subhorizontal feeding burrows. They are more irregular than the spiral burrows of the true Cancellophycus (which in any case is a junior synonym of Zoophycos).

The bedded limestone units of the Cuzieu Flags often show small-scale cross-bedding. This is commonly

revealed on weathered surfaces, where the carbonate components have been superficially dissolved away, leaving thin laminae of detrital quartz grains standing out in relief. Where burrows due to "Cancellophycus" occur, the cross-bedding is disturbed. The shales, which are intensely burrowed, show no cross-bedding at all, and provide an excellent example of "bioturbation".

(ii) Laboratory study.

(a) General.

Thin sections cut from limestones and shales of the Cuzieu Flags were subjected to point count analyses (data in Appendix). The results of these analyses, which illustrate the distribution of each component vertically through the Flags, are shown graphically in fig.15. It has been found convenient to discuss these distributions along with those for the overlying basal Ambléon Limestone (chapter 5).

(b) The limestones.

The limestones are made up of alternating laminations of tightly-packed detrital quartz and loosely-packed calcareous components (see plate 6). The calcareous bands consist of fine-grained bioclastic debris (echinoderm, mollusc and/or brachiopod fragments and Foraminifera) apparently "floating" in a cement of coarsely-crystalline calcite. Fine-grained dark material, of a type characterising the shales, forms about 10% of the limestones. This material reacts positively to alizarin red S and safranin (chapter 18), and is believed to be clay-bearing calcilutite.

In the silicified zones only two depositional components are consistently recognisable. These are quartz grains and single-ray sponge spicules. Occasionally relics of former calcareous bioclastic debris, now replaced by silica, can be identified. More usually, however, the spicules and quartz grains are set in an indeterminate groundmass of chalcedony. Sponge spicules have only been observed within the silicified zones. Here they appear to be aligned sub-parallel to the cross-laminations of quartz grains. It appears that the spicules were deposited, like the quartz, as detrital grains throughout the rock. Their present restriction to the silicified nodules is attributed to the post-depositional migration of the opaline silica, of which they were originally composed, away from the unsilicified parts of the rock.

It has been pointed out that in the unsilicified zones, the bioclastic grains "float" in a cement of spar. There would thus have been sufficient space for the spicules formerly to have been present throughout these unsilicified zones. The migration of silica from these zones would have provided a suitable source for the chalcedony which is observed to have replaced the former bioclastic debris, and to have cemented up the pore-spaces in the chert nodules. Grains of detrital quartz seem to be somewhat more loosely packed in the silicified than in the unsilicified zones of the rock. This substantiates the field observation that the Upper Cuzieu Flags appear to be differentially compacted.

(c) The shales.

The thin nodular bands which make up the shaly layers of the Cuzieu Flags have been found invariably to be silicified. The clastic components of these shales are essentially the same as in the more resistant limestone beds, detrital quartz, sponge spicules and Foraminifera being prominent. However, there is a notably greater proportion of clay-bearing calcilutite in the shaly layers. This appears to be concentrated in the burrows of "Cancellophycus", as earlier noted in the field observations.

C. STRATIGRAPHICAL AGE.

Apart from the bioclastic debris and the burrows, fossils in the Cuzieu Flags are sparse. The unbroken fauna is as follows:-

Lobothyris sp.
Miliolidae
Nodosaridae
Lenticulina sp.
Ophthalmidae
Textularidae
Euhoploceras sp.
Belemnite
"Cancellophycus" scoparius (Thiollière)

French authors attribute the "marnes à Cancellophycus" (seemingly equivalent to the Cuzieu Flags,) to the murchisonae Zone of the Aalenian. The Upper Cuzieu Flags, exposed at the confluence of the Gland and Agnin, have yielded small (?stunted) specimens of Euhoploceras sp. This genus ranges in age from the Aalenian to the Lower Bajocian.

D. FAUNAL EVIDENCE OF PALAEO-ENVIRONMENT.

(i) Sponge spicules.

Of the bioclastic debris, the sponge spicules provide the most useful indications of environment. These all belong to the Monaxonida order of siliceous (originally opaline) Desmospongea. Each spicule is characterised by a central canal. They are consistently identifiable when seen in longitudinal section, but their appearance in cross section and in certain oblique sections, may often be confused with the patterns produced by pore-filling colloform chalcedony.

The slender single rays of the spicules preserved in the Cuzieu Flags would have been very susceptible to breakage during deposition. Yet, they differ from other bioclastic debris in being virtually unabraded. Although clearly derived, it is not thought that the spicules could have travelled far. Their palaeo-ecology may, therefore, indicate the character of a nearby environment.

Fresh-water sponges have simple monaxonid spicules. However, the Cuzieu Flags with their ammonites, belemnites and other marine fauna, were clearly deposited in sea-water. The waters of a nearby environment may nevertheless have been sub-saline. Monaxonid sponges normally inhabit shallow, marine waters, not far from the coast, generally at a depth of less that 50m. There is a general concensus of opinion (Carter, 1871; & de Laubenfels, 1936 & 1957) that, regardless of water depth, sponges depend for food on material carried from land. For example, present day sponges flourish off-shore

from river mouths (de Laubenfels, 1957). The evidence from the sponge spicules suggests that the Flags were near-shore deposits.

(ii) "Cancellophycus" burrows.

The presence of tubes, burrows and tracks in sediment generally indicates a shallow-water, marine environment (Howell, 1957). It is commonly considered that extensively burrowed sediments are near-shore or inter-tidal deposits (Croneis, 1934; Twenhofel, 1935; Large, 1949; and Howell, 1957).

It is interesting to consider why the burrows in the Cuzieu Flags are invariably filled with the dark clay-bearing calcilutite or marl. While eating their way through the Cuzieu sediments the burrowing organisms may have had a preference for assimilating the finer-grained terrigenous material in the deposit. This material is likely to have had a better food value than the coarser terrigenous clastics or the bioclastic debris of the sediment. The organic content of the sediment, the burrower's food, was probably attached to the surface of the individual grains in the deposit. The greater surface area per unit volume for a fine-grained sediment, compared with a coarse deposit, would cause the fine-grained material to be the richer in available food. If, therefore, the burrowing organism selectively assimilated the dark marl for food, the fine-grained inorganic detritus remaining would have been excreted, and therefore been concentrated in the burrows. However,

quite apart from the contents of the burrows, there is more dark marl in the shaly layers of the Cuzieu Flags than in an equivalent thickness of unburrowed limestone. Furthermore, a thin (1cm.) continuous band of blue-black marl has been found within the friable shales. It appears that the two types of sediment (calcarenite and dark marl), normally admixed in the Flags, were preserved here in separate bands. A more satisfactory explanation for the concentration of marl in the burrows thus becomes apparent. It is proposed that marl was being continuously laid down throughout the deposition of the Cuzieu Beds. This initially gave rise to the poorly-resistant, dark, Cuzieu Shales (chapter 3). The deposition of each cross-bedded limestone in the Cuzieu Flags is believed to have taken place rather rapidly, so interrupting the relatively slower but steady accumulation of marl. Burrowing organisms could have eaten their way through the upper part of each calcarenite layer during the periods of slow marly sedimentation. The open burrows in the unconsolidated limestone would thus have become filled with dark marl. Strong current action heralding the arrival of the next calcarenite unit could have re-worked all the marl deposited except that which had seeped into, and filled the open burrows. On rare occasions, when currents were weak, a complete band of dark marl may have been preserved. Normally, however, the shaly layer between successive limestones would have been formed by the upper, burrowed part of each calcarenite

unit, with its "bioturbation" structures and increased marl content.

(iii) Foraminifera

The Foraminifera of the Guzieu Flags are preserved in pyrite or its oxidation product, haematite. Thin sections show a relative abundance (up to 5%) of Foraminifera, but these are only seen in random section (plate 6). Such sections are not normally conducive to any complete identification of this fauna. The thin band of blue marl, mentioned in the previous section, as well as some of the friable burrowed shales, were therefore selected for disaggregation in an attempt to separate some whole Foraminifera. Only a limited number of such whole specimens were isolated. With these, and the evidence from specimens seen in thin section, Dr.C.G.Adams was able to identify the Foraminifera to family and sometimes generic level.

The largest proportion of Foraminifera present are almost equally divided between the Miliolidae and the Ophthalmidae. Occasional Textularidae and a few rather fragmental Nodosaridae (Lagenidae), including Lenticulina are present. The suite is completed with a number of specimens of a coiled and apparently single chambered foraminifer with a rather indeterminate wall structure. These specimens could be attributed to Cornuspira, Spirillina or Ammodiscus.

Sediments in which Miliolidae occur are generally of shallow-water origin. Where this family abounds it may be reasonably supposed that the original sediment was deposited on

a sea-floor lying below not more than 50 metres of water. Similarly the occurrences of Ophthalmidae and Textularidae are usually indicators of shallow-water conditions. The suite of Foraminifera therefore, indicates a shallow-water origin for the sediments of the Cuzieu Flags.

The Miliolidae and other Foraminifera of the Cuzieu Flags could have survived equally well on a soft muddy sea floor or a hard sea bottom, providing that there was a substantial food supply for the organisms (Dr. Adams: personal communication). There does appear to be a decrease in proportion of Foraminifera as the fine-grained Cuzieu sediments give way upwards to the very much coarser Lower Ambléon calcarenites. This could well reflect the presence of less food in the coarse-grained Ambléon calcarenites.

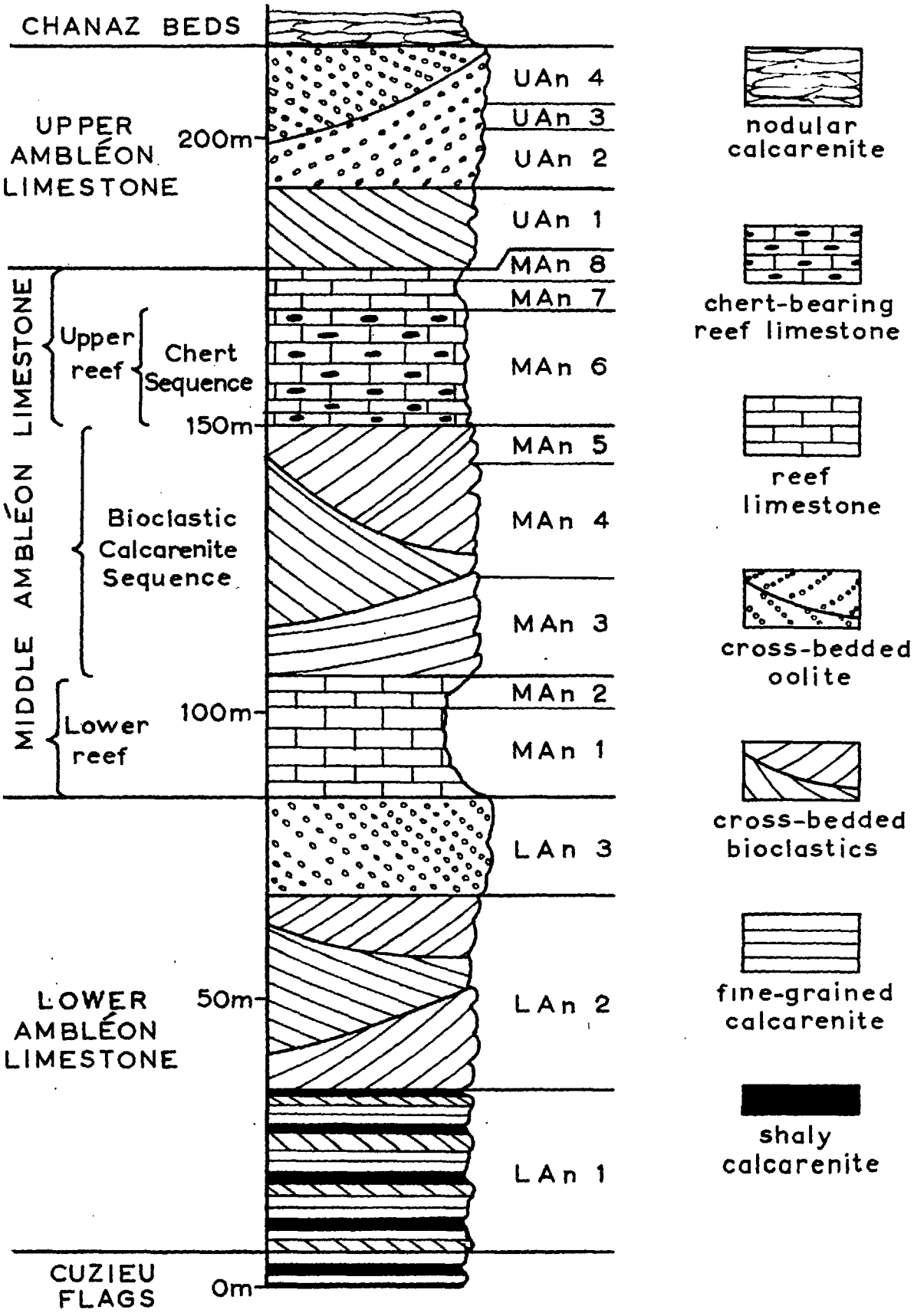
E. SUMMARY OF GEOLOGICAL HISTORY.

During the Aalenian and possibly the early Bajocian, the southern French Jura is believed to have been submerged below sea water to a depth of about 50m (see fig. 30). The area received a good deal of terrigenous detritus. This, and the abundance of sponge spicules, suggests a near-shore environment, possibly close to the mouths of rivers. The Massif Central, emergent some 70km. to the west of the area could well have been the source of the terrigenous clastics and the food for the nearby sponge colonies.

It is considered that dark marl had been accumulating slowly and steadily throughout the Toarcian (Cuzieu Shales),

and the Aalenian and (?) early Bajocian (Cuzieu Flags). In the time represented by the latter two stages, however, a great deal of coarser grained bioclastic and terrigenous material was also carried into the sedimentary basin. The cross-bedding in these coarser units indicates that they were deposited quite rapidly. The sedimentary basin is believed to have become filled in with sediment, so that the relatively deep-water conditions of the Upper Lias gave way gradually to a shallower water environment in the Lower Dogger. The sea-floor, however, is not believed to have reached the wave-base (generally situated at depths of less than 30m.) since the rather poorly-sorted calcarenites of the Cuzieu Flags had clearly not been subjected to winnowing currents.

SIMPLIFIED VERTICAL COLUMN OF THE AMBLÉON LIMESTONE



CHAPTER 5.

THE AMBLEON LIMESTONE.

A. GENERAL.

The Ambléon Limestone was described in general terms under the name "Lucey Limestone" by Khouri (1960). His descriptions were made from somewhat poorly exposed outcrops in the Montagne de la Charvaz (map 3). More complete sections of this lithological unit, offering good exposure and an abundant fauna, were found around the village of Ambléon near the centre of the area mapped by the present author (map 1). The formation was therefore re-named the Ambléon Limestone.

The Ambléon Limestone is resistant to erosion and characteristically stands out in prominent escarpments (plate 37). The formation is broadly divisible into Lower bioclastic calcarenites, Middle reef limestones, and Upper oolites (see fig.13). Each division is a distinctive mapping unit. All three members of the Ambléon Limestone are well-exposed at the triangle of roads near the confluence of the Gland and Agnin (fig.14). The exposures here form the type section for the Lower and Middle Ambléon Limestone. The Upper Ambléon Limestone, which is rather inaccessible at this section, has been described from samples collected 2 km. further south from the ridge running through Veyrin (map 1).

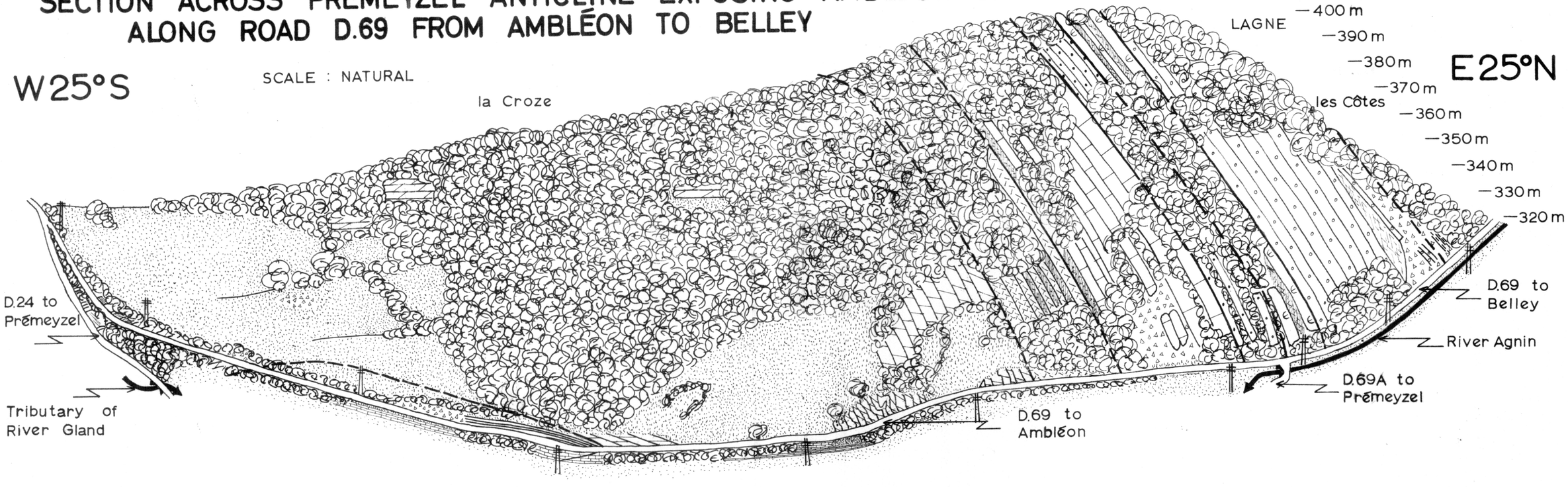
A number of different distinctive lithologies have been recognised within each of the three broad divisions of the Ambléon Limestone (see fig.13). Many of these sub-

SECTION ACROSS PRÉMEYZEL ANTICLINE EXPOSING AMBLÉON LIMESTONE ALONG ROAD D.69 FROM AMBLÉON TO BELLEY

W25°S

SCALE : NATURAL

E25°N

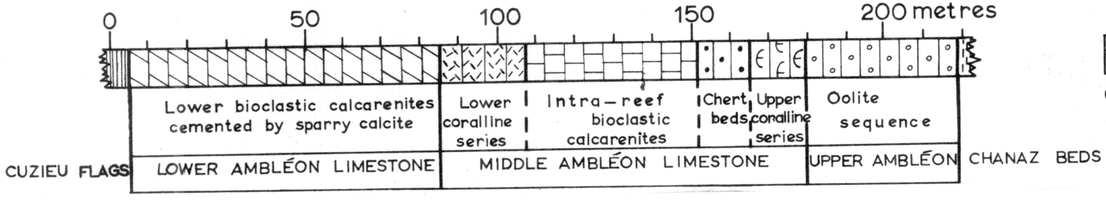


Observed lithological boundaries

Inferred lithological boundaries

Grass

Boxwood & Scrub

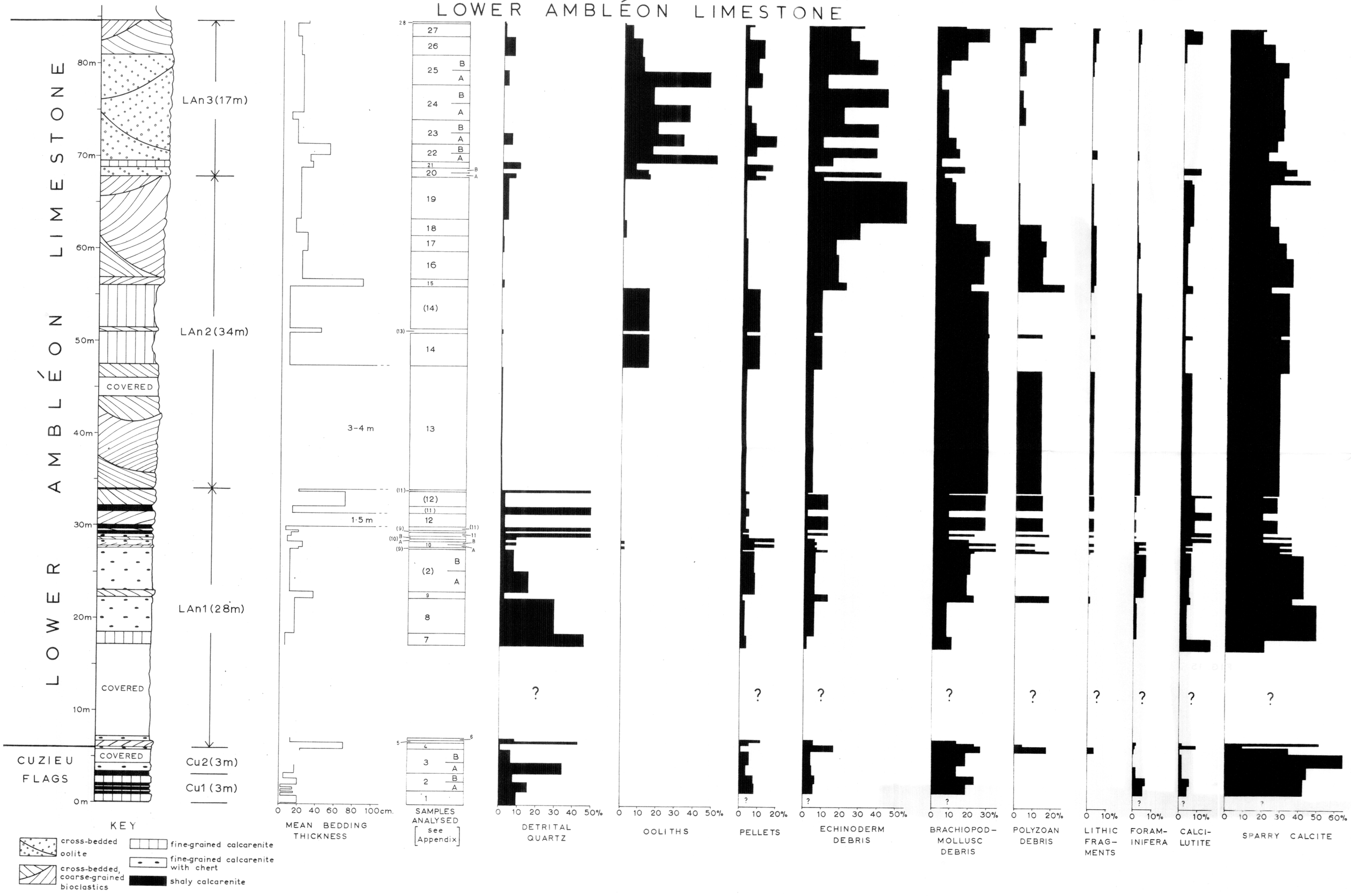


Quaternary Screes & Gravels

divisions are consistent over the area investigated, and can be considered as potential mapping units for future study. Other changes in lithology appear to be of local importance only. All the sub-divisions recognised have been numbered according to their position within the major divisions of the Ambléon Limestone. For example, the basal Ambléon Limestone has been called Lower Ambléon Limestone 1 (LAn 1) and the uppermost Middle Ambléon Limestone called Middle Ambléon Limestone 8 (MAn 8), etc. The petrography of each of these sub-divisions is described (section B. of this chapter) from samples collected at the type sections for the Ambléon Limestone. Indication is given where a certain lithology is traceable over a wide area.

The Ambléon Limestone has three extensive, but generally composite surface outcrops, the distributions of which are directly controlled by the combination of geological structure and geomorphology. The three surface outcrops occur in the eroded cores of the Ambléon-Prémeyzel and Molard Dedon-Colomieu anticlines (see maps 1 & 2). The outcrops are composite, since they consist of numerous exposures of the Ambléon Limestone separated by Quaternary and Recent deposits. Within the area mapped the base of the formation is seen only in the Ambléon-Prémeyzel anticline. It might be expected that the Ambléon Limestone should crop out in the extreme north of the area, where the Molard Dedon-Colomieu anticline is deeply dissected by part of the

VERTICAL DISTRIBUTION OF LITHOLOGY & COMPONENTS THROUGH THE LOWER AMBLÉON LIMESTONE



Ambérieu-Culoz cluse. However, scree here covers all formations older than the Oignon Beds (see map 1).

B. PETROGRAPHY.

(i) Lower Ambléon Limestone.

(a) Field study.

The majority of the Lower Ambléon Limestone is made up of coarse-grained bioclastic calcarenite. The junction between Cuzieu Flags and Ambléon Limestone was taken in the field at the lowest horizon of coarse-grained calcarenite.

LAn 1. The basal 28m. of the Lower Ambléon Limestone (LAn 1 in figs.13 & 15) consist of alternating coarse- and fine-grained calcarenite. Coarse calcarenites form only 15% of this sub-division at the type section. The unit has been recognised elsewhere in the area.

The fine-grained material consists mainly of detrital quartz. Occasionally the beds are true quartz sandstones, the predominant calcareous material present being calcite cement. More commonly, however, the fine-grained calcarenites contain quartz grains disposed in cross-laminations, as in the limestones of the Cuzieu Flags (chapter 4). As a further analogy to this lower formation, the laminated beds of LAn 1 are often superficially burrowed, and traces of "Cancellophycus" occur along some bedding planes. There is, however, an absence of definite shaly layers in the Lower Ambléon Limestone. Incipient chert nodules are found in the fine-grained calcarenites of LAn 1. Differential compaction

Plates 7 & 8

PLATES 7 & 8.

PLATE 7. Graded beds in Lower Ambléon Limestone at the type section.

PLATE 8. Coarse-grained skeletal calcarenite, cemented by sparry calcite & dolomite. Lower Ambléon Limestone at type section. Plane polarised light (XII).

around these has given the beds a nodular appearance, as also seen in the Cuzieu Flags.

The coarse bioclastic calcarenites of LAn 1 are generally cross-bedded. This, however, is on a much grander scale than that seen in the finer-grained limestones of the sub-division. Foreset beds are normally of the order of 6 cm. thick. The bioclastic components appear to be cemented by coarsely-crystalline calcite. Accessory glauconite is also found in these rocks. Coarse bioclastic calcarenite, although poorly represented in LAn 1, predominates in the next sub-division of the Lower Ambléon Limestone, LAn 2. It can be seen that LAn 1 represents the transition zone between fine-grained calcarenite (Cuzieu Flags) and coarse-grained calcarenite (LAn 2).

An interesting feature of LAn 1 is the occurrence in it of several graded beds forming a unit 65cm. thick. The beds (see plate 7) each have a lower part of coarse bioclastic calcarenite, which is not laminated. This is overlain, without an intervening bedding plane, by fine-grained calcarenite containing detrital quartz. The upper parts to the graded units are cross-laminated. There is a remarkable selectivity in the distribution of the chert nodules in this sequence of graded beds. The cherts tend to occur widely in the laminated fine-grained upper parts, but have never been observed in the lower, coarse bioclastic calcarenites.

LAn 2. This sub-division, some 34m. thick at the type section (see fig.15) consists generally of cross-bedded coarse-grained calcarenite. The lithology of LAn 2 forms the main part of the Lower Ambléon Limestone throughout the southern French Jura. Bedding thicknesses (up to 3m.) are extremely variable, since one unit may truncate another below it. Furthermore, it is often difficult to assess thickness accurately by direct measurement because apparent master bedding planes may fade, or pass into foreset bedding planes in an adjacent unit.

The features of the coarse bioclastic calcarenites of LAn 2 correspond in the main to those already described for rocks of this type in LAn 1. Essentially, LAn 2 consists of the coarse-grained debris of echinoderms, brachiopods, lamellibranchs and polyzoa, set in a cement of clear calcite. There appears to be little or no fine-grained matrix present. The skeletal components do not have a uniform distribution in these rocks. For example, at the top of LAn 2, bands consisting almost exclusively of echinoderm debris are found (fig.15). In other samples, flat brachiopod and lamellibranch valves are the principal components.

LAn 3. This sub-division is 17m. thick at the type section. Its diagnostic feature is an appreciable content of oolite. Oolite is not found in the Lower Ambléon Limestone further east in the Charvaz-Col du Chat area (Khouri, 1960).

In LAn 3 beds consist of alternating laminae of

oolite and coarse bioclastic debris (see fig.15). In the thinner bedded units the laminae are parallel to the master bedding planes. The more thickly bedded strata, however, are made up of foresets, which in themselves consist of alternating laminae of coarse skeletal debris and oolite. The mixed oolite and bioclastic calcarenite sequence of LAn 3 is overlain by the calcilutites of the basal Middle Ambléon Limestone.

(b). Laboratory study.

The lithological sub-divisions of the Lower Ambléon Limestone, which had been recognised in the field, were also studied in the laboratory from samples collected at the type section. Point count analyses were made of thin sections from each characteristic lithology (for details see Appendix). In this way, the distributions of the various components in the Lower Ambléon Limestone were found throughout the vertical exposure at the type section. These distributions are expressed graphically in relation to the observed lithological changes in fig.15.

Detrital quartz. There is a marked change in the distribution of detrital quartz from LAn 1 to LAn 2, (fig.15). Detrital quartz forms a principal component of the fine-grained limestones of LAn 1. The bands of coarse bioclastic calcarenite in LAn 1 contain only accessory quartz grains. The same situation prevails throughout LAn 2. A slight increase in the detrital quartz content occurs with the appearance of oolite in LAn 3 (see fig.15).

The distribution of detrital quartz in the Lower Ambléon Limestone puts a major lithological boundary between LAn 1 and 2. This boundary is equally as marked as that adopted in the field to separate the Cuzieu Flags from the Ambléon Limestone. However, the latter boundary is maintained since it was found easier to recognise the first band of coarse calcarenite than the last horizon of fine-grained, quartz-bearing calcarenite.

The slight, but nevertheless significant, change in proportion of detrital quartz at the boundary between LAn 2 and 3 is consistent with the importance of the lithological change that this boundary represents in the field.

Ooliths. At the type section, the oolite of the Lower Ambléon Limestone predominates in LAn 3. In this subdivision laminations of oolite alternate with bands of almost pure echinoderm sand (see fig.15). Other skeletal debris is only sparsely represented. A minor occurrence of ooliths is found in the coarse bioclastic calcarenites of LAn 2, (see fig.15). These are believed to have heralded the later arrival of the oolitic sequence, LAn 3, which is found some 20m. higher up in the succession. Ooliths have also been found in the graded beds of LAn 1. These were probably carried in, and deposited from outside their environment of formation.

Pellets. In the rocks studied spherical or

ellipsoidal grains, consisting of homogeneous fine-grained carbonate, are called "pellets". These grains have approximately the same grain size as ooliths but lack any concentric or radiating structure. They may be faecal in origin, or be accretionary aggregates.

In the fine-grained limestones of the Cuzieu Flags and LAn 1, the pellets are dark, and correspond to the Bahaman faecal pellets described by Illing (1954). They appear to make up a relatively consistent 8% of the rocks concerned (see fig.15). In LAn 2 and 3 the pellets have a much lighter colour. Here their distribution closely follows that of the ooliths (see fig.15). The light coloured pellets are consequently thought to have had a similar origin to the ooliths.

Echinoderm & brachiopod/lamellibranch debris. These two suites of skeletal debris generally show similarly placed distribution maxima and minima, in the fine-grained limestones of the Cuzieu Flags and LAn 1. In the coarse bioclastic calcarenites of LAn 1 and 2, however, maxima in the distribution of echinoderm fragments occur alongside minima for flat shelly material, and *vice versa* (see fig.15). This substantiates the observation earlier made in the field that the echinoderm and flat shelly fragments often occur in individual bands, in which they are segregated both from each other and from other skeletal debris. The distribution of echinoderm and brachiopod/lamellibranch debris suggests that the hydrodynamic properties of each type of fragment are

contrastingly different.

Polyzoa and lithic fragments. Fragments of polyzoa have not been found in the fine-grained limestones of the Guzieu Flags and LAn 1. They commonly form about 15% of the coarse bioclastic calcarenites of LAn 1 and 2. Thus the horizon at which polyzoan debris appears in this part of the succession corresponds to the boundary adopted in the field between the Guzieu Flags and Ambléon Limestone (see fig.15).

The principal components of LAn 2 are echinoderm, brachiopod/lamellibranch and polyzoan debris. The polyzoan material considered here is coarse-grained (plate 8) and clearly derived from large colonies of benthonic polyzoa. The debris did not have its origin in colonies of polyzoa which had encrusted small shell fragments, etc.

Maxima in the distribution curve for polyzoan material (see fig.15) correspond neither to those for echinoderm, nor to those for brachiopod/lamellibranch fragments. Instead the polyzoan fragments tend to be most abundant where these other two main components are equally (and poorly) represented. The most common calcarenites in the Lower Ambléon Limestone (illustrated in plate 8) are those which lack bands concentrated in flat shelly debris or echinoderm fragments. These well-mixed calcarenites are characterised by a relatively high proportion (up to 30%) of polyzoan debris.

The distribution of lithic fragments closely follows that of polyzoan debris (see fig.15). Colonies of polyzoa, which have a benthonic existence, would experience the same

forces of erosion at the sea floor as any nearby partially lithified sediment. Polyzoan debris would thus tend to be carried away together with lithic fragments. In the Lower Ambléon Limestone, lithic fragments and polyzoan debris have approximately the same size and shape. The two types of grain, therefore, probably had similar hydrodynamic properties, as well as a common origin. From this it might be expected that their distribution curves should be analogous.

Foraminifera. As has been mentioned earlier, Foraminifera form up to 5% of the Cuzieu Flags. This proportion persists into LAn 1(see fig.15). Where coarse bioclastic calcarenites occur in LAn 1, however, the percentage of Foraminifera is much less. In LAn 2 Foraminifera only make up an average of 0.5% of the rocks. These organisms rarely occur at all in the oolitic limestones of LAn 3.

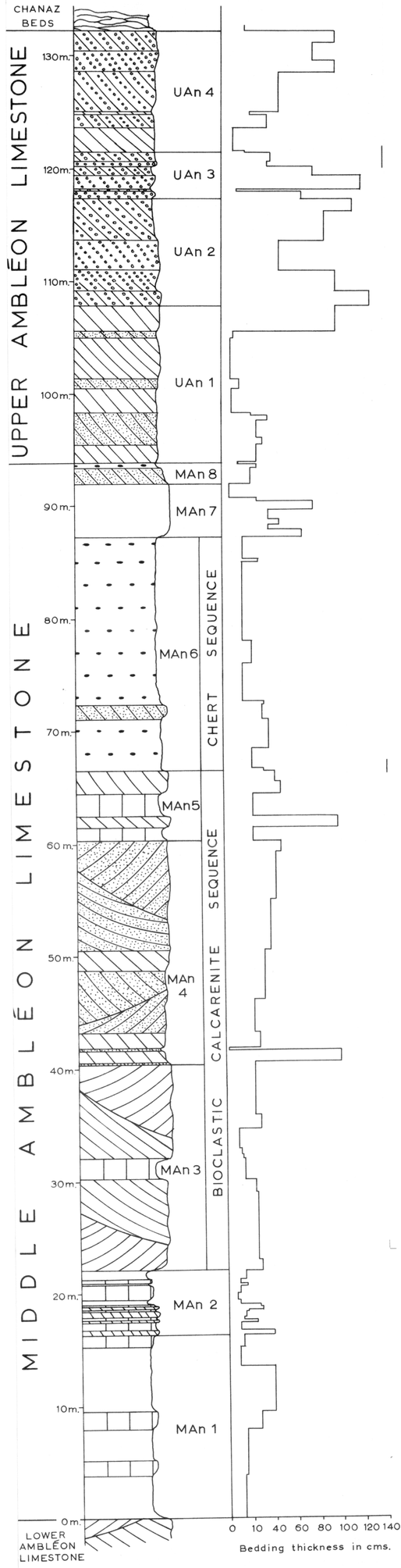
Coarsely-crystalline cement & fine-grained matrix. The distribution of these two components generally oppose each other. Both form the infillings to original pore-spaces in the rocks. The limestones of the Cuzieu Flags and LAn 1 are characterised by a relatively high (average 10%) proportion of fine-grained sediment. In contrast the original pore-spaces of LAn 2 and 3 generally carry coarsely-crystalline calcite to the exclusion of fine-grained matrix.

(ii) Middle Ambléon Limestone.

(a) Field study.

MAn 1. At the type section the lowermost 16m.

VERTICAL COLUMN OF THE MIDDLE & UPPER AMBLÉON LIMESTONE



KEY

- coarse-grained, well-sorted calcarenite
- mixed coarse- & fine-grained calcarenite
- coralline calcilutite
- coralline calcilutite with scattered skeletal debris
- chert-bearing, coralline limestone
- mixed oolite & bioclastic calcarenite
- oolite
- fine-grained Chanaz calcarenites

Plates 9 & 10

PLATES 9 & 10.

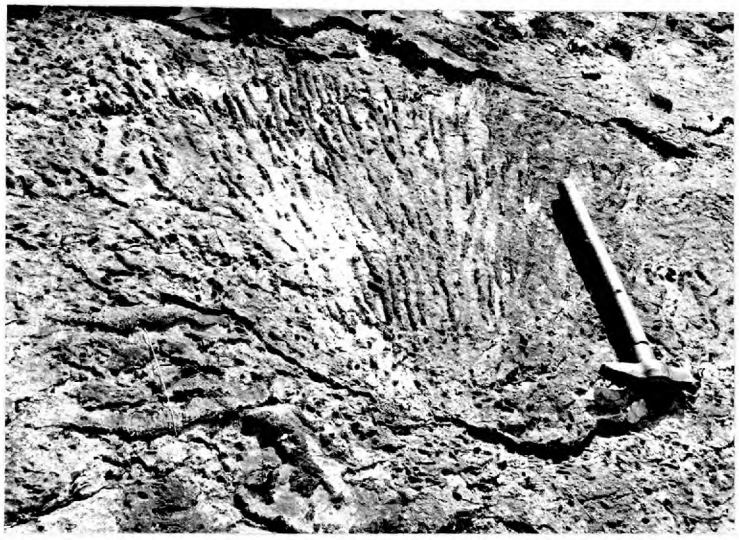


PLATE 9. Large ramose coral above thin bands of thamnastraeoid coral. Lower reef horizon of Middle Ambléon Limestone, near Ambléon (Ain).

PLATE 10. Massive coral with well-preserved corallites. Middle Ambléon Limestone near Prémeyzel (Ain). x1½.

of the Middle Ambléon Limestone, MAn 1, consists predominantly of blue calcilutite (fig.16). This appears in great contrast to the underlying coarse calcarenites of LAn 3. The calcilutites occur in poorly-bedded units, and are characterised by numerous cavity infillings (up to 4cm.across) containing coarsely-crystalline dolomite & calcite. The dolomite can usually be recognised by the customary yellow iron-oxide stain, which permeates the cleavages of its crystals.

Pectinid lamellibranchs, thamnastraeoid & phaceloid corals are common throughout the blue calcilutites of MAn 1. The corallites of the phaceloid corals are usually infilled by coarsely-crystalline calcite, & the yellow, iron-oxide stained dolomite mentioned earlier. In places the branching form of the ramose corals stands out in relief on the weathered surfaces of the rocks (plate 9). It is rare however, to find the internal structure of the corallites preserved. In contrast the corallites of the thamnastraeoid corals are made up of finely-granular calcite, in which the structure of the corallites is quite apparent (plate 10). The restriction of dolomite to the ramose corals suggests that the corallites of these were originally composed of the metastable aragonite which went into solution early in diagenesis. The open vugs remaining would have been zones of high permeability, suitable for the subsequent passage of dolomitising solutions.

Three bands of lighter blue, & more resistant limestone alternate with the "vuggy" calcilutites & make up 25% of MAn 1 (see fig.16). These limestones have the same bedding features as the blue calcilutites, but contain an appreciable

amount of coarse bioclastic debris. They carry shells of pectinids, but no corals have been found. Iron-oxide stained dolomite appears to be relatively uniformly distributed along with the calcite in the cement of the rock. This is considered to be the cause of the lighter colour of these rocks compared with the associated blue calcilutites.

MAn 2. Light blue limestones made up of coarse-grained skeletal debris in a calcilutite matrix (see MAn 1) predominate in MAn 2 (fig.16), a sub-division which is 5½m. thick at the type section. As in MAn 1, the limestones are dolomitic. The proportion of coarse detritus in MAn 2 has been found to vary up the column. Thus the sub-division consists of an alternation of relatively well- and poorly-sorted coarse bioclastic calcarenites.

The poorly-sorted calcarenites (63% of MAn 2) are generally well-bedded and blue in colour. Corals and shells of pectinids occur widely in a supporting framework of calcilutite. Iron-oxide stained dolomite occurs both as an infilling to large isolated vugs, and as part of the inter-granular cement.

Those calcarenites which are rich in coarse skeletal debris are characteristically well-bedded. In these rocks dolomite appears only to occur in the inter-granular cement. Corals have not been found in these relatively well-sorted coarse-grained calcarenites.

MAn 1 and 2 together represent the first reef complex of the Middle Ambléon Limestone. These reef limestones are traceable over wide areas in western Bas-Bugey

and the Molard Dedon Range. They are not found in the south-eastern Jura (Khouri, 1960).

MAn 3. This unit (18m. thick at the type section) makes up the lower part of the Bioclastic Calcarenite Sequence of the Middle Ambléon Limestone (see figs. 13 & 14).

The passage from reef limestones of MAn 1 and 2 to the calcarenites of MAn 3 is marked in the field by a sharp increase in resistance to weathering (fig.16). Man 3 is made up of well-bedded limestones. Cross-laminations are diffuse or absent.

The calcarenites are cemented by coarsely-crystalline calcite. The principal detrital components of these rocks are echinoderm fragments. Brachiopod/lamellibranch and polyzoan debris is of subsidiary importance. The calcarenites closely resemble the rocks of LAn 2. Iron-oxide stained dolomite occurs as part of the pore-filling cement in some of the beds of MAn 3.

A gully in the topography is formed over a particularly poorly-resistant band in the middle of MAn 3. The rocks of this band resemble those of MAn 2, both in lithology and resistance to erosion. This suggests a transitory return to a reef environment in the middle of MAn 3.

MAn 4. This sub-division, which is 20m. thick at the type section, consists of coarse- and fine-grained calcarenite (see fig.16). The coarse calcarenites represent a continuation of the lithology in MAn 3. The finer grained components are difficult to determine with a

hand lens.

The limestones are well-bedded and cross-laminated. At the base of MAn 4 the coarse and fine fractions appear to be mixed. For example, large crinoid ossicles and lamellibranch shells were noted to "float" in a fine-grained groundmass. Higher up the coarse- and fine-grained components appear segregated in alternating cross-laminations.

Iron-oxide stained dolomite occurs only sparsely in this sub-division, except in the uppermost metre, where the mineral forms part of the pore-filling cement.

MAn 5. This unit (6m. thick at the type section) consists of cross-bedded, coarse-grained bioclastic calcarenites with inter-bedded coralline limestones. The presence of thamnastraeoid corals here is the principal criterion for separating MAn 5 from the sub-division below.

The coral-bearing limestones are poorly resistant to weathering, as in MAn 1 and 2. They contain much iron-oxide stained dolomite, both in isolated vugs and as a pore-filling cement. In contrast to the lower reef complex, however, the coralline beds of MAn 5 are essentially coarse bioclastic calcarenites, apparently without any calcilutite matrix. The limestones inter-bedded with the coralline units are cross-bedded and well-sorted, suggesting deposition in a high-energy environment. The corals in the associated beds might thus have been derived, though they do not appear to have been rolled. Since their corallites have a delicate structure made up of

finely granular calcite, they clearly could not have survived extensive transportation.

The coarse bioclastic calcarenites inter-bedded with the coralline limestones of MAn 5 generally occur in well-bedded units. One of these beds, however, has an irregular contact with the coral-bearing limestone below. It appears that the upper surface of this coral bed was channelled as the overlying calcarenites were deposited. Above the second coralline bed comes a well-bedded unit, consisting predominantly of separated and somewhat broken lamellibranch valves. The flat valves were probably concentrated by re-working on account of their distinctive hydrodynamic properties.

MAn 3, 4 and 5, recognised at the type section, are sub-divisions of the Bioclastic Calcarenite Sequence of the Middle Ambléon Limestone (fig.13). This Sequence can be traced over a wide area in the region, west of Belley.

MAn 6. This sub-division (20 m. thick at the type section) is characterised by an abundance of chert. The sub-division, which is known as the Chert Sequence (fig.13), is a potential mapping unit for future studies in western areas.

Chert, generally occurring in regularly shaped nodules, elongated parallel to the bedding, may form up to 30% of the rocks in this sub-division. The host rock is essentially a fine-grained, buff-coloured, calcarenite. Except where chert is very abundant, bedding planes are well-developed.

There is an abundance of iron-oxide stained

dolomite in MAn 6. The dolomite occurs as a pore-filling cement and in small vugs. The dolomite is notably absent within the chert nodules. Narrow envelopes surrounding the silicified zones are also lacking in dolomite. The significance of this distribution is discussed later (chapter 19).

MAn 7. This unit, some 5m. thick at the type section, is recognisable over a wide area and consists essentially of well-bedded, off-white calcilutites (see fig.16). These are much more resistant to weathering than the underlying calcarenites of MAn 6.

The calcilutites of MAn 7 contain layers of thamnastraeoid corals and numerous vugs of iron-oxide stained dolomite. The basal bed of the sub-division is particularly interesting since it contains a band of Rhactorhynchia rhacta (a form typically associated with reefs,) immediately below a coral horizon. In the lower part of MAn 7 numerous large lamellibranch shells were found accumulated in nodules. These were clearly not preserved in life position.

MAn 8. The uppermost 2m. of the Middle Ambléon Limestone consist of grey, fine-grained calcarenites of the type found in MAn 6. These calcarenites form part of a transition from the upper coralline beds of the Middle Ambléon Limestone to the bioclastic calcarenites at the base of the Upper Ambléon Limestone.

(b) Laboratory study.

MAn 1. Only the features of the blue, coralline calcilutites of MAn 1 are described here. The poorly-sorted

Plate 11.

PLATE 11.

Thin band of thamnastraeoid coral in calcilutite. Lower contact of coral & host rock is silicified. Thin section stained with alizarin red S & potassium ferricyanide in dil. HCl. Lower reef horizon of Middle Ambléon Limestone at type section. Plane polarised light (X3½)

calcarenites, which form subsidiary bands in this sub-division, occur more widely in MAn 2. Their microscopic features are therefore described in the next section.

The coralline calcilutites of MAn 1 are typified by the thin section shown in plate 11. The coral, which is thamnastraeoid, occurs in a narrow band, separated from the calcilutite below by a thin layer of chalcedony. Although the basal part of the coral is often replaced by chalcedony, it is uncertain whether or not the whole layer of silica observed is of replacement origin. Staining (chapter 18) has shown the thecae and septa of the corals to be made up of ferrous-iron free calcite. The calcite cement within the corallites, however, is coarsely-crystalline and predominantly ferroan. The host rock consists essentially of ferrous-iron free, microcrystalline calcite. This material was no doubt derived from the corallites, which were probably being continually broken up by the strong wave action, characteristic of reef environments.

Scattered echinoderm, lamellibranch and polyzoan fragments have been found "floating" in the calcilutite matrix. Of note are an abundance of small equidimensional cavity fillings of coarsely-crystalline calcite. These are believed to represent the sites of former mollusc fragments, made up of the metastable aragonite. A number of larger vugs contain the iron-oxide stained dolomite, first noted in the field. This dolomite has been shown, by artificial staining, also to contain ferrous-iron within its lattice.

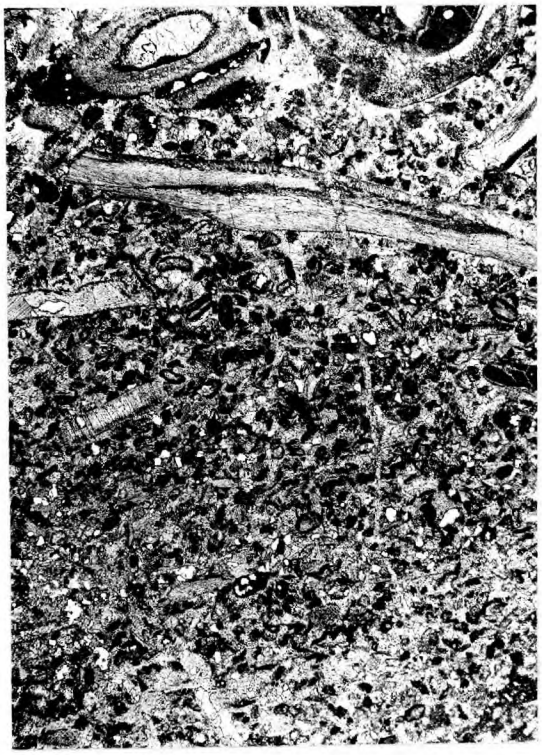
PLATE 12

PLATE 12.

Poorly-sorted calcarenite, with partially silicified skeletal debris. Plane polarised light(X13). Lower reef horizon of Middle Ambléon Limestone at type section.

Plate 13.

PLATE 13



Alternation of coarse-grained skeletal calcarenite & fine-grained detrital quartz- and pellet-bearing calcarenite. Bioclastic Calcarenite Sequence of Middle Ambléon Limestone at type section. Plane polarised light (X15).

MAn 2. The light blue calcarenites of MAn 2, illustrated in plate 12, contain principally echinoderm, lamellibranch and polyzoan fragments. Fine-grained pellets, merging into calcilutite in the poorly-sorted rocks, partly infill the inter-granular pore-spaces. The remainder of these are cemented by calcite and dolomite of varying ferrous-iron content. It is interesting to note that certain skeletal fragments are silicified whereas their surrounding fringes of calcite cement are not. This suggests that silicification pre-dated cementation.

MAn 3. The calcarenites of MAn 3, illustrated in plate 52, are well-packed and generally cemented entirely by coarsely-crystalline calcite. However, some fine-grained material is found in the inter-granular pore-spaces in the limestones at the base of the sub-division, where a transition exists between MAn 2 and 3. Whereas the poorly-sorted calcarenites of MAn 2 contain a relatively even proportion of echinoderm, lamellibranch and polyzoan fragments, the well-packed, and probably clean-washed calcarenites of MAn 3 are almost pure crinoidal limestones (see plate 52).

MAn 4. This unit was noted in the field to consist either of alternating coarse- and fine-grained calcarenite or a mixture of the two factions. Plate 13 shows the coarse and fine grades segregated into adjacent bands. The coarse calcarenite, as noted in the field, is basically the same

Plates 14 & 15

PLATES 14 & 15

PLATE 14. Calcilutite containing scattered, coarse-grained skeletal debris, & exhibiting vugs of calcite & dolomite after original corallites. Chert Sequence of Middle Ambléon Limestone at type section. Plane polarised light (X5).

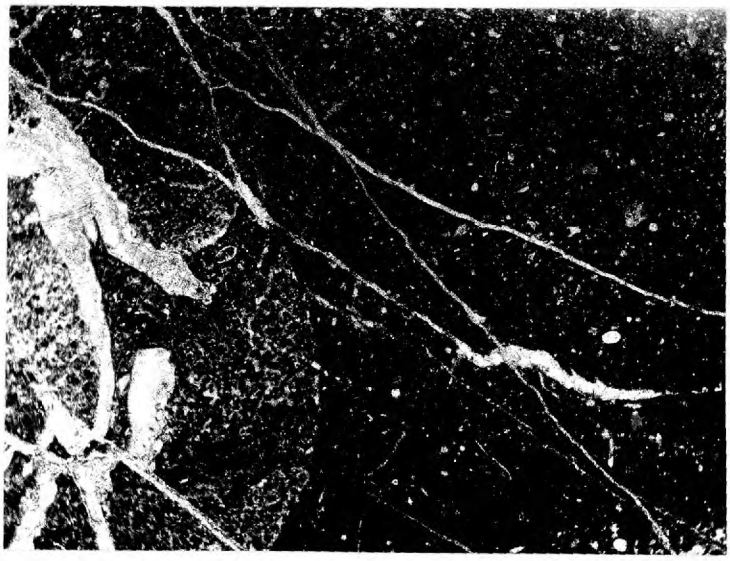


PLATE 15. Broken bivalve, with an internal sediment of fine-grained pellets cemented by sparry calcite, in a host rock of calcilutite. Upper reef horizon of Middle Ambléon Limestone at type section. Plane polarised light (X16).

as that of MAn 3. The bands of fine-grained limestone, however, contain a relative abundance of detrital quartz, pellets and some Foraminifera, as well as fine-grained representatives of those components in the coarse calcarenites.

MAn 5. Thin section evidence substantiates the field observation that this division is really a continuation of MAn 4 below, and that the only basis for separating MAn 5 is on the occurrence of thamnastraeoid corals in these beds.

MAn 6. The chert which characterises this subdivision is made up of cryptocrystalline silica, probably as a mixture of chalcedony and opal.

The host rock contains much calcilutite which forms the groundmass either to scattered sand-size skeletal debris, or to coarser bioclastic grains. Plate 14 shows an example of the latter type of limestone. In the top left hand corner of the photomicrograph, an almost circular vug-infilling of coarsely-crystalline calcite and dolomite is found. The outline of this vug closely resembles that of a corallite, seen in the centre of the field of view. The septa and thecae of this corallite are also filled with coarsely-crystalline calcite and dolomite (both ferroan). The evidence suggests that the small sub-circular vugs of iron-oxide stained dolomite, observed in the rocks, represent the sites of former corallites to ramose corals.

It is interesting to note the different roles played by the calcilutite fraction in the rocks containing sand-size

skeletal debris. It may occur as a matrix supporting the skeletal fragments, or in pellet-like aggregates where the bioclastics provide the supporting framework. It is possible that during compaction the pellets merged to give calcilutite in the former case.

MAn 7. Calcilutites, and skeletal calcarenites with calcilutite matrices are prominent in the reef limestones of MAn 7 (cf. MAn 1). A somewhat different lithology is found forming the internal sediment to a band of bivalves, seemingly indigenous to these coralline calcilutites (see plate 15). This sediment consists predominantly of fine-grained pellets cemented by coarsely-crystalline calcite. It is feasible that the original coralline sediment was made up mainly of pellets, but that during compaction these merged to form calcilutite. The bivalve shells are believed to have locally protected the pellets from the forces of compaction.

MAn 8. As concluded from the field evidence the rocks of MAn 8 resemble the calcarenites of the Chert Sequence, MAn 6.

(iii) Upper Ambléon Limestone.

(a) Field study.

The grey calcilutites containing fine-grained skeletal debris at the top of the Middle Ambléon Limestone pass upwards into less resistant, cross-bedded bioclastic calcarenites. The change in lithology takes place gradually in a transition zone, involving both MAn 8 and UAn 1.

UAn 1. At the type section (Veyrin Hill) the basal 14½m. of the Upper Ambléon Limestone (UAn 1) is made up of well-sorted, coarse, bioclastic calcarenites alternating with poorly-sorted calcarenites. In the latter, coarse debris appears to "float" in a matrix of finer grained calcarenite, the components of which are not readily recognisable in hand specimen. Both representatives of UAn 1 are cross-bedded, and both carry coarsely-crystalline calcite cement. The well-sorted calcarenite generally occurs in units 1-3m. thick, alternating with thinner bands of the poorly-sorted material.

The lithology of the well-sorted calcarenites of UAn 1 resembles that of LAn 2 and MAn 3, described earlier. In the poorly-sorted calcarenites, the coarse fraction is very distinctive, consisting mainly of large ossicles of Isocrinus and almost whole oyster shells. Polyzoan fragments are not so common here. The combination of well- and poorly-sorted calcarenite described above is analagous to the situation in MAn 4.

UAn 1 is recognisable over wide areas in the west and is similar both in lithology and stratigraphical position to the entire Upper Ambléon Limestone of the south-eastern Jura. This, according to Khouri (1960), is 20m. thick.

UAn 2. This begins with the first significant occurence of oolite in the Upper Ambléon Limestone (fig.16). The sub-division, which is 10m. thick, consists of cross-bedded oolite and coarse skeletal debris. At the base of the unit the two components are inter-mixed with large Isocrinus ossicles

and oyster shells (20% of the rock) "floating" in a groundmass of oolite. Higher up, the coarse-grained skeletal debris and oolite occur in alternate bands with the oolitic sequences becoming thicker upwards. At the very top of UAn 2 the limestones consist almost wholly of oolite save for a few cross-laminations concentrated in skeletal debris. This lithology is similar to that of LAn 3.

UAn 3. Apart from rare oyster shells and *Isocrinus* ossicles, UAn 3 (4½m. thick at the type section) consists entirely of oolite. The sub-division below, UAn 2, forms a natural transition between the coarse skeletal calcarenites of UAn 1 and the almost pure oolites of UAn 3.

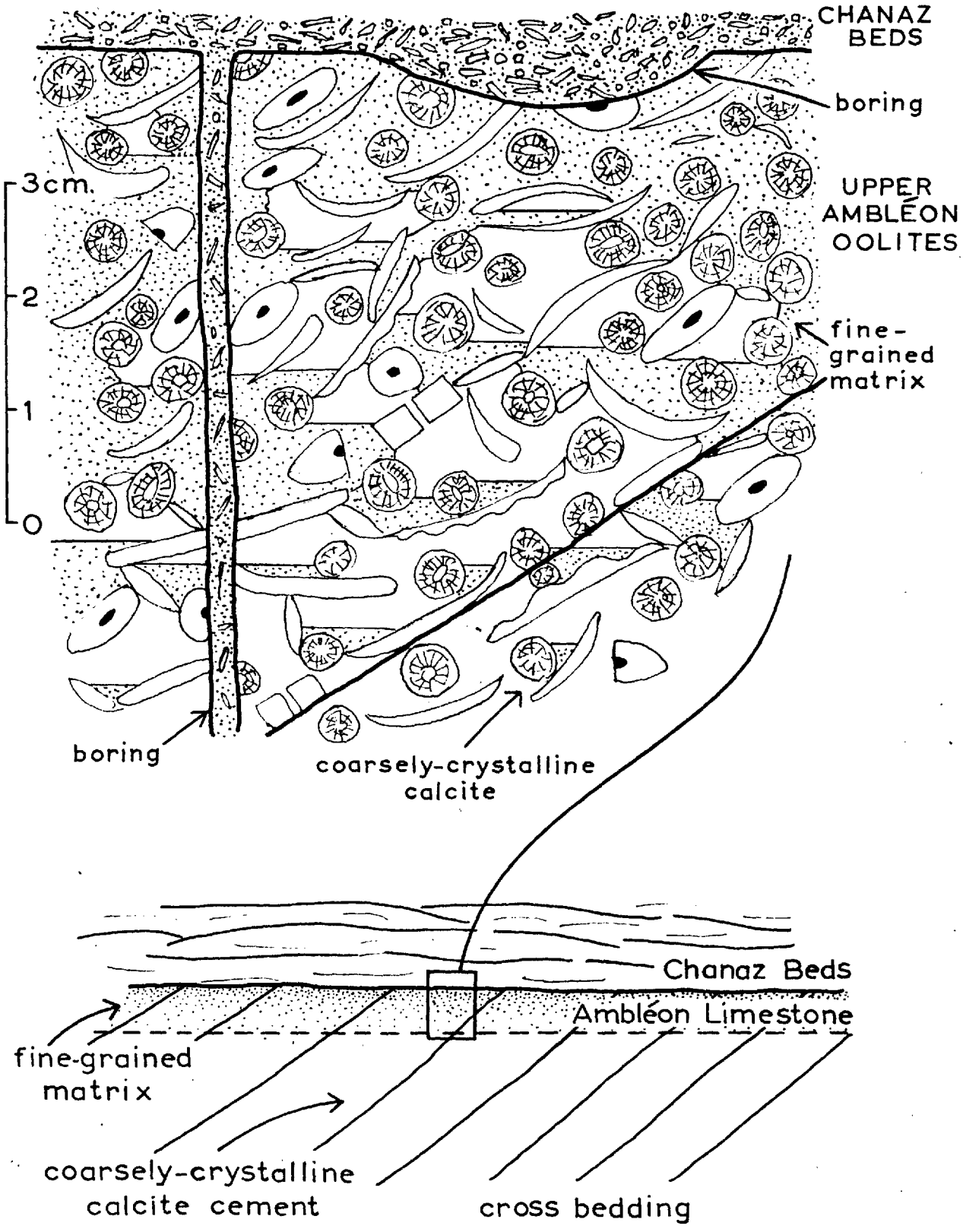
The uppermost surface of UAn 3 is oyster-covered and penetrated by numerous borings. These are about 2cm. in diameter and ½cm. deep. The horizon no doubt represents a halt in the sedimentation.

UAn 4. This unit terminates the Ambléon Limestone. It is 10m. thick at Veyrin Hill, and is a repetition of the sequence seen in UAn 2 (see fig.16). Thus the succession through UAn 2, 3 and 4 represents a complete cycle of sedimentation leading from the deposition of skeletal calcarenite up to an oolite sequence and back again.

The basal 2m. of UAn 4, immediately above the bored surface of UAn 3, is made up almost entirely of valves of oysters which form a calcirudite. This lithology is repeated in a 25cm. bed higher up. It appears that sedimentation was slow to start again after the halt at the end of

FIG. 17

SCHEMATIC DIAGRAM OF THE CONTACT BETWEEN THE AMBLÉON LIMESTONE AND CHANAZ BEDS



Plates 16 & 17

PLATES 16 & 17

PLATE 16. Contact between cross-bedded, oolitic Upper Ambléon Limestone & nodular Middle Chanaz Beds. Bois du Molard Dedon (Ain).

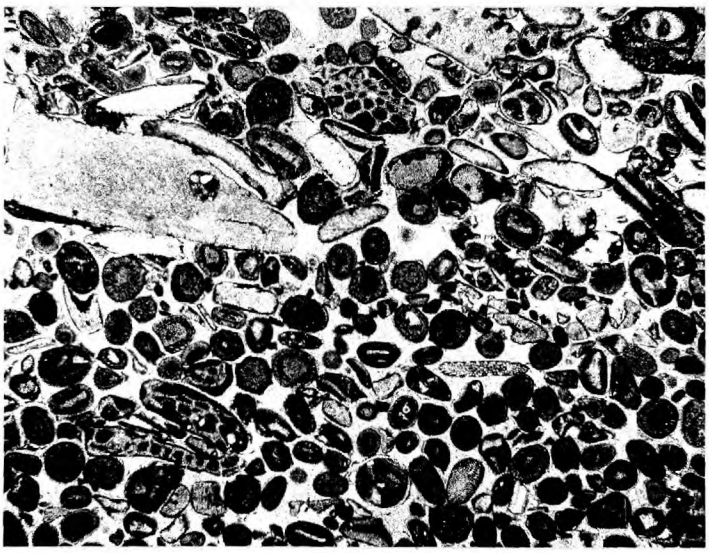


PLATE 17. Alternation of oolite, and oolitic skeletal calcarenite. Upper Ambléon Limestone, Veyrin Hill (type section). Plane polarised light (X12).

UAn 3.

The uppermost part of UAn 4, both at the type locality and elsewhere in the area west of Belley, is a cross-bedded oolite containing thin laminations of coarse skeletal debris. The stratigraphical contact between these cross-bedded oolites and the overlying, horizontally-bedded Chanaz Beds (chapter 6) has the appearance of a sharp angular unconformity (see plate 16). This is clearly not the case, however, since the master bedding planes in UAn 4 conform to the stratification in the Chanaz Beds. The apparent angular unconformity is due to discordance between the foreset beds of the oolite and the normal stratification in the overlying Chanaz Beds.

The uppermost surface of UAn 4 appears to have been bored by two different types of organisms (see fig.17). The surface is penetrated by numerous narrow and deep borings. It is also covered by relatively shallow and wide excavations, similar to those found at the top of UAn 3. Both the types of boring are infilled with fine-grained calcarenite recognised as belonging to the Chanaz Beds. The evidence suggests that a stratigraphical break exists at the top of the Ambléon Limestone.

The main body of the oolites of UAn 4 is cemented by coarsely-crystalline calcite. However, the ooliths of the uppermost 5-6cm. of this unit are set in a fine-grained groundmass. The band of oolite carrying a calcilutite matrix

transgresses the cross-laminations seen in UAn 4 (see fig.17). Foreset laminations are undisturbed where they pass from rock containing coarsely-crystalline calcite cement, to oolite with a fine-grained groundmass. The evidence indicates that the calcilutite matrix was not deposited with the ooliths; nor was it introduced by re-working, since the foreset bedding is undisturbed. Instead, the fine-grained material must have infiltrated down into the bed at some stage subsequent to its deposition.

(b) Laboratory study.

UAn 1. While the principal coarse-grained components of UAn 1 were readily identifiable in the field, the finer-grained detritus was undetermined. In thin section this is seen to consist of pellets and fine-grained skeletal debris, some with oolitic jackets (pseudo-ooliths). Some calcilutite is found in the cavities of bivalves. These may have been derived from a region of calcilutite deposition, for example, as represented by the Middle Ambléon reef limestones.

UAn 2. The bands of coarse skeletal debris which alternate with oolite in the UAn 2 consist predominantly of echinoderm, lamellibranch and polyzoan fragments, some of which are coated with oolitic jackets. The interstices between these coarse grains are filled by finer grained ooliths and pseudo-ooliths. The interstitial material is thus of the type found concentrated in the alternate bands of pure oolite. Plate 17 illustrates the junction between a

band of oolite and an adjacent lamination of coarse skeletal calcarenite.

UAn 3. This sub-division consists of three types of oolite.

The first is made up of ooliths which have undergone considerable mechanical compaction (see plate 59). In such rocks the outer concentric layers of the ooliths have been broken and partially "spalled off". The phase of mechanical compaction represented here may be dated in relation to the overall cementation history of the rock (see chapter 20).

The second type of oolite contains unbroken, well-rounded ooliths which have not suffered significant mechanical compaction (see plate 55).

Skeletal fragments, not coated with oolithic jackets, in either of the oolites already mentioned, have given rise to a distinctive form of calcite cement. The crystals of this cement are oriented onto those of the host skeletal fragments. Hence monocrystalline echinoderm fragments have overgrowths in optical continuity with the calcite of the host grains. Similarly the laminated calcite crystals of the polycrystalline brachiopod and lamellibranch shells are continued out into the pore-filling cement. In contrast, ooliths and pseudo-ooliths are rimmed by finely-crystalline calcite needles (plates 55 & 56).

In the third type of oolite in UAn 3, also unaffected by mechanical compaction, the ooliths, pseudo-ooliths and skeletal debris alike, all have well-developed fringes of

Plate 18.

PLATE 18.

Oolitic calcarenite from Upper Ambléon Limestone, Veyrin Hill. Thin section stained with acidified potassium ferricyanide. Texture of first iron-free phase of cement consistent over all types of grains. Replacement of skeletal fragments & fringing cement by chalcedony seen in centre of left-hand field of view. Plane polarised light(X22).

fine-grained calcite needles (see plate 18). Staining (chapter 18) has shown this calcite to be characteristically free of ferrous-iron. Most of the inter-granular pore-spaces within the rock have been filled with this iron-free calcite. The larger of these former cavities, however, also contain ferroan calcite belonging to a later phase of cementation (plate 18). The texture of the inner, ferrous-iron free calcite is remarkably consistent no matter what form of nucleus is present. This appears in great contrast to the texture of the cement in the oolites described earlier. Furthermore, the iron-free cementation calcite of the third type of oolite is, in places, replaced by chalcedony (see left-hand side of plate 18). In such partially silicified rocks it is usually found that the skeletal debris, rather than the pore-filling cement, has been preferentially replaced by silica. It has been pointed out, however, (page 129) that such preferential silicification of skeletal debris in the Ambléon Limestone probably pre-dated cementation. If this was the case it appears that, under the prevalent physico-chemical conditions, silica replaced carbonate instead of being directly precipitated. Certainly, the chalcedony in the oolites being described appears to have had a replacement origin, since it cuts across skeletal debris to invade the cement (plate 18). Nowhere are crystals of cement seen to have seeded themselves onto the chalcedony. The evidence suggests an unusually early phase of cementation in these oolites, pre-dating silicification. It is significant that this third

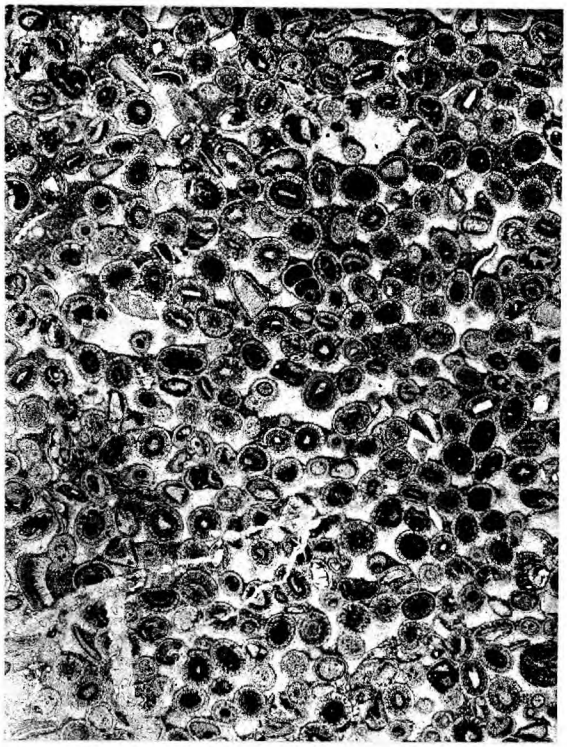
type of oolite occurs immediately below the bored, oyster-covered surface, already described from field observations. It is believed that the origin of the unusual texture of the pore-filling cement is connected in some way with the probable halt in sedimentation represented by the bored surface. It is proposed, as an hypothesis, that the oolite at the top of UAn 3 was initially cemented by aragonite. The petrographical evidence already given is discussed in the light of this hypothesis in the following paragraphs.

The needle-like fringes of calcite crystals which occur around ooliths, monocrystalline and polycrystalline skeletal debris alike, could well originally have been precipitated as aragonite. As a mineral distinct from calcite, aragonite could not have oriented itself in lattice continuity with the calcite of the skeletal debris. Instead, the orthorhombic needles would have seeded themselves similarly over all the available free surfaces. In time the meta-stable aragonite would have altered to calcite, the stable allotropic form of calcium carbonate. This would explain the unusually consistent texture of the first phase of cement observed in the oolites at the top of UAn 3.

The first phase of cementation in these rocks was early, in that it pre-dated silicification. Studies made on Recent carbonates indicate that cementation by aragonite is commonly extremely rapid in the inter-tidal zone, for example around Bikini Atoll (Emery et alia, 1954) and along the Trucial Coast of the Persian Gulf (Mr.D.J.J.Kinsman: personal

Plate 19.

PLATE 19.



Oolite of Upper Ambléon Limestone at contact with overlying Chanaz Beds, Appregnin (Ain). Proportion of fine-grained groundmass diminishes downwards. Numerous pore spaces are only partially filled by fine-grained sediment. Here the upper surfaces to the internal sediment are level & consistently face upwards. Many of the slender shell fragments have acted as traps for the internal sediment & have given rise to "umbrella" effects. Plane polarised light (X6½).

communication). The oyster-covered and bored surface at the top of UAn 3 could well have formed during temporary emergence in the inter-tidal zone. This fact, and the unusual texture of the first phase of cementation leads the writer to believe that the oolites at the top of UAn 3 constitute a fossil beach rock, which was initially cemented by aragonite.

The orthorhombic aragonite can take in very little ferrous-iron into its lattice. In contrast ferrous-iron forms a partial substitution series for calcium in calcite. The complete absence of ferrous-iron in the first phase of cement indicates that this could formerly have been aragonite. Subsequent solid-state inversion of such iron-free aragonite to calcite would have prevented iron from entering the new generation of calcite.

<u>UAn 4.</u> Of particular interest are the microscopic features of the band of oolitic and skeletal calcarenite at the very top of UAn 4 (see fig.17 & compare with plate 19). In thin section the borings which penetrate the uppermost surface of the oolite are seen to cut indiscriminately across ooliths, skeletal fragments, and where present, fine-grained matrix. Thus the boring organisms had clearly not pushed aside unconsolidated sediment but had instead, penetrated a relatively rigid, partially lithified framework. As observed in the field, the borings are filled with fine-grained skeletal debris embedded in a calcilutite matrix. This sediment characterises the lithology of the overlying Chanaz Beds. It is reasonable to assume that the irregular upper surface of the Ambléon Limestone was

infilled and covered by the basal Chanaz calcarenites.

The calcilutite matrix to the uppermost 5-6m. of UAn 4 matches the groundmass of the overlying Chanaz calcarenites. However, although much of the skeletal debris of the Chanaz calcarenites is sufficiently fine-grained to have penetrated the pore-spaces of UAn 4, no such debris is found here. This suggests that the pore spaces had already been filled with calcilutite prior to the deposition of the Chanaz calcarenites.

C. STRATIGRAPHICAL AGE.

The well-preserved fauna from the Ambléon Limestone (that is, excluding the abundant, generically indeterminate skeletal debris) is as follows:-

Lower member: *Rhactorhynchia rhacta* Buckman
Crustacean indet.
Miliolidae
Ophthalmidae
Ostrea sp.
Pecten sp.

Middle member: *Rhactorhynchia* cf. *R. rhacta* Buckman
Lobothyris buckmani (Davidson)
Isastraea explanata (McCoy)
Thamnasteria sp.
Thecosmilia sp.
Pecten sp.

Upper member: *Rhactorhynchia* sp.
Isocrinus cf. *I. andraea* Desor
Parallelodon (*Beushausonia*) sp.

TABLE III

TABLE III

AMMONITE ZONES of Pelletier (1960)	LITHOFACIES of Pelletier (1960)	LITHOLOGICAL SUB-DIVISIONS recognised by the present author.
Parkinsonia parkinsoni	faciès marno-calcaire-oolithique	UAn 4 UAn 3 UAn 2
Garantiana garantiana *Strenoceras subfurcatum*	faciès marno-spathique	UAn 1
Stephanoceras humphriesi	deuxième niveau de faciès coralligène	MAn 8 MAn 7 MAn 6 Chert sequence.
Otoites sauzei	faciès à entroques	MAn 5 Bioclastic MAn 4 Calcarenite MAn 3 Sequence
Witchellia loeviuscula	premier niveau de faciès coralligène	MAn 2 MAn 1
Sonninia sowerbyi	faciès marno-spathiques à chailles	LAn 3 LAn 2
Ludwigia (*Graphoceras*) *concavum*	marnes et calcaires à entroques	LAn 1
Ludwigia murchisonae	marno-sables, siliceuses, et micacées à "*Cancellophycus*" *scoparius* (Thiollière)	Cuzieu Flags

In the area studied, the Ambléon Limestone overlies the Cuzieu Flags, of probable Aalenian age, and underlies the Chanaz calcarenites which have yielded Lower to Upper Bathonian ammonites from within 4m. of their base. Ammonites have not been found in the Ambléon Limestone by any of the team from Imperial College. However, Rhactorhynchia rhacta is relatively common and suggests a Bajocian age for the formation.

Riche (1893) and later Pelletier (1960) described the ammonite-bearing "Bajocien" outcrops of the Mont d'Or district near Lyon (eastern margin of the Massif Central). They compared and attempted to correlate these successions with certain "Bajocien" sequences in the Southern Jura. Pelletier, in addition, found rare ammonites within the "Bajocien" of the Southern Jura. He used these to establish a complete zonal stratigraphy based on changes in the morphology of corals up the succession. Neither Riche nor Pelletier gave detailed petrographical descriptions of the "Bajocien" rocks. Nevertheless it has been possible to recognise the broad lithofacies named and zoned by Pelletier (see Table III). The sub-divisions of the Ambléon Limestone succession, as described in detail by the present author, can therefore be zoned by correlation with the results of Pelletier's research (see Table III). It is felt that the combined biostratigraphical work of Pelletier and lithostratigraphical study of the present author, provides a valuable contribution to the knowledge of the Bajocian stratigraphy

of the French Jura.

D. FAUNAL EVIDENCE OF PALAEO-ENVIRONMENT.

(i) Lower Ambléon Limestone.

The skeletal debris of the Ambléon Limestone probably represents an originally indigenous fauna, which after death became broken up by strong wave action. The abundance of this bioclastic material and the rarity of well-preserved fauna suggests general deposition in a high-energy environment above the wave-base (that is at depths of probably less than 30m). *Rhactorhynchia rhacta*, found relatively commonly in the Lower Ambléon Limestone, is a robust form with a reinforced pedicle opening. It would probably have been able to survive the rough-water environment envisaged for the deposition of the Lower member of the formation. The bands concentrated in lamellibranch valves (mainly of *Ostrea* and *Pecten*) probably represent slow accumulation of detritus.

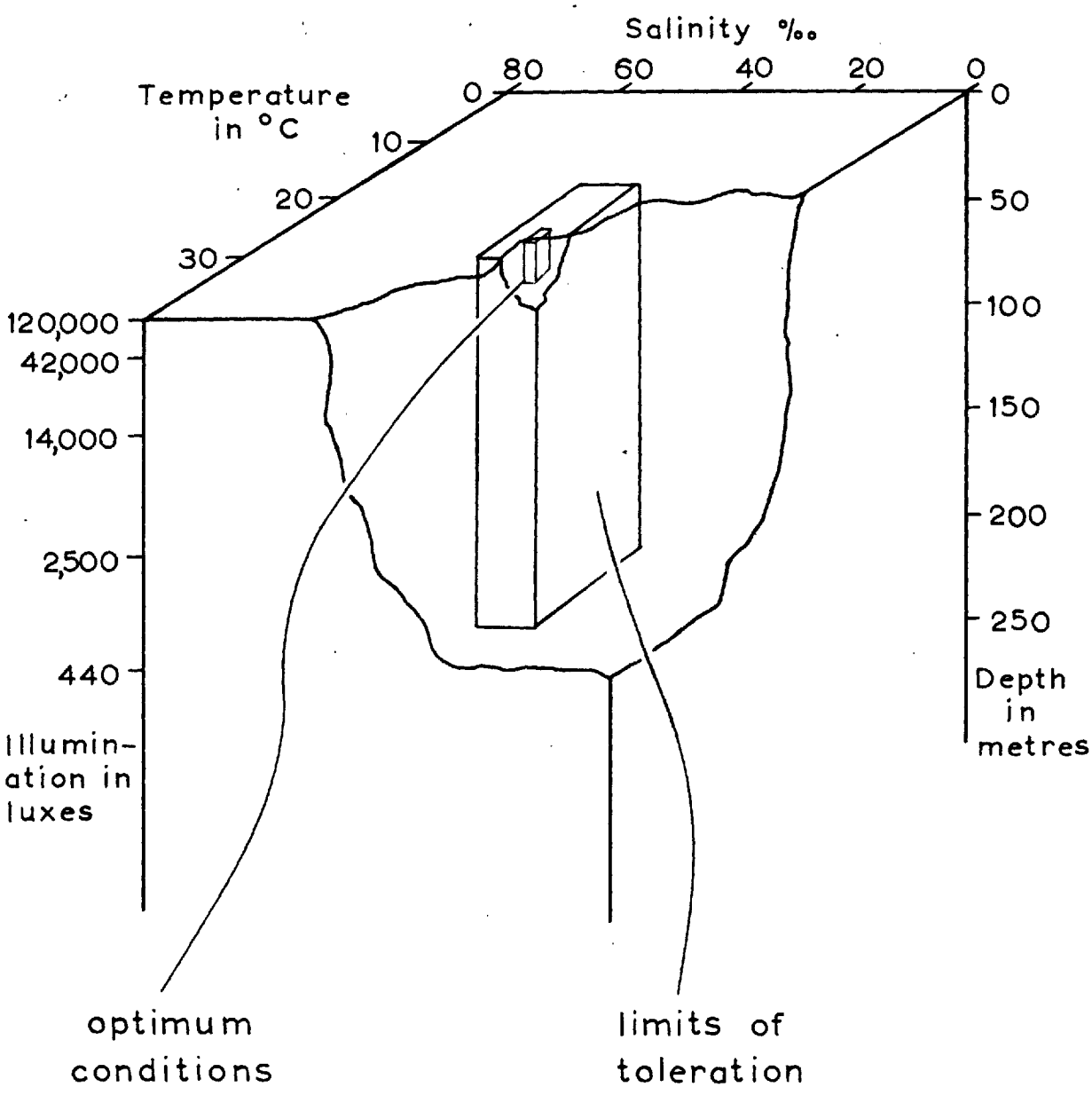
The Foraminifera in the Lower Ambléon Limestone are of the same suite as those in the Cuzieu Flags (Miliolidae and Ophthalmidae). They are far less abundant in the coarse skeletal calcarenites than in the fine-grained limestones. This is believed to have been due to a lack of food in the coarse-grained, clean-washed sediments.

(ii) Middle Ambléon Limestone.

The coarse-grained skeletal calcarenites of the Middle Ambléon Limestone indicate the same high-energy environment of deposition as for the Lower member.

FIG. 18

PHYSICAL CONDITIONS FOR THE SURVIVAL OF MODERN HERMATYPIC CORALS, after Wells (1957).



The calcilutites of the Middle member, however, carry a fairly abundant well-preserved fauna consisting in particular of bands of thamnastraeoid coral (plates 10 & 11) and of great masses of ramose corals (see plate 9) preserved in position of growth. Horizons concentrated in Rhactorhynchia and Lobothyris, also probably in near-life position, have been found immediately below thamnastraeoid corals in MAn 7. The rhynchonellid, with its tendency towards asymmetry and its strengthened pedicle opening is a characteristic reef associate (Dr.Ager: personal communication). So too, are the pectinid lamellibranchs which are found widely in the Middle Ambléon reef limestone.

The reefs in the Mesozoic succession of the area mapped, were built of hermatypic corals. Wells (1957) has summarised the closely defined physical conditions, which must be met at the present day before modern corals of this type can grow successfully. Nearly all these conditions are imposed by the algae associated with the corals. Such associations probably also occurred in the Mesozoic. If this is so, Fig.18 taken from Wells (1957), indicates the restricted environment, which would be represented by the Middle Ambléon coral-bearing limestones.

It has been proposed earlier (p. 126) that the calcilutite in the reef limestones was derived from the corals, which were being broken down and comminuted by wave action.

Although such wave action is considered to have been significant, it is not believed to have been as strong as in the deposition of the coarse skeletal calcarenites. Had it been as strong, the calcilutite host sediment would probably have been winnowed away, the corals would have been more abraded, and the bands of Rhactorhynchia and Lobothyris would have at least been disturbed.

(iii) Upper Ambléon Limestone.

Rhactorhynchia and Parallelodon occur in the coarse-grained skeletal calcarenites of UAn 1. These sediments represent a similar environment of deposition as the coarse calcarenites of the Lower Ambléon Limestone. The oolitic divisions, UAn 2, 3 & 4, have yielded no unbroken fauna. This probably indicates a higher energy environment of deposition for oolite than for skeletal calcarenite.

E. SUMMARY OF GEOLOGICAL HISTORY.

During the deposition of the basal Ambléon Limestone the sea floor is believed to have been gradually raised above the wave-base (see fig.30). Poorly-sorted, fine-grained calcarenites of a type found in the Cuzieu Flags alternate with clean-washed, coarse-grained skeletal calcarenites. The latter type of calcarenite, which forms the main part of the Lower Ambléon Limestone higher up, is cross-bedded on a grand scale and was clearly laid down where bottom currents were active. The coarse-grained calcarenite at the base of the graded beds in the Lower Ambléon Limestone is believed to have been derived from a nearby sea floor, elevated above the wave-base. The

fine-grained, cross-laminated calcarenites at the top of each graded unit is taken to represent the "normal" sediment of the environment (which is thought to have been situated just below the wave-base). The last bed of poorly-sorted, fine-grained calcarenite represents the end, in this cycle of sedimentation, of deposition below the wave-base.

The main part of the Lower Ambléon Limestone is considered to have been laid down in a shallow-water, high-energy environment. The oolite at the top of the member probably represents chemically precipitated calcium carbonate, laid down in both extremely agitated, and shallow water, probably in the inter-tidal zone. The oolite at the top of the Lower Ambléon Limestone is not found further south-east. It is likely that the water became too deep for oolite formation in this direction towards the Dauphinois trough.

In the area west of Belley, Middle Ambléon coralline calcilutites surmount the oolites at the top of the Lower member. From the evidence of modern hermatypic corals it seems that these reef limestones were laid down in extremely shallow tropical waters (about 5m. in depth). The energy of the environment, however, is believed not to have been as high as that for the skeletal and oolitic calcarenites below.

The most common corals of the Middle Ambléon Limestone are phaceloid (plate 9), and thamnastraeoid (plate 10). The corallites of the former are almost entirely replaced by ferroan dolomite and calcite. In certain apparently noncoral-bearing rocks, vugs of dolomite have been found showing traces

of septa (plate 14). It seems likely that many of the corals formerly present in the Middle Ambléon sediments were obliterated during diagenesis and that they are now represented in the rock only by vugs of ferroan dolomite. The massive thamnastraeoid corals, in contrast to the ramose forms, consist of iron-free calcite. It could be that the phaceloid corals were formerly made up of aragonite, and the thamnastraeoid corals of high-magnesium calcite. The magnesium exsolved from the massive corals could now be represented in the ferroan dolomite, which fills the former corallites of the ramose corals. Skeletal calcarenites which contain abundant ferroan dolomite are generally found to belong to an overall reef complex. The dolomite tends only to occur in isolated vugs in the poorly-permeable calcilutites. These vugs no doubt represent local zones of weakness, for example formerly aragonitic corallites. In the more permeable calcarenites the dolomite is widely distributed in the pore-filling cement and in the formerly aragonitic parts of mollusc shells.

The lower reef complex of the Middle Ambléon Limestone (21½m) is followed by more skeletal calcarenites representing a return to a high-energy environment. Coralline calcilutites re-appear forming a second reef complex (27m.) at the top of the Middle Ambléon Limestone. The total of 48½m. of reef limestone in the west compares with 12m. found by Taha in eastern Bas-Bugey. Further south-east, in the Col du Chat area, Khouri (1960) reported the almost complete absence of corals in the Ambléon Limestone (known by him as the Lucey

Limestone). This was probably again due to deepening of the water towards the Dauphinois trough, so that corals were only able to survive in the shallow western areas.

The skeletal calcarenites found at the base of the Upper Ambléon Limestone in western areas appear to correlate with the entire Upper Ambléon Limestone of the south-east. Evidence is presented later (see chapter 6) to suggest that the Upper Ambléon oolites pass south-eastwards into marl belonging to the Lower Chanaz Beds. This facies change again indicates deepening of water to the south-east. In western areas the Upper Ambléon oolites represent deposition in extremely shallow waters. The presence of bored surfaces even indicates possible emergence. Hence the cycle of sedimentation, which had begun with the continental Triassic and had passed through the relatively deep-water Liassic, was terminated in the area mapped by an oolitic sequence towards the end of the Bajocian.

CHAPTER 6.

THE CHANAZ BEDS.

A. GENERAL

The Chanaz Beds were described by Khouri (1960) from exposures over the Montagne de la Charvaz (map 3). Ferruginous oolites at the very top of the formation, exposed near the village of Chanaz, became celebrated as far back as the late eighteen-hundreds for their abundance of well-preserved Lower Callovian ammonites. Influenced by the wealth of fauna from this exposure, Parona and Bonarelli (1897) significantly adopted the name "Chanasien" for the "Callovien inférieur" of Savoie. Although the term "Chanasien", as a stratigraphical stage name, did not catch on, it is felt that the Chanaz Beds, in part of Lower Callovian age, are aptly named.

At the type locality in the south-eastern Jura the formation is divisible into Lower shales and much tougher Middle and Upper calcarenites. In the area west of Belley the shaly Lower Chanaz Beds are absent, so that the Middle Chanaz calcarenites lie directly over the uppermost Ambléon Limestone (see plate 16).

The Middle and Upper Chanaz Beds have been mapped by the present author as a single entity, although in future field studies these members could be treated as separate mapping units. The Middle Chanaz Beds are generally well-exposed at the top of the Ambléon Limestone cliffs. They crop out extensively as a cap to the eroded core of the

Ordonnaz-Ambléon-Prémeyzel anticline, and in particular to the subsidiary Molard-Dedon-Colomieu fold (see map 1). In the area mapped, the Chanaz Beds are especially shaly at the top. In consequence, this part of the formation is poorly-exposed and gives rise to fertile, soil-covered strike vales along with the overlying marly Chavoley Beds. Due to the shaly character of the uppermost Chanaz Beds in the area, no completely exposed sections of the formation were found. However, by combining the data from two of the best sections available, a vertical column was established affording relatively good exposure throughout the formation. The situations of these sections are as follows:

A limited exposure of the strata near the junction between Chanaz and Chavoley Beds is to be found just south of the point where the Arborias syncline becomes faulted (see map 2). Also exposed here are the main parts of the Middle and Upper Chanaz Beds, including the lithological boundary with the underlying Ambléon Limestone. A second, almost completely exposed section in the Chanaz Beds, is found ½ km. south of the summit of the Molard Dedon (map 1), where a stream has cut down through the basal Chavoley Beds, through the Chanaz Beds, and has penetrated the Upper Ambléon Limestone.

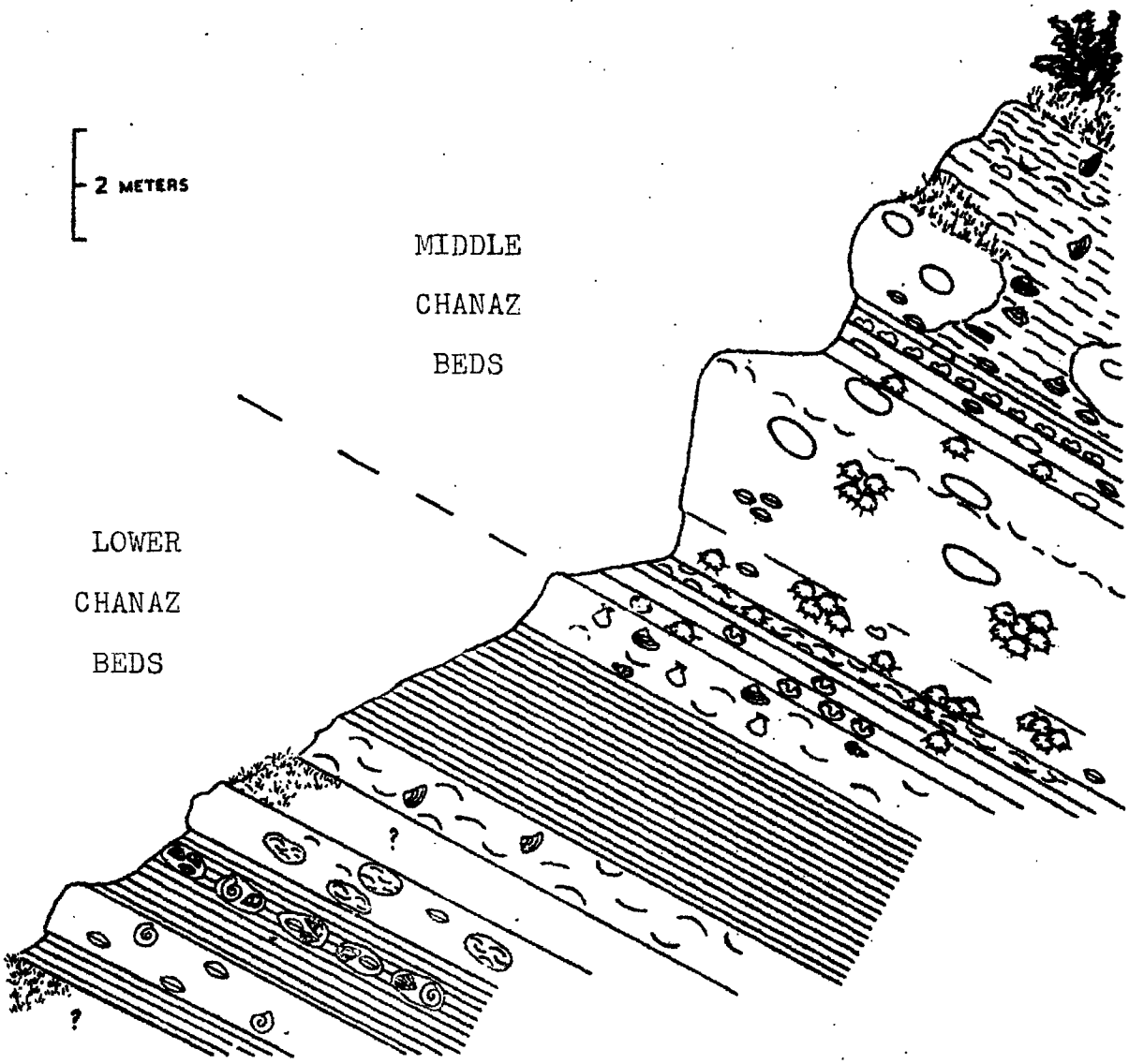
B. PETROGRAPHY.

(i) Lower Chanaz Beds.

In eastern Bas-Bugey and the Col du Chat area the Lower Chanaz Beds consist of approximately 15 m. of poorly

FIG. 19

SECTION OF CHANAZ BEDS IN EASTERN BAS - BUGEY after AGER (1963b).



Key to rocks

- IRREGULARLY BEDDED CALCARENITE
- MASSIVE CALCARENITE
- WELL-BEDDED CALCARENITE
- SHALES
- CALCAREOUS NODULES

Key to fossils

- IRREGULAR ECHINOIDS IN LIFE POSITION
- GASTROPODS
- AMMONITES [DAMAGED]
- BELEMNITES
- BURROWING PELECYPODS IN LIFE POSITION
- BURROWING PELECYPODS NOT IN LIFE POSITION
- PECTINIDS [DAMAGED]
- LIMA
- TRIGONIA
- BROKEN PELECYPODS
- TEREBRATULIDS WITH STRAIGHT COMMISSURES
- TEREBRATULIDS WITH BIPLICATE COMMISSURES
- ACANTHOTHIRIS

resistant calcareous shale inter-bedded with minor tough, grey limestones (fig.19). There is a notable occurrence within the shales of a band of calcareous nodules made up mainly of Lima shells. The marly Lower Chanaz Beds give rise to gentle grassy slopes between the cliffs formed by the Upper Ambléon Limestone and the Middle Chanaz Beds.

(ii) Middle Chanaz Beds.

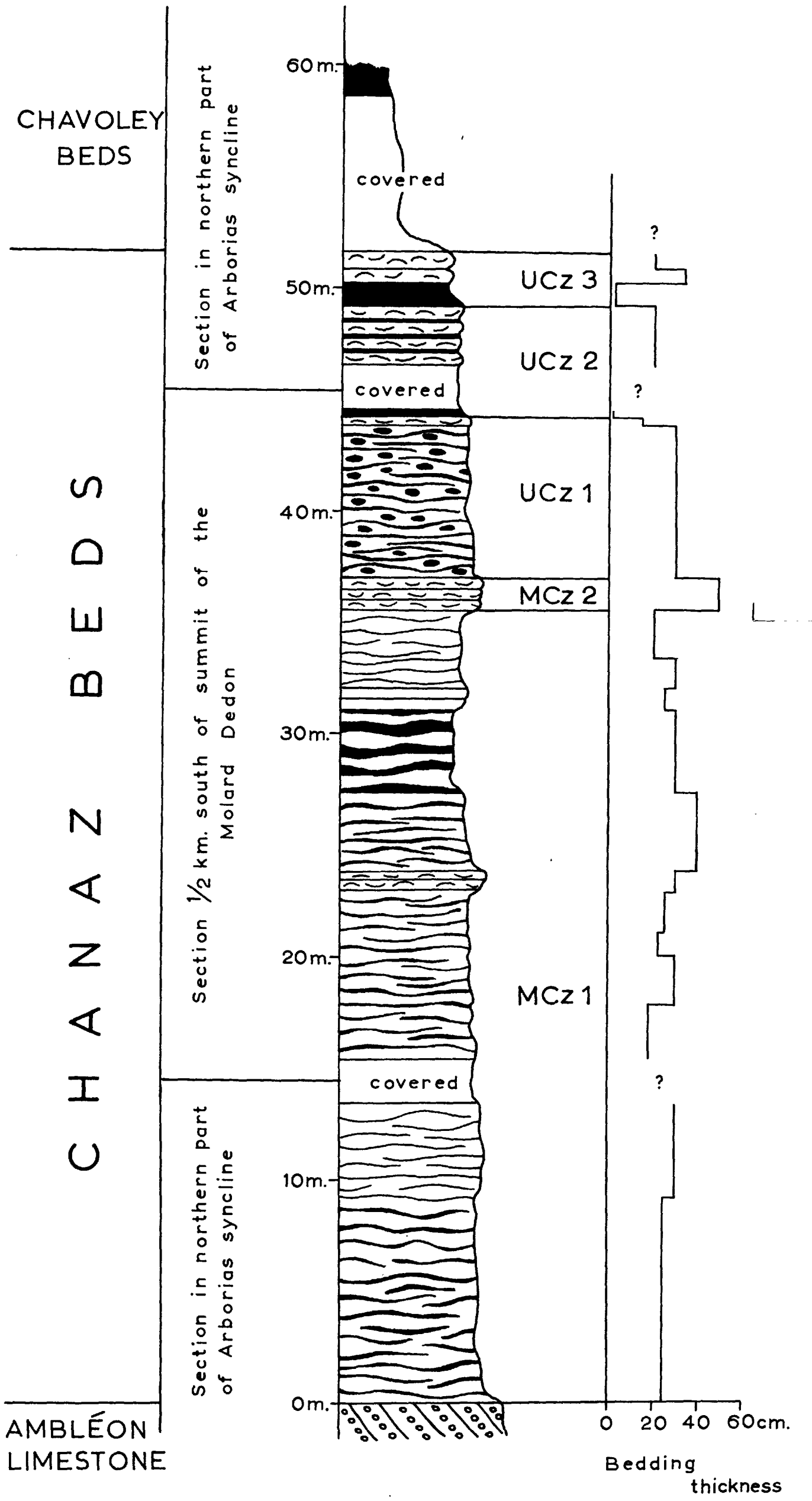
(a) Field study.

The Middle Chanaz Beds are irregularly bedded, poorly-sorted calcarenites, characterised throughout the area investigated by the team from Imperial College, by their content of ferruginous pisoliths. The member may also be recognised in the field by the abundance of Acanthothiris, a spinose rhynchonellid which is here found in clusters probably in near-life position (fig.19). At the measured sections in the area west of Belley, the Middle Chanaz Beds are 36½ m. thick. They lie directly above the Ambléon Limestone (plate 16). The lithological change from cross-bedded and generally well-sorted oolite to horizontally laminated, poorly-sorted calcarenite, is without transition and recognisable with precision in the field. In the south-eastern Jura the pisolitic calcarenites of the Middle Chanaz Beds surmount the shales of the Lower member.

MCz 1. The lower and principal unit of the Middle Chanaz Beds, MCz 1, is 35 m. thick (see fig.20). It consists of irregularly bedded, brown and grey limestones, and similarly coloured nodular shales. The shales seem to differ from

FIG. 20

VERTICAL COLUMN OF THE CHANAZ BEDS



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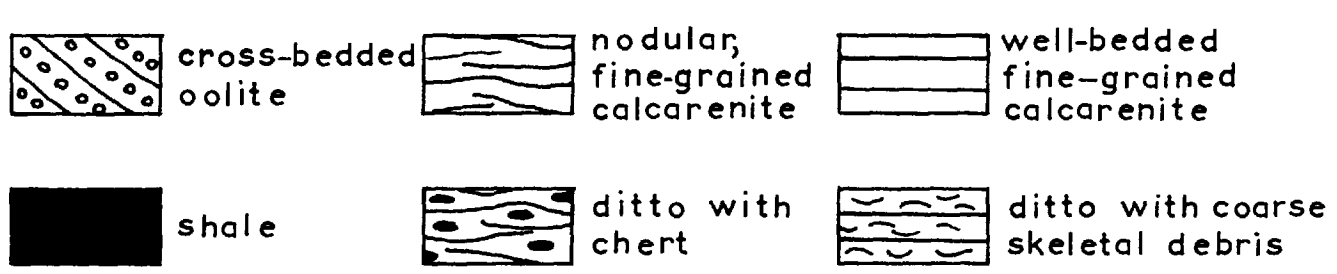


the limestone bands merely in being more heavily stylolitised. Compositionally both lithologies appear to be the same, consisting of fine-grained skeletal debris and ferruginous pisoliths, set in a calcilutite matrix.

The pisoliths, which generally measure about 1-3mm. across, are normally iron-oxide stained. On rare occasions, however, limestones have been found showing central blue cores surrounded by buff-weathered envelopes. In these rocks, the pisoliths have a rusty appearance only in the outer weathered zones. The central parts contain dark blue pisoliths. Similarly blue-hearted and buff-weathering limestones have been noted in the Ambléon Limestone and Cuzieu Flags below, but on a much reduced scale. The blue colour is believed to be due to finely granular pyrite, protected from oxidation in the central unweathered parts of the rock.

Large, irregularly-shaped nodules of partially silicified calcarenite are common in the limestones of MCz 1.

MCz 2. The Middle Chanaz Beds end with a resistant 1½m. marker band, MCz 2 (see fig.20). This consists of three 50cm. beds separated by well-defined bedding planes. The unit is distinct from MCz 1 since its base marks the end of the ferruginous pisolite sequence. The marker band is included in the Middle Chanaz Beds, however, since it contains no fully silicified zones. Immediately above, in the Upper Chanaz Beds, chert forms 30-40% of the rock (fig.20).

The beds of MCz 2 are made up of tough, off-white

Plates 20 & 21.

PLATES 20 & 21.

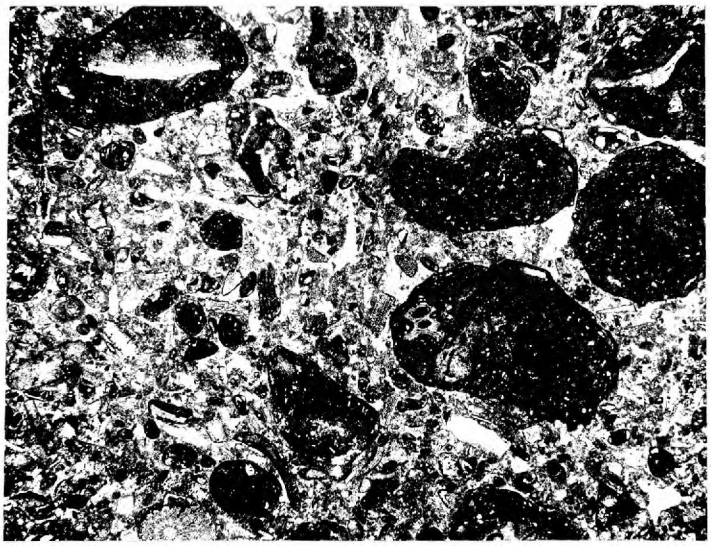


PLATE 20. Pisolithic & skeletal calcarenite of the Middle Chanaz Beds (northern part of Arborias syncline). Plane polarised light (X12).

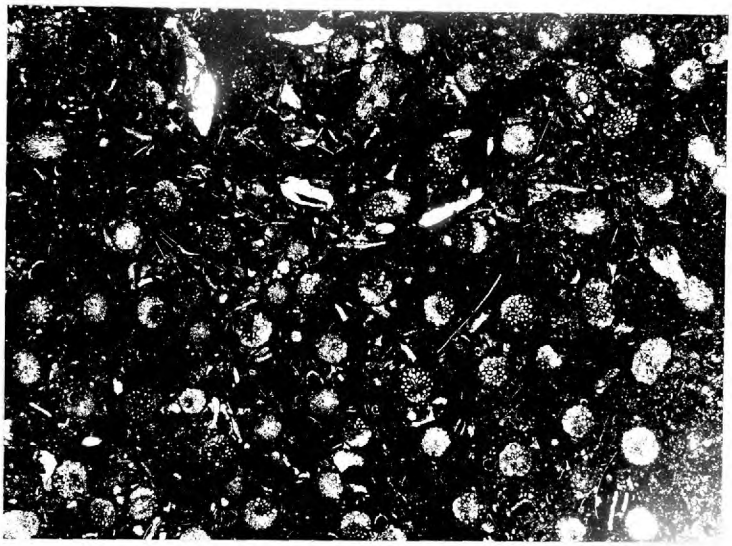


PLATE 21. Silicified polyzoan colony. Upper Chanaz Beds, northern part of Arborias syncline. Plane polarised light(X5).

calcilutite and fine-grained calcarenite. This host rock provides a supporting framework for accumulations of broken lamellibranch valves. Where shelly fragments are concentrated, iron-oxide stained dolomite is found as part of the pore-filling cement.

(b) Laboratory study.

MCz 1. The ferruginous pisoliths which characterise this sub-division are seen in thin section to be centred mainly on coarse skeletal debris (plate 20), broken lamellibranch valves, crinoid ossicles and polyzoan fragments being prominant. Lithic fragments such as grains of cemented oolite also occur as the cores to these pisoliths. The pisolithic jackets have a concentric structure, the foundation of which is calcite disposed in cells, probably of polyzoan, but possibly of algal origin. Much calcilutite, some fine-grained skeletal debris and a little quartz silt is incorporated in this cellular framework. The original structure of the cells is thus greatly masked.

The host grains to the pisoliths are approximately the same size as the skeletal fragments of the coarse, well-sorted calcarenites in the Ambléon Limestone. In the Ambléon Limestone, however, the skeletal debris is only slightly encrusted with polyzoa or algae. The cores to the pisoliths could have been derived from sediments similar to those of the Ambléon Limestone, and have become encrusted during transportation. Many of the skeletal cores to the pisoliths are

silicified whereas their pisolithic jackets are not. This indicates that an important time interval elapsed between the fragmentation of the original fauna and ultimate pisolith formation.

Bioclastic debris of the same grain size as the skeletal nuclei of the pisoliths also occur in the calcarenites of MCz 1. These grains carry only rudimentary encrustations. Their outer surfaces may even be quite clean. Fragmentation of the fauna producing such debris was clearly followed by a shorter interval before burial than for the skeletal fragments enmeshed in pisolithic jackets. The relatively clean debris in the MCz 1 calcarenites could thus have been locally derived.

A finer grade of skeletal and other debris occurs in the spaces between the coarse fragments in the rock. Included in this interstitial material are dark pellets, whole Foraminifera, and fine-grained echinoderm, brachiopod and/or lamellibranch debris. Detrital quartz, which normally occurs in the fine-grained fraction of skeletal debris, is notably rare in MCz 1.

The coarse and fine fractions of the MCz 1 calcarenites are partially embedded in a matrix of calcilutite and in part cemented by coarsely-crystalline ferroan calcite.

<u>MCz 2.</u> Apart from the rudite size lamellibranch valves, the rock appears to be composed essentially of fine-grained skeletal debris, embedded in a matrix of pellets

merging into dark calcilutite. The pellets are dark, spherical or ellipsoidal grains similar to the Bahaman faecal pellets described by Illing (1954). The fine-grained clastics which "float" in the calcilutite matrix are essentially similar to those which make up the fine-fraction of the MCz 1. calcarenites.

(iii) Upper Chanaz Beds.

(a) Field study.

The Upper Chanaz Beds are generally composed of fine-grained calcarenites. They differ from the Middle member below in lacking pisoliths and in containing only rare Acanthothiris. The Upper Chanaz Beds carry abundant fully silicified chert nodules which are not found in the Middle member.

UCz 1. At the base of the Upper Chanaz Beds occurs a 7m. unit of chert-bearing, grey to buff-coloured calcarenite, UCz 1 (see fig.20). As in MCz 1, limestones alternate with rather nodular stylolitised shales. Both shales and limestones alike are made up of fine-grained calcarenite. The chert-however, appears to be restricted to the limestone bands. Partially, or more often completely silicified chert nodules form up to 40% of these limestones. The nodules tend to occur in irregular shapes like the incipient cherts of MCz 1, and are often centred on fossils preserved in opaline silica. Over weathered surfaces the partially silicified nodules are generally somewhat decalcified so that a delicate network of residual silica is found.

UCz 2. Approximately 5m. of rather poorly-exposed limestones and shales (UCz 2) surmount the chert-bearing beds of UCz 1 (see fig.20). The principal difference between the two units is the rarity of chert in UCz 2. On account of this the upper unit is less resistant to erosion than the lower.

The limestones of UCz 2 are well-bedded. They consist mainly of fine-grained calcarenite which provides the supporting framework to scattered coarse skeletal debris. Iron-oxide stained dolomite commonly forms part of the pore-filling cement where coarse-grained shelly debris occurs. Cherts of the type found in UCz 1 also exist in UCz 2, but these form less than 5% of the rock (cf. 30-40% in UCz 1). The limestones of UCz 2 generally exhibit blue hearts surrounded by buff-weathered envelopes.

UCz 3. The uppermost lithological unit of the Chanaz Beds in the area mapped is more shaly than the subdivisions seen below (see fig.20). In the section exposed in the north of the Arborias syncline, UCz 2 is followed by a 1m. band of soft shale, which is surmounted by 1½m. of well-bedded, fine-grained calcarenites. These calcarenites are similar to those of UCz 2, except at the very top where they are much coarser grained. Exposure is lacking for the next 7m. of the vertical column, after which marls belonging to the Lower Chavoley Beds are seen. The lithological junction between the Chanaz and Chavoley Beds is not observed,

although nowhere else in the area is the gap of non-exposure between the two formations so narrow. In a completely exposed succession, the last band of calcarenite would have been taken as representing the top of the Chanaz Beds. The 7 m. of non-exposure above UCz 3 (see fig.20) suggests the presence here of a very poorly-resistant unit, probably entirely made up of marl. It is likely, therefore, that the uppermost exposed calcarenites of UCz 3 in fact correspond to the top of the Chanaz Beds.

(b) Laboratory study.

UCz 1. The cherts, which characterise UCz 1, contain relics of calcareous skeletal debris and are therefore of replacement origin. Apart from this residual carbonate the cherts are made up of a complex association of quartz, chalcedony, and opal.

The unsilicified parts of the principal limestones in UCz 1 consist of a supporting framework of fine-grained echinoderm fragments, dark ellipsoidal pellets, fine-grained shelly debris and detrital quartz, in order of importance in the rock. The inter-granular pore-spaces of the sediment are cemented with coarsely-crystalline calcite. Calcilutite matrix is notably sparse. The rocks thus appear to be relatively well-sorted.

The thin inter-bedded shales are made up of similar fine-grained skeletal debris, some pellets and detrital quartz. In contrast to the limestones, however, these grains are seen to "float" in a dark calcilutite matrix which has

the same colour and consistency as the enclosed pellets. Many of these pellets have diffuse boundaries against the matrix.

The author considers it likely that most of the calcilutite in the shales of UCz 1. had been in the form of pellets in the original sediment. These pellets are thought to have provided the supporting framework to the scattered skeletal debris and detrital quartz grains, which are now seen to "float" in calcilutite. Subsequent compaction is considered to have caused the pellets to merge into one another to form an apparently homogeneous calcilutite matrix. In contrast, the original sediment lithifying as the limestone beds contained a much smaller proportion of pellets. A rigid framework was therefore established in the sediment by the tough skeletal debris and quartz grains present. Upon compaction these resistant grains are believed to have taken the strain. In such a case, pellets in the inter-granular pore-spaces would have been preserved intact and cemented by coarsely-crystalline calcite. Those compressed between rigid grains would have given rise to a small amount of calcilutite, such as that now seen in these limestones.

Junctions between pellet-bearing limestones and calcilutite-bearing shales are notably sharp. Hence no convincing transitions have been found to confirm that the calcilutite in the shales was produced by the merging of original pellets. Nevertheless this is believed to have been the case in the light of the consistent difference in supporting framework between limestone and shale. The similar local preservation

of pellets in a rock composed essentially of calcilutite, has already been described from the Middle Ambléon Limestone (p.132). Here too, the calcilutite is thought to have been derived from the merging of pellets during compaction.

UCz 2. Save for the rarity of chert in UCz 2, the limestones and shales of this unit closely resemble those of UCz 1. below, as already noted from the field observations.

The limestones differ from those of UCz 1. in containing some whole Miliolidae and also in carrying a small proportion of rudite-size skeletal fragments. This coarse fraction is almost exclusively made up of brachiopod and lamellibranch shells. Iron-oxide stained dolomite (shown in the laboratory also to contain ferrous-iron), commonly infills the formerly aragonitic parts of molluscan shelly debris. The dolomite, along with ferroan calcite, also occurs as a pore-filling cement in these coarse-grained, and probably formerly more porous zones of the rock.

The shales of UCz 2. consist of a supporting framework of calcilutite in which fine-grained skeletal debris and a fair abundance of detrital quartz is embedded. It is considered that, as for the shales of UCz 1, the matrix was produced during compaction when a former supporting framework of pellets was squeezed into relatively homogeneous calcilutite.

Minute granules of pyrite (8-35 μ in size) have been found in the blue, unweathered zones of the rock. They occur in clusters in the matrix, or as a replacement of fine-

grained shelly debris and of Miliolidae.

UCz 3. The prominence of shale in UCz 3 was the criterion adopted in the field for separating this unit from UCz 2 below. However, thin section studies show the shales and lowermost limestones of UCz 3 to be similar to those of UCz 1 and 2. Nevertheless, a significant lithological change is seen in the coarse-grained calcarenites at the very top of the exposed Chanaz Beds. The coarse fraction of these rocks is almost equi-granular. It consists predominantly of sub-rounded lithic fragments and accessory echinoderm and shelly debris. The components are cemented partly by coarsely-crystalline calcite, and in part embedded in a calcilutite matrix.

The lithic fragments in the rock are made up of fine-grained skeletal debris embedded in calcilutite. In lithology they resemble the shaly units of the Upper Chanaz Beds. The fragments were no doubt derived from partially lithified shales by penecontemporaneous re-working. The limestones at the top of the exposed Chanaz succession are therefore intra-formational "micro-breccias".

C. STRATIGRAPHICAL AGE.

(i) Lower Chanaz Beds.

The complete fauna collected from the Lower Chanaz Beds by the team from Imperial College is as follows:-

Lobothyris buckmani (Davidson)

Lytoceras sp.

Parkinsonia sp.

Goniomya V-scripta (J.Sowerby)

Lima (Plagiostoma) cf. L.rigidula (Phillips)

L.rodburgensis Whidborne

L. schimperi Branco

Pholadomya crassa (Agassiz)

P. lyrata (J.Sowerby)

The shaly Lower Chanaz Beds of eastern areas have yielded numerous indeterminate species of Parkinsonia. This genus ranges from the Upper Bajocian to the Lower Bathonian. Pelletier (1960) reported a typical parkinsoni Zone fauna from similar shales cropping out to the north of the area investigated by members of Imperial College. It seems likely therefore that the Lower Chanaz shales of eastern areas belong to the uppermost Bajocian. The Lower Chanaz Beds hence appear to be the time equivalents of the Upper Ambléon oolites in the west. The regional distribution of lithofacies in the Ambléon Limestone and Chanaz Beds certainly favours such a correlation (see fig. 21C).

(ii) Middle Chanaz Beds.

The abundant fauna from the Middle Chanaz Beds is as follows:-

Acanthothiris cf. A.spinosa (Lamarck)

Stiphrothyris tumida (Davidson)

Collyrites sp.

Holectypus depressus (Leske)

Perlina cf P.sublaevis (J.L.R.Agassiz)

Pygomalus analis (J.L.R.Agassiz)

Stomechinus sp.

Miliolidae

Bomburites cf.B. bombur (Oppel)

Choffatia sp.

Grossouvria sp. indet.

Hecticoceras sp.

Kheraiceras cf.K.cosmopolita (Parona & Bonarelli)

Oppelia (Oxycerites) sp.

Parkinsonia cf. P.convergens (Buckman)

Parkinsonia sp.

Perisphinctes (Alligaticeras) sp.

"Perisphinctes" aff. P.scopinsis (Neumayr)

Phylloceras sp.

Procerites sp.

Wagnericeras sp.

Anisocardia cf. A.truncata (Morris)

Oxytoma (?) sp.

Pleuromya uniformis (J.Sowerby)

Pholadomya inornata (J.de C. Sowerby)

P. lyrata (J.Sowerby)

Trigonia aff. T.costata J.Sowerby

A specimen of Parkinsonia collected from within 1m. of the base of the Middle Chanaz Beds near St.Bois (map 1) has been identified by Dr.Callomon as a form restricted to the parkinsoni and zigzag Zones. A bed 2m. higher up has yielded

Wagnericeras sp. and Choffatia sp. probably of the Upper Bathonian.

In a road-side exposure just north of Colomieu fossiliferous calcarenites, probably near the top of the Middle Chanaz Beds, have yielded Bomburites cf. B.bombur and Kheraiceras cf. K.cosmopolita of the calloviensis Zone and Perisphinctes (Alligaticeras) sp. of the athleta Zone.

Parkinsonia cf. P.convergens of the Lower Bathonian and Procerites of the Middle Bathonian have been extracted from the Middle Chanaz Beds exposed in the section just south of the summit of the Molard Dedon.

The evidence from the ammonites suggests that the Middle Chanaz Beds are characterised by a number of condensed sequences and that the member ranges in age from the Lower Bathonian (and possibly from the uppermost Bajocian) to the Upper Callovian athleta Zone.

The Lower Callovian ferruginous oolite seen at the top of the formation near Chanaz (Khouri, 1960) has not been found in the area mapped by the present author. The "dalle nacrée" (nacreous flagstone), considered by Choffat (1878) to represent the macrocephalus Zone in the Jura, also appears to be missing. However, as Riche (1893) correctly pointed out, the "dalle nacrée" is a lithofacies carrying no strict implication of age. Its absence in the area can therefore only be of environmental significance.

(iii) Upper Chanaz Beds.

The fauna collected from the Upper Chanaz Beds is

as follows:-

Acanthothiris cf. A.spinosa (Lamarck)

Dictyothyris coarctata (Parkinson)

Miliolidae

Grossouvria sp.

Pholadomya lyrata (J.Sowerby)

Polyzoan indet.

The fauna of the Upper Chanaz Beds is much scarcer than in the Middle or Lower members. Of the rare ammonites found, only one was identifiable (Grossouvria sp). This suggests a Callovian age for the Upper member. The Upper Chanaz Beds are overlain by marls of the Lower Chavoley Beds which contain Middle and Upper Oxfordian ammonites. There appears therefore, to be a clear stratigraphical break at this horizon in the succession. It is significant in this context that the uppermost Chanaz calcarenites are intra-formational "microbreccias". The breccias were probably formed by re-working during temporary emergence.

D. FAUNAL EVIDENCE OF PALAEO-ENVIRONMENT.

The Lower Chanaz shales, which pass westwards into the Upper Ambléon oolites, were probably laid down in waters which were deepening towards the Subalpine trough. Unlike the Ambléon Limestone below, the Chanaz Beds do not contain corals. This and the co-existence of ammonites and Lima shells in the Lower Chanaz Beds favour Arkell's observation (1933) that molluscs with delicate shells, such as ammonites, Lima and Trigonia are not found in high-energy reef environments.

The Lower Chanaz Beds contain numerous Goniomya and Pholadomya. The present day Pholadomya is found in the abyssal depths, but in the fossil record it invariably occurs as a burrowing form like Goniomya, with relatively shallow-water assemblages. Where preserved in life-position in the Lower Chanaz Beds, Pholadomya tends to be restricted to the tougher limestone bands, whereas Goniomya is found more typically in the actual shales. These well-preserved burrowing forms indidate that the Lower Chanaz Beds were laid down in quiet waters, probably well below the wave-base.

The pelagic ammonites and burrowing Pholadomya persisted from the shaly facies of the Lower Chanaz Beds into the less muddy environment represented by the Middle member. However, Goniomya, the mud-burrower with a long siphon, apparently did not survive the paucity of shale in the Middle Chanaz Beds. Nevertheless, mud was not entirely lacking in the new environment and the mixed calcarenite and calcilutite of the Middle Chanaz Beds seems to have favoured the existence of Trigonia. Accumulated palaeo-ecological evidence shows this benthonic genus to have inhabited shallow, but quiet marine waters. "Nests" of Acanthothiris (fig.19) probably representing true colonial associations during life, are widespread in the Middle Chanaz Beds. No doubt these rhynchonellids were prevented by their spines from sinking into what was probably rather a soft sea floor. Occasional bedding planes in the Middle Chanaz Beds furnish an abundance of irregular echinoids in life position (see fig.19). The five genera represented in

the area mapped are all thin-shelled burrowing forms, characteristically lacking ornament. These, too, were adapted to life in soft bottom sediments.

The abundant fauna preserved in near-life position in the Middle Chanaz Beds suggests that most of the sediment at the sea floor had been insignificantly disturbed by wave action. Certain bands of limestone, especially at the top of the Middle Chanaz Beds (MCz 2) have concentrates of broken shell debris. These limestones were no doubt deposited near to the wave-base, suggesting shallower water sedimentation than for the Lower Chanaz Beds.

Ammonites, burrowing Pholadomya and clusters of Acanthothiris persist to the top of the exposed Chanaz succession, but they are all much scarcer than in the under-lying Middle member. The absence of thin-shelled echinoids and of the delicate Trigonia in the Upper Chanaz Beds is attributed to an increase in the energy of the depositional environment. This is furthermore indicated by the relative abundance of broken shell debris in the calcarenites of the Upper Chanaz Beds.

A hemispherical silicified polyzoan colony, seen in thin section in plate 21, was found, apparently in growth position, in the Upper Chanaz Beds. The polyzoan, which is significantly unbroken, has a structure similar to that of the polyzoa occurring as debris in the Ambléon Limestone below (compare plates 21 and 8). Duncan (1957) pointed out that the sessile living polyzoan colonies occupied narrowly restricted

habitats. Shifting sands deposited above the wave-base were unsuitable since the zoaria would have been continually liable to breakage. In contrast, entirely muddy sea floors would lack anything hard, to which the free-swimming larvae could become attached. In the fossil record unbroken polyzoan colonies occur most profusely in fine-grained calcarenite, such as that of the Upper Chanaz Beds. The colonies grew best where food was constantly being replenished by marine currents. It appears that the organisms occupied the zone immediately below the wave-base, where free circulation of the water was maintained, but where the delicate zoaria were not broken by powerful currents.

It seems that the Upper Chanaz Beds were deposited just below the wave-base, in shallower water than the majority of the sediments in the Middle member.

E. SUMMARY OF GEOLOGICAL HISTORY.

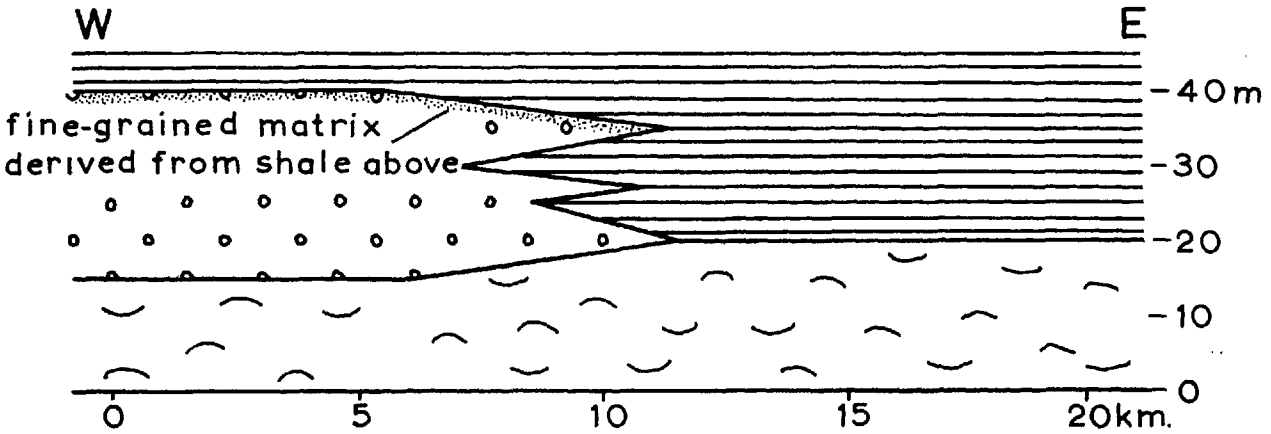
It is believed that during the parkinsoni Zone, oolite was being deposited in western areas (UAn 2, 3 & 4), while shale was being laid down in the east (Lower Chanaz Beds). The cause of the facies change is considered to have been due to an increase in depth of water and diminution of energy of environment eastwards towards the Subalpine trough.

Evidence has been found to suggest that some shaly marl was deposited above the oolites in the west, before the Middle Chanaz calcarenites were laid down. This evidence comes from the fine-grained matrix seen in the uppermost 5-6cm. of the UAn 4 oolites. It was argued in chapter 5 that this matrix had infiltrated down into the open pore-spaces of the upper-

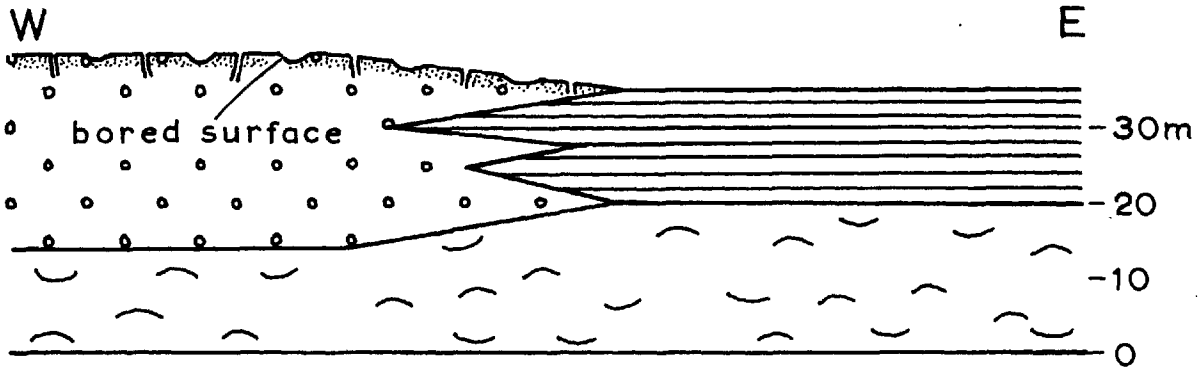
FIG. 21

CORRELATION BETWEEN THE UPPER AMBLÉON OOLITES IN THE WEST & THE LOWER CHANAZ SHALES IN THE EAST

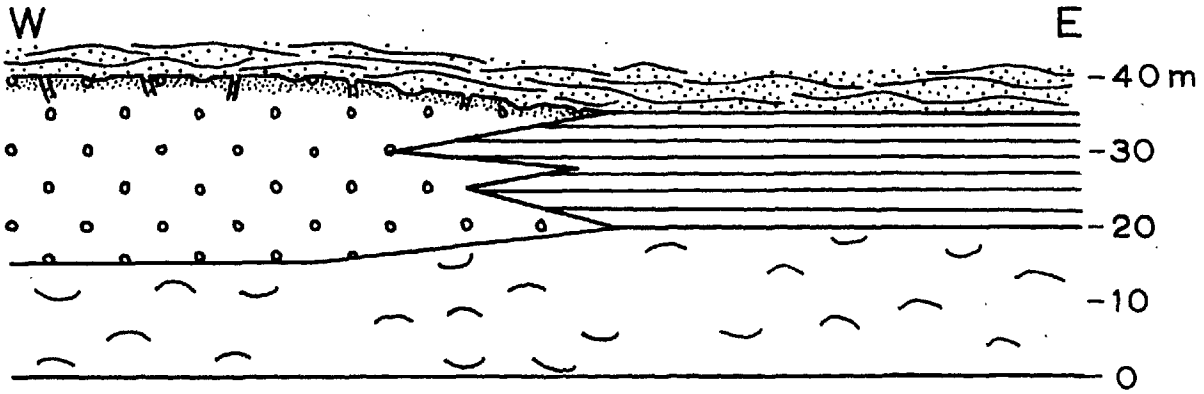
A. After deposition of shale in the east & oolite in the west



B. After period of erosion &, in the west, boring by organisms



C. Present distribution of litho-facies



Upper Ambléon bioclastics

Upper Ambléon oolite

Lower Chanaz shales

Middle Chanaz calcarenites

most Ambléon oolites prior to the deposition of the Middle Chanaz calcarenites. It is proposed that the matrix was derived from a thin development of Lower Chanaz shales, deposited above the UAn 4 oolites (see fig.21A). Penecontemporaneous erosion is believed to have removed all the shale except that trapped in the pore-spaces of the oolite (fig.21B). The oolite, which had been partially cemented prior to the influx of the fine-grained matrix (see chapter 20), was sufficiently lithified to resist such re-working. The earlier period of erosion therefore changed to one of non-deposition, during which it is believed that the upper surface of the Ambléon Limestone became bored. The borings were ultimately filled with poorly-sorted, fine-grained calcarenite belonging to the Middle Chanaz Beds (see fig.17). Thus it could be that in western areas the Lower Chanaz Beds are represented by the 5-6 cm. band of fine-grained matrix in the uppermost Ambléon oolites.

In the Lower Bathonian, conditions seem to have become more uniform with the deposition of fine-grained calcarenite and pisoliths over the entire southern French Jura. The poor sorting and lack of cross-bedding in these limestones suggestthat sedimentation had taken place in quiet waters below the wave-base. The same indications come from the abundant benthonic fauna which is predominantly preserved in near-life position.

Deposition near to the wave-base is indicated for the Upper Chanaz Beds, due to the increased content of broken

shell debris and the presence of better-sorted calcarenites in this member. A polyzoan colony found in situ near the top of the unit favours the suggestion of deposition in well-circulated waters, but below the level of strong wave action. The The intra-formational breccias at the top of the exposed succession in the area mapped probably represent emergence leading up to the stratigraphical break, which spans the Lower Oxfordian at the Chanaz to Chavoley Beds junction.

The Upper Chanaz Beds in the area west of Belley were probably all laid down during the Upper Callovian. The ferruginous oolites at the top of the Chanaz Beds, near Chanaz village, are of Lower Callovian age, suggesting earlier emergence in eastern areas.

In the area mapped the Chanaz Beds represent a subsidiary cycle of sedimentation (fig. 30). The near-emergent reef and oolite complex of the Ambléon Limestone is followed by poorly-sorted Middle Chanaz calcarenites laid down below the wave-base. The cycle is completed by shallowing and emergence of the sea floor as the Upper Chanaz Beds were laid down.

CHAPTER 7.

THE CHAVOLEY BEDS.

A. GENERAL.

The Chavoley Beds are a thick sequence (approximately 200 m) of soft shaly marls and more resistant argillaceous limestones. Limestone beds are rare at the base of the succession, but increase in proportion upwards to predominate over shale at the top.

The Chavoley Beds were mapped as a single entity. Under favourable conditions of exposure the formation is divisible into Lower, Middle and Upper members. Throughout the area examined the poorly-resistant Lower and Middle Chavoley Beds (mainly soft marl) were found to occupy strike vales along with the uppermost Chanaz Beds. The Upper Chavoley Beds tend to be well-exposed in scarp features along with the overlying Oignon Beds. It was thus necessary to select a type area for the formation which affords, in particular, good exposure in the poorly-resistant Lower and Middle Chavoley marls. Fortunately, these marls are a valuable cementstone and the Lower and Middle Chavoley Beds have been extensively quarried to obtain the raw material for the local cement industry. The least resistant part of the formation may thus be conveniently studied from quarry exposures. Four such exposures occur in the strike vale, running south-eastwards through the village of Chavoley, which gives the formation its name.

The marly Lower and Middle Chavoley Beds tend to be

covered by thick soil which gives rise to natural pastureland. The limestones of the Upper Chavoley Beds are generally scree-covered. They tend to support a profuse vegetation of boxwood, such as that seen below the cliffs of Innimont (plates 37 & 40, G-M/26-30).

The Chavoley Beds occupy a deep V-shaped valley in the high ground of the Bois du Molard Dedon, above Meyrieux (see maps 1 and 2). Farther south in Bas-Bugey where the topography is much more mature, a wider strike vale is found over the outcrop of the Lower and Middle Chavoley Beds (plate 40, G/24). This valley carries the river Agnin and its flood plain from St.Germain-les Paroisses to south of Colomieu. The valley is overlooked from the west by the dip slope of the Middle Chanaz Beds and is dominated from the east by the scarps of the Upper Chavoley and Cignon Beds. South of St.Bois, the river Gland follows the valley of the Lower and Middle Chavoley Beds. The orientation of the valley swings with the strike over the crest of the Ambléon-Prémeyzel anticline (see map 1). Where the Gland cuts across the western steep limb of the boxfold, the strike vale of the Chavoley Beds swings northwards and is occupied by the marsh to the south-west of Prémeyzel.

Complete exposure through the Chavoley Beds has nowhere been found in the area studied. The best sections through the formation have been cut by streams running off the high ground in the north of the Molard Dedon-Colomieu anticline.

B. PETROGRAPHY.

(i) General.

The Lower and Middle Chavoley Beds are the least competent of all the lithological units in the exposed Mesozoic succession of the area. As a result of the deformation which affected the Jura, these incompetent beds are often minutely contorted and fractured (see plate 42). They underwent tectonic thickening and thinning as they moulded themselves around the adjacent competent members of the succession. This and the poor exposure involved, make it difficult to assess the pre-tectonic thickness of the Chavoley Beds. Nevertheless, it is apparent that the formation (on average 200 m. thick) is one of the principal lithological divisions of the succession.

(ii) Lower Chavoley Beds.

The basal 15 m. of marl, belonging to the Chavoley Beds are extremely poorly-exposed. They are followed by a further 15 m. of more resistant, well-bedded calcilutites. These beds, which terminate the Lower Chavoley Beds, are generally well seen in minor wooded ridges interrupting the grassy strike valleys of the formation (plate 38/H-I/6-7). The calcilutites, which are grey in colour, occur in beds 30-40 cm. thick, separated by subordinate shales. The limestones are extremely tough and rather porcellanous, often splintering under the hammer. Fracture surfaces have a mottled appearance due to the presence of small reddy-brown spots on the grey background of the host rock. The limestones also contain numerous vugs, about 1 cm. in diameter, filled with soft

powdery iron-oxide and dolomite, shown by artificial staining to be ferroan. Sponges are extremely common in the resistant limestones and the entire rock is in places made up of a framework of sponges in a calcilutite matrix. Both the limestones and the inter-bedded shales contain an abundant ammonite fauna representing the Upper Oxfordian transversarium Zone. The beds appear to correlate both from their lithology and fauna with the sponge-reef facies of the Birmensdorf Beds, described by Moesch (1867) from the transversarium Zone of the northern Swiss Jura near Baden (see fig.1). Occasional lenses of coarse crinoidal calcarenite have been found in the resistant calcilutites of the Lower Chavoley Beds. These could be channel infillings, or even pebbles derived from elsewhere. Of particular significance in this context, is the local occurrence of several plicatilis Zone ammonites in the grey calcilutites of the Lower Chavoley Beds near the summit of the Molard Dedon. These ammonites have a light brown internal sediment, which has not been recognised elsewhere in the Mesozoic succession, and which is certainly foreign to the grey calcilutite of the host rock. The plicatilis Zone ammonites were very likely re-worked like the crinoidal calcarenite mentioned above.

(iii) Middle Chavoley Beds.

The Middle Chavoley Beds, which overlie the resistant grey calcilutites of the Lower member, form the thickest and least exposed part of the formation (approximately 100 m).

The poorly-resistant marls of the Middle Chavoley Beds are the principal cause for the strike vales which generally characterise the formation.

Due to the impervious nature of the marls in the Chavoley Beds, the water table is very much higher along their outcrops than along those of the formations above and below. In many instances the water table lies at or above the surface. Where the Chavoley marls occur down-dip from the more permeable Chanaz Beds below, a line of springs is often found delineating the boundary between the two formations. This especially the case over the alluvium-covered junction between the Chanaz and Chavoley Beds, north-east of Innimont. In addition, the Middle Chavoley strike vales are often the sites of lakes, for example "lac de Morgnieu", ½km. west of Chavoley (map 2). One of the disused quarries near Virieu-le Grand was found to be filled with water, showing that the lakes form over the Chavoley Beds, rather than boulder clay deposited in the strike vales. In the area mapped by the present author "lac d'Arborias" could well lie over an impervious layer of Chavoley marls. The lake, which occupies a syncline flanked by the permeable Chanaz Beds (map 1), has no nearby exposures of the Chavoley Beds. However, the presence of this formation below the lake (see enclosure 4, section VI), would explain why the lake and its peripheral marsh remains un-drained. A further indication of the high water table associated with the Middle Chavoley Beds came during the particularly dry summer of 1962. The boxwood and scrub over the permeable Chanaz and Upper

Chavoley Beds became burnt up by the sun, while the vegetation over the Middle Chavoley marls remained lush green.

The marls of the Middle Chavoley Beds are blue and pyritic. In thin section they are seen to be composed principally of cryptocrystalline to microcrystalline calcite. Skeletal debris, which forms only about 3% of the rock, "floats" in the calcilutite matrix. The bioclastic material is mainly unrecognisable, being so fine-grained. However, monocrystalline echinoderm fragments have been found. On account of their simple crystallography these grains can be consistently identified even in very fine-grained rocks. Certain of the polycrystalline fragments present are clearly derived from Foraminifera, though the families involved are indeterminate.

When dissolved in dilute acid, samples from the Middle Chavoley Beds yield an appreciable insoluble residue of fine-grained material. The same samples react positively to safranin, suggesting that clay minerals are prominent in these beds. The rocks of the Middle Chavoley Beds thus appear to be true marls.

(iv) Upper Chavoley Beds.

Well-bedded limestones become increasingly important up the succession until, in the Upper Chavoley Beds (approximately 70m. thick) they are dominant. Since the passage from the Middle to Upper Chavoley Beds involves a gradual transition, the definition of a sharp boundary between the two members would be artificial, if feasible.

However, in general, where the formation is composed predominantly of limestone, that is in the Upper Chavoley Beds, resistance to erosion is sufficient to yield a prominent scarp feature. Consequently it is common to find the Upper Chavoley Beds commencing at the foot of scarps capped by the overlying Oignon Beds.

Blue, pyritic limestones weathering to buff have been found in certain bands in the Upper Chavoley Beds. These blue-hearted limestones are especially prominent in the fossiliferous horizons, in which the fauna is preserved almost exclusively in yellow granular pyrite.

In thin section the limestones of the Upper Chavoley Beds are seen to consist mainly of cryptocrystalline to microcrystalline calcite, like the marls of the Middle member. "Floating" in this calcilutite matrix is up to 10% fine-grained skeletal debris. The most significant difference between the Middle and Upper divisions, seen in thin section, is the occurrence of up to 5% quartz silt and of some finely-granular glauconite ($<1\%$) in the Upper Chavoley Beds.

C. STRATIGRAPHICAL AGE.

(i) Lower Chavoley Beds.

The fauna collected from the Lower Chavoley Beds is as follows:-

plicatilis Zone:

Perisphinctes (*Arisphinctes*) sp.

P. (*A*). cf. *P.* (*A*). *pickeringius* (Young & Bird)

P. (*Kranaosphinctes*) cf. *P.* (*K*) *promiscuous* (Bukowski)

transversarium Zone:

Lacunosella visulica (Oppel)

Ornithella moeschi (Mayer)

Bolanocrinus subteres Munster.

Cidaris cf. C.coronata Schlotheim.

C.glandifera Goldfuss.

Amoeboceras sp. indet.

Creniceras sp.

Dichotomosphinctes cf. D.wartae Bukowski.

Discosphinctes cf. D.schilli (Oppel)

Neomorphoceras chapuisi (Oppel)

Ochetoceras canaliculatum (von Buch)

O. stenorhynchum (Oppel)

O. (Trimarginites) arolicum (Oppel)

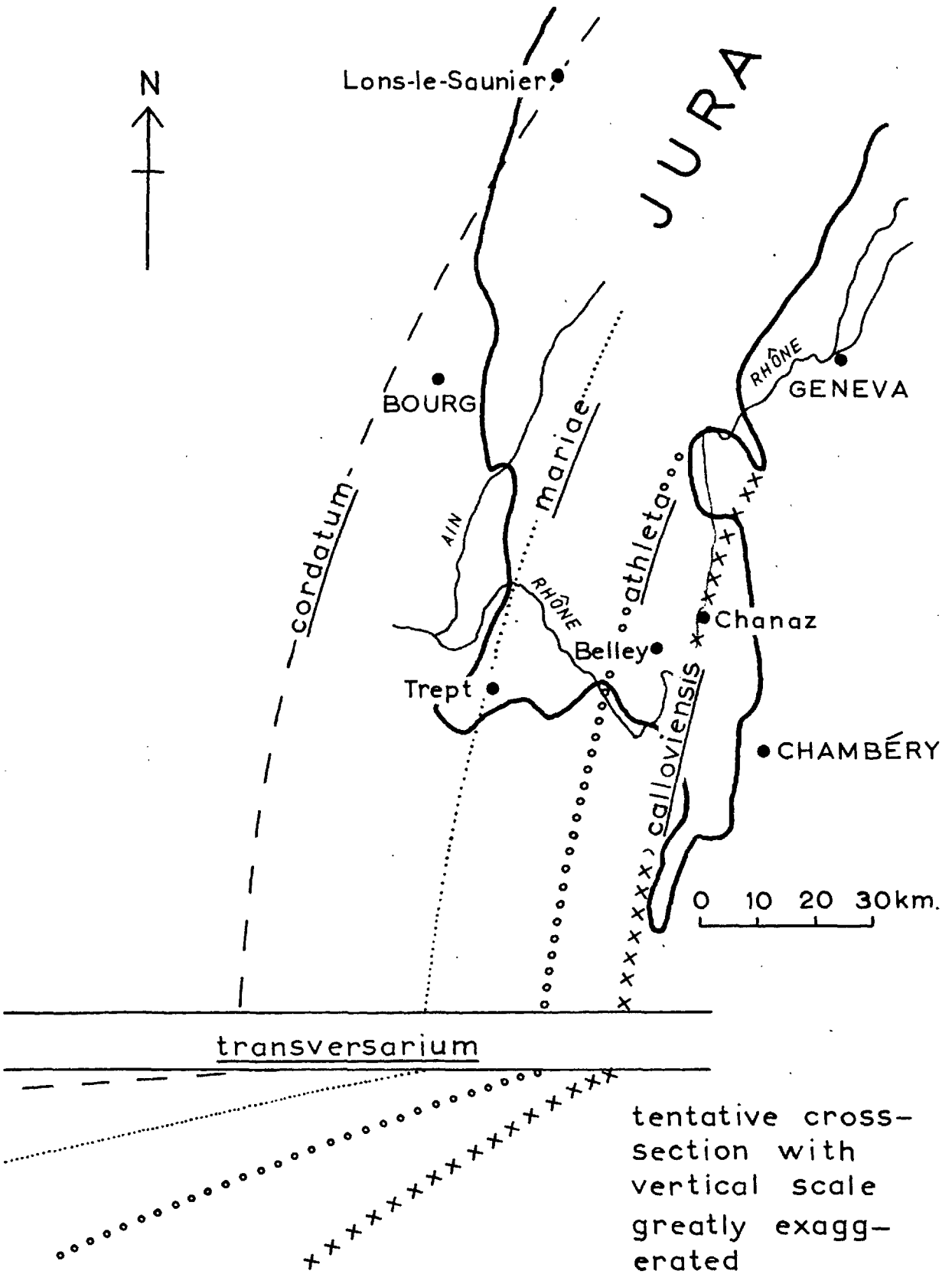
Perisphinctes deriazi Siemiradzki.

In the area studied the entire Lower Oxfordian and possibly the uppermost Callovian is represented in a discontinuity at the Chanaz to Chavoley Beds junction. The highest ammonite Zone recognised in the Upper Chanaz Beds is that of athleta, while ammonites from the basal Chavoley Beds are a mixed plicatilis and transversarium Zone fauna. The age equivalents of most of the Oxford Clay at Oxford are thus missing in the area mapped.

Arkell (1956) correlated the plicatilis Zone of Great Britain with the transversarium Zone of Continental Europe. Although ammonites from both these Zones are found locally to co-exist in the resistant calcilutites of the Lower

FIG. 22

PROBABLE DISTRIBUTIONS OF CALLOVIAN & OXFORDIAN AMMONITE ZONES PRIOR TO THE TRANSVERSARIUM ZONE TRANSGRESSION



Chavoley Beds, those of the plicatilis Zone are thought to have been derived. Dr.Callomon (personal communication) considers the plicatilis Zone to represent the Middle Oxfordian, and to be older than the transversarium Zone. It seems, therefore, that the plicatilis Zone ammonites in the basal Chavoley Beds were re-worked from an older formation, not represented in the area.

It has been pointed out that the Lower Chavoley Beds have the same age as, and a similar lithology to the Birmensdorf Beds farther north. They also appear to correlate with "Argovian I" of de Loriol (1896-1904).

The discontinuity involving the Lower Oxfordian is not found throughout the Jura. In the Ledonian region a complete Lower Oxfordian succession is found overlain by the Birmensdorf Beds (transversarium Zone). This Zone overlaps progressively older beds in a south-easterly direction (see fig.22). In the area mapped the Lower Chavoley Beds (transversarium Zone) lie above the athleta Zone. Further east, near Chanaz, the basal Chavoley Beds directly overlie the ferruginous oolites attributed by Parona and Bonarelli (1897) to the Lower Callovian (calloviensis Zone). At Trept, in the Ile de Crémieu, the transversarium Zone overlies beds considered by Arkell (1956) to belong to the mariae Zone.

The Lower Oxfordian and Upper Callovian of eastern areas were either never deposited, or they were laid down and subsequently eroded away. The sea-floor is believed to have become gradually shallower throughout the deposition of the

Chanaz Beds. The intraformational breccias at the top of the formation have been interpreted to represent emergence. Since the breccias are followed by a discontinuity, it is believed that the emergence was followed by non-deposition through the uppermost Callovian and Lower Oxfordian. It appears, therefore, that the sea withdrew to the north-west during the Callovian and Lower Oxfordian, and did not return until the transversarium Zone transgression (see fig.22).

(ii) Middle and Upper Chavoley Beds.

The fauna from the Middle and Upper Chavoley Beds is as follows:-

bimammatum Zone:

Acanthorhynchia lorioli (Rollier)

Aspidoceras sp. indet.

Divisosphinctes bifurcatus von Buch.

Euaspidoceras aff. E.hypselum (Oppel)

Idoceras sp.

Ochetoceras (Glochiceras) cf. O.(G). fialar (Oppel)

Peltoceras (Epipeltoceras) uhligi Oppenheim.

Sowerbyiceras sp.

Sutneria sp.

Taramelliceras tricristatus (Oppel)

Trimarginites sp.

"Aporrhais" s.l.

Astarte extensa Phillips.

Fimbria guirandi (de Loriol)

Gervillella aff G.siliqua (Eudes-Deslongchamps)

Lima (Plagiostoma) notata Goldfuss

Lucina sp.

Modiolus bipartites (J.Sowerby)

Pleuromya uniformis (J.Sowerby)

tenuilobatum Zone:

brachiopods & lamellibranchs as above.

Amoeboceras (*Amoebites*) sp. indet.

Ataxioceras cf.*A.inconditum* (Fontannes)

Streblites sp.

The fauna of the Middle and Upper Chavoley Beds appears to be concentrated at certain levels. Fossils have not been seen in the lower part of the Middle Chavoley Beds since the marls concerned are nearly always unexposed. Only one fossiliferous band, about 10m. thick, has been found in the upper part of the Middle member. The Upper Chavoley Beds are also characterised by a single band of fossiliferous strata (again about 10m. thick) occurring in the middle of the member.

The ammonites from the Middle Chavoley Beds belong to the *bimammatum* Zone. It is quite likely, however, that the lower, very poorly exposed part of the member represents a continuation of the *transversarium* Zone. The marly cement-stone facies here is certainly analagous to the Effingen Beds, described from the northern Swiss Jura by Moesch (1867). It also resembles "Argovien II" of de Loriol (1896-1904). Both these divisions are attributed to the Upper *transversarium* Zone farther north in the Jura.

Basal Kimmeridgian ammonites, belonging to the *tenuilobatum* Zone, occur in the fossiliferous band of the

Upper Chavoley Beds. Hence the Oxfordian terminates near the lithological boundary created between the Middle and Upper Chavoley Beds.

(iii) "Argovien" and "Rauracien".

The marly Lower and Middle Chavoley Beds, as it has already been pointed out, correspond to the "Argovien" of de Loriol. It was formerly thought that the "Rauracien", a reef and oolite complex found in north-eastern Jura, was younger than the "Argovien". The two terms, "Argovien" and "Rauracien" became accepted as stratigraphical stage names. It has subsequently been shown that the "Argovien" marls and the "Rauracien" reefs and oolites are facies, having the same age. Up to quite recently, however, the two terms have been maintained as the names of independent stratigraphical stages. The confusion, which this has brought about, led the Luxemburg Jurassic Colloquium (1962), and subsequently the British Mesozoic Committee (Ager, 1963b), to standardise the nomenclature of the Upper Jurassic stages (Table II), and to recommend that the terms "Argovien" and "Rauracien" should be discarded.

D. FAUNAL EVIDENCE OF PALAEO-ENVIRONMENT.

(i) Lower Chavoley Beds.

The rarity of skeletal debris and an abundance of well-preserved ammonites, brachiopods and hexactinellids indicates quiet-water deposition for the Lower Chavoley sediments.

The hexactinellid sponges are predominantly of irregular shape, and crowded together. They are found characteristically in the basal parts of the tough, grey limestones immediately overlying shaly partings. This indicates that they grew on a soft sea floor. A few symmetrical discoid and vase shaped specimens were seen, clearly in position of growth, but these were difficult to extract whole from the porcellanous host rock.

The hexactinellids found belong to the Hyalospongea. According to Caster (1941), Hyalospongea lived in shallow waters up to the end of the Carboniferous, but since the Permian they have been confined to the deep sea. De Laubenfels (1957) believed that except in polar regions, present day hexactinellids are most abundant between depths of 1000 m. and 10,000 m. Reid (1958 & 1962) agreed that modern hexactinellids are deep-water organisms. He pointed out, however, that Hexactinellida have their richest known development at the present day between the depths of 200 m. and 400 m. Sponges, according to de Laubenfels (1957), thrive where currents are gentle and where a plentiful supply of food is available from land. No doubt the food for the Lower Chavoley sponges was derived from the Massif Central, emergent some 70 km. to the west.

<u>Lacunosella</u>, a thin-shelled rhynchonellid, is widespread in the Lower Chavoley Beds. It was typically non-gregarious. Dr.Ager (personal communication) has pointed out that this genus has falcifer type crura, which seem to be

characteristic of rhynchonellids found in soft sea floor sediments. Ager (1962) has suggested that such forms might have been epiplanktonic (i.e. fixed to sea-weed, etc. in life). This would account for the scattered distribution of Lacunosella in the Lower Chavoley sediments, which would have offered a very soft sea floor for direct peduncular attachment. It is possible, however, that the rhynchonellids were fixed in life to the sponge colonies. Such an association in the Faringdon Sponge Gravel was described by Middlemiss (1962).

The fauna from the Lower Chavoley Beds seems to indicate quiet-water sedimentation at depths exceeding 200 m. The sea floor was probably very soft throughout.

(ii) Lower and Middle Chavoley Beds.

Hexactinellids are not found in the Middle or Upper Chavoley Beds. Dreyfuss (1954) pointed out that the Massif Central became totally submerged in the "Rauracien" (seemingly equivalent to the Upper bimammatum Zone). The supply of food from land was therefore probably cut off. This could have led to the disappearance of the sponges. It is also likely that the sea floor became too shallow for hexactinellids to flourish during the deposition of the Middle and Upper Chavoley Beds.

The lamellibranchs present in the Middle and Upper members are nearly all burrowing forms adapted to life in soft sediment. The valves of these are generally separated,

indicating some disturbance of the sediment.

Acanthorhynchia, a small thin-shelled spinose rhynchonellid, is quite common in the Middle and Upper Chavoley Beds. Dr.Ager (Ager & Evamy, 1963) pointed out the superficial resemblance of this genus to the spinose Acanthothiris, its probable ancestor, found in "nests" in the Chanaz Beds. Unlike Acanthothiris, however, Acanthorhynchia was non-gregarious and has falcifer-type crura, instead of the more customary radulifer crura. Like Lacunosella, it is a possible epiplanktonic form. Dr.Ager (personal communication) suspects that the modification from Acanthothiris to Acanthorhynchia was due to adaptation to the change in environment from a hard to soft sea floor.

The lack of hexactinellids and the wealth of burrowing lamellibranchs suggests that, during the deposition of the Middle and Upper Chavoley Beds, waters were a good deal shallower than represented by the Lower member. A depth of 100m. is the maximum envisaged (see fig.30).

E. SUMMARY OF GEOLOGICAL HISTORY.

The uppermost Chanaz Beds were probably laid down in extremely shallow water, while the Lower Chavoley Beds are thought, principally from their content of hexactinellids, to have accumulated at depths exceeding 200m. A forceful subsidence must clearly have taken place prior to the deposition of the Lower Chavoley Beds. Dreyfuss (1954) has pointed out that the sponge-reef facies of the Birmersdorf

Beds represents active down-warping wherever it is found in the Jura.

The sudden deepening of the water at the onset of the transversarium Zone seems to have been followed by a more gradual shallowing, leading up to the second reef complex of the Mesozoic succession, in the Virieu Limestone.

Plate 22.

PLATE 22.

Blue-hearted & buff-weathered limestones of the Oignon Beds, Colomieu (Ain) X 3/5.

CHAPTER 8

OIGNON BEDS.

A. GENERAL

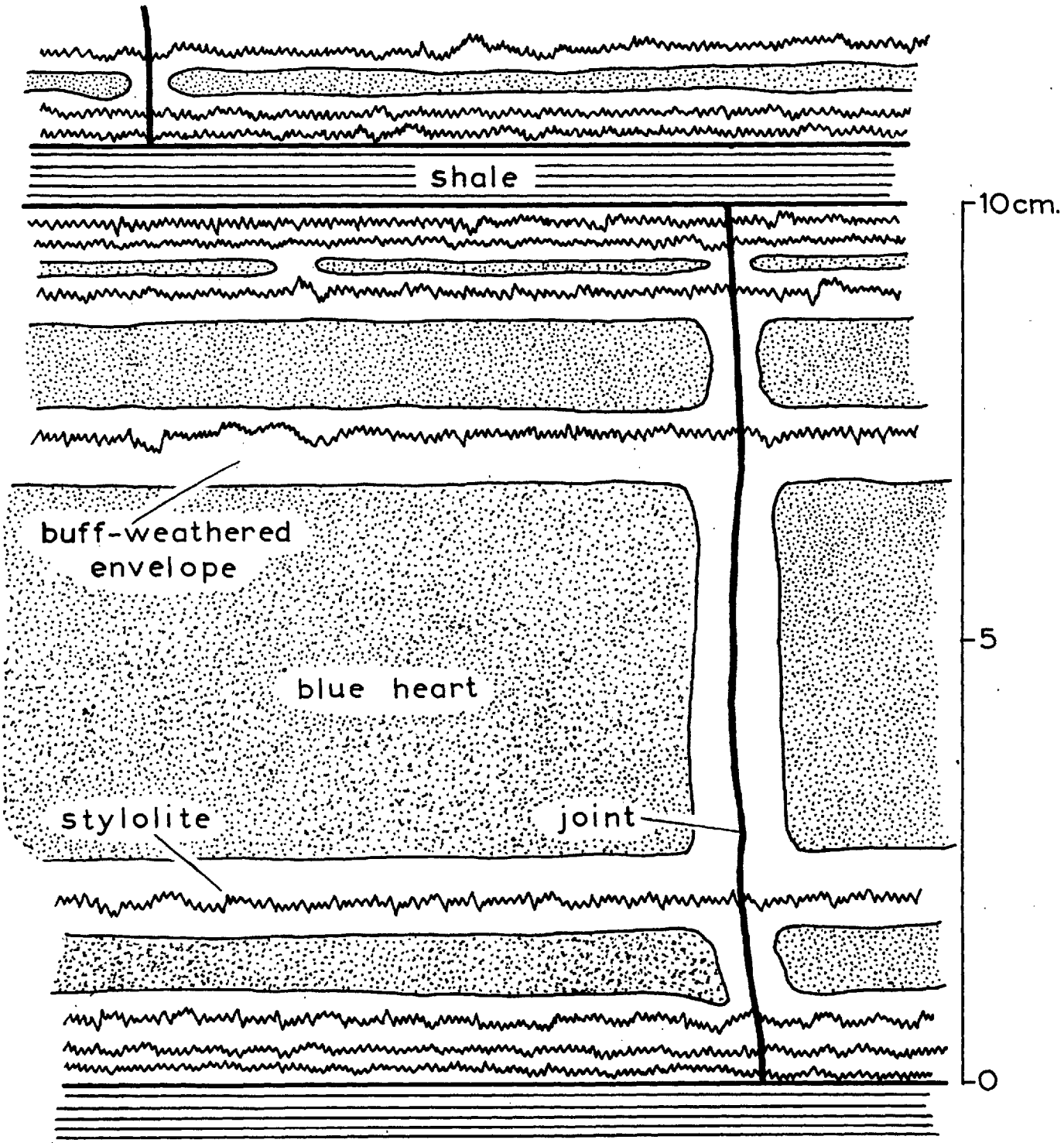
The Oignon Beds, named after the "Molard d'Oignon" near Chavoley, are a formation of thinly and regularly bedded limestones and shales. The formation usually has a most distinctive appearance in the field, since in many places exposures resemble man-made walls. The limestones, generally 10-20cm. thick, consist typically of blue-hearted and brown-weathering calcilutites (plate 22). The interbedded shales are extremely thin (1-4cm.).

The formation as a whole is generally about 60m. thick, and very sparsely fossiliferous. The Oignon Beds are less easily eroded than the underlying Chavoley Beds. They tend to crop out in scarp features between the Upper Chavoley Beds and the even more resistant Virieu Limestone. The stratigraphical position of the thinly-bedded Oignon Beds, below the competent Upper Virieu Limestone, caused them to be intensely crumpled, out of harmony with the form of the main folds, during the deformation which affected the region (see fig. 37 & plate 43).

In the area west of Belley, the Oignon Beds are displayed best in sections along and to the north of the road from Colomieu to Arbignieu (see map 1). The formation caps the Innimont plateau (see plate 36), where it forms extensive limestone pavements over the sub-horizontal roof to the main

FIG. 23

SCHEMATIC DIAGRAM ILLUSTRATING THE DISTRIBUTION OF STYLOLITES & BLUE HEARTS IN THE OIGNON BEDS



Ambléon-Prémeyzel boxfold.

B. PETROGRAPHY.

The limestones throughout the Oignon Beds, exposed to the east of Colomieu, are blue-hearted and brown-weathering (plate 22). The calcilutites, of which they are composed, tend to be rather porcellanous and splinter under the hammer. They are seen in thin section to consist of microcrystalline to cryptocrystalline calcite. Skeletal debris is generally lacking, but detrital quartz occurs consistently in accessory quantities (up to 1%). Like the Chavoley Beds, the Oignon Beds yield an appreciable insoluble residue of fine-grained material. The beds react positively to safranin, indicating the presence of clay minerals. Thin and polished sections of blue hearts appear riddled with tiny blue to black spots, which are not seen in the brown weathering envelopes. These spots, which clearly give rise to the blue colour of the unweathered limestones, are indicated in chapter 19 to be of finely-granular pyrite.

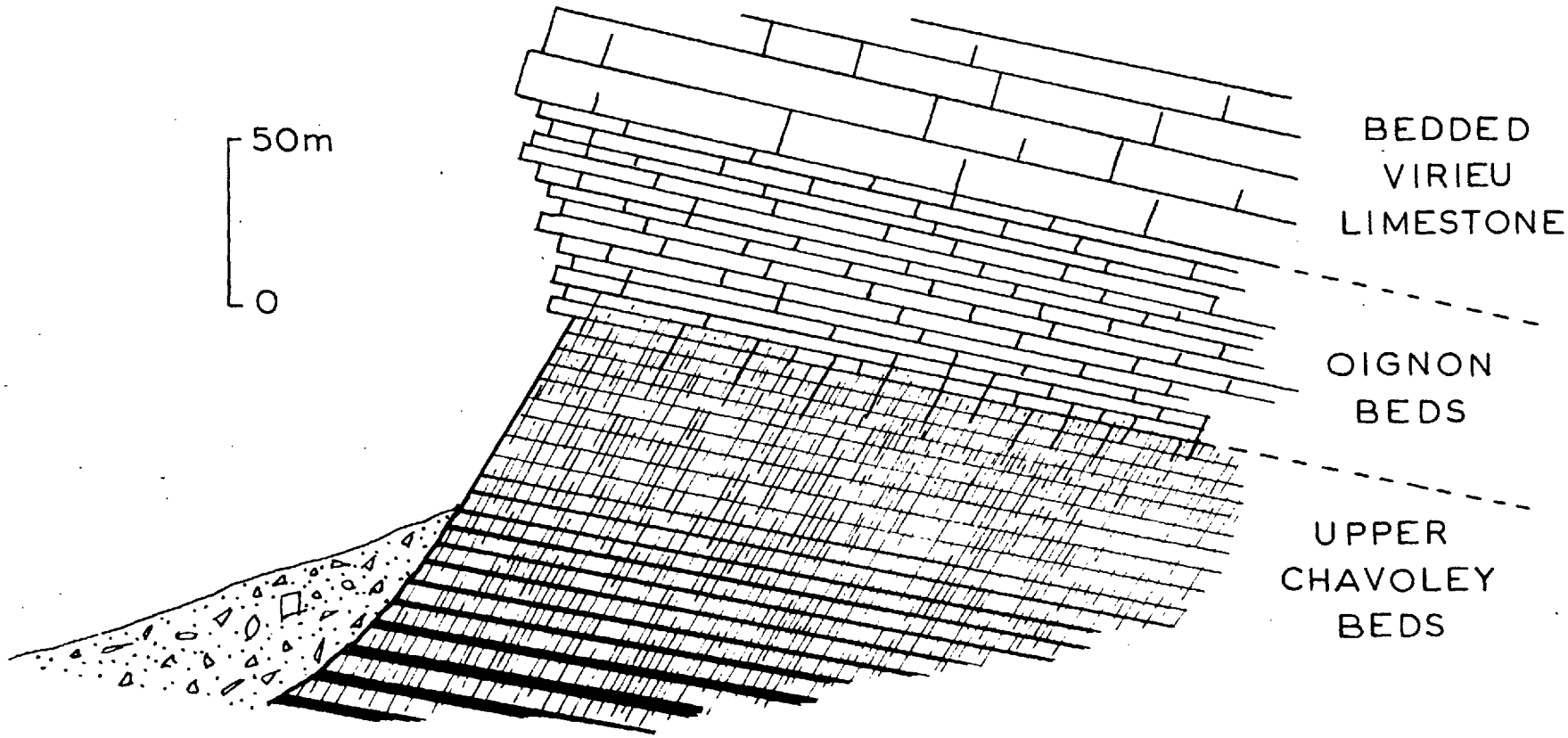
In the basal 20m. of the Oignon Beds near Colomieu, the blue-hearted limestones alternate with extremely thinly-laminated "paper-shales", made up of dark brown calcilutite. Characteristically the limestone beds are increasingly affected by stylolites towards the bedding planes separating them from the shales (see fig.23). The stylolites, which appear dark against the background of the host rock, predominantly lie sub-parallel to the bedding. In places it is difficult with the naked eye to distinguish the shaly laminations of sedi-

mentary origin from the stylolites brought about during diagenesis. With a hand lens, however, the irregular and pitted stylolitic surfaces are readily differentiated from the contrastingly smooth planes between the shaly laminae. Miniature blue hearts are often seen between those stylolites which are relatively widely separated (fig.23). This indicates that oxidising agents had passed through the rock along the zones of weakness opened up by the stylolites. Any pyrite formerly in the "paper-shales" would have been oxidised by solutions passing along the numerous partings in the shales.

Approximately 20m. from the base of the Oignon Beds, exposed to the east of Colomieu, the poorly-resistant shales undergo a significant change. They lose their laminated appearance and take on a buff to yellow colour. They consist almost wholly of soft, crumbly fine-grained dolomite. At the same horizon the blue-hearted limestones undergo an analogous change. Instead of being composed essentially of calcilutites, etched surfaces of these limestones exhibit numerous dolomite rhombs, "floating" in calcilutite. The dolomite is by no means uniformly distributed. Instead, rhombs (approximately 50μ in length) often occur in small clusters. The cause for this rather patchy distribution is not clear. It could be that the dolomite has preferentially replaced fossils, which are now unrecognisable. Superimposed on the irregular distribution of dolomite is a tendency for the mineral to be present in the blue cores, but absent in the buff envelopes. The significance

FIG. 24

WEATHERING FEATURES OF THE UPPER CHAVOLEY & OIGNON BEDS RELATED TO THE ASSOCIATED FRACTURE SYSTEMS



of this distribution is discussed in chapter 19, where problems concerning dedolomitisation are presented. It is clear that the upper part of the Oignon Beds is made up of a rhythmic alternation of thin dolomites and thicker well-bedded dolomitised calcilutites. A similar sequence is found in the Oignon Beds at the type locality. In the extreme west of the area mapped however, dolomite is apparently entirely lacking from these beds. The very top of the Oignon Beds, east of Colomieu, is exposed about 50m. north of the road section. Here the blue-hearted limestones carry small cavity-fillings of coarsely-crystalline calcite, giving them the mottled appearance of a "bird's-eye" limestone.

The Oignon Beds are a natural continuation of the Upper Chavoley beds below. Both units consist of thinly-bedded limestones and subsidiary shales. The Upper Chavoley Beds, however, are typically more fractured than the Oignon Beds. Consequently bedding, which is equally well-developed in both units, is more clearly seen in the Oignon Beds. In extreme cases of deformation, the true dip of the Upper Chavoley Beds may be disguised by narrowly separated fracture planes, which pass straight through the formation, and which superficially resemble bedding laminations (see fig.24). Joints in the Oignon Beds are commonly widely separated (20cm. or more apart), and irregularly spaced from bed to bed. On account of this, the Upper Chavoley Beds give rise to a scarp slope, the steepness of which depends on the angle of the fracture system involved, while the Oignon Beds commonly form

vertical or overhanging cliffs (fig.24). It is considered that the distribution of blue-hearted limestones in the Upper Chavoley and Oignon Beds is determined by the extent of fracturing in the rocks. It is thought that the Upper Chavoley Beds were originally pyritic throughout, like the Oignon Beds. The pyrite content of the former unit, however, is believed to have been almost completely oxidised by solutions penetrating deeply via the numerous fracture planes. The limestones of the Oignon Beds are generally only superficially oxidised. This is thought to be due to their inherent impermeability being little altered by the small amount of jointing present.

In general, therefore, well-developed blue-hearted and brown-weathering calcilutites in the area can be attributed to the Oignon Beds. Where, however, this formation is intensely contorted and more than usually fractured, blue-hearted limestones are altogether lacking from this part of the succession. Under these circumstances, the Oignon Beds can only be recognised from their position in relation to the regional stratigraphy. This task is assisted by the presence of a distinctive algal pisolite directly overlying the Oignon Beds in western areas.

The present author began mapping the area with the opinion, derived in part from previous workers, that the Oignon Beds, as defined above, were a distinctive mapping unit. The blue hearts, however, which appeared to characterise the formation, owe their presence or absence to a combination of degree of fracturing and weathering, and not to depositional factors.

It is therefore proposed that for future field studies the formation should not be mapped separately, but should be included with the Upper Chavoley Beds.

C. STRATIGRAPHICAL AGE.

The fauna collected from the Oignon Beds is as follows:-

Acanthorhynchia spinulosa (Oppel)

Loboidothyris zieteni (de Loriol)

Ornithella sp.

Septaliphoria astieriana (d'Orbigny)

Ammonites gen. *et* spp. indet.

Regrettably none of the rare ammonites collected from the Oignon Beds were sufficiently well preserved even for generic identification. The remainder of the fauna from the formation is not critically diagnostic of stratigraphical age. It is fortunate, however, that ammonites in the basal Virieu Limestone belong to the *tenuilobatum* Zone. This Zone is also represented in the Upper Chavoley Beds, from which it can be deduced that the Oignon Beds too belong to the *tenuilobatum* Zone of the Lower Kimmeridgian. This indicates that the *tenuilobatum* Zone in the area mapped is at least 100m. thick.

D. FAUNAL EVIDENCE OF PALAEO-ENVIRONMENT.

The fauna from the Oignon Beds is extremely rare. The limestones of the formation, however, exhibit numerous vague, tube-like outlines (plate 22), which may be burrows or relics of other fossils.

Rare solitary crinoid ossicles have been seen on

bedding plane surfaces towards the base of the formation. Higher up in the succession, exposed to the east of Colomieu, a wash-out was found, appearing as a lenticle, 40cm. wide and 11cm. thick. The lenticle consists of dolomitic calcilutite (upper Oignon Beds) acting as a matrix to numerous cream-coloured crinoid ossicles and several specimens of Acanthorhynchia spinulosa. This skeletal material appears to have been derived from another environment. Thin bands (2-5cm. thick) of skeletal debris in a calcilutite matrix have been found at two other horizons in the formation, one below and one above the level of the wash-out. Each of these have yielded indeterminate ammonites. The highest of the two bands of skeletal calcarenite, which occurs just below the pisolite, contains several unbroken specimens of Septaliphoria. This asymmetrical rhynchonellid, with a large reinforced pedicle opening is characteristic of a shallow-water reef environment, such as was to follow. The incursions of coarse-grained, skeletal debris were probably derived from a shallow-water environment, where fragmentation of calcareous organisms was taking place above the wave-base. Their increase in importance upwards suggests that the shallow-water, high-energy environment was gradually approaching. The pisolite above the Oignon Beds is believed to represent a major influx of skeletal debris, which became encrusted by algae.

The lithology of the Oignon Beds suggests that the sea floor at the time of deposition was soft, as for the Chavoley Beds. It would be expected, therefore, that the brachiopods

should be epiplanktonic rather than benthonic. Acanthorhynchia spinulosa, a probable epiplanktonic form has been found in the Oignon Beds, but only in a wash-out, which suggests derivation from elsewhere. Contrary to the evidence from the Oignon sediments, a fossiliferous band at the base of the formation near St.Germain-les Paroisses (map 1) has yielded several relatively shallow-water, benthonic brachiopods (Loboidothyris & Ornithella). The brachiopod band also contains some shell fragments, so it is possible that peduncular attachment was made onto these, rather than the soft sediment.

E. SUMMARY OF GEOLOGICAL HISTORY.

The lower part of the Oignon Beds is believed to have been laid down in quiet waters at about the same depth as suggested for the Upper Chavoley Beds (see fig.30). The algal pisolite of the basal Virieu Limestone was probably formed at depths of less than 30m. The upper Oignon Beds must therefore represent considerable shallowing of the sea floor. This is also suggested by the increasingly important incursions of coarse bioclastic calcarenite up the succession. This skeletal material is believed to have been derived from a nearby shallow-water, high-energy environment.

The dolomite shales of the upper Oignon Beds in eastern areas occur in thin continuous bands suggesting a near-primary depositional origin. If the dolomite here is not primary, it must have had a preference for replacing the material in the shale since the limestones are only partially

dolomitised. Messrs.Curtis, Evans, Kinsman and Shearman (1963) have found some of the Recent aragonite muds of the Sabkha (Persian Gulf) to have been replaced by dolomite. It could be that the dolomite shales of the Oignon Beds were formerly of aragonite, whilst the limestones were originally of calcite mud. In any event the dolomite shales of the upper Oignon Beds suggest a shallow-water, rather highly saline environment of deposition.

CHAPTER 9.

THE VIRIEU LIMESTONE.

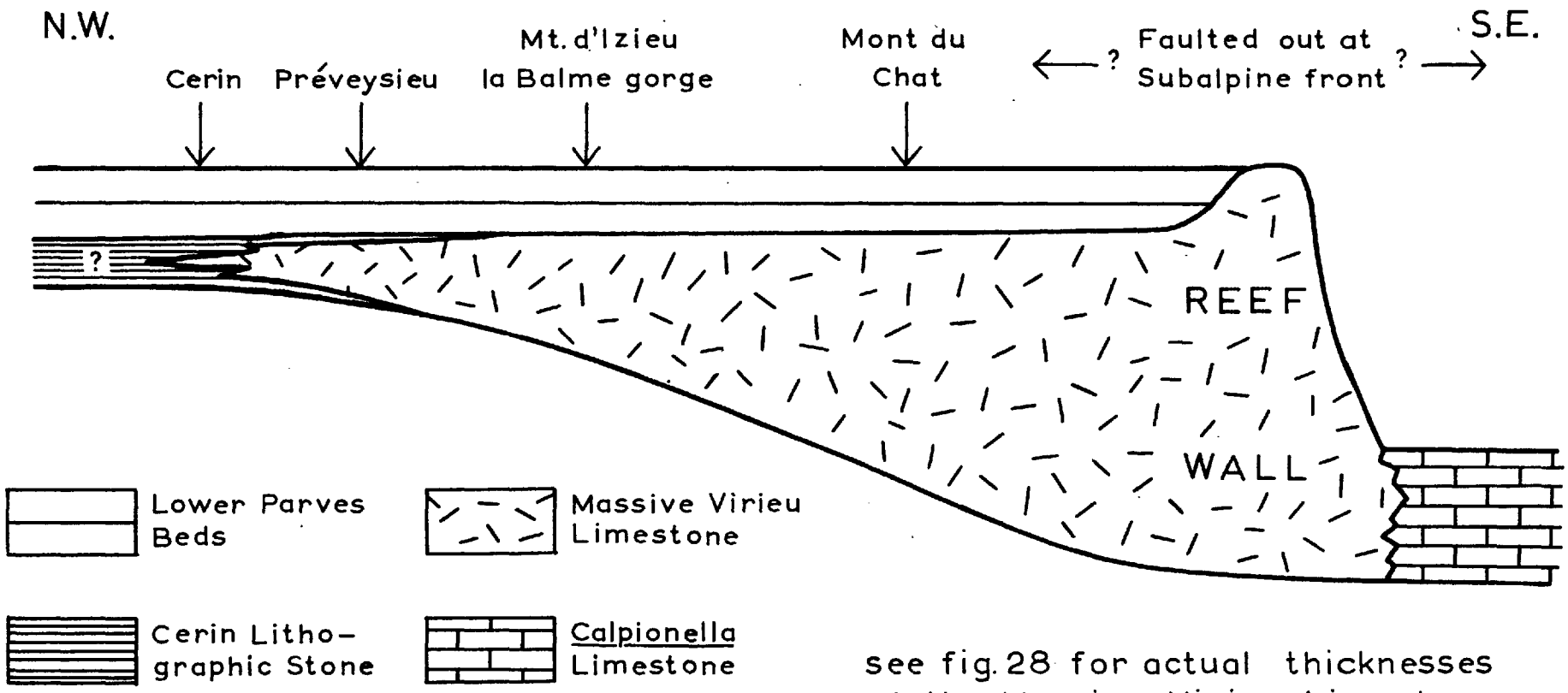
A. GENERAL.

The Virieu Limestone is made up of a Lower or "Bedded" member of calcilutite (50-70m), surmounted by an Upper or "Massive" unit of superficially indeterminate crystalline limestone. This Upper unit is typical of reef limestones, since it contains numerous corals and has an extremely variable thickness (100-400m). The Massive Virieu Limestone is the most resistant lithological unit of the exposed Mesozoic succession in the southern French Jura. Except over the anomalous lowland region of Bas-Bugey, the unit crops out in tall, tufa-covered cliffs, which dominate the local scenery. For example, the jagged teeth of the "Dents du Chat" (plate 2A) are composed of Massive Virieu Limestone. The formation as a whole is well seen in the Montagne de Séremond, which overlooks the type locality, Virieu-le Grand. This mountain (plate 39) is the eastern part of a typical "box-anticline", and it is the tectonically competent Massive Virieu Limestone which has controlled the form of the fold. Less competent Oignon Beds below have been contorted out of harmony with the shape of the main anticline. The type section for the Virieu Limestone lies along, and to the east of the "route nationale" 504 at the north-eastern exit of the village.

The Virieu Limestone as a whole shows a number of interesting facies changes. Of particular importance is the

FIG. 25

SCHEMATIC DIAGRAM OF PROBABLE FACIES CHANGES FROM THE SOUTHERN JURA INTO THE SUBALPINE TROUGH IN UPPER KIMMERIDGIAN & PORTLANDIAN TIMES



see fig. 28 for actual thicknesses of the Massive Virieu Limestone & positions of above localities

Plates 23 & 24

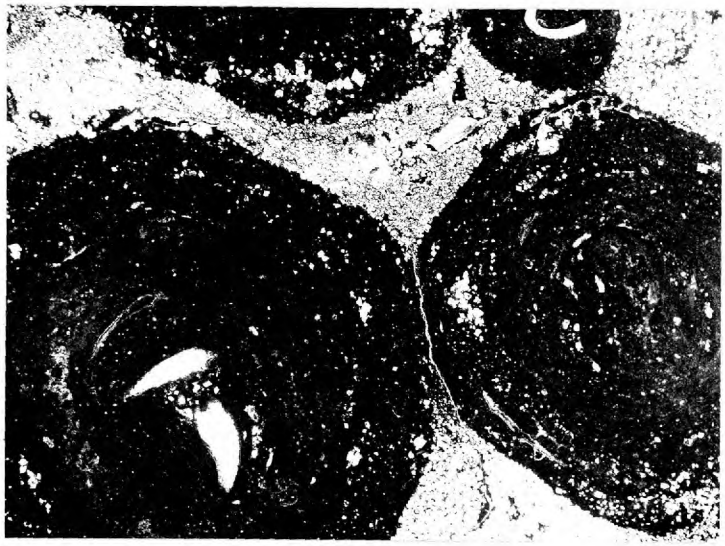


PLATE 23. Pisolite with preferentially dolomitised matrix. Bedded Virieu Limestone, Brognin (Ain). Thin section stained with acidified alizarin red S. Plane polarised light (X14).

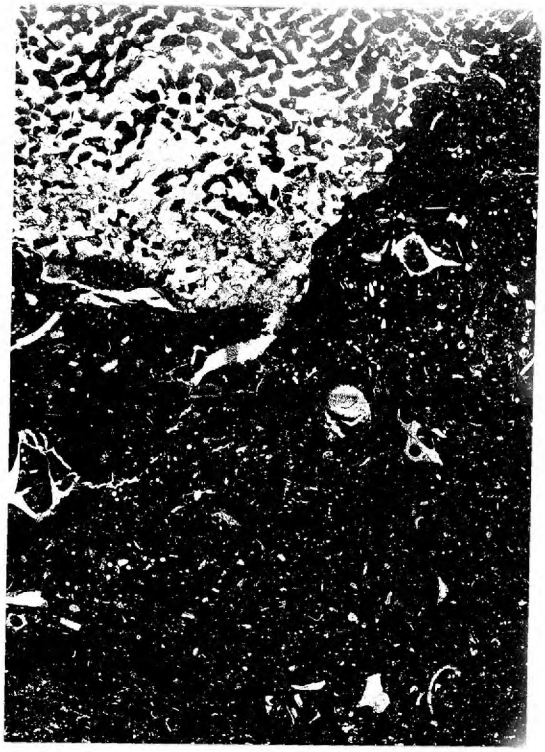


PLATE 24. Calcilutite containing scattered skeletal debris & the cellular structure of stromatoporoids. Bedded Virieu Limestone, Colomieu (Ain). Plane polarised light (X5).

north-westerly thinning and lateral passage of the Massive Virieu reef limestone into the Cerin Lithographic Stone, west of Préveysieu (see map 1 & fig.25). In the region of Préveysieu poorly-exposed, and greatly contorted lithographic limestone occurs both above and below typical Massive Virieu Limestone. For convenience in mapping, these thinly-bedded limestones were included with the bedded members above and below, namely the Lower Parves Beds and the Bedded Virieu Limestone. Around Cerin, however, it was possible to delineate the lithographic stone as a separate mapping unit (see map 1).

B. PETROGRAPHY.

(i) Bedded Virieu Limestone.

In the area mapped the most complete and readily accessible section, revealing Bedded Virieu Limestone in "normal" facies, commences 1km. east of Colomieu and 1km. north of the road leading to Arbignieu (map 1). Here the Bedded Virieu Limestone is made up of four recognisable sub-divisions, Bedded Virieu 1 (BVu1), etc. The petrography of these units is described and, where applicable, their facies changes discussed.

The pisolite (BVu1). In thin section, Mr.G.F.Elliott has recognised fragments of calcareous algae of indeterminate genera, making up the concentric structure to the pisoliths (plate 23), found at the base of the Virieu Limestone. In the field, the algal pisolite is a resistant and well-exposed unit, which can be traced over wide areas in Bas-Bugey and the Molard Dedon Range. It has also been found farther north in the Nantua region (fig.8). In these areas, it forms an excellent marker

band. The unit, however, is known to thin in a general south-easterly direction. At Brognin, in the area mapped, it is 20m. thick, compared with 12m. at the section east of Colomieu. Near Prémeyzel, it is either absent or rudimentary. The pisolite has not been found at all farther east in the region studied by Khouri (fig.11). Where the pisolite is not found, in the area mapped by the present author, the boundary between the Oignon Beds and the Bedded Virieu Limestone is generally marked by several bands of coarse bioclastic calcarenite. The skeletal fragments in these bands closely resemble the nuclei to the pisoliths seen to the north-west. The south-easterly passage from algal pisolite into un-encrusted skeletal debris could reflect a deepening of the water at the time of deposition towards the Subalpine trough. Alternatively part of the great south-easterly thickening of the Massive Virieu Limestone could be due to the lateral passage of the Bedded member into the Massive unit. In this case the pisolite may have formed behind the earliest "Virieu reefs". Such a suggestion would be best analysed by a detailed study of the Chat and Epine ridges (map 3), where the Massive Virieu Limestone has its thickest known development.

The pisolite, exposed at the section east of Colomieu, is a buff to brown coloured limestone, occurring in beds, generally 40-70m. thick. The limestone is a calcirudite composed of a self-supporting framework of pisoliths up to 3cm. in diameter. The spaces between large pisoliths are in places filled with smaller pisoliths and arenite-size pellets.

Generally, however, the pisoliths are well-sorted. In each case, the remaining pore-spaces are occupied by brown calcilutite. The uppermost 3m. of the pisolite unit, east of Colomieu, consists of pellet limestone, also buff to brown in colour. In these limestones, calcilutite forms the matrix to a self-supporting framework of arenite-size pellets. Pellet limestones commonly overlie the pisolite of the basal Virieu Limestone, and for convenience they are included in the pisolite unit.

In thin section, the skeletal nuclei to the pisoliths are seen to be mainly brachiopod, echinoderm and mollusc fragments, but rare corals, polyzoan fragments and rotaliids have also been found. Very coarse-grained skeletal material, such as large pieces of stromatoporoid[1] and whole specimens of Septaliphoria astieriana tend not to have pisolithic jackets. These organisms could have been living on the sea floor as the pisolite was forming.

In the area mapped the pisolite was found to become gradually dolomitised from south to north over a transition 2½km. long. South of lac d'Armaille (map 2), the pisolite is entirely undolomitised. Here the matrix to the pisoliths resembles the material in the pisolithic jackets, except for the concentric structure of the latter. Between Brognin village and the lake,

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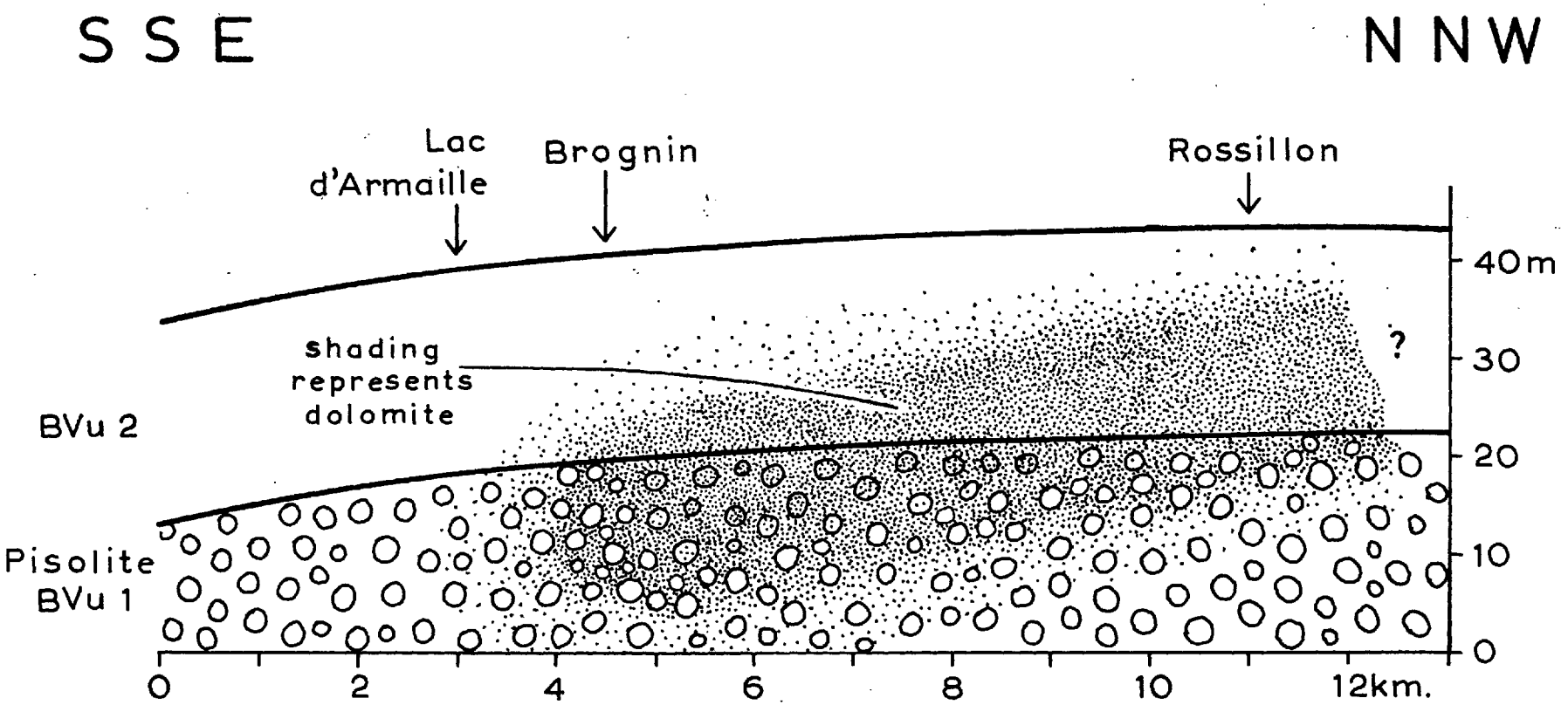
1. Although formerly considered as mainly Palaeozoic fossils, stromatoporoids are being found in increasing numbers in the Mesozoic.

FIG. 26

DISTRIBUTION OF DOLOMITE IN THE BEDDED VIRIEU LIMESTONE



the matrix and any internal sediment to the skeletal nuclei is found to have been preferentially replaced by dolomite. Dolomite rhombs have also marginally encroached into the pisoliths so that these have jagged outlines against the groundmass (plate 23). In the same rocks, the concentric pisolithic jackets are only partially dolomitised (plate 23). Such preferential replacement indicates that the pisolithic jackets had a lower permeability for the passage of dolomitising solutions than the matrix or internal sediment. This was very likely due to a tighter packing in the jackets, due to their probable mode of origin (a combination of algal encrustation and mechanical accumulation by "snow-balling").

In the northern side of Brognin Hill (map 2), the pisolite is hardly recognisable, since it is fully dolomitised. Still further north, the marker appears to pass gradually back into undolomitised limestone. The distribution of dolomite in the pisolite over the line connecting lac d'Armaille and Rossillon is illustrated diagrammatically in fig.26.

BVu2. The sub-division above the pisolite is about 20m. thick, east of Colomieu. It consists mainly of alternating limestones and shales, which yield an abundant brachiopod and lamellibranch fauna, as well as ammonites of the tenuilobatum and pseudomutabilis Zones (Kimmeridgian). The limestones are thinly-bedded (20-40cm), brown calcilutites, occasionally showing a mottled iron-staining. These are separated by thin (approximately 10cm.) shaly bands. An appreciable part of each band of shale belongs to the adjacent limestone beds. These

are so heavily stylolitised at their margins that it becomes difficult to separate stylolitised limestone from true shale of sedimentary origin. A few thicker beds of calcilutite (1-1½m.) in BVu2 are seen not to contain the abundant mollusc and brachiopod fauna. Instead, they locally exhibit a cellular texture reminiscent of stromatoporoids (plate 24). Small cavity-fillings of coarsely-crystalline calcite give these rocks the appearance of "bird's-eye" limestones. These thicker-bedded calcilutites seem to have reacted in a rather brittle fashion to deformation. They show numerous fractures, now filled by vein calcite.

The fossiliferous limestones of BVu2 are locally found to contain almost spherical chert nodules, about 10cm. in diameter. In the area mapped, the cherts are only found in one locality, about ½km. north-west of lac d'Armaille. Similar cherts were seen by Khouri (1960) in the lower part of the Bedded Virieu Limestone at la Balme gorge, but nowhere else in his area.

In thin section, the cherts are seen to consist mainly of small spherulites of chalcedony in a groundmass of opaline silica. Sponge spicules are lacking. The rare occurrence of echinoderm fragments, preserved in chalcedony suggests that the silica is at least partly of replacement origin.

The limestones of BVu2 are somewhat dolomitised in places. The distribution of dolomite is closely related to that in the pisolite (BVul) below (see fig.26). However, the limestones of BVu2 only begin to show dolomite in Brognin Hill, that

is above almost fully dolomitised pisolite. Furthermore, these limestones become increasingly dolomitised farther north towards Rossillon (see fig.26), where the underlying pisolite is only partially replaced. It seems that the "wave" of dolomitisation transgressed the bedding planes.

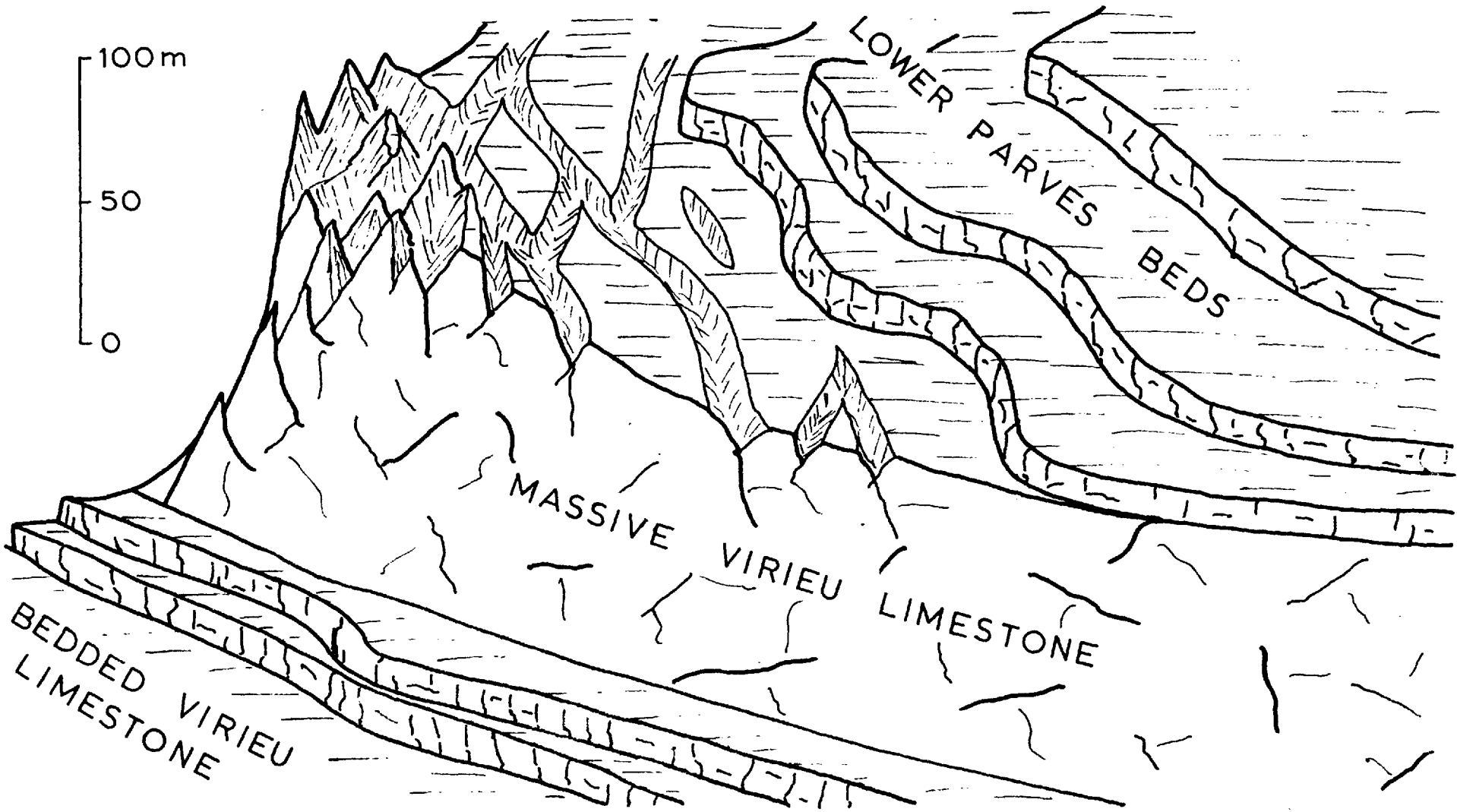
BVu3. In the section east of Colomieu, which is typical of the Bedded Virieu Limestone, BVu3 (27m. thick) consists of a monotonous sequence of thickly-bedded calcilutites (about 1-1½m), without shales. These beds, which lack a mollusc/brachiopod fauna, contain scattered stromatoporoids. The latter become increasingly important up the succession. The calcilutites resemble the thickly-bedded limestones of BVu2, both lithologically and faunistically.

To the north-west of lac d'Armaille, BVu3 is represented by thinly-laminated bituminous shales, which were formerly quarried for their oil content. In the early eighteen-hundreds, while the quarrying was in progress, an abundant well-preserved flora and vertebrate fauna was extracted. This made the lac d'Armaille bituminous shales geologically famous and the object of numerous field excursions. At the present day, however, the shales tend only to yield indeterminate debris of fish, and an extremely compressed mollusc fauna. The latter suggests considerable compaction of the shales.

In thin section, the shales are seen to be made up of thin laminations of small pellets and calcilutite. The laminations are interrupted along their length by numerous "knots" of chalcedony. In places these are relatively large chert

FIG. 27

BEDDING AND WEATHERING FEATURES OF THE MASSIVE VIRIEU LIMESTONE



nodules, clearly observable in the field. Where chert occurs, the bedding is rather irregular.

In the area mapped, the bituminous shales have a very local development, and it may be significant that they occur above the equally restricted chert beds of BVu2.

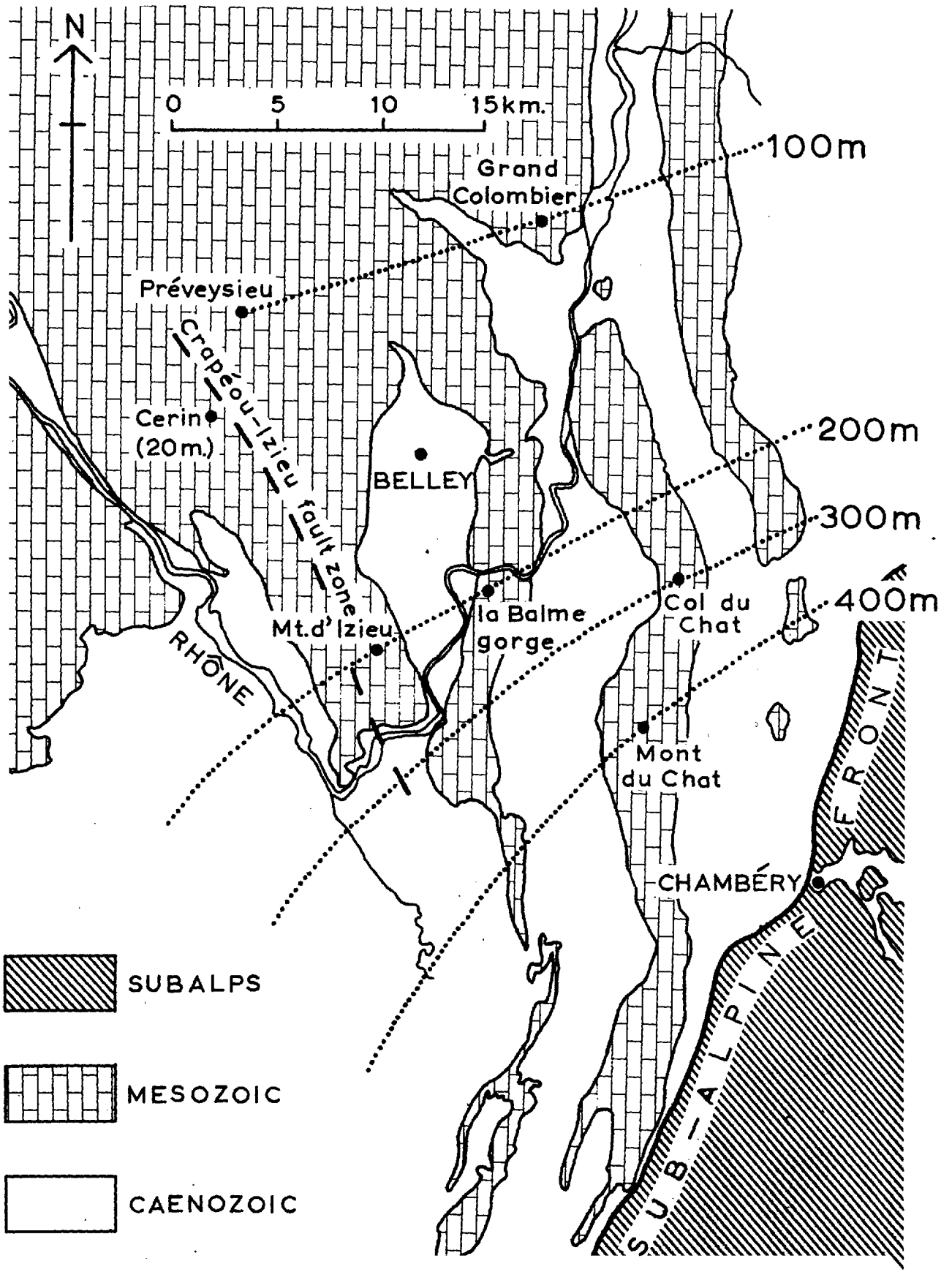
BVu4. The uppermost 17m. of the Bedded Virieu Limestone, east of Colomieu, (BVu4) are cream-coloured calcilutites with a crystalline lustre. In this, they differ from the limestones below, which like the Upper Chavoley and Cignon Beds, give a dull, brown fracture. Bedding in BVu4 is consistently thin (about 50cm.) compared to the Massive Virieu Limestone, which follows. Some of the beds of BVu4 are characterised by scattered white pellets which have rather diffuse boundaries against the host calcilutite. Stromatoporoids are particularly abundant in this sub-division.

(ii) Massive Virieu Limestone.

The Massive Virieu Limestone has well defined upper and lower delineating bedding planes (see fig.27). This is particularly well seen in the southern face of the cluse above Rossillon, where the underlying Bedded Virieu Limestone is exposed and the overlying Parves Beds have not been entirely eroded away. Within the Massive Virieu Limestone, bedding is absent or confused. On account of this, dip determinations taken on the unit are considered unreliable. The Massive member is in fact a single bed of limestone. Its thickness can only be consistently deduced from the width of its outcrop and the regional dip (estimated from the adjacent bedded

FIG. 28

MAP SHOWING TENTATIVE ISOPACHYTES FOR THE MASSIVE VIRIEU LIMESTONE



members). The absence of bedding planes for reference within the unit, makes it difficult to assess the exact stratigraphical position of specimens collected from the Massive Virieu Limestone. It was therefore not practicable to sample the unit regularly up the column. Where the cap of Parves Beds is absent, the Massive Virieu Limestone is weathered like a relatively homogeneous unit. Deep V-shaped gullies tend to exist, where erosion has not completely removed the bedding plane separating the Virieu Limestone and Parves Beds (see fig.27). This situation is exemplified over the eastern flank of the Montagne de Séremond and over the Montagne de St.Benoît, south of the Gland cluse. Series of impressive pinnacles are found over the Massive member, where erosion has been more intense (see fig.27). These are seen in the cliffs of the Ambérieu-Culoz cluse, north-west of Rossillon.

The Massive Virieu Limestone is 200m. thick in the north face of the Montagne d'Izieu (see fig.28), in the south of the area mapped. The division also has this thickness farther north-east in la Balme gorge, (Khouri, 1960). However, the unit is found to thin progressively north-westwards (see figs. 25 & 28) becoming only 100m. thick in the Grand Colombier, and in the Ambérieu-Culoz cluse above Rossillon. In the Col du Chat area (fig.28), Khouri found 260-300m. of Massive Virieu Limestone, whilst Gidon (unpublished manuscript) reported 400m. of the seemingly equivalent "Calcaire Kimmeridgien" farther south along the Mont du Chat. As shown in figs. 25 and 28, the evidence suggests thickening in a general south-easterly direc-

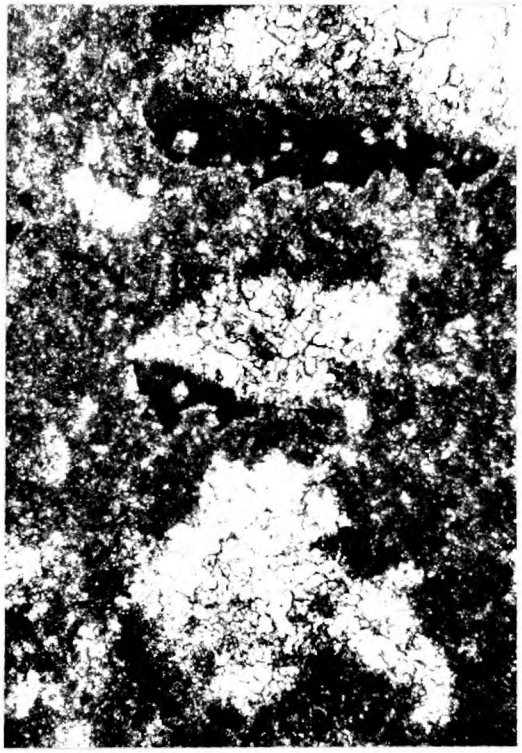
tion, that is towards the Subalpine trough.

The Massive Virieu Limestone is predominantly orange to yellow in colour. Fracture surfaces have a characteristic crystalline lustre. Most hand specimens appear virtually featureless, regarding their composition. In thin section, such rocks are seen to consist of calcilutite or fine-grained pellets merging into calcilutite. In many places they are extensively dolomitised. More rarely, the orange limestones are made up of arenite-size pellets, cemented by coarsely-crystalline calcite. The pellets are quite distinct in hand specimen. In thin section, it is common to find rudite-size pisoliths (probably of back-reef origin) and lithic fragments of calcilutite along with the pellets. Both the "featureless", and the pellet limestones locally contain branching and solitary corals, clearly in position of growth. The corals are composed of white, coarsely-crystalline calcite. Their original structure has been so obliterated, presumably by re-crystallisation, that it has not been possible to identify their species.

The crystalline rocks of the Massive Virieu Limestone are found from thin section studies to contain zones concentrated in skeletal debris, derived in particular from formerly aragonitic molluscs, and various calcareous algae. Echinoderm and polyzoan fragments have also been recognised, but no undoubted brachiopod debris has been recognised. The rarity of brachiopods is a typical feature of Jurassic to Recent reefs. The robust rhynchonellid types tend only to occur marginally to

Plate 25

PLATE 25.



Former cavities in Massive Virieu Limestone, Colomieu (Ain). Level upper surfaces to the internal sediment of these cavities afford "way-up" evidence. Internal sediment contains scattered composite calcite rhombohedra. Junction of internal sediment with host rock follows margins of former dolomite rhombs. Dolomite now replaced by calcite.
Plane polarised light (X22).

reef limestones, (Dr.Ager, personal communication).

The Massive Virieu limestones contain numerous cavity-fillings of coarsely-crystalline calcite. In certain pellet limestones, the former cavities appear so numerous as to indicate that the original sediment had been like a sponge, and had carried a mass of bubbles. An early cementation of these cavities prior to compaction is invoked to explain the preservation of the texture in the lithified rock.

Bodies of grey, coarsely-crystalline dolomite in the Massive Virieu Limestone were found by Shearman, Khouri and Taha (1961) to pass into cream-coloured limestone without dolomite. These authors showed much of the calcite in these limestones to have replaced the dolomite by the process known as dedolomitisation. Neither the dolomite, nor the calcite after dolomite yield a recognisable fauna. It is, however, sometimes possible in thin section to see "ghosts" of parts of former pellets within the dolomite rhombs and the mosaics of calcite after dolomite. These "ghosts" appear to continue out, and to connect up with undoubted pellets in the zones unaffected by the original dolomitisation. In certain rocks (plate 25), the only indication of dolomitisation or dedolomitisa-tion comes from the jagged boundaries seen between the host rock and the internal sediment to some former cavities. Clearly these boundaries, seen in plate 25, are made up of the margins to a number of rhombs. It appears that the host rock was fully dolomitised, whilst the internal sediment was little

Plates 26 & 27

PLATES 26 & 27

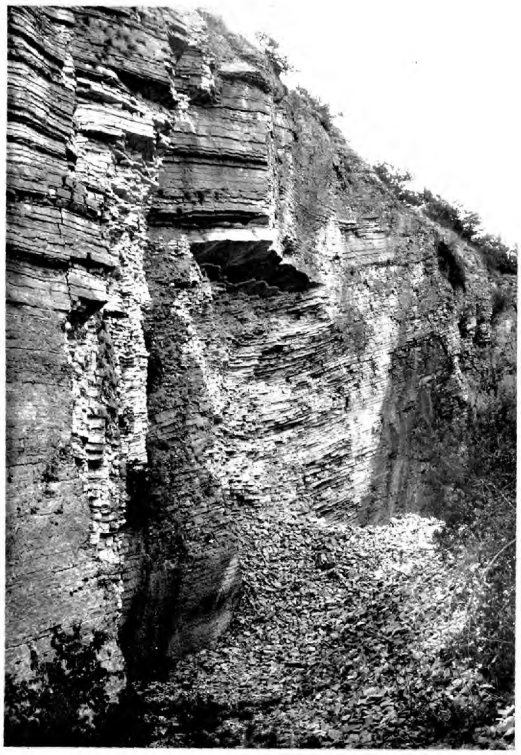


PLATE 26. Quarry in Cerin Lithographic Stone. Type locality, Cerin (Ain).

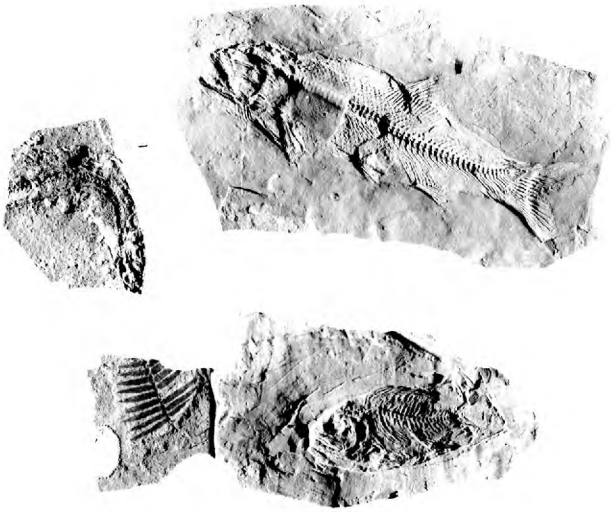


PLATE 27. Fossil fern & fish from the Cerin Lithographic Stone (X 1/5). Photographed by kind permission of Abbé Cou of Lamartine College, Belley.

affected. This is believed to have given rise to the jagged boundary. The whole rock is now preserved in calcite, indicating subsequent dedolomitisation.

(iii) Cerin Stone.

In the high ground, east of Cerin (see map 1), only 20m. of massively bedded Upper Virieu pellet limestones are found. This represents a drastic reduction in thickness westwards from Rossillon, where the division is 100m. thick (see figs. 25 & 28). The marked change takes place across the Crapéou-Izieu fault zone, and it is believed that much of the transitional thinning has been faulted out.

At Cerin the beds immediately underlying the Massive Virieu Limestone are covered by scree. Above comes the Cerin Lithographic Stone, which was exploited by the early nineteenth century printing industry, and which is exceedingly well-exposed in a large disused quarry (plate 26). The Cerin Stone is 20m. thick, and overlain by typical Lower Parves Beds. It is made up of thin beds (2-10cm. in thickness) of calcilutite, which fractures and splinters like porcelain. The low porosity and thin, regular bedding (see plate 26) made the Stone suitable for lithography. Some of the thicker beds contain numerous vugs of coarsely-crystalline calcite and are typical "bird's-eye" limestones.

The Cerin Stone has yielded an abundance of well-preserved vertebrates and plants, which have been extensively studied by many authors in the past (see chapter 2). It is

comparable to the famous Solenhofen Stone of about the same age.

In the region of Préveysieu (see map 1), the Massive Virieu Limestone is both over- and under-lain by about 10m. of thinly-bedded calcilutite, lithologically indistinguishable from the Cerin Stone. These calcilutites have behaved incompetently to deformation, and have become intensely contorted (see plates 45A & B). They die out within a short distance southwards, not being represented south of lac d'Armaille.

The Cerin Stone is the unit of thinly-bedded calcilutites between the Massive Virieu Limestone and Parves Beds farther west. It is not known if lithographic limestone occurs below the Massive Virieu Limestone here, due to the cover of scree. It is considered likely, however, that such beds do occur, and that the Massive Virieu Limestone thins and passes into lithographic stone westwards from Préveysieu, as shown in fig.25. The Cerin Lithographic Stone crops out in the north of the Tantainet-St.Benoît anticline (map 3). Farther south in this structure, lithographic stone is lacking and the Massive Virieu Limestone appears as a thick (200m.) coral-bearing member. The Tantainet-St.Benoît anticline is only locally faulted, so it should be possible, by studying this structure in detail, to trace the full transition from massive coralline limestone to thinly-bedded lithographic stone. The present author has not ascertained the areal extent of the lithographic stone westwards. The stone could well be an isolated lithofacies, passing back into massive reef-limestone

farther west. One might expect, however, the whole of the Massive Virieu Limestone to pass into lithographic stone westwards.

C. STRATIGRAPHICAL AGE.

The fauna and flora of the Virieu Limestone is as follows:-

Lower or "Bedded" member: Indeterminate algae
Indeterminate ferns
Indeterminate fish debris
Epithyris sp.
Loboidothyris zieteni (de Loriol)
Ornithella sp.
Septaliphoria astieriana (d'Orbigny)
Trichothyris sp. nov.
Stromatoporoids (?) *Actinostromaria* sp.
Inoceramus cf. *I. cunningtoni* Cox
Rotaliidae
Aspidoceras (*s.s.*) sp.
(?) *Ataxioceras* cf. *A. discobolum* (Fontanne
Ataxioceras cf. *A. lothari* (Oppel)
Ataxioceras (*Parataxioceras*) *corlari* (Oppel)
Lithacoceras sp.
Pachysphinctes cf. *P. grandti* Spath
P. aff. *P. linguiferus* Spath
Progeronia aff. *P. progeron* (von Ammon)
P. cf. *P. pseudopolyplocoides* (Geyer)
P. cf. *P. subachilles* (Wegele)

	Rasenia sp.
	Indeterminate belemnites
	"*Nerinea*" sp.
	Arcomya aff. *A.latissima* Agassiz
	Aulocomyella sp.
	Chlamys (*Radulopecten*) *laurae* Etallon
	Entolium sp.
	Gervillella aff *G.siliqua* (Eudes- Deslongchamps)
	Gryphaea aff *G.dilatata* (J.Sowerby)
Upper or "Massive" member:	*Actinoporella podolica* Alth
	Clypeina jurassica Favre
	Solenopora sp.
	Acicularia sp.
	Calamophyllia sp.
	Isastraea sp.
	Montlivaltia sp.
	Miriophyllia sp.
	Thamnasteria sp.
	Miliolidae
	Textularidae
Cerin Stone:	For systematic descriptions and illustrations of the flora and vertebrate fauna from Cerin, see Thiollière (1854), Falsan (1871), Lortet (1892), Woodward (1889, 1895), Eastman (1914) and de Saint-Seine (1949).

Ammonites in the fossiliferous beds towards the base of the Bedded Virieu Limestone (BVu2) represent the lower two

zones of the Kimmeridgian of the western Tethys. Mr.N.J.Morris (personal communication) believes that the Pachysphinctes and Progeronia fauna, which occurs at one horizon in this part of the Bedded Virieu Limestone, represents the boundary between the polyplocum and balderum sub-Zones of the tenuilobatum Zone. Dr.Callomon has attributed Aspidoceras (s.s.), also from this sub-division of Bedded Virieu Limestone, to the pseudomutabilis Zone.

The remainder of the Virieu Limestone has not yielded fossils critically diagnostic of stratigraphical age. The Massive Virieu Limestone underlies the "Purbeckian" facies of the Lower Parves Beds. Towards the base of this comes the "premier niveau d'eau douce" of Donze (1958). On the basis of ostracod and, where applicable, ammonite correlation across Europe, Donze concluded that this basal fresh-water band belongs to the giganteus Zone of the former English Portlandian. It seems therefore that the Virieu Limestone spans most of the Kimmeridgian and in addition the lower part of the Portlandian in the new sense, now approved by the British Mesozoic Committee (Table II).

D. FAUNAL & FLORAL EVIDENCE OF PALAEO-ENVIRONMENT.

The algal pisolite at the base of the Virieu Limestone was probably formed at depths of less than 30m., where there was at least an adequate transmission of sunlight for photosynthesis. The asymmetrical rhynchonellid Septaliphoria, with its large reinforced pedicle opening, is a form which is

characteristically associated with reefs in the Mesozoic (Dr.Ager, personal communication). In the area mapped, Septaliphoria occurs in the fossiliferous limestones above the pisolite, and it is significant that these are followed, first by beds rich in stromatoporoids, and then by massive limestones with corals in position of growth. This faunal succession is analogous to that described for the Frasnian reefs of the Ardennes by Lecompte (1954). Most of the fauna of the Virieu Limestone suggests deposition in shallow, rough-water at or above the wave-base. The corals in particular indicate very shallow water (see fig.18).

Locally, however, the water must have been calm. For instance, the ferns and fish from the bituminous shales near lac d'Armaille would have required a low-energy environment for their preservation. De Saint-Seine (1949) suggested that the depositional environment for these shales had been similar to that of the present day mangrove swamps. The Cerin Lithographic Stone must in addition have been deposited in exceedingly quiet water. This is indicated by its fine-grained character, its thin and regular bedding, and its content of well-preserved reptiles, fish and plants. There can be little doubt that the Cerin Stone was laid down in lagoons behind the Virieu reefs (see fig.25). This interpretation agrees with that of de Saint-Seine (1949), who compared the "Kimmeridgien" palaeo-environment with present day conditions around the Australian Great Barrier Reef.

Most of the fossils from the quarry at Cerin are kept in the Natural History Museum at Lyon. A few are to be found in the British Museum, London, the Carnegie Museum, U.S.A., and the museum of Lamartine College, Belley. Few fossils have been found since the quarry fell into disuse. The present author has extracted the imprints of ferns, but no vertebrates. Plate 27 shows some of the fish and plant remains of Cerin, which are kept at Lamartine College, Belley.

E. SUMMARY OF GEOLOGICAL HISTORY.

During most of Kimmeridgian and Lower Portlandian times, the south-eastern Jura is believed to have been the site of a reef complex, forming a barrier between the Subalpine trough and the main shelf-area to the west (see fig.25). The reef limestones, which were probably formed in rough-water, are found to thin north-westwards. In this direction they pass into back-reef lithographic stone, which is thought to have been laid down in protected lagoons. To the east, rocks of equivalent age seem to be the Tithonian breccias and fine-grained limestones of the Subalps. These beds, which contain a pelagic fauna of rare ammonites and abundant *Calpionella*, are generally considered to have been deposited in deep water. For instance, they contain the supposedly deep-water brachiopod, *Pygope janitor* Pictet (named "*janitor*" from its occurrence at the "Porte de France" at Grenoble). The passage from the "reef-wall" to the *Calpionella* limestones is unfortunately faulted out in the Subalpine frontal thrusts.

In the area mapped, the deep-water conditions represented by the Chavoley Beds were finally brought to an end with the formation of the algal pisolite at the base of the Virieu Limestone (fig.30). Following this, stromatoporoid biostromes, and then coral reefs developed, as relatively uniform shallow-water conditions became established. It is probable that the entire vertical and lateral extent of the reef complex was laid down in waters not more that 10m. deep. A much greater subsidence during deposition is therefore indicated for the Mont du Chat area, where the reef is thickest, than for the regions farther west (see fig.25). This is another of the numerous examples in the geological record, illustrating that corals grew best along actively subsiding "hinge-lines". The "hinge-line" in the present case lay between the shelf area of the Jura and the Subalpine, or Dauphinois geosyncline.

Bourgeat (1888) made a regional study of the Upper Jurassic reefs of the Central and Southern Jura. From his investigations, he was led to believe that these reefs had developed at successively higher stratigraphical levels south-eastwards towards the Subalpine trough. He connected "Rauracien" reefs in the region of Lons-le-Saunier (fig.7B) with "Ptérocerien" reefs near St.Claude. These he, in turn, joined with the "Calcaire Kimmeridgien" (seemingly the equivalent of the Massive Virieu Limestone) in the south-eastern Jura. Bourgeat's ingenious hypothesis is much quoted, for example by Gignoux (1950). In the area investigated by the

present author, the Upper Kimmeridgian/Lower Portlandian reefs (Massive Virieu Limestone) pass north-westwards into the Cerin Lithographic Stone, of probable back-reef origin. Reef limestones have not been found below the lithographic stone, so there is no evidence in this region that the Upper Jurassic reefs become older in a north-westerly direction. It is, however, possible that the Massive Virieu reefs formed a barrier between the "Purbeckian" lagoonal facies and the Tithonian deep-water limestones in the Upper Portlandian times (see fig.25 & chapter 10).

CHAPTER 10.

THE PARVES BEDS.

A. GENERAL.

The Parves Beds are named after the Montagne de Parves, which dominates the Belley syncline from the east (see map 3 & plate 40, E / 18 - 21). The formation is well seen along the road which climbs the ridge from Belley to the village of Parves. The well-bedded limestones at the top of the Parves ridge appear in great contrast to the pronounced "scar" of the underlying Massive Virieu Limestone. The Parves Beds are also well-exposed in la Balme gorge, where the Rhône cuts through the Parves-Tournier ridge (map 3). It was here that Favre and Richard (1927) made their classic biostratigraphical study on the uppermost Jurassic of the south-eastern Jura. The section was also subjected to a detailed lithostratigraphical analysis by Khouri(1960).

In the field, the Parves Beds are readily divisible into three mapping units. The Lower member, generally 110m. thick, consists of bedded calcilutite, breccias and fine-grained dolomites. The Middle Parves Beds consistently about 20m. thick, are composed of soft marls and pellet limestones, deeply stained with iron-oxide. The Upper member, some 50m. thick, is not iron-stained. It is made up of resistant yellow to white pellet limestones. Soft marl is lacking.

As has been pointed out in Chapter 9, the thin development of lithographic stone above the Massive Virieu Limestone in the region of Préveysieu has been mapped in with

the Lower Parves Beds. This was done since it was not possible to map the greatly contorted and poorly-exposed lithographic stone, consistently as an independent unit, on a scale of 1/20,000.

The ferruginous Middle Parves Beds are poorly-resistant to erosion compared to the Lower and Upper members. Consequently they form vegetated strike vales, or platforms between cliff features exposing the Lower and Upper Beds. These double-cliff features characterise the Parves Beds throughout the area investigated. On account of this, the formation can generally be recognised from a considerable distance. For example, plate 40 shows the double-cliff feature of the Parves Beds in the area mapped (G/20,H-I/10-12). The same feature appears in the middle distance, in the Parves ridge (E / 18-21). The double-cliff feature is also prominent in the Fier gorge, through the Chambotte ridge (plate 2B). Here it is seen overlying massively bedded Virieu Limestone in the core of a symmetrical anticline. It is clear that the distinctive ferruginous marls and pellet limestones of the Middle Parves Beds form one of the best marker bands in the Mesozoic succession.

In the area studied by the present author, the Parves Beds are involved in numerous minor folds (maps 1 & 2), generally with amplitudes of about 200m. These folds are particularly well-developed in the regions of Préveysieu and north of Sillignieu. Clearly the Parves Beds behaved less competently than the underlying Massive Virieu Limestone to

deformation.

The Parves Beds have their widest outcrop in the area mapped over the Montagne d'Izieu, where the formation is a cap to the south-easterly plunging Ambléon-Prémeyzel anticline (see map 1). The scarp and dip slopes of the Montagne d'Izieu are best seen from the Montagne de Parves to the north-east, (see plate 34). In the very south of the area mapped, this dip-slope has been dissected by erosion so that the characteristic double-cliff feature of the Parves Beds stands out on all sides (see map 1 and compare with plate 35A).

B. PETROGRAPHY.

(i) Lower Parves Beds.

In the area mapped, the Lower Parves Beds form a lagoono-lacustrine complex in typical "Purbeckian" facies. To the south-east, in the Subalps, however, the succession is fully marine. The rocks of the "Purbeckian" facies in the Swiss Jura have been studied in great detail by Maillard (1884), Favre and Joukowsky (1913) and Carozzi (1948). Donze (1950) investigated the same sequence in an analysis of the Jurassic to Cretaceous boundary in the Maritime Alps, Provence, the Subalps and the French Jura. These and the works of Favre and Richard (1927) and Khouri (1960) on la Balme gorge, made it only necessary to summarise the petrography of the "Purbeckian" rocks in the area. The Lower Parves Beds are made up of several distinctive lithologies, which are discussed in the following paragraphs.

Porcellanous calcilutites and fine-grained breccias. Resistant beds of off-white calcilutite, with little porosity, are common in the Lower Parves Beds. Apart from being more thickly-bedded (20-30cm), they are somewhat similar to the Cerin limestones, and often carry small vug-infillings of coarsely-crystalline calcite ("bird's-eye" limestones). These porcellanous calcilutites of the Lower Parves Beds correspond to the "calcaires compacts", described by Carozzi (1948) and Donze (1958). In thin section, they are seen to consist of cryptocrystalline calcite. In some rocks, this supports rare miliolids, textularids and molluscan skeletal debris. Usually however, the limestones are rich in fresh-water charophytes. The calcilutites therefore seem to represent either marine or fresh-water environments.

Some of the porcellanous calcilutites contain either black or multi-coloured angular fragments. These fragments generally measure 3-4mm. in length. Their boundaries against the host rock are rather diffuse in thin section, since they consist of the same type of crypto-crystalline calcite. These fine-grained breccias occur in regular beds at various levels in the Lower Parves Beds, throughout the area mapped.

Carozzi (1948) suggested that similar black breccias in the Swiss Jura were derived from sapropelic lagoono-lacustrine environments along the axes of almost emergent embryonic anticlines. He considered the breccias to have been re-deposited with the "calcaires compacts" in the relatively deeper, and often marine, waters of embryonic synclines.

Plates 28 & 29

PLATE 28. Intraformational breccia horizon. Lower Parves Beds, Izieu (Ain).

PLATE 29. Bedding-plane exposure of compound coral. Upper Parves Beds, Izieu (Ain).

The multi-coloured breccias were thought by Carozzi to represent re-working from a wider and not specifically sapropelic, provenance.

It is not possible, in the area mapped, to obtain evidence either to corroborate or to destroy Carozzi's interesting hypothesis. Due to erosion, the Lower Parves Beds are only preserved along the flanks, or the south-easterly plunge of the Ordonnaz-Ambléon-Prémeyzel anticline (map 1). This is where re-worked debris from the axis of an embryonic fold would be expected to be deposited.

Coarse-grained breccias. Breccias, made up of large angular limestone pebbles in a matrix of soft, grey to green marl occur at various levels in the Lower Parves Beds. The limestone pebbles can be matched with the lithology of the associated strata, and pebbles of porcellanous calcilutite and black breccia are notable constituents. Plate 28 shows a typical coarse-grained breccia band in the Lower Parves Beds, exposed ½km. south-west of Izieu (map 1). Fragments in the basal part of this breccia are seen to belong to the underlying limestone bed. This bed becomes more and more disturbed and fragmented upwards. The origin of the pebbles in the upper part of the breccia cannot certainly be attributed to the limestone bed below, but the overall transitional increase in brecciation upwards suggests that this is the case. The marly matrix to the breccias is in places represented on its own without limestone pebbles. The impermeability of the marls causes them to be the sites of springs. They, and the

breccia horizons, are poorly resistant to erosion and give rise to a series of dank, mosquito-infested caves along the cliffs of the Lower Parves Beds.

The coarse-grained breccias often have a very variable thickness. Khouri (1960) figured a number of these in washouts in the Lower Parves Beds of la Balme gorge. Similar washouts have been found in the area mapped by the present author. Carozzi (1948) described a pile of coarse-grained breccias (5½m. thick) near la Dôle in the Swiss Jura. He pointed out that this thick development is only local and occurs against the southern steep limb of an asymmetrical anticline. He used this data to support his hypothesis on embryonic folding in the Jura, proposing that the asymmetry of the fold had existed in "Purbeckien" times, and that the breccias represent scree from its southern steep limb.

<u>Nerineid limestones.</u> Calcilutites packed with nerineid gastropods occur at several horizons in the Lower Parves Beds. The texture of these limestones is somewhat different from that of the porcellanous calcilutites described earlier. The limestones are relatively thickly-bedded (30-40cm.), heavily veined, and much more porous than the porcellanous calcilutites.

<u>Pellet limestones.</u> Pellet limestones occur at the top of the Lower Parves Beds, but except locally (see later), they are extremely rare lower down in the division. The pellet limestones are generally well-bedded, from 20-30cm. thick, and white to yellow in colour.

In thin section, the pellets (of arenite-size) are found to co-exist with a relative abundance of miliolids, textularids, somewhat silicified molluscan skeletal debris and rare echinoderm fragments. The Lower Parves pellet limestones all appear to be of marine origin. They are generally cemented by coarsely-crystalline calcite, but matrices of fine-grained, microcrystalline calcite have been found in places.

In the region of Préveysieu there is a local development of cross-bedded, mixed pellet and bioclastic calcarenite immediately overlying the lithographic stone. The unit is 5m. thick and extremely ferruginous. Master bedding planes are generally covered with oyster valves in bands, up to 10cm. thick. In many ways the lithology resembles that of the Middle Parves beds, which come about 100m. higher in the succession.

<u>Fine-grained dolomites, and dolomitic limestones.</u> The basal 20-30m. of the Lower Parves Beds, in the area investigated by members of Imperial College, are characterised by several units of fine-grained, bedded dolomite. This appears to be the only lithology of the Lower member, which is restricted stratigraphically. The others are found at various levels throughout the division. In the north of the area mapped by the present author, each unit of bedded dolomite is about 4-5m. thick. Further south, they are found to thin, and in the Montagne d'Izieu (map 2) they are only rudimentary. The bands of dolomite are equally thin in la Balme gorge farther east. It seems that the bedded dolomite

of the Lower Parves Beds is another feature which diminishes in thickness in a general south-easterly direction (cf. the Ambléon reefs and oolites, and the Bedded Virieu pisolite below). Donze (1958) has shown the whole facies of the "Purbeckien" (Lower Parves Beds) to become more predominantly lagoonal north-westwards away from the Subalpine zone. Since the bedded dolomite becomes thicker in this direction, it seems likely that it formed in a lagoonal environment. A present day example of a lagoonal environment in a carbonate complex (along the Trucial Coast of the Persian Gulf) has yielded early diagenetic, fine-grained dolomite after aragonite, (Curtis et alia, 1963). It seems possible from this evidence that the bedded dolomites of the Lower Parves Beds were formerly aragonite muds. In thin section, the dolomites are seen to consist of fine-grained rhombs, each about 26 μ in length, poikilitically cemented by large crystals of calcite. No relics of a former limestone texture have been observed. This would be easily understood, if the original sediment had been composed of the metastable aragonite.

Dolomitic calcilutites are common in the Lower Parves Beds and are often found to be associated with the bedded dolomites. It has been suggested in chapter 8, that a similar association in the Oignon Beds reflects an original alternation of aragonite and calcite muds.

(ii) Middle Parves Beds.

In the area mapped, the Middle Parves Beds are best exposed, and most readily accessible near Murs along, and to

the north of, the road from Belley to Brégnier-Cordon.

The upper surface of the Lower Parves Beds is irregular and pitted. The irregularities, which could have been caused by solution, are filled with ferruginous pellet limestone belonging to the Middle Parves Beds.

The Middle member, which is ferruginous throughout, commences with alternating tough pellet limestones and soft marls. The alternations are each approximately 30cm. thick. The marls contain numerous whole specimens of Pseudocyclammina lituus, whilst prominent in the pellet limestones is much skeletal debris, such as broken lamellibranch valves and crinoid ossicles. The shaly marls are replaced upwards by cross-bedded pellet limestones in units 1-2m. thick. In thin section the pellets, of arenite-size, are seen generally to be cemented by coarsely-crystalline calcite. Bioclastic grains such as brachiopod, echinoderm, mollusc and polyzoan debris, are represented in small quantities. Accessory detrital quartz is also present. Specimens of Miliolidae, Textularidae, and Rotaliidae form 5-10% of the detrital grains, as seen in thin section. Sections through Pseudocyclammina have been found, which show this foraminifer to have built its shell from pellets and detrital quartz. The organism clearly had a preference for the rare quartz grains in the sediment, since this material is considerably more abundant in the walls of the specimens than in the host rock.

The heavy iron-oxide stain, which characterises the

Middle Parves Beds, is seen in thin sections of the pellet limestones to be present as a varnish around the surface of the pellets.

(iii) Upper Parves Beds.

The Upper Parves Beds consist almost entirely of cream-coloured pellet limestones, disposed in well-bedded units ½-1½m. thick. The beds are generally cross-laminated. Bands of skeletal material, including whole nerineids and the valves of oysters, are concentrated in some of the foresets. There is a complete lack of marl. In thin section, the pellet limestones of the Upper Parves Beds closely resemble those of the Middle member, save for the lack of iron staining in the former. Towards the top of the Upper Parves Beds, several bands of a silicified compound coral have been found (see plate 29). These bands are generally about 15-20cm. thick. The corals have been found in extensive bedding plane exposures in the Préveysieu and Izieu regions. They seem to form a good marker horizon in the Upper Parves Beds.

C. STRATIGRAPHICAL AGE.

The flora and fauna collected from the Parves Beds are as follows:-

Lower member: *Actinoporella podolica* Alth.
Clavator reidi Craves.
C. grovesis Harris.
Clypeina jurassica Favre.
C. parvula Carozzi.

Miliolidae

Textularidae

Nerinea sp.

Ostrea sp.

Middle member: *Sellithyris* (?) *russillensis* (de Loriol)

"*Terebratula*" *moutoniana* (d'Orbigny)

Miliolidae

Pfenderina aff. *P.neocomiensis* (Pfender)

Pseudocyclammina litmus (Yokohama)

Rotaliidae

Textularidae

Leviathania sautieri (Coquand)

= *Natica leviathan* of many authors

= *Ampullina leviathan* (Pictet & Campiche)

Nerinea sp.

Upper member: *Parachaetetes hadramautensis* Elliott.

Anthozoa

Nerinea sp.

Pseudomelania sp.

Cardium sp.

Lucina sp.

Ostrea sp.

The Lower Parves Beds contain the mixed fresh-water and marine fossils characteristic of the "Purbeckien" of the Jura, described by Carozzi (1948) and Donze (1958). The member overlies undoubted Kimmeridgian (Bedded Virieu Limestone), and underlies a Berriasian fauna in the Middle Parves

Beds. Clearly the Lower Parves Beds represent the lagoono-lacustrine "Purbeckian" facies of north-west Europe, and thus have an Upper Portlandian age, in the new sense (see Tables I & II).

Cream-coloured pellet limestones at the top of the Lower Parves Beds contain Miliolidae and Textularidae. These beds are overlain by the distinctive iron-stained Middle Parves Beds, which have a consistently marine fauna. The large gastropod, Leviathania sautieri, although rare in the Middle Parves Beds of the area investigated, is a typical Berriasian form of the Southern Jura (Marie & Mongin, 1957). The combined mollusc and foraminiferal fauna of the Middle Parves Beds suggests a Lower Cretaceous age. The basal Cretaceous marine transgression, however, appears to be represented in the pellet limestones at the top of the Lower Parves Beds. The junction between the Jurassic and Cretaceous in the area mapped thus lies within a mapping unit, and the horizon seems not to coincide with any great change in lithology.

The distinctive lithology of the Middle Parves Beds appears to continue into the Subalps, where about 15m. of ferruginous, mixed pellet, oolitic and bioclastic calcarenites (the "calcaires grossiers de Montagnole") occupy about the same stratigraphical position. As well as containing the same fauna as the Middle Parves Beds, including L.sautieri and Pseudocyclammina lituus (see Donze, 1958), these beds have yielded ammonites of the boissieri Zone of the Middle Berriasian (Gidon, 1948).

The Upper Parves Beds contain *Parachaetetes hadramautensis*, a diagnostic Lower Cretaceous alga (Mr. Elliott, personal communication). The notable coral horizon in this member makes the facies comparable to that of the "Marbre Bâtard", a rock with a shelf facies occurring in the Lower Valanginian of the Subalps.

D. FLORAL AND FAUNAL EVIDENCE OF PALAEO-ENVIRONMENT.

Of all the fossils collected from the Lower Parves Beds, only the charophytes represent a fresh-to brackish-water environment. These algae occur in great numbers, concentrated in bands, 1-2cm. thick. Other limestones in the same sequence contain a normal marine fauna of Foraminifera and nerineids. Donze (1958) recognised an intermediate lagoonal environment with dwarfed miliolids. It seems that the Lower Parves Beds were laid down in a series of very shallow-water lakes and lagoons, which were invaded from time to time by the sea.

Uniform marine conditions became established with the basal Cretaceous. The compound corals and calcareous algae of the Upper Parves Beds indicate a restricted environment of very shallow, clear tropical seas (see fig.18).

E. SUMMARY OF GEOLOGICAL HISTORY.

The lacustrine and lagoonal sediments of the Lower Parves Beds may have been deposited behind a vertical continuation of the Massive Virieu barrier reef at the margin of the Dauphinois geosyncline (see fig.25). This is difficult to prove since the zone between the "Purbeckian" facies of the

Jura and the "Tithonian" facies of the Subalps is faulted out at the Subalpine front.

The sedimentary environment seems to have become relatively uniform over a wide area in Berriasian times with the deposition of the Middle Parves Beds over the southern French Jura and the seemingly equivalent, shallow-water "calcaires grossiers de Montagnole" over the Subalpine region. It is believed that these uniform conditions were maintained in the Lower Valanginian, and that the Upper Parves Beds correlate approximately with the shallow-water "Marbre Bâtard" of the Subalps. The pellets, which make up most of the Middle and Upper Parves Beds in the area mapped, are either of faecal or accretionary origin. Similar deposits are widespread over the present day shelf area of the Bahama Banks (Illing, 1954).

The subsidiary coral reef horizon in the Upper Parves Beds (plate 29) seems to occur at about the same level as a band of corals, found by Bourgeat (1888), in the Grand Salève. Bourgeat considered the Valanginian reef limestones of Salève to connect up with the main Upper Jurassic reef complex of the Southern Jura (chapter 9), and to represent the continued diachronous migration of these reefs south-eastwards towards the Subalpine trough. However, this is clearly not the case since Upper Jurassic reefs are also found in the Grand Salève (Carozzi, 1954a & b), and these are separated from the Valanginian by lagoono-lacustrine rocks of typical "Purbeckian" facies (Carozzi, 1948). The uniformity of environmental conditions over the Jura and Subalps during Berriasian and Lower Valangin-

ian times, moreover, indicates that the Massive Virieu barrier reef had broken down before the beginning of the Cretaceous.

The present author is therefore led to believe that Massive Virieu reef limestones formed a barrier between the shelf area of the Jura and the geosynclinal zone of the Subalps through uppermost Kimmeridgian and Portlandian (s.l.) times. The reef limestone is thought to pass north-westwards into back-reef Bedded Virieu Limestone, Cerin Stone, and Lower Parves Beds. The reef wall, while undoubtedly diachronous, is not considered to have migrated great distances across the Jura, as proposed by Bourgeat (1888). The barrier reefs are interpreted to have broken down at the end of the Jurassic. This is contrary to the opinion of Bourgeat, who maintained that they connect up with the Valanginian reefs of the Grand Salève.

CHAPTER 11.

THE BOURDEAU BEDS.

A. GENERAL.

The tough, pale pellet limestones of the Upper Parves Beds are overlain by a formation of poorly-resistant ferruginous calcarenites and marls, named the Bourdeau Beds by Khouri (1960). The formation is particularly well-exposed in road cuttings along the steep descent from the Col du Chat to the village of Bourdeau (map 3). Khouri, who studied these sections in detail, found the Bourdeau Beds here to be 150m. thick. This compares with a thickness of about 60m. measured by the present author in the area west of Belley.

The Bourdeau Beds are characteristically iron-oxide stained and commonly glauconitic. The formation has a marked vertical variability, being made up of rhythms of marl and cross-bedded, bioclastic calcarenite and oolite. Khouri recognised several subsidiary cycles of sedimentation in the Bourdeau Beds of the Col du Chat area. Similar cycles have been found by the present author in the region west of Belley.

Lithologically the marls and calcarenites of the Bourdeau Beds are very similar to those of the Middle Parves Beds (chapter 10). Both units give rise to subdued topography due to their poor resistance to erosion. The Bourdeau Beds break down to form a fertile soil, which supports a profuse vegetation. Consequently the formation tends to be poorly-exposed except in road cuttings and river gorges.

PLATE 30.

PLATE 30.

Looking down onto Pugieu gorge from the north. In the distance on the left is Mont Tournier, of the Chain Jura. To the right are the Montagnes d'Izieu & St.Benoît of Haut-Bugey. The remainder of the field of view takes in most of Western Bas-Bugey. In the foreground on the left is the Andert-Contrevoz platform, part of the Rossillon-Belley syncline. In the middle distance on the right are the sub-parallel ridges of the greatly eroded part of the Ordonnaz-Ambléon-Prémeyzel anticline. Scrub-covered limestone pavements of the Chambotte Limestone cap the Andert-Contrevoz platform. The pavements are locally interrupted by a marsh-filled solution hole, seen on the left. Where the Chambotte Limestone is covered by drumlins or boulder clay, the vegetation changes abruptly from scrub to grass or silver birch. Cavernously weathering Bourdeau Beds are exposed below the Chambotte Limestone in Pugieu gorge, seen in the foreground.

The Bourdeau Beds are represented in the two synclines of the area mapped by the present author, namely the Rossillon-Belley syncline and the Crapéou-Izieu "synclinal" fault zone (map 2). Parts of the formation are well-exposed along the roads from Belley to St.Germain-les Paroisses and from Arbignieu to Colomieu. The upper part of the Bourdeau Beds is well-displayed in the cliffs of Pugieu gorge (plate 30). Here the formation weathers cavernously below a protective capping of Chambotte Limestone.

B. PETROGRAPHY.

The basal 6m. of the Bourdeau Beds, in the area mapped consist of an alternation of orange pellet limestones and deeply iron-stained marls. The beds of limestone are from 65-100cm. thick. Their upper surfaces are characteristically covered with *Ostrea* valves. The uppermost bed of the unit appears also to have been bored by nerineids. These gastropods are found with their apices consistently facing upwards and with their bases embedded in the pellet limestone. In thin section the pellet limestones are seen to contain rare miliolids and skeletal fragments. These and the arenite-size pellets are cemented by coarsely-crystalline calcite. As in the Middle Parves Beds, the pellets have a superficial varnish of iron-oxide.

The ferruginous marls, which alternate with the pellet limestones are generally about 25 cm. thick. They have yielded nerineids and abundant *Pseudocyclammina lituus*, making

the analogy with the Middle Parves Beds even closer.

The main part of the Bourdeau Beds (about 55m.thick) consists of mixed bioclastic and pellet limestone, and of oolite. Subsidiary bands of marl are also found. Glauconite occurs, generally in accessory quantities, throughout this part of the Bourdeau Beds.

The bioclastic and pellet limestones usually occur in cross-bedded units, 1-2m. thick, with foresets 10-15cm. thick. In thin section the skeletal debris is seen to be heavily iron-stained. For example, iron-oxide commonly fills the canals of polyzoan and echinoderm fragments. This ferruginous material may well be an alteration product of glauconite, which is also found in the canal systems of the skeletal debris present. Many of the bioclastic fragments have been encrusted by polyzoa, and have the appearance of small pisoliths. The pellets have a superficial varnish of iron-oxide, which seems to have inhibited the growth of poly-crystalline cement from their surfaces. Most of the cementation calcite appears to have grown out in the form of overgrowths from the monocrystalline echinoderm fragments present. Due to the relative abundance of these fragments, overgrowths were not able to attain great sizes.

The oolite, and some of the bioclastic calcarenites occur in nodular beds, generally ½-1½m. thick. The nodules, which are well-cemented and partially silicified, are usually in the form of compressed spheres, measuring about 10cm. by 15cm. These are set in a groundmass of poorly-cemented,

crumbly oolite and skeletal debris. The nodular bands are generally over- and under-lain by bands of marl. It is considered likely that these nodular units were formerly cross-bedded, and that the nodules were formed by differential cementation and silicification during diagenesis. The relatively impermeable marls above and below each band, could have played an active role in confining siliceous solutions to the beds which are now nodular.

Silicification is generally only partial in the nodular limestones. However, some almost pure cherts have been found. Except for specks of green glauconite, these cherts are quite white and appear in great contrast to the associated ferruginous beds. The white chert nodules have a high porosity, which was probably brought about by the solution of unsilicified residual carbonate. Such a mechanism of leaching would also explain the lack of iron-oxide in these cherts.

C. STRATIGRAPHICAL AGE.

The fauna collected from the Bourdeau Beds is as follows:-

Lamellaerhynchia hauteriviensis Burri

Pseudocyclammina lituus (Yokohama)

Miliolidae

Leopoldia (?) sp.

Nerinea sp.

Astarte transversa (Leymerie)

Gervillia alaeformis (J.Sowerby)

Ostrea sp.

Pholadomya gigantea (J.de C.Sowerby)

Trigonia carinata (Agassiz)

T. longa Agassiz.

"*Venus*" (*Flaventia*?) *clupiniana* d'Orbigny.

The Bourdeau Beds have yielded only one ammonite, which is a poorly-preserved specimen resembling, according to Dr.Casey, the Hauterivian form, *Leopoldia*. The additional presence of *Lamellaerhynchia hauteriviensis* confirms a Hauterivian age for the Bourdeau Beds (*teste* Burri, 1956, who attributed this rhynchonellid to the *radiatus* Zone of the basal Hauterivian). In addition to having a Hauterivian age, the Bourdeau Beds lithologically resemble the marls, bioclastics and oolites of Hauterive, the type locality of this stage. Although unproven, the Barremian stage may also be partly represented in the Bourdeau Beds.

D. FAUNAL EVIDENCE OF PALAEO-ENVIRONMENT.

The fauna of the Bourdeau Beds suggests a number of different environments of deposition. This is also indicated by the great vertical variability of lithology through the formation.

The *Ostrea*-covered surfaces (one also with nerineid borings) in the basal pellet limestones of the Bourdeau Beds are typical "hard grounds", indicative of periods of erosion and re-working.

Lamellaerhynchia tends to occur in the bioclastic calcarenite of the Bourdeau Beds. It is a rhynchonellid with a strengthened pedicle opening, like *Rhactorhynchia* of

the Ambléon Limestone and Septaliphoria of the Bedded Virieu Limestone. Lamellaerhynchia probably indicates a shallow, rough-water environment. This is also suggested by the cross-bedded host sediment, which consists predominantly of skeletal debris. No doubt this debris was derived from organisms with more fragile shells than Lamellaerhynchia.

The nodular oolites have not yielded any unbroken fauna. The oolites seem to have been deposited in a higher energy environment than the bioclastic calcarenites. This deduction has already been made from a similar suite of rocks in the Ambléon Limestone (chapter 5).

Certain bands of marly calcarenite in the Bourdeau Beds contain a relatively well-preserved fauna of thin-shelled, burrowing lamellibranchs (Astarte, Gervillia, Pholadomya, Trigonia & "Venus"). These indicate a relatively low-energy environment, as Arkell (1933) inferred, when he pointed out that this type of assemblage tends to occur away from reefs.

E. SUMMARY OF GEOLOGICAL HISTORY.

The sediments and fauna of the Bourdeau Beds indicate an alternation between periods of deposition and periods of re-working and erosion.

Deposition is considered to have taken place in shallow marine waters throughout. Only the energy of the environment is believed to have varied. Thus in Hauterivian

times the sea floor is thought to have been, on the average, close to the wave-base, that is at a depth of about 30m. (see fig.30). The alternations between phases of deposition and erosion are considered to reflect slight variations away from this mean depth.

CHAPTER 12.

THE CHAMBOTTE LIMESTONE.

A. GENERAL.

The Mesozoic succession of the area mapped is terminated by about 20m. of rather massively-bedded, pale pellet limestones and white calcilutites. These beds form the lower part of a thick formation of dazzling white limestones, named the Chambotte Limestone after the village of la Chambotte and the Gros Foug-Chambotte ridge (map 3). The formation is well-exposed in cuttings along the road, which climbs from the Rhône valley to the village of la Chambotte. Its full thickness (approximately 160m.) is seen in the Fier gorge through the Gros Foug-Chambotte ridge (plate 28), where the formation is overlain by glauconitic marls, attributed by French geologists to the "Gault".

The Chambotte Limestone is very pure and, in contrast to the underlying Bourdeau Beds, does not readily break down to form a soil. In consequence the formation stands out in prominent cliffs above the heavily forested Bourdeau Beds of the Chambotte ridge. In the area mapped by the writer, the base of the formation caps the Andert-Contrevoz platform (map 1). Here the Chambotte Limestone weathers to form extensive limestone pavements. These are interrupted by solution hollows, some of which are relatively large and deep and partially filled with marsh (plate 30). The grass-covered drumlins, which are scattered over the Andert-Contrevoz plat-

Plate 31.

PLATE 31.

Bedding plane covered with the cemented valves of *Exogyra*. Chambotte Limestone, Gevrin (Ain).

form (map 1) appear in great contrast to the adjacent limestone pavements, which support, at the most, a sparse vegetation of boxwood scrub (plate 30).

B. PETROGRAPHY.

The basal 12m. or so of the Chambotte Limestone consists of cross-bedded pellet limestones in massive units each about 3m. thick. The lower parts of these beds tend to be rather ferruginous and less resistant to weathering than the upper parts, which are quite white. This causes the basal Chambotte limestones to weather cavernously. The alternation between ferruginous and pure pellet limestone is believed to represent a gradual transition from the underlying, deeply iron-stained Bourdeau Beds. Master bedding planes between the basal cross-bedded pellet limestones are commonly covered with the cemented valves of Exogyra. These represent "hard grounds", similar to those found in the Bourdeau Beds.

The uppermost part of the Chambotte Limestone, exposed in the area mapped, consists predominantly of white calcilutite and subordinate pellet limestone. The calcilutites contain an abundant fauna of branching corals in position of growth. Bedding planes are commonly covered with valves of Exogyra (plate 31), as in the beds below. It is significant that the oysters over the "hard grounds" of the Chambotte Limestone are Exogyra, instead of Ostrea (as in the Bourdeau Beds), since Exogyra is commonly associated with reefs, which are represented in the Chambotte Limestone, but not in the Bourdeau

Beds. In thin section, the calcilutites are seen to be composed essentially of cryptocrystalline calcite. Small vug-infillings of coarsely-crystalline calcite are found within the host rock. These can nearly all be referred, from their shape, to originally aragonitic molluscan debris. The former cavities are commonly partially filled with an internal sediment of micro-crystalline calcite. The pellet limestones, found in the upper part of the Chambotte Limestone of the area mapped, are seen in thin section to contain occasional miliolids, textularids and rare molluscan skeletal debris. Composite calcite rhombs in these rocks indicate a diagenetic history complicated by phases of dolomitisation and dedolomitisation.

C. STRATIGRAPHICAL AGE.

The fauna collected from the Chambotte Limestone in the area mapped is as follows:-

Anthozoa

Miliolidae

Rotaliidae

Textularidae

Cucullaea forbesi (Pictet & Campiche)

Exogyra falco (Coquand)

E. latissima (Lamarck)

E. minos (Coquand)

According to Dr.Cox, *Cucullaea forbesi* is an Aptian form, and the *Exogyra* fauna of the Chambotte Limestone ranges

through the Neocomian and Aptian. Apart from these fossils, the fauna collected is not critical of stratigraphical age. The Chambotte Limestone overlies known Hauterivian (Bourdeau Beds) and, in the Fier gorge, underlies marls, attributed to the "Gault" (Lower Albian) by French workers. It seems likely therefore that the Chambotte Limestone represents most of the Barremian and Aptian. It is therefore significant that the formation has a reef facies, since massive reef limestones at about this stratigraphical level form the so-called "Urgonian" facies, which rims the convex margin of the Alps from its type locality at Orgon in Provence, to as far as Bulgaria.

D. FAUNAL EVIDENCE OF PALAEO-ENVIRONMENT.

The presence of numerous colonies of compound corals, apparently in position of growth suggests that the Chambotte Limestone was deposited in clear tropical waters at depths of less than 10m.. (fig.18).

The "hard grounds" of the Chambotte Limestone are covered predominantly with the cemented valves of Exogyra, but Cucullaea is also represented. Both these lamellibranchs are robust, thick-shelled forms. Jourdy (1924) made extensive investigations into the habitat of Exogyra and concluded that, in general, the benthonic organism favoured high-energy, shallow-water environments, which were also occupied by corals or rudistids.

The combined coral and mollusc fauna of the Chambotte Limestone thus appears to be a typical reef assemblage repre-

senting shallow- and rough-water conditions.

E. SUMMARY OF GEOLOGICAL HISTORY.

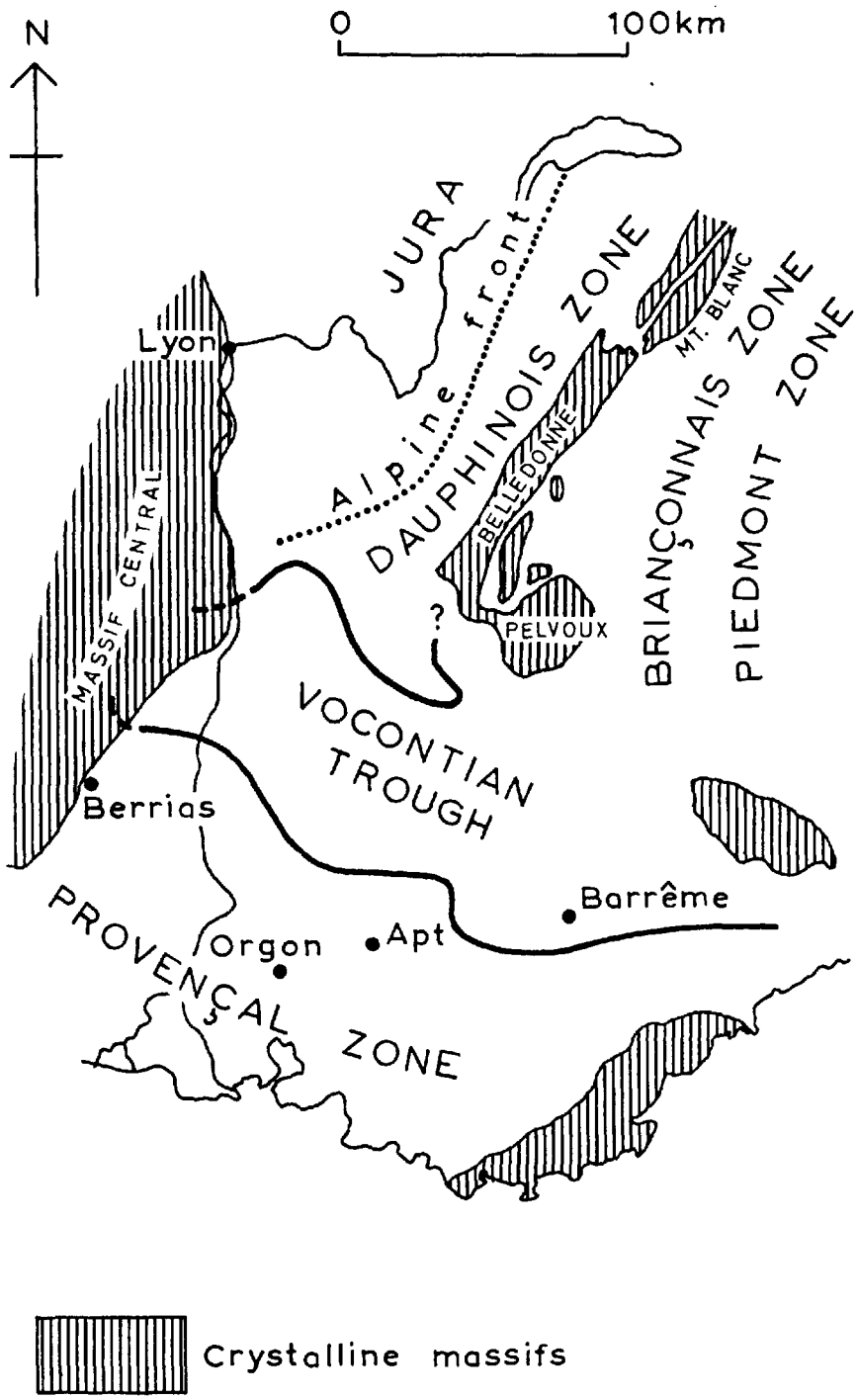
In Aptian, and probably also Barremian times, the third main reef complex of the Mesozoic succession of the area became established. The reefs of the Chambotte Limestone indicate a continuation of the shallow-water conditions, which had been prevalent since the growth of the Upper Virieu reefs. Unlike the reefs of the Ambléon and Massive Virieu Limestones, therefore, those of the Chambotte Limestone do not terminate a principal cycle of sedimentation (fig.30).

The Chambotte Limestone apparently belongs to the "Urgonian" facies, which is also represented in Provence, the Subalps, and along the convex border of the Alpine chain to as far as Bulgaria.

FIG.29

SEDIMENTARY DOMAINS OF THE MESOZOIC IN SOUTH-EASTERN FRANCE

modified after Gignoux, 1950.



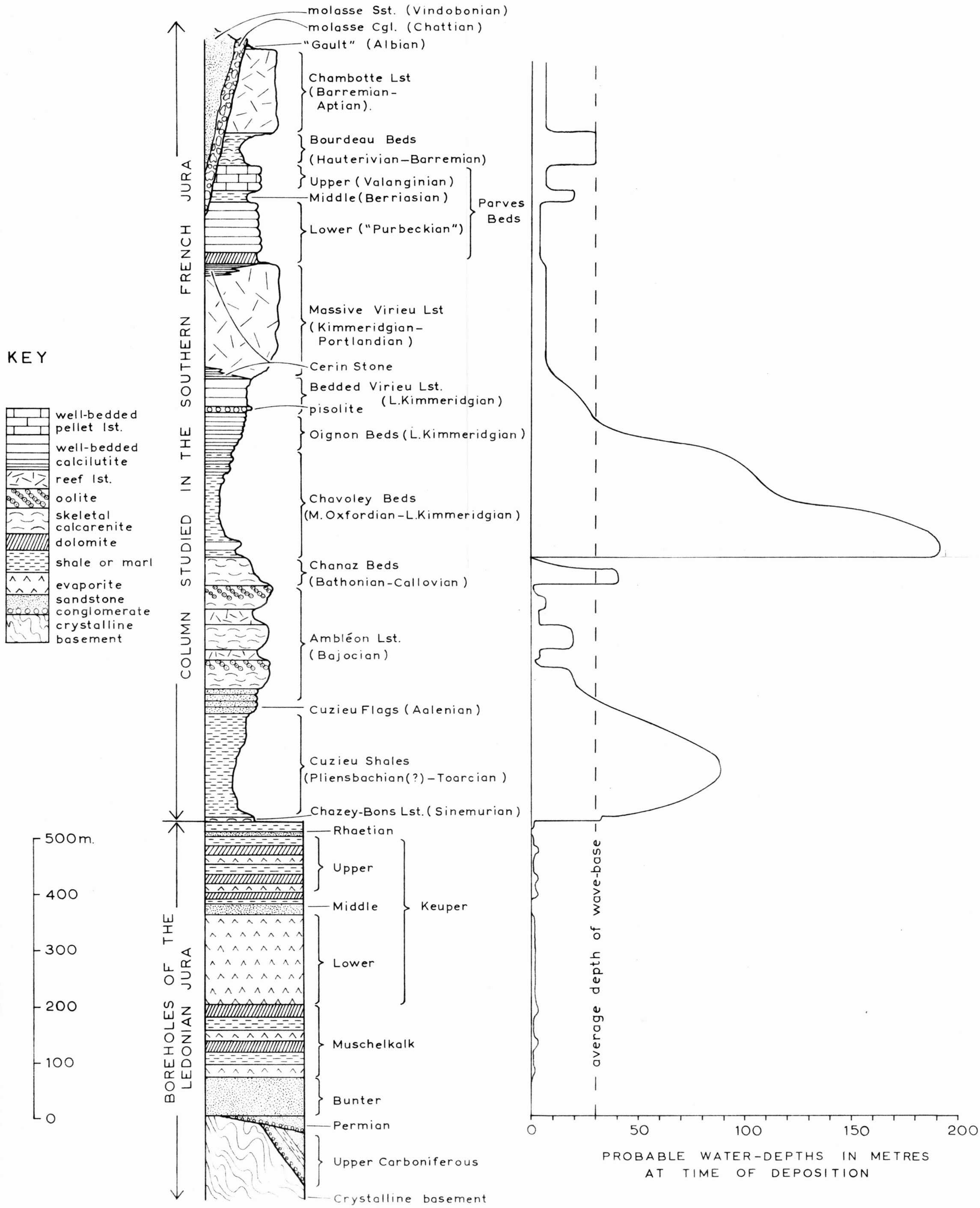
CHAPTER 13.

THE STRATIGRAPHY OF THE FRENCH JURA & SUBALPS COMPARED.

The Jura are separated from the Subalps, or Dauphinois zone by the frontal thrusts of the western French Alps (see fig.29). In turn, the Dauphinois zone is bounded to the east by the crystalline massifs of Mont Blanc, Belledonne and Pelvoux (fig.29).

In Permo-Carboniferous and Triassic times, conditions were much the same over the regions now occupied by the Jura and Subalps. The crystalline basement below both zones represents the main Variscan fold belt. Intermontane limnic coal basins formed during the Upper Carboniferous and were folded into tight synclines towards the end of the Variscan orogeny. The coal measures of these basins are unconformably overlain by Red Beds belonging to the Permian and Triassic. The Permian deposits overlap extensively onto the crystalline basement, whilst the Triassic, of typical German facies, is generally believed to have covered the Jura and Dauphinois zones entirely. Towards the eastern margin of the latter, however, the Triassic is of a "reduced" German facies having only about one-eighth its usual thickness. These thin deposits are generally considered to have been laid down over a ridge. This, the Vindelician ridge, is believed to have separated the shelf area of the Jura and Dauphinois zones from the geosyncline farther east comprising

CYCLIC SEDIMENTATION IN THE MESOZOIC OF THE FRENCH JURA



the Briançonnais and Piedmont zones of the internal French Alps (see fig.29). A similar distribution of facies is found in the Rhaetian. Limestones, of Swabian type, with Rhaetavicula contorta (Portlock) and numerous bone beds are found in the Jura and Dauphinois zones. These pass eastwards into beds with a coral/brachiopod fauna in addition to R.contorta, an assemblage typical of the Rhaetian in the internal Alps. Clearly marine conditions were more firmly established over these internal zones than over the external, foreland region. After the Variscan orogeny, but prior to the Jurassic, therefore, the Jura and Dauphinois zones formed an extensive shelf area. The Variscan fold belt was eroded during the Upper Carboniferous and Permian. Peneplaination was achieved in Triassic times and a marine transgression spread north-westwards across the former continent during the Rhaetian.

With the commencement of the Jurassic, the former foreland region of the Jura and Subalps became divided into two distinct sedimentary domains. The Jura continued to be a foreland zone, characterised by cyclic sedimentation in generally shallow seas (see fig.30). However, the Dauphinois zone subsided to form a geosyncline, which received a great accumulation of deep-water sediments.

In the French Jura, the shallow-water Gryphaea, or Chazey-Bons Limestone (Sinemurian) is followed by about 180m. of dark shale yielding a predominantly pelagic fauna of ammonites. In Bas-Bugey these belong to the Toarcian, but in

the Ledonian Jura the Pliensbachian is also represented. The total thickness of about 200m. for the Lias in the French Jura compares with a thickness of over 1000m. in the Subalps. The Subalpine Lias consists mainly of dark marl with some limestones in the lower part. It contains a rare fauna of ammonites preserved in pyrite.

The Middle Jurassic rocks of the southern French Jura begin with detrital quartz-bearing calcarenites, containing "Cancellophycus" (Cuzieu Flags). These pass upwards into a Bajocian sequence of strongly cross-bedded bioclastic calcarenites, oolites and limestones with in situ corals (Ambléon Limestone). The oolite and reef complex reflects the shallow-water conditions at the end of the first main cycle of Mesozoic sedimentation over the foreland zone (fig.30). The oolites (Upper Ambléon Limestone) pass south-eastwards into deeper-water shales (Lower Chanaz Beds). Still farther east, in the Dauphinois geocyncline, the Middle Jurassic consists of a relatively thin (approximately 100m.) development of dark marl, similar in facies to the underlying Lias of this zone. It appears therefore, that the first main cycle of Mesozoic sedimentation recognised over the southern Jura, is entirely unrepresented in the Subalps.

In the southern French Jura, a subsidiary cycle of sedimentation involving the Bathonian and Callovian (Middle and Upper Chanaz Beds) is believed to have been followed by emergence (see fig.30). Upper Callovian intraformational

breccias (Upper Chanaz Beds) are overlain by deep-water sponge limestones and marls of the Upper Oxfordian (Chavoley Beds), and the Lower Oxfordian is represented by a discontinuity. The Callovian and Oxfordian succession of the Subalps, some 500m. thick, appears to be complete. Sediments are essentially marly like the Lower and Middle Jurassic. They are followed upwards by fine-grained limestones and breccias (approximately 200m. thick) containing Calpionella, rare ammonites, and Pygope janitor Pictet. These limestones constitute the supposedly deep-water Tithonian facies of the Subalps. The Upper Jurassic sediments of the Dauphinois geosyncline all appear to have been deposited in deep water. In contrast, the shelf area of the southern Jura saw a complete cycle of sedimentation (fig.30), beginning with the deep-water Upper Oxfordian marls (Chavoley Beds) and terminating with the Kimmeridgian/Portlandian reefs (Massive Virieu Limestone), and back-reef deposits (?Bedded Virieu Limestone, Cerin Stone and Lower Parves Beds).

In Lower Cretaceous times, the deep-water geosynclinal zone migrated southwards and became established as the Vocontian trough between the Subalps and Provence (see fig.29). The marly sediments of this trough are rich in ammonites, and it is in this, and adjacent regions that the type localities for the Barremian and Aptian stages lie (fig.29). In the Subalps, the Lower Cretaceous is made up of a mixed "Jurassian" and "Vocontian" facies, that is of alternating shallow-water

limestones and deep-water marls. The "calcaires grossiers de Montagnole", the Berriasian of the Subalps, are believed to correspond in age and facies with the Middle Parves Beds of the Jura. They are therefore thought to be relatively shallow-water sediments. The Upper Parves Beds, with their coral horizon, appear to be similar in facies to the Lower Valanginian "Marbre Bâtard" of parts of the Subalps, and to the deeper-water Valanginian marls of other parts. The shallow-water, ferruginous Bourdeau Beds (the Hauterivian of the southern French Jura) are equivalent, in the main, to poorly fossiliferous Vocontian-type marls in the Subalps.

Above the Bourdeau Beds of the Jura comes the coral- and Exogyra-bearing Chambotte Limestone, some 160m. thick. This formation has a Barremian to Aptian age and is very similar to the massive "Urgonian" reef limestones, which occupy this level at Orgon in Provence. The same facies of the Barremian-Aptian occurs in the Subalpine ranges, in the Helvetics, and around the convex rim of the Alpine chain to as far as Bulgaria.

The cyclic sedimentation, which had characterised the Jura during the Jurassic, seems to have migrated into the Dauphinois zone in the Lower Cretaceous times. At the same time deposition over the Jura took place in consistently shallow water (fig.30). Thus there was a tendency for the Dauphinois zone to become a shelf region again in the Lower Cretaceous times, as it had been during the Triassic.

PART III

CAENOZOIC STRATIGRAPHY.

CHAPTER 14.

TERTIARY (MOLASSE) DEPOSITS.

A. GENERAL.

The molasse of the area mapped begins with a limestone conglomerate, mainly of local derivation. This is overlain by grey-green, micaceous sandstones with a more distant, Alpine provenance. The molasse deposits are found principally in the synclinal zones. For example, they form a wide outcrop in the central section of the Rossillon-Belley syncline. Here, and in the other broad synclines of the southern French Jura, the molasse is infolded with the Mesozoic succession. It is not known for certain whether these deposits were only laid down in the synclines, or whether they did formerly exist over the anticlines, prior to the later erosional history. Within the area mapped, the molasse is known to overlie all the Cretaceous formations, and in addition the uppermost Jurassic (Lower Parves Beds). The marked unconformity below the molasse, and the presence of a basal conglomerate of local origin suggests considerable uplift and erosion prior to its deposition. The evidence, therefore, indicates that at least the basal molasse conglomerates were only deposited in the synclines.

The molasse provides a fertile soil, which is cultivated for growing grain and vines. This is one of the reasons why the broad, molasse-bearing synclinal valleys are the sites of the principal settlements of the region, for example Belley,

Yenne and Seyssel (map 3). The change in vegetation and scenery from the molasse-bearing Rhône valley to the Mesozoic terrain of the Chambotte ridge, and back to the molasse of the Franco-Swiss Plain is illustrated in plate 2B.

The molasse and Quaternary deposits of the region are usually difficult to distinguish, since both are generally covered by thick developments of soil. All poorly-exposed material, unless known definitely to belong to the Tertiary has been mapped as "undifferentiated Caenozoic" sediment (see map 1).

Very little of the molasse-bearing part of the Rossillon-Belley syncline occurs in the area studied to the west of the Furan. Small exposures of the basal molasse conglomerate have been found over the Andert-Contrevoz platform, and near Peyzieu (map 1). Farther west, molasse gravels have been seen in the Crapéou-Izieu fault zone, but these exposures lie outside the region of detailed investigation.

B. PETROGRAPHY.

The most characteristic molasse deposits of the southern French Jura are the grey-green, cross-bedded micaceous sandstones. These are often seen to contain re-worked pebbles of partially lithified shale. The sandstones are poorly-cemented and break down readily to form a good soil, so that they tend only to be exposed in stream sections and road cuttings. They form the bulk of the molasse of the Belley syncline. However, in the area mapped, the

underlying basal limestone conglomerate is the more widely represented lithology of the molasse. These conglomerates are relatively well-cemented and quite resistant to erosion. Consequently they tend to be better exposed than the overlying micaceous sandstones. The conglomerates are found forming outliers over the Andert-Contrevoz platform, the north-westerly continuation of the Belley syncline (map 3). Exposures are to be seen along the road from Andert-Condon via Andert to Belley (map 1). Here the conglomerates are apparently unbedded. They are made up of relatively well-rounded boulders with an average size of 40cm. by 30cm. These are embedded in a matrix of gravel, which is quite well-cemented. The pebbles can generally be matched with the local Mesozoic succession, except for some rare angular fragments of red jasper. The Bourdeau Beds are well represented by pebbles of glauconitic, ferruginous bioclastic calcarenite. Pebbles of calcilutite and pellet limestone are also prominent, but no detritus attributable to the lower part of the Mesozoic succession (Cuzieu Beds to Bedded Virieu Limestone) has been found. The conglomerates lie over eroded Bourdeau Beds, whilst their outcrop is dominated from the east by cliffs exposing upper Bourdeau Beds and Chambotte Limestone. It is probable therefore that most of the pebbles were derived from these cliffs. There is no evidence of faulting in the Mesozoic succession here. It is hence believed that the limestone conglomerates were deposited in gullies, developed over the Andert-Contrevoz platform during a period of early Tertiary erosion.

Plate 32.

PLATE 32.

Limestone conglomerates of the basal molasse showing an alternation of large boulders, and finer-grained gravel. Peyzieu (Ain).

The boulder conglomerates near Andert are overlain by 4m. of relatively well-bedded limestone gravel and coarse-grained calcarenite. The gravel occurs in beds, about 20cm. thick, separated by calcarenite, disposed in more shaly bands, each approximately 5cm. thick. Rare shell fragments, regrettably unidentifiable, have been found in the gravels. This bedded sequence, above the boulder conglomerates, is overlain by a 1m. band of nodular limestone, made up almost entirely of tufa. The exposure is terminated upwards by a further 1-2m. of somewhat cross-bedded gravel, again containing rare shell fragments. The bedded gravels dip gently eastwards below the poorly-exposed molasse sandstones of Belley.

Limestone conglomerates, indistinguishable in composition from those seen near Andert, are exposed 800m. north-west of Peyzieu (map 1). These conglomerates occur in well-bedded units dipping at about 30° eastwards, apparently concordantly with the underlying Upper Parves Beds. The beds of conglomerate, each approximately 1m. thick, are usually graded. Boulders, measuring on the average 25cm. by 10cm. occur in the basal 75cm. or so of each bed. The upper parts to these beds are made up of cross-laminated gravel. In places, the graded beds are replaced by bedded alternations of conglomerate and gravel (see plate 32). Overlying the boulder conglomerates north-west of Peyzieu, come a series of rather ferruginous, cemented gravels lacking any large boulders. These beds are separated from the exposures of grey-green, cross-bedded micaceous sandstone north-east of Peyzieu (map 1) by 1½km.

of non-exposure.

Limestone conglomerates carrying boulders 50cm. or so in diameter have been found ½km. north-east of Peyzieu (map 1). These conglomerates are very poorly sorted, and pebbles of all sizes down to gravel are to be found. Most of the material is locally derived, but some small exotic pebbles of quartzite have been seen.

All the conglomerates in the area mapped, attributed to the basal molasse since they dip below the undoubted molasse sandstones of the Belley syncline, are well-cemented and of local origin. Quaternary gravels, which are also commonly well-cemented, are characteristically made up entirely of exotic pebbles of metamorphic and igneous rock. Conglomerates, made up principally of locally derived limestone pebbles, have been found lying on Oignon Beds in the Innimont syncline, 1km. north-east of Innimont village (map 2). Although these conglomerates were first thought to belong to the Quaternary, the possibility of a Tertiary age cannot be excluded.

C. STRATIGRAPHICAL AGE.

The molasse gravels of the area mapped have yielded broken shell debris, but no identifiable fossils. A few poorly-preserved Foraminifera were separated from the micaceous sandstones (which disaggregate readily). These were identified by Dr.Murray as probable Upper Cretaceous forms, and it seems likely that they were derived from a distant provenance, like the bulk of the cross-bedded host sediment.

Douxami (1898) appears to have been the only geologist to have published on the stratigraphy of the molasse in the Belley syncline. He described the section on the north-eastern border of the syncline, at Magnieu, outside the area mapped by the present author. Douxami found the molasse here to overlie an eroded "Valanginien" (Upper Parves Beds) surface, and to dip into the Belley syncline with approximately the same inclination as the underlying Mesozoic succession. Douxami reported the molasse at Magnieu to begin with a locally derived conglomerate, undoubtedly equivalent to the basal molasse described by the present author. On the 1/80,000 Chambéry sheet and in the accompanying "notice explicative" (1901), Douxami attributed these conglomerates to the "Chattien" (Oligocene). The basal conglomerates at Magnieu are, according to Douxami (1898), overlain by marly limestones with the marine "Burdigalien" species, Pecten praescabriusculus Fontannes. These could correlate with the limestone gravels containing shell debris, found in an equivalent position in the area mapped by the present writer. The molasse succession, described by Douxami, is terminated by sandstones with oyster debris, attributed to the "Vindobonien". These probably refer to the cross-bedded micaceous sandstones noted by the present author.

D. SUMMARY OF GEOLOGICAL HISTORY.

The basal molasse conglomerates in the area mapped have been found overlying the Mesozoic succession from the

Lower Parves Beds to the Chambotte Limestone. Possible molasse conglomerates also occur over the Oignon Beds near Innimont. The transgressive disposition of the conglomerates indicates that the Mesozoic terrain was extensively eroded prior to, or during the deposition of the basal molasse. The local origin of the pebbles here suggests further, that this period of erosion actually produced the debris now incorporated in the conglomerates. In order to have yielded pebbles of boulder size, a considerable gravity gradient must have been established between the zones of provenance and deposition. It is considered likely that this was accomplished during an early phase of Tertiary deformation when, it is believed, the Mesozoic terrain was folded into a series of embryonic anticlinal ridges and synclinal depressions. Streams running off the flanks of the anticlines, could have swept large boulders of the local Mesozoic succession down into the synclinal valleys. Larger rivers, moving down the axes of these synclines, like the present day Rhône between Colombier and Chambotte, would have carried pebbles from more distant sources. This could account for the presence of the exotic debris mixed in with the locally derived material in some of the basal molasse conglomerates of the area (for example, those seen to the north-east of Peyzieu).

The sediments of the molasse in the area mapped all appear from their petrography to be typically fluviatile. However, Douxami (1898) found several marine organisms in these deposits. This apparently paradoxical situation is in

fact general for the molasse sediments of the eastern Jura and the Franco-Swiss Plain. The principal environment of deposition was one of fluviatile sedimentation. Occasionally the sea invaded the region, when the rivers deposited their load into waters supporting a marine fauna.

Plate 33.

PLATE 33.

Grass-covered drumlin, Andert-Condon (Ain).

CHAPTER 15.

QUATERNARY DEPOSITS.

A. GENERAL.

Much of the area investigated is covered by Pleistocene moraine and outwash gravel, and Recent alluvium. The majority of what has been mapped as undifferentiated Caenozoic terrain (p.275 & map 1) is probably Quaternary.

Drumlin-like features, such as that shown in plate 33, are common locally. The distribution of these mounds is shown on map 1, from which it can be seen that they are restricted to the low-lying ground of the Rossillon-Belley syncline. The drumlins, and moraine in general, characteristically support a vegetation of grass or silver birch, and appear in great contrast to the surrounding scrub-covered limestone pavements of the Andert-Contrevoz platform (plate 30). The internal composition of only one of the drumlins, in the area mapped, is exposed. This feature occurs to the west of the road from Peyrieu to Brégnier-Cordon (map 1). The drumlin, which lies on Upper Parves Beds, is made up of large blocks of Oignon Beds (measuring 3-4m. across), embedded in a finer-grained boulder clay. The blocks of Oignon Beds were probably not far derived, and could well have come from the cliffs of Mont Tournier, which dominate the locality from the east (map 2). The drumlins of the area are commonly the sites of Chateaux (for example, those of Andert and Peyrieu), since

they afford good vantage points over the surrounding countryside.

Uncemented, pre-Recent river gravel is well-exposed in workings, ½km. north of Contrevoz. The gravels are made up of pebbles of metamorphic and igneous rock, probably of Alpine origin. Their composition thus differs markedly from the lithified conglomerates at the base of the molasse succession. The Quaternary gravels are cross-bedded on a grand scale, and probably represent deposition on the slip-off slope to the embankment of a large river. The foresets dip south, so that such a river would have flowed either in an east-west or west-east direction. It is suggested in chapter 16 that the Rhône once flowed from east to west via the Ambérieu-Culoz cluse (see fig.8). The river gravels, found to the north of Contrevoz, could well have been deposited from such a pre-Recent Rhône. Similar river gravels, exposed 1½km. farther north-west, are being eroded by the present day river Furan, which is here involved in a waterfall. These gravels are relatively well-cemented, no doubt by the waters of the Furan. All the streams in the area are heavily charged with calcium carbonate, and waterfalls such as that of the Furan, have spectacular aprons of tufa behind them.

The screes of the area, which have been mapped as a separate lithological entity (map 1), are all made up of locally derived, angular fragments of limestone. These fragments are generally 5-10cm. in length, but locally large

fallen blocks also occur, for example in the cluse above Rossillon, and in the north face of Mt.d'Izieu. Very little scree is forming at the present day. The scree slopes are generally somewhat vegetated; they are inclined at about 30°, which is less than the angle of rest. Consequently they are more stable, and less treacherous than the screes of the Alps, which are developing at the present time. No doubt the screes of the southern French Jura formed in the periglacial period which followed the retreat of the last glaciers from the region. Particularly extensive screes are found in the Ambérieu-Culoz cluse (plate 41). Those on the north side of this valley are commonly cultivated for growing vines. Due to a combination of the position and slope of these screes, the vines here receive more than the usual amount of sunlight.

Large erratic blocks of dark green mica schist have been found, both over the low and high ground of the area, for example on the Andert-Contrevoz platform east of the Furan, and above the 1000m. contour near the cross of Innimont. Some of these blocks measure 4-5m. long. They were clearly carried from the Alps by glaciers.

Marshy ground is widespread in the region. It tends to occur where the relatively impermeable marls of the Mesozoic succession crop out, and over boulder clay, that is where the water-table is high. Most of the lakes in the area appear to have a similar origin. They support a fresh-water fauna of numerous fish. Lac d'Armaille (Frontispiece) has also yielded

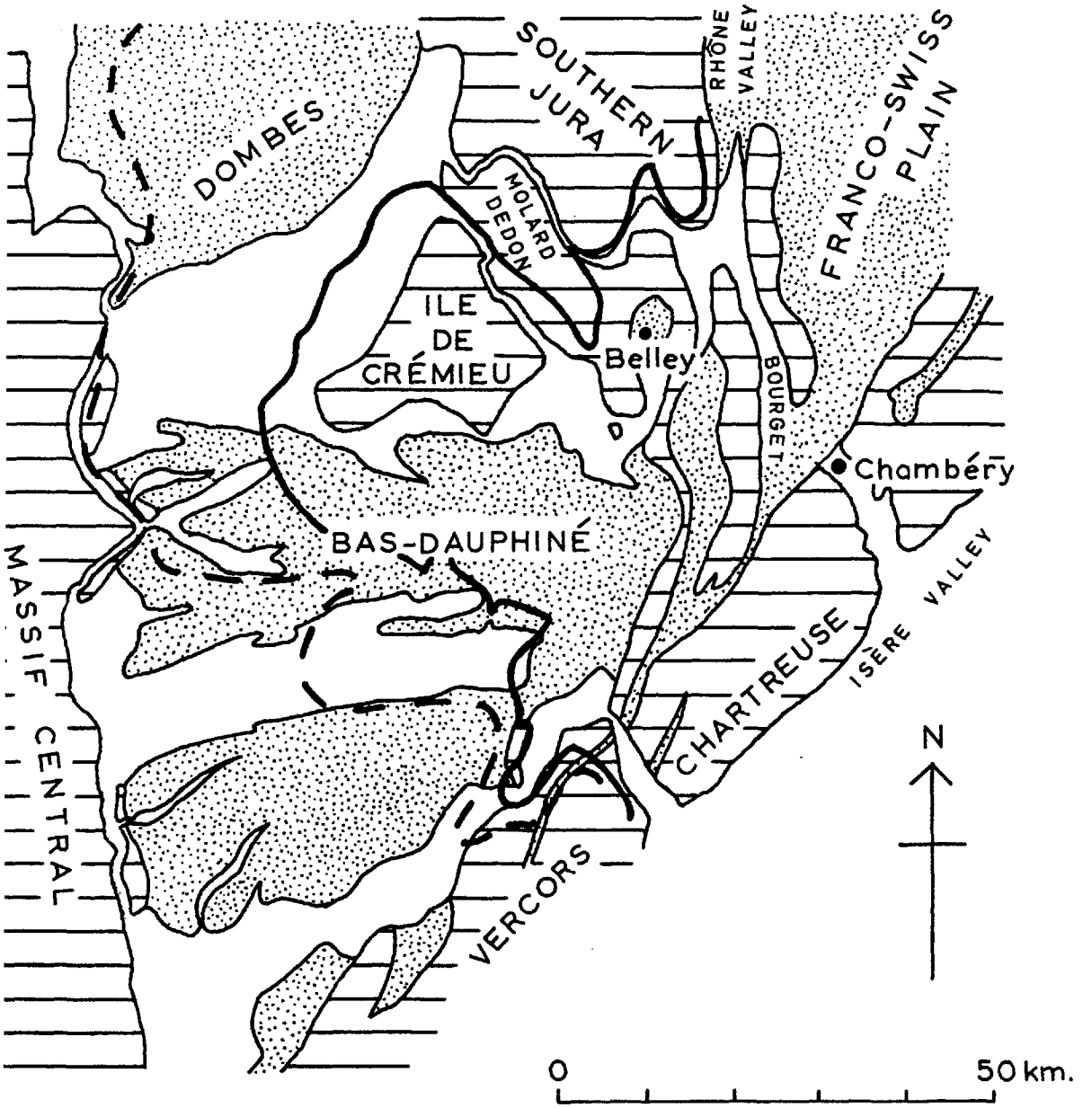
various molluscs including Anodonta cygnea (Linné) and Lymnaea stagnalis (Linné). The two principal marshes of Bas-Bugey are those of Pugieu (covering about 1½ sq.km.) and Lavours (more than 15 sq.km. in extent). These occur respectively at the feet of the Grande Montagne de Virieu and the Grand Colombier (map 3 and plate 40, F/8 & E/11-12), along the northern margin of Bas-Bugey. They probably overlie boulder clay. On a smaller scale, there is a good deal of marsh along the western border of the area mapped, between Ambléon and the Montagne d'Izieu. This corresponds with the western limit of Bas-Bugey. In this region, the steeply dipping beds of the Crapéou-Izieu fault zone and the western limb of the Ambléon-Prémeyzel anticline are planed off and grooved, presumably by ice. No doubt the marsh here overlies boulder clay deposited from the glaciers, which eroded the area. Marshy ground and small residual lakes occur along the length of the Ambérieu-Culoz cluse (plate 41). These probably overlie glacial or inter-glacial deposits.

Marsh also occurs in small depressed hollows over many of the limestone pavements in the area mapped. Plate 30 shows a typical hollow, developed in the Chambotte Limestone of the Andert-Contrevoz platform. This hole is about 200m. long, 70m. wide and 10m. deep. It supports a vegetation of marsh-grass growing in yellow-brown stagnant water. It appears that the limestone here has locally been dissolved

FIG.31

WESTERN LIMITS OF RISSIAN AND WÜRMIAN MORAINES

modified after Gignoux, 1960



Palaeozoic & Mesozoic — Tertiary — Quaternary

Rissian — Würmian

away and the resulting hollow has reached the water-table. No doubt solution was aided by the humic acids, derived from the decaying vegetation in the stagnant waters.

B. SUMMARY OF GEOLOGICAL HISTORY.

The Quaternary deposits indicate that Pleistocene glaciers passed over the entire region. There is also evidence that a river, of considerably greater force and magnitude than those found today, flowed through the Ambérieu-Culoz cluse during the Quaternary.

Only the last two of the four Alpine glacial advances are represented in the Jura. During the Rissian, the Rhône glacier spread from the Alps, across the Franco-Swiss molasse plain, and impinged upon the eastern limestone wall of the Jura. Ice from the Isère glacier joined that from the Rhône via the Chambéry cluse and lac du Bourget (fig.31). Together these glaciers spread from east to west across the high ranges of the Jura and reached the low-lying plains of Bresse, Dombes and Bas-Dauphiné beyond (fig.31). After the retreat of the Rissian ice sheets came the Würmian re-advance of the Rhône glacier. In the Central Jura, this ice sheet scarcely rose above the eastern scarp of the Jura. It certainly did not pass over the Range, like the earlier Rissian glaciers. The Würmian ice sheets did, however, penetrate deeply into the southern French Jura and, according to Gignoux (1960), only the highest part of the Molard Dedon Range escaped this glaciation (see fig.31). It is likely

therefore, that the large erratics of green mica schist, found above the 1000m. contour near the cross of Innimont, belong to the Rissian glaciation.

The river gravels exposed in workings north of Contrevoz are overlain by poorly-exposed morainic material, which gives rise to an undulose topography with several sink holes (map 1). The moraine was probably deposited by the Würmian glaciers, which would indicate that the underlying gravels belong to the Riss-Würm inter-glacial period. This is also the opinion of Gignoux (1914).

PART IV

GEOMORPHOLOGY & GEOLOGICAL STRUCTURE.

CHAPTER 16.

GEOMORPHOLOGY & GEOLOGICAL STRUCTURE OF THE SOUTHERN FRENCH JURA.

A. DESCRIPTION.

The division of the southern French Jura, into three structural and four geomorphological units, has been discussed by way of an introduction in chapter 1 (see fig.8). The structure of each geomorphological element of the region will now be analysed in greater detail.

(i) Ile de Crémieu.

This triangular region, on average 300m. high, is a southern outpost of the Tabular Jura. It derives its name from the fact that it is almost entirely surrounded by water. The Rhône flows around its north-eastern border. Its southern margin overlooks the numerous lakes and marshes, which cover the molasse terrain of Bas-Dauphiné, while the north-western escarpment dominates the combined flood plains of the Rhône and Ain, and in the distance the lakes of Dombes.

In the extreme south-west of the Ile de Crémieu, a small outcrop of the Massif Central crystalline basement is found. This is believed by French geologists to be in faulted contact with the Lias of the south-easterly dipping Mesozoic succession. The rocks of the Ile de Crémieu are cut by numerous faults and its north-western edge is a prominent scarp (fig.7C). Due to the gentle dip-slope developed over the Jurassic sequence (Lias-"Purbeckian"), the Ile de Crémieu

appears as a tilted plateau, with altitude gradually diminishing away from the cliffs of the terminal fault scarp in the north-west.

(ii) Molard Dedon Range.

This range, a part of Haut-Bugey, is a general upland area (on average 800m. high), extending eastwards from the western scarp of the Folded Jura (fig.8). It terminates with the sudden fall in topography, immediately east of the Montagnes de St.Benoît and Tantainet, and the summit of the Molard Dedon (map 2). The structural units of the Molard Dedon Range, taken from west to east, are as follows:-

(a) Mareraie anticline.

This structure is greatly faulted. Evidence that it is an anticline comes from the disposition and distribution of outcrops in the Bois de la Mareraie (map 3). The anticline, which strikes north-west/south-east, plunges below the Rhône alluvium just west of Groslée. Its structural contact with the Tabular Jura, though likely to be a thrust fault, is unexposed.

(b) Lhuis-Groslée syncline and fault zone.

At the southern extremity of this syncline, just north of Groslée, molasse deposits exist (map 3). From Groslée to Lhuis the structure is apparently unfaulted. Farther north-west the two flanking anticlines are tightly bunched together, being separated only by a zone of faults.

(c) Tantainet-St.Benoît anticline.

Over much of its length, this anticline has two

axial planes, and is the most westerly of the recognisable "box-folds" of the southern French Jura. It plunges south-eastwards below the Rhône alluvium just north of St.Genix. This is the point where the Rhône, having flowed in a general south-westerly direction from Geneva, abruptly turns north-westwards.

Over its southern part, in the Montagne de St. Benoît, the anticline was found by Murray (unpublished manuscript) to be very asymmetrical. Where exposed, the western limb is vertical or slightly overturned, whereas the eastern limb dips gently at only 20° or less (see enclosure 4, section III). South of Glandieu, only the flat crest and gentle eastern flank of the anticline are seen (sections I and II). The western limb is believed to have been eroded away by a branch of the Würmian glaciers. Stavrinou suggested that a transverse fault exists through the valley of lac de Pluvis, displacing the axis of the anticline to the west (maps 2 & 3) before the whole structure plunges out of sight.

Farther north, in the Montagne de Tantainet, both limbs tend to the vertical, and a fold fault runs along the eastern axial plane. Murray (op. cit) found that, where exposed at depth, the western limb of the anticline is less steep than the eastern flank. This change in the anticline's shape with depth is an example of the disharmonic folding prevalent in the region.

Plate 34.

PLATE 34.

The south-easterly plunge of the box fold in the Montagne d'Izieu, viewed from the Mt.de Parves to the north-east. In the foreground on the right is the fertile molasse terrain of Belley, and on the left the flood plain of the Rhône.

(d) Crapéou-Izieu fault zone.

The Tantainet-St.Benoît anticline is separated from the next anticline to the east by a shatter zone, in places involving at least three major strike dislocations. These are generally high-angled reversed faults (see enclosure 4, sections I-VI). Two of the faults in the Izieu region have been found to meet lower down in the exposed structure. This interesting occurrence is described in greater detail in chapter 17. It is likely that all the dislocations of the Crapéou-Izieu shatter belt pass into a single fault at depth.

The complexity of the shatter zone is shown up in exposures between Crapéou and Conzieu where slither after slither of different lithological formations occur together in a narrow band between two major dislocations. West of Crapéou, steeply dipping molasse gravels have been found in the fault zone.

(e) Ordonnaz-Ambléon-Prémeyzel anticline.

This structure has been studied in detail by the author. As shown on map 2 its northern part lies over high ground (c.900m) in the Molard Dedon Range. The central section passes through Bas-Bugey at approximately 350m. Farther south the anticline regains some of its former altitude in the Montagne d'Izieu (700m), a part of the Molard Dedon Range and Haut-Bugey. A south-easterly plunge to the anticline south of Prémeyzel, however, causes all this increased altitude in the Montagne d'Izieu to be lost once more within four kilometres, as the anticline disappears beneath the Rhône alluvium (see plate 34).

In the Montagne d'Izieu, the anticline is a typical "box-fold" with two axial planes (enclosure 4 section II). Both eastern and western limbs are steep and in places

Plate 35. A & B.

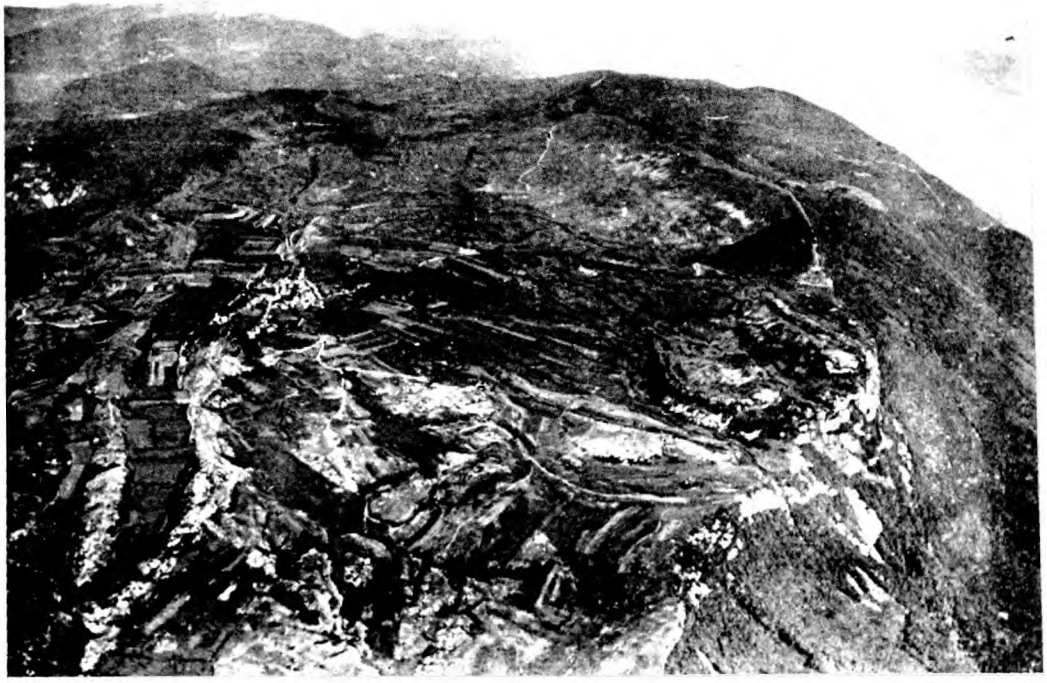
PLATE 35. A & B.

A. The Montagne d'Izieu viewed from Mt.Tournier to the south. The double-cliff feature of the Parves Beds can be seen on the left. The sharp monoclinal flexure of the eastern flank of the Ambléon-Prémeyzel anticline, follows the line of shadow north of the Rhône. In the distance are the northern & western walls of Bas-Bugey.

B. Close-up of steeply dipping Lower Parves Beds belonging to the eastern flank of the Ambléon-Prémeyzel boxfold. This exposure lies to the left of the Rhône & the road in plate 35A.

Plate 36.

PLATE 36.



Oblique air photograph of the Molard Dedon from the south (after Cholley, 1932). In the foreground are the bare limestone pavements of the Oignon Beds over the Innimont Plateau. On the left is the subsidiary Innimont anticline. On the right are the cliffs of Innimont & the Molard Dedon-Colomieu anticline. In the central distance is the Innimont syncline, the northern continuation of the Innimont plateau, & the roof to the main Ambléon-Prémeyzel boxfold.

slightly overturned. The roof to the boxfold is tilted gently to the north-east. The "box" appearance of the anticline is maintained throughout the south-easterly plunge of the structure (section I). Mont Tournier, which dominates the Montagne d'Izieu from the south-east (map 2), is a good point for viewing the plunging roof and steep eastern limb of the Ordonnaz-Ambléon-Prémeyzel anticline (plate 35A). The steep eastern limb is represented on the photograph by a dark line of shadow, running along the foot of the Montagne d'Izieu. The road, which can be seen alongside the Rhône passes by steeply dipping Lower Parves Beds. A close-up of these is shown in plate 35B.

The amplitude of the main Ambléon-Prémeyzel anticline, as seen in the Montagne d'Izieu and near Prémeyzel (sections I-III), is abruptly reduced by about ½km. north of St.Bois (section IV). This is brought about by two main transverse faults between St.Bois and Peyzieu (maps 1 & 2). The structure of the St.Bois shatter zone is described in chapter 17.

Subsidiary anticlines arise on each flank of the main fold farther north (map 2 & sections V-X). Near Innimont, structure contours on the Oignon Beds over each subsidiary anticline are higher than those over the roof of the main boxfold (sections VIII-X). Here, therefore, the roof is synclinally disposed between the two subsidiary flanking anticlines, as illustrated in plate 36. This example of the

Plate 37.

PLATE 37.

The Molard Dedon-Colomieu anticline viewed from Appregnin (Ain), to the south in Bas-Bugey. On the right is the Ambléon Limestone escarpment belonging to the eastern flank of the fold. The anticlinal structure is apparent from bedding features seen in the centre of the field of view. On the left are the cliffs of Innimont. Here the eastern monocline of the Ambléon-Prémeyzel boxfold is in faulted contact with the western limb of the Molard Dedon-Colomieu anticline.

Plate 38

AIR PHOTOGRAPH OF THE MOLARD DEDON–COLOMIEU ANTICLINE

by kind permission of the Institut Géographique National de France

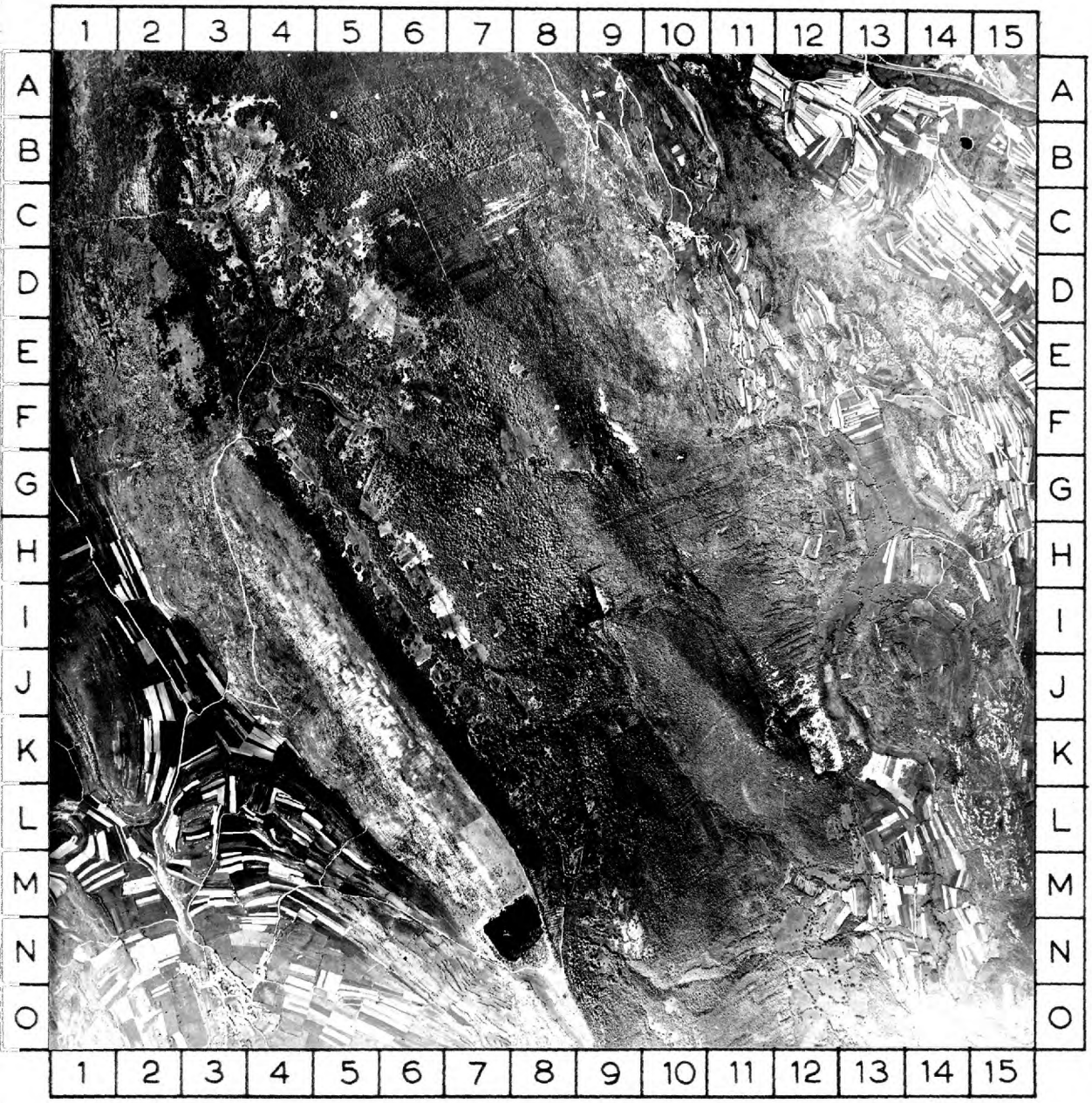


PLATE 38

development of two anticlines from the limbs of a single fold (shown diagrammatically in fig.2) affords a possible mechanism for the observed increase in the number of anticlines northwards into the Central Jura. The development of subsidiary anticlines could be a reflection of the thinning of the Massive Virieu Limestone to the north-west (chapter 9). Certainly this unit is more competent in the south of the area mapped (sections I & II) than in the north, where it is involved in a minor fold (see section X and chapter 17).

The eastern subsidiary anticline (the Molard Dedon-Colomieu fold on map 2) arises just south of Colomieu (section V). In Bas-Bugey it is separated from the main structure by a syncline, named after lac d'Arborias, under which it passes (map 2). The syncline tightens north-westwards and passes into a minor reversed fault in the cliffs below the cross of Innimont (section VIII & plate 37). This interpretation conflicts with that of Riche (1898 & 1910), who considered a normal fault along the Arborias valley to pass into a syncline in the cliffs of Innimont. The eastern subsidiary anticline develops a north-westerly plunge just north of the summit of the Molard Dedon (map 1). This is clearly observable in the air photograph shown in plate 38. The form of the fold is particularly well-seen in the north face of the cluse above la Burbanche (plate 41). Here it has a steep western and gentle eastern limb. A few kilometres north-west of the cluse the fold plunges out altogether (map 2). Near Préveysieu the Molard Dedon-Colomieu anticline exhibits much

disharmonic folding. Minor flexures are developed in the Parves Beds and in the Bedded Virieu Limestone/Oignon Beds, respectively above and below the relatively competent Massive Virieu Limestone (map 2). These minor folds are discussed more fully in chapter 17.

In the south of the area mapped, the formation seen on the eastern limb of the Ordonnaz-Ambléon-Prémeyzel anticline are also represented on the western flank (sections I & II). In this region, the Crapéou-Izieu fault zone is no more than a narrow faulted syncline. Farther north, however, as lower parts of the structure become exposed, much of the western flank is seen to be faulted out (sections III-VI), and the contact with the adjacent anticline to the west is via a genuine shatter belt. Apart from this, the Ordonnaz-Ambléon-Prémeyzel anticline is affected only by minor faults (see chapter 17).

(iii) Bas-Bugey.

Bas-Bugey is the lowland region centred on Belley. Topography ranges in altitude predominantly between 250m. and 350m. The boundaries of Bas-Bugey cut across the structural trend of the southern French Jura. The only structural unit confined to the area is the Rossillon-Belley molasse-bearing syncline, which is described below. The structure of eastern Bas-Bugey is described in the section dealing with the Chain Jura, for, as it will be shown, there are structural affinities between the two regions. The geomorphology of Bas-Bugey as a whole is considered in some detail after its structure has

been analysed (see section B).

(a) Rossillon-Belley syncline.

The syncline widens from the strait between the Montagne d'Izieu and Mont Tournier in the extreme south, to measure 5km. across at the latitude of Belley (map 3). It is characterised in this widest part by poorly-exposed molasse deposits. These are horizontal where seen near Belley, but steeply dipping at both margins of the syncline. North-west of Belley, the syncline narrows again, becoming 3km. wide at Contrevoz. Mesozoic rocks emerge from beneath the molasse and form the Andert-Contrevoz platform, (plate 30). These rocks remain still much concealed by Quaternary deposits. Beyond Cheignieu-la Balme, the flanking anticlines are only ½km. apart. In the high ground of Haut-Bugey, above Rossillon, the syncline passes into a fault zone, in which molasse deposits were found by Taha. This shows that at least part of the deformation which affected the southern French Jura post-dated molasse deposition.

The western flank of the Rossillon-Belley syncline is unfaulted. In contrast, the eastern border, exposed between the Montagnes de Virieu and Parves, is a shatter zone incorporating the western flank of the adjacent anticline. The faults of this shatter zone near Chazey-Bons have a combined throw of at least 650m. bringing the Chazey-Bons Limestone (Sinemurian) into close proximity to the Bourdeau Beds (Hauterivian-L.Barremian). While unexposed further south,

Plate 39.

PLATE 39.

The roof & eastern monoclinal fold of the Sérémond "box"-anticline, and the western flank of the Valromey "box"-syncline viewed from Vellien (Ain) to the south. In the foreground is the quarried strike vale of the Chavoley Beds, south-east of Virieu-le Grand.

the fault zone is believed to continue at the foot of the Parves-Tournier ridge. A major dislocation must certainly exist at the foot of Mont Tournier, since this huge mass of limestone lies on top of the southerly plunging Ambléon-Prémeyzel anticline, south of the Rhône (maps 2 & 3).

(iv) Chain Jura.

The Chain Jura are represented along the entire concave border of the Jura facing the Alps. The zone was originally defined by Bertrand (1885), in a combined structural and geomorphological sense, as a region of anticlinal ridges and synclinal valleys. In the southern French Jura, some of the anticlines and synclines of the Chain Jura pass through the anomalous lowland area of Bas-Bugey. These folds are described here since, in the structural sense, they form part of the Chain Jura. The fact that they also partly belong to the geomorphological unit of Bas-Bugey is discussed later.

(a) Sérémond-Tournier anticline.

The Montagne de Sérémond, which dominates Virieu-le Grand from the north, displays the eastern monoclinal flexure, and part of the roof of a major "box"-anticline (plate 39). Minor contortions in the lower part of the structure illustrate the disharmonic folding, characteristic of the region. The complex system of faults, which separate the western steep limb of this "box-fold" from the Rossillon-Belley syncline is well exposed in the south face of the Grande

Montagne de Virieu.

North of Virieu-le Grand, a syncline develops in the roof of the "box-fold". This becomes four kilometres broad at Hauteville (map 3). The flanking anticlines rise from the limbs of the boxfold, seen at Virieu-le Grand. An example of this mechanism, whereby the number of anticlines increases northwards, has already been found in the Ordonnaz-Ambléon-Frémeyzel anticline farther west. Two further examples are indicated in Martin's interpretation of the French Survey maps of the Southern Jura (see fig.7C).

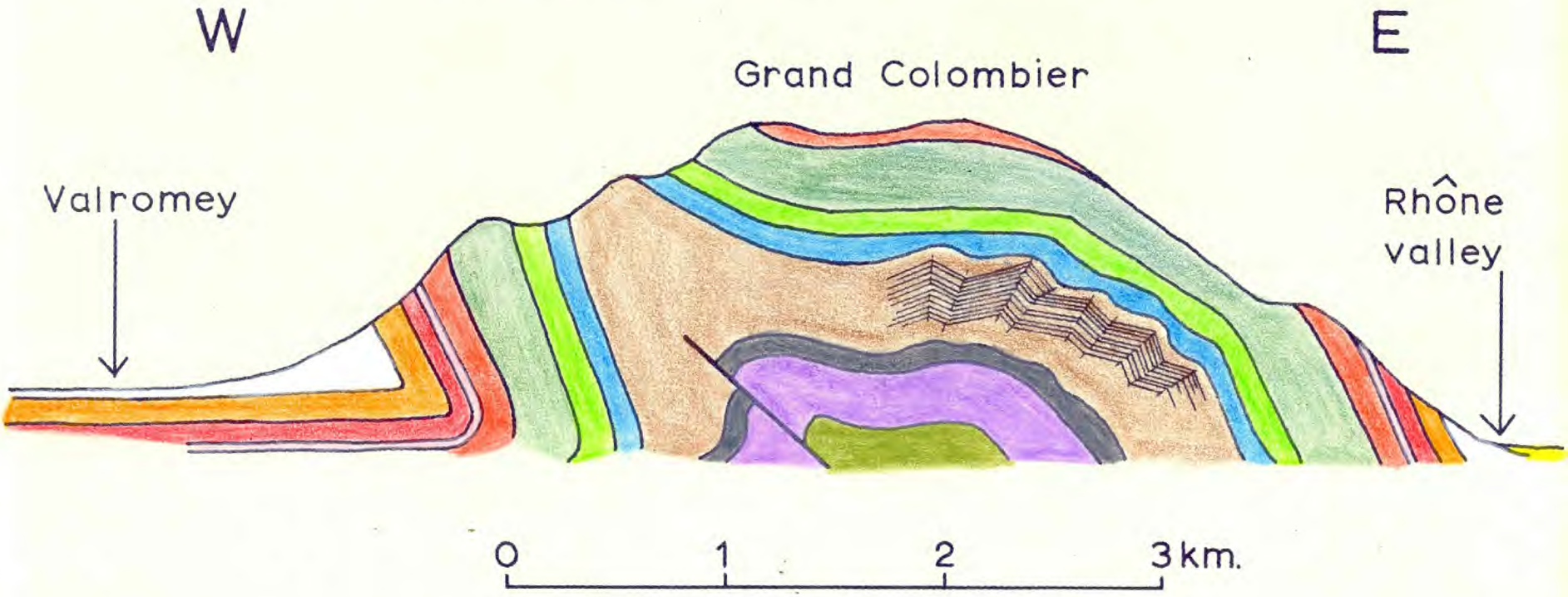
The "boxfold" of Sérémond strikes south-eastwards into the Mesozoic terrain of eastern Bas-Bugey. This consists of a succession of strata tilted at about 30° to the north-east, and separated from the Rossillon-Belley syncline by a shatter zone. The strike continues into the Montagne de Parves, which embodies a recumbent anticline, overturned to the west. Further south in the Tournier ridge, the overturned limb is unexposed, presumably having been covered by molasse and Rhône alluvium. In consequence all the Mesozoic strata dip gently to the east. Beyond Les Echelles, this anticline is the sole representative of the Jura Range. At Voreppe it abuts against the Chartreuse and Vercors Ranges of the Subalps.

(b) Valromey-Yenne-Novalaise syncline.

Perhaps the best example of a "box"-syncline in the southern French Jura is Valromey, situated between the well-displayed monocline, east of Sérémond (plate 39), and

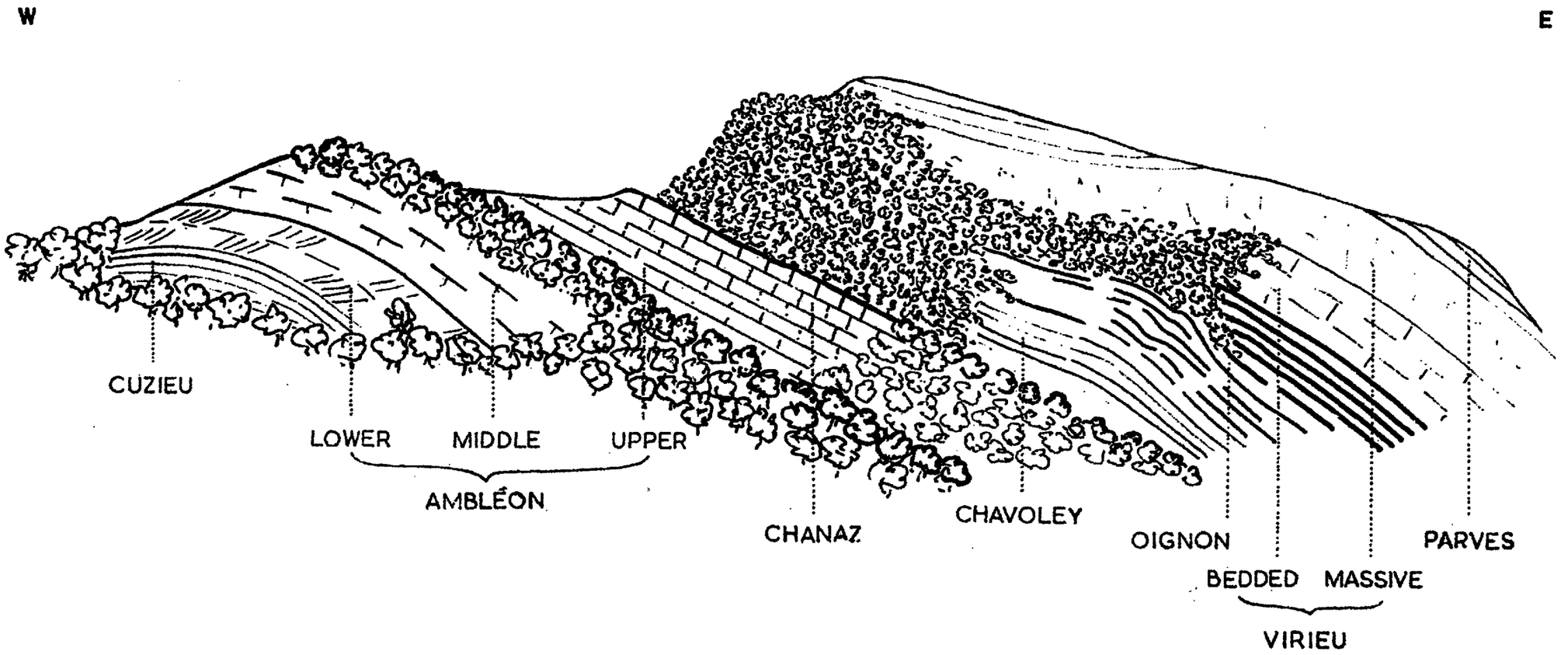
FIG. 32

SCHEMATIC SECTION THROUGH THE GRAND COLOMBIER NORTH OF CULOZ



Key to formations on Enclosure 4

FIG. 33



SKETCH INTERPRETATION OF THE SOUTH-EAST FACE OF THE GRAND COLOMBIER AS SEEN FROM JUST WEST OF CULOZ ON THE ROAD TO VIRIEU-LE-GRAND.

the less well-exposed monocline at the foot of the Grand Colombier (fig.32). Molasse deposits occur in this syncline, and are locally faulted against the Mesozoic succession.

The syncline of Valromey swings south-eastwards below the Marais de Lavours, diminishing in width to a mere 2km. between the Parves and Charvaz ridges (map 3). South of Yenne, the structure widens again to 5km., and molasse deposits become widespread. Révil (1896) showed the syncline near Novalaise to be strongly asymmetrical, with a steep eastern limb dipping off the Epine anticline, and a gentle western limb following the inclination of the Mesozoic succession of the Tournier ridge. Later (1913), he reported "Pontien" strata discordantly overlying the "Vindobonien" deposits, and dipping gently westwards in exposures north of Novalaise. This discovery accurately dated the period of folding, which affected both the Mesozoic and early Tertiary sediments of the region.

(c) Colombier-Chat-Epine anticline.

A natural cross-section through this anticline exists in the face of the Grand Colombier north of Culoz (map 3). The structure here, which is somewhat masked by vegetation, is illustrated schematically in fig.32. A more exact interpretation of the better exposed eastern part of the Grand Colombier is shown in fig.33. The ridge is a "box"-anticline capped by sub-horizontal Parves Beds. In the east, these beds flex over in a sharp monocline, which in a short distance brings them

down to the level of the Rhône valley. A subsidiary anticline, developed over the western axial plane of the structure, elevates the capping strata above the level of the "box"-roof. The western limb of the Colombier anticline is overturned.

South of Culoz, the Rhône leaves the synclinal valley it has followed from Bellegarde, 28km. to the north and, shunning the open path available via lac du Bourget (fig.4), turns east across the axes of the Colombier anticline. The isolated Mesozoic outcrops of Vions and Lavours are probably remnants of the anticline which have resisted erosion.

South of Vions the Mesozoic terrain rises again into the Montagne de la Charvaz and the Mont du Chat, in which only the eastern limb of the Colombier anticline is represented. Strike faults along the western border of these ridges are believed to have cut out the western limb of the anticline. The Lierre ridge, which runs parallel and to the west of the Montagne de la Charvaz embodies a subsidiary anticline (map 3), overturned to the west.

The Mont du Chat strikes southwards into the Montagne de l'Epine (map 3), in which truly anticlinal features are found. The structure is a symmetrical fold with a single axial plane (i.e. not a "box").

South of Culoz, the Colombier-Chat-Epine ridge has a characteristic cross section, appearing like an acute-angled triangle. The acute angle locally takes the form of impressive pinnacles, hewn out of the Massive Virieu Limestone, and

known as the "Dents du Chat" (plate 2A). The ridge has a general north-south disposition (map 3). Local variations in orientation, however, give rise to the curvature of the Charvaz-Chat ridge. These curves, and the general triangular shape of the ridge caused de Margerie (1936) to liken the Charvaz-Chat-Epine range to a "gigantic snake running from the foot of the Alps into the Jura". South of Les Echelles, the anticline disappears under the Subalpine frontal thrusts.

(d) Rhône valley - Lac du Bourget syncline.

From Bellegarde to Culoz, the Rhône follows the axis of a molasse-bearing syncline, which takes its name from the great river it carries. South of Culoz, the syncline passes under the Lac du Bourget. At the northern margin of the lake, the structure is divided for a short distance by a subsidiary anticline, overturned to the west.

Immediately north of Aix-les-Bains, the syncline is flanked by anticlines exposing Mesozoic rocks of shelf, or "Jurassian" facies. Here the syncline is apparently unfaulted and from 3 to 4km. broad, a width which has been maintained from Seyssel some 30 kms. farther north. South of the latitude of Chambéry, the width of the syncline rapidly diminishes to less than one kilometre across, in a distance of 10km. This narrowing is due to the westerly encroachment of the Subalps. The southern extremity of the syncline is overthrust from the east by Mesozoic rocks belonging to the Grande Chartreuse Range.

(e) Gros Foug-Chambotte anticline.

The Gros Foug-Chambotte ridge runs parallel and to the east of the Rhône valley and Lac du Bourget. It embodies an anticline stretching for 35kms. from Frangy southwards to Aix-les-Bains (map 3). At both these extremities, the fold is seen to plunge below the Tertiary deposits of the Franco-Swiss Plain. South of Aix-les-Bains the structure may be represented in the small anticline, which at the surface consists entirely of folded molasse deposits. However, a second small anticline, involving the Chambotte Limestone, is found a little farther east. Gidon (1950) suggested that both these subsidiary folds connect northwards with the main Gros Foug-Chambotte structure.

The main anticline is best seen 3km. south of Seyssel, where the Fier gorge cuts transversely across the ridge (plate 2B). Here the anticline is capped by the Lower Cretaceous succession (Parves Beds to Chambotte Limestone). At this level the anticline is "boxed", having a relatively flat roof, and steep flanking limbs. Below the Massive Virieu Limestone (also seen in plate 2B), the structure has only one axial plane. Certain of the incompetent members of the exposed succession in the Fier gorge have been intensely contorted as an expression of disharmonic folding.

Farther south, the anticline becomes overturned to the west. Gidon (1950) has demonstrated the presence of one and locally two fold faults affecting the steep western limb.

PANORAMA FROM THE CROSS OF INNIMONT

PLATE 40

Towards the southern extremity of the anticline, the fold faults die out and some of the former symmetry of the structure is restored. Beyond the alluvium of the river Leysse, the Mesozoic strata belong to the Subalpine, Grand Chartreuse Range.

B. RELATIONSHIP BETWEEN STRUCTURE & GEOMORPHOLOGY WITH PARTICULAR REFERENCE TO BAS-BUGEY.

In the Ile de Crémieu, the gentle slope developed over the Mesozoic succession is directly related to the regional dip. This, and the presence of a marked fault in the north-west shows that here topography is directly controlled by the geological structure.

The Molard Dedon Range is made up of three anticlines. Although both flanks of these are represented in each case, the western limbs are generally partly faulted out in the narrow shatter zones, which separate the anticlines. Over immature terrain, anticlines appear as ridges and synclines as valleys. It seems that the Molard Dedon Range is a general upland region, because an immature landscape has here developed over three anticlines, which are tightly bunched together. Wide valleys are absent due to the substitution of fault zones for synclines.

The boundaries of Bas-Bugey with the adjacent uplands (figs. 7A & 8) are particularly well-seen from the cross of Innimont (plate 40). The northern border passes along the foot of the Montagnes de Virieu and Sérémond (plate 40, F/5-7), traverses Valromey (E-F/6-8), and invades the Grand Colombier

(D-E/9-10). The eastern margin is rather sinuous (fig.8), taking in the central section of the Gros Foug-Chambotte ridge (plate 40, D/10-13), the northern part of the Charvaz ridge (D/14-16), and lastly the Parves-Tournier ridge (E/18-25). In the south, Bas-Bugey is bounded by the Montagne d'Izieu (E-F/25-27). The western wall (E-M/28-35) may be considered to follow the 500m. contour along the foot of the combined St.Benoît-Tantainet and Molard Dedon ridges (map 2).

It is clear that Bas-Bugey straddles the axes of the Ordonnaz-Ambléon-Prémeyzel anticline, the Sérémond-Tournier anticline and the Colombier-Chat-Epine fold. In the extreme west (map 2), it also cuts into the Crapéou-Izieu fault zone, and in the east it incorporates a part of the Rhône valley syncline. It is immediately apparent that the geomorphological unit of Bas-Bugey was formed by a process which could lower topography independent of geological structure. This may have been initiated by a drainage system, superimposed upon the Jura structures from a molasse cover. However, the presence of drumlins, moraine, large erratic blocks of schist and some glacially polished pavements, also suggests that glacial erosion played an important role. At the present day, the landscape of Bas-Bugey is relatively mature. Rivers customarily lie over their own flood plains, for example the Agnin (see plate 40, G-H/24-25). Resistant formations give rise to marked ridges and soft lithologies form deep strike vales. The roof to the Ambléon-Prémeyzel anticline is eroded away,

so that only the flanks remain standing up as independent ridges (plate 40, F-H/27) separated by marshy terrain. It is thus clear that, subsequent to glaciation, a prolonged period of fluviatile erosion has made Bas-Bugey into a significantly more mature region than the adjacent uplands.

Cholley (1932) proposed a more complex evolution of Bas-Bugey. This author recognised a 400m. peneplain, developed over "Pontien" sediments on the Ile de Cremieu. He attributed this erosion surface to the Pliocene, and correlated it with the level of Bas-Bugey. The peneplain, according to Cholley, is developed over the molasse of Belley, and the Mesozoic succession of western and eastern Bas-Bugey. It hence passes indiscriminatingly over anticlines, synclines, fault zones, and both soft molasse and resistant Mesozoic limestone. Cholley considered that the reduction of all these structures and lithologies to one level could not have taken place in the short time represented by the Pliocene. Instead he believed that the erosion surface had developed prior to the main Miocene deformation. Cholley considered the peneplain to have been faulted and warped during the Miocene and subsequently re-worked to the level of 400m. in the Pliocene. Although the present author considers some of the topography of the area to have developed prior and during molasse deposition, he believes that Cholley's interpretation of the formation of Bas-Bugey to be unnecessarily complicated.

The Chain Jura, or zone of anticlinal ridges and

synclinal valleys lies to the east of Bas-Bugey. In this easternmost zone of the Jura, there is a return to immature terrain, with the form of the land once more following the underlying geological structure.

It can be seen that over the greater part of the southern French Jura topography and geological structure are closely related. This is also found to be the case in the Central Jura (see fig.6). The lowland region of Bas-Bugey is an anomalous exception to the general rule. Western Bas-Bugey, incorporating part of the Crapéou-Izieu fault zone and the Ordonnaz-Ambléon-Prémeyzel anticline, belongs to the region of relatively unfaulted anticlines and intermediate fault zones, that is the Molard Dedon Range. The Rossillon-Belley, molasse-bearing syncline and eastern Bas-Bugey form part of the region, in which anticlines are separated by broad synclines. Had the structures of Bas-Bugey not been reduced almost to a common level, the Rossillon-Belley syncline would no doubt have been a broad valley lying to the west of an anticlinal ridge, connecting the Montagnes de Séremond and Parves. It is considered on these grounds that the area east of, and including the Rossillon-Belley syncline is akin to the Chain Jura.

C. THE CENTRAL & SOUTHERN JURA COMPARED.

The southern French Jura have been shown to be made up of three structural units (fig.8), the Tabular Jura (Ile de Crémieu), the zone of anticlines separated by fault zones (Molard Dedon Range), and the zone of anticlinal ridges and

synclinal valleys (Chain Jura). Farther north, in the Central Jura, where the longitudinal zones of the Jura were first defined by Thurmann (1852) and Bertrand (1885), two zones occur between the Tabular and Chain Jura. These are The Vignoble in the west, and the Plateaux in the east. The Vignoble consists of Triassic and Liassic marls, which have been squeezed into nappe-like structures, and thrust over the Tertiary of the Bresse plain (see fig.35). The Plateaux are made up of faulted compartments of sub-horizontal Middle Jurassic calcarenites and coral limestones. The Vignoble disappears southwards below the first of these plateaux. It seems likely that The Vignoble is a depth zone, rather than a longitudinal zone of the Jura. It may represent the surface outcrop and structural appearance of the Liassic and Triassic marls as they exist below the Jura Range as a whole. There would thus be only the zone of Plateaux between the Tabular and Chain Jura, and this zone would seem to correlate by position with the Molard Dedon Range in the south. Both regions are greatly faulted. However, whereas the strata between faults in the Central Jura form unfolded plateaux, those farther south have been buckled into anticlines. The increased foreshortening on account of this in the southern French Jura provides one contributing factor towards the northerly expansion of the Jura Range. A second contributing factor causing this expansion is the known increase in the number of folds northwards through the Chain Jura.

Plate 41.

PLATE 41.

Looking north-west over the Ambérieu-Rossillon cluse, which cuts through the Southern Jura in a number of relatively straight sections. The section in the foreground cuts across the strike and exposes the Molard Dedon-Colomieu anticline above la Burbanche. The section in the middle distance, on the left, which carries the lakes of Les Hôpitaux, runs sub-parallel to the strike.

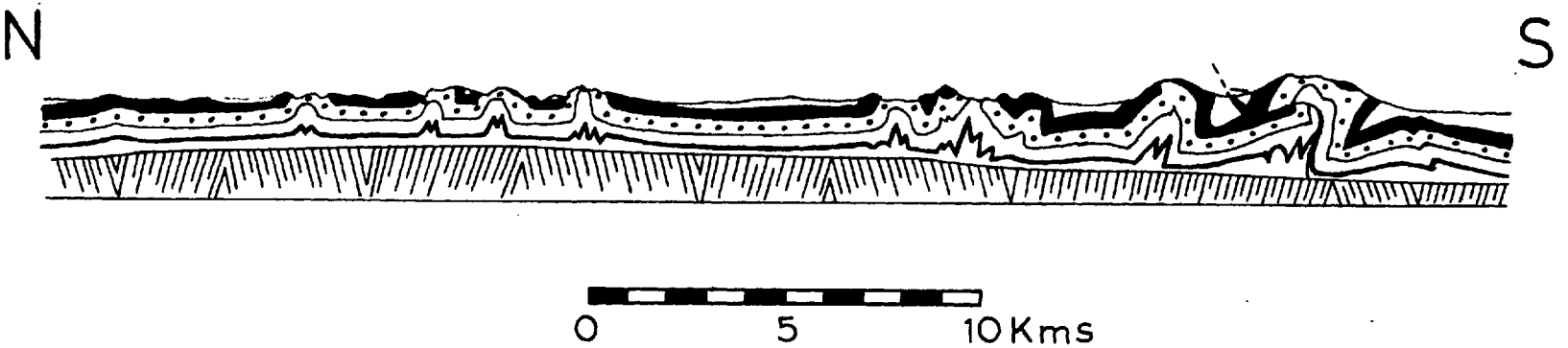
D. THE AMBÉRIEU-CULOZ CLUSE.

The Molard Dedon Range is separated from the greater part of Haut-Bugey to the north by a deep gorge, which traverses the Jura from Ambérieu to Rossillon (see plate 41). Beyond Rossillon, the gorge, or cluse opens out into the lowland area of Bas-Bugey, which extends eastwards to Culoz (fig.8). Like the cluse, Bas-Bugey cuts indiscriminatingly across the structural trend of the southern French Jura and may, in a broad sense, be considered as a continuation of the cluse. French authors consider the northern limit of Bas-Bugey (the high ground of the mountains of Virieu, Séremond and Colombier) to be the northern wall of the cluse, the southern wall having been eroded away. Even if the topography of Bas-Bugey had not been lowered, the "cluse" from Rossillon to Culoz would not have had steep cliffs over its entire length. They would have been absent through the synclinal zones of the Chain Jura (fig.2).

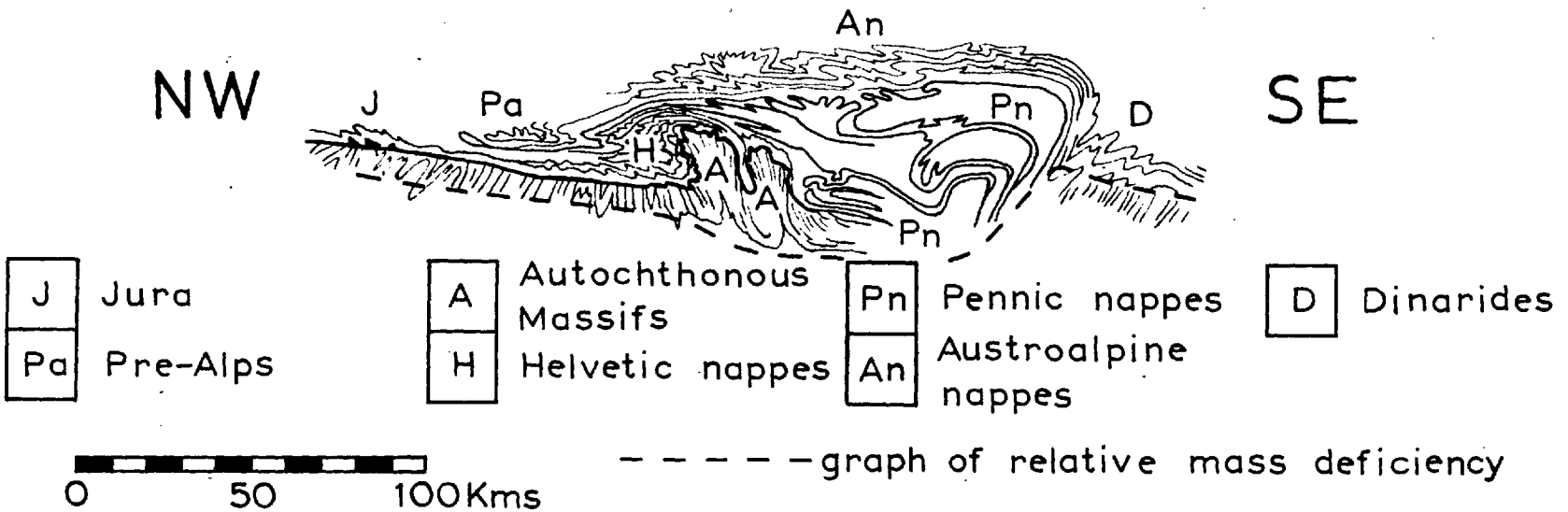
The 55km. long cluse traverses all the folds of the southern French Jura except for the Gros Foug-Chambotte anticline. Collet (1927) believed that the cluses of the Jura were cut by rivers older than the geological structure. He considered such rivers to have maintained their base levels during folding. In the area investigated, however, an oblique shear fault exists along the la Burbanche-Rossillon section of the Ambérieu-Culoz cluse (see chapter 17 & map 2). The natural plane of weakness afforded by this shear fault could

FIG. 34

Section through northern Swiss Jura illustrating the concept of 'abscherung' or 'décollement' of the Mesozoic cover from the Hercynian basement, (after A. Buxtorf, 1916.).



Structural relationship between the Jura and Alps, (after A. Heim, 1918.).



well have been the factor controlling the formation of the cluse here. Throughout its length, from Rossillon to Ambérieu, the cluse is made up of relatively straight sections (fig.8). These could all follow the zones of weakness caused by transverse and strike faults. If the path of the cluse was controlled by the tectonics, as is believed to be the case, some of the deformation must have pre-dated its formation, contrary to the supposition of Collet.

The valley floor of the cluse reaches a maximum height of 360m. in its central region near Les Hôpitaux. West and east of here, the rivers Albarine and Furan follow gentle 1/250 gradients, which fall to the level of the present-day Rhône. Neither the Albarine nor the Furan, in their present form, could have carved out the cluse. Between Rossillon and Contrevoz, there are extensive terraces at 360m., made up of pre-Recent river gravel. It has been suggested in chapter 15 that these gravels were deposited on the slip-off slope of a large river flowing either east-west or west-east. It seems likely that the Rhône, which today passes close to Culoz and Ambérieu once flowed from east to west along the cluse. This conclusion was also reached by Depéret (1899) and Martin (1911), from observations made on terraces near Ambérieu.

E. THE CONTACT OF THE JURA & SUBALPS.

The general relationship between the Swiss Jura and Alps is illustrated in fig.34. The Helvetic nappes, shown here, pass southwards into the Subalpine zone, which converges with the southern French Jura, as indicated in fig.4. The molasse

plain, which engulfs Mont Salève south of Geneva, narrows to a tight syncline at Aix-les-Bains. North of Salève, distinction between the Jura and Alps is simple since both ranges are separated by the wide Franco-Swiss molasse plain. South of Geneva, a combination of criteria involving differences in tectonic style and facies of the Mesozoic rocks is employed to distinguish between them.

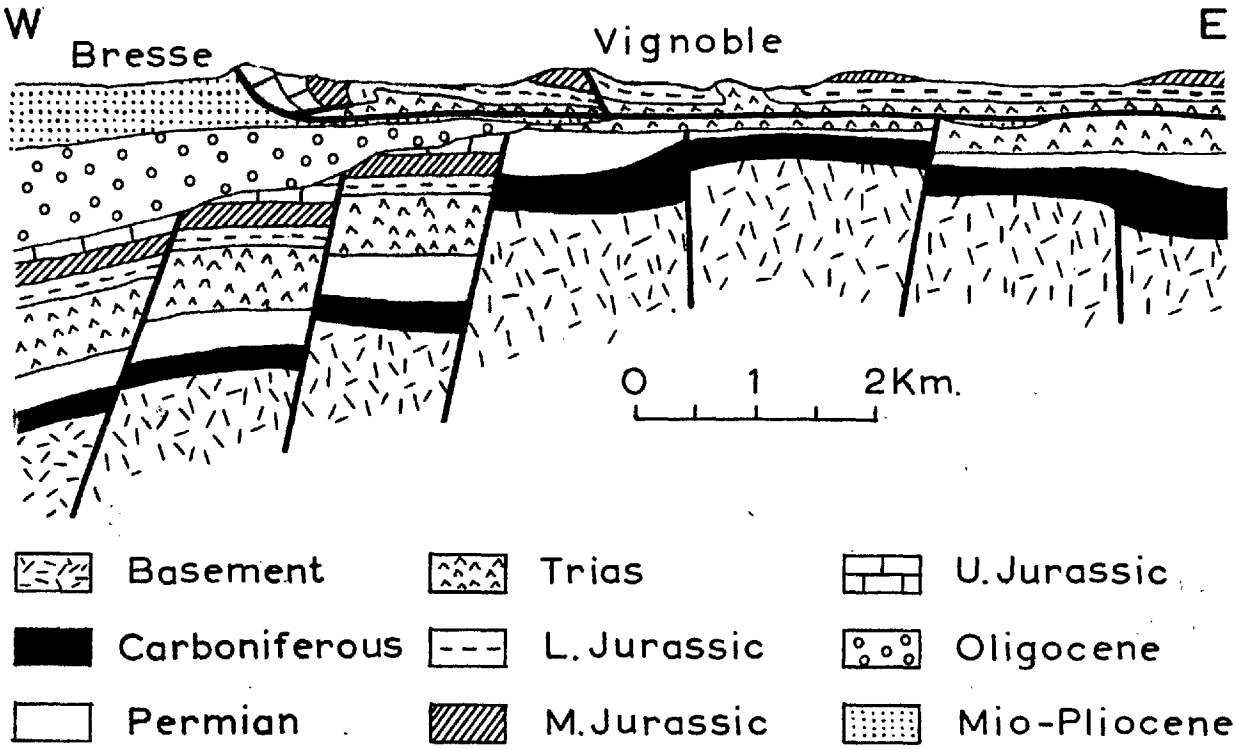
Both the Subalps and Jura are made up of folded and faulted, unmetamorphosed Mesozoic calcareous sediments. The intensity of folding tends to be much greater in the Subalps, and faulting here commonly gives rise to a "schuppen" structure, not seen in the Jura.

The Mesozoic rocks of the Jura were all deposited in relatively shallow seas whilst, in the Jurassic, the Subalpine or Dauphinois zone was a deep-water geosyncline (chapter 13). Hence the Jura and Subalps can generally be distinguished by the difference in facies of the Jurassic rocks. This ease of distinction is, however, aided by the tectonics, since much of the transition zone between the two sedimentary domains is faulted out in the Subalpine front. The shelf-sea or "Jurassian" facies of the rocks in Mont Salève places this ridge quite definitely in the Jura. In contrast, the deep-water Jurassic rocks of the nearby Bauges Range (fig.4) belong to the Subalpine domain.

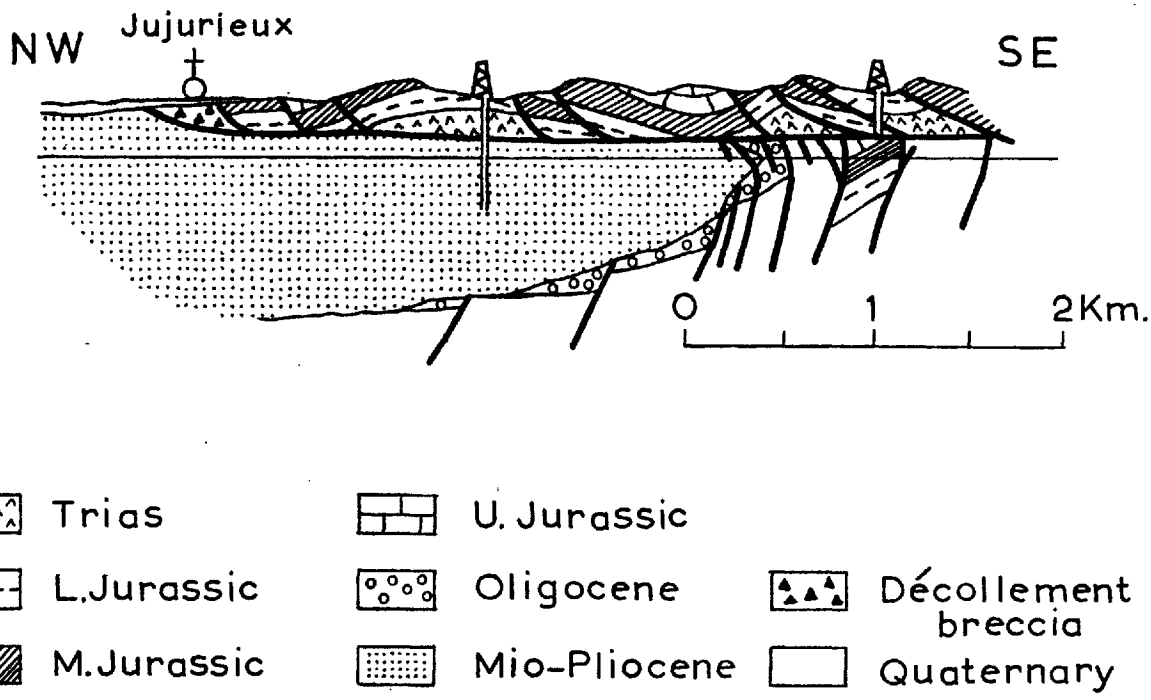
Throughout the southern French Jura, the western limbs of anticlines tend to be cut by fold faults, whereas their eastern flanks are generally complete. This suggests

FIG. 35

WESTERN BORDER OF THE CENTRAL JURA
after Lefavrais, Lienhardt & Ricour (unpublished)



WESTERN BORDER OF THE SOUTHERN JURA
after Michel & Caillon (in Ricour, 1962)



that the deformation, which affected the region was directed from the Alpine front in the east. This is also indicated from the evidence of deep borings, which have penetrated the basal décollement plane of the Jura. A borehole, put down in the Fier gorge (map 3 & plate 2B) has shown the folded Mesozoic succession to overlie the Permo-Carboniferous and basement, as illustrated in fig.34. Other boreholes along the western margin of the Jura (fig.35) indicate that here the Jura folds have been thrust several kilometres over the Tertiary deposits of the plain of Bresse and Dombes.

CHAPTER 17.

SPECIAL STRUCTURAL TOPICS.

A. REACTION OF DIFFERENT LITHOLOGIES TO DEFORMATION.

Many of the lithological divisions, recognised from their petrographical features, are also distinctive on account of their individual reactions to deformation. It has been found that there is an overall relationship between style of deformation and bedding thickness.

The Ambléon Limestone, some 200m. thick, is the lowest competent unit of the exposed succession. It tends to control the shape of the folds at depth (fig.32). The shaly Liassic succession below (Cuzieu Beds) is poorly-exposed, and its tectonic role is not clearly seen at the surface. It is likely, however, that the marls of the Lias and Keuper behaved incompetently, and became squeezed into the cores of the anticlines above the basal décollement plane of the Jura, as illustrated diagrammatically in fig. 2. Although considered as a major competent unit, the Ambléon Limestone at the confluence of the Gland and Agnin exhibits some disharmonic folding. A few of the foreset beds of the Lower Ambléon Limestone here have been contorted on a minor scale, out of harmony with the form of the main fold (fig.14). In the area mapped, the Chanaz Beds have always been found folded in the same way as the underlying Ambléon Limestone.

The second incompetent unit of the Mesozoic succession is about 300m. thick. It includes the Chavoley and

Plates 42 & 43

PLATES 42 & 43.

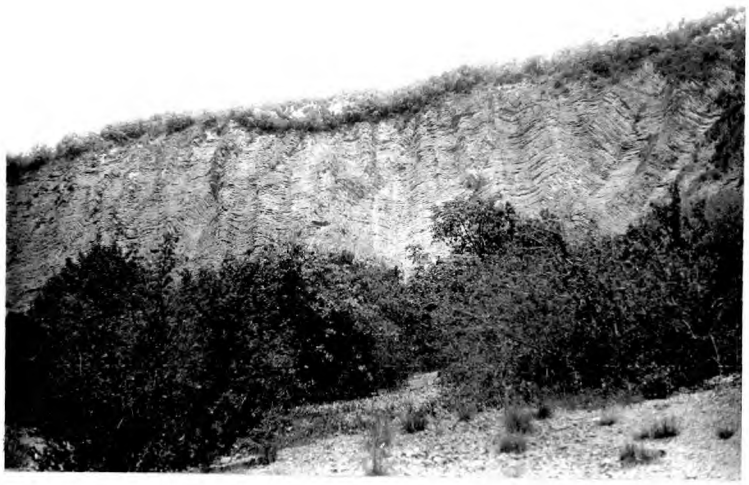
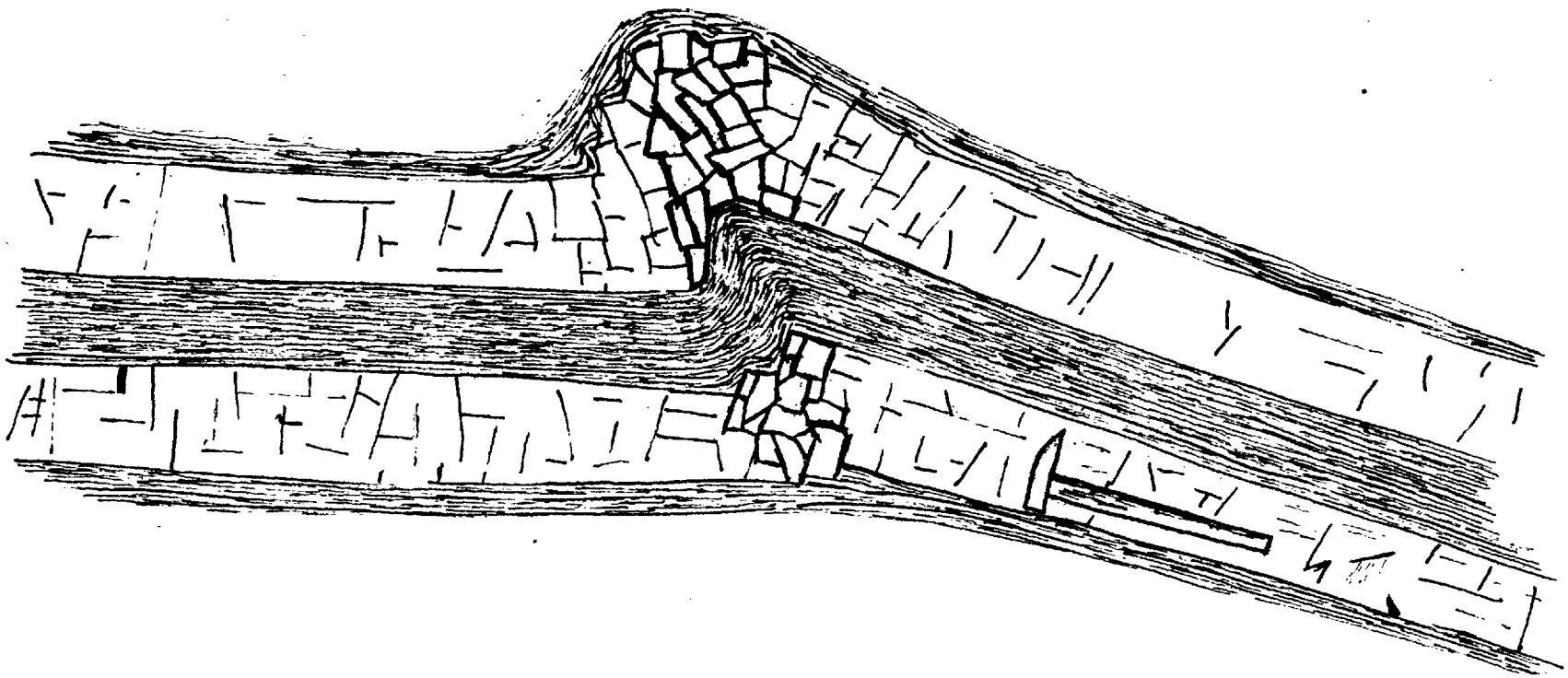


PLATE 42. "Zig-zag" folds in the Middle Chavoley Beds of the Grand Colombier (Ain).

PLATE 43. Minor contortion in the Oignon Beds exposed along the road from Contrevoz to Ordonnaz (Ain).

FIG.36

SMALL FOLD IN THE UPPER CHAVOLEY BEDS BELOW THE CLIFFS OF INNIMONT



Oignon Beds as well as the Bedded Virieu Limestone. The marls of the Lower and Middle Chavoley Beds are characteristically contorted into minor "zig-zag" folds. These are particularly well exposed in the south face of the Grand Colombier (see plate 42 & compare with fig.32).

The limestones of the Upper Chavoley Beds appear to have had a very brittle reaction to deformation and, even in relatively undeformed regions, the member is strongly fractured. Where folding is found to be strong in the Oignon Beds, for example along the road from Contrevoz to Ordonnaz (fig.37), the underlying Upper Chavoley Beds are found to be fractured in three almost mutually perpendicular directions. This causes the limestones to break up into small cubes. Fracture planes are so well developed that the bedding is obscure. Lower down in the member, brittle limestones alternate with thin shales. Where these shales are folded, the interbedded limestones are intensely fractured. Consequently, over the axes of the folds, the limestones are represented by breccias. These pass laterally into less fractured limestone over the unfolded parts (fig.36).

The Oignon Beds are commonly found to have been compressed into tight, small-amplitude folds. Khouri (1960) reported "zig-zag" folds of this type developed in the formation near the Col du Chat. Small concentric folds also exist in the Oignon Beds of the Séréemond boxfold (plate 39) and the Grand Colombier (fig.32). In the area mapped, contorted Oignon Beds are well-exposed along the road from Contrevoz

FIG. 37

SECTION IN CONTORTED OIGNON BEDS
ALONG ROAD D.32 FROM CONTREVOZ TO ORDONNAZ

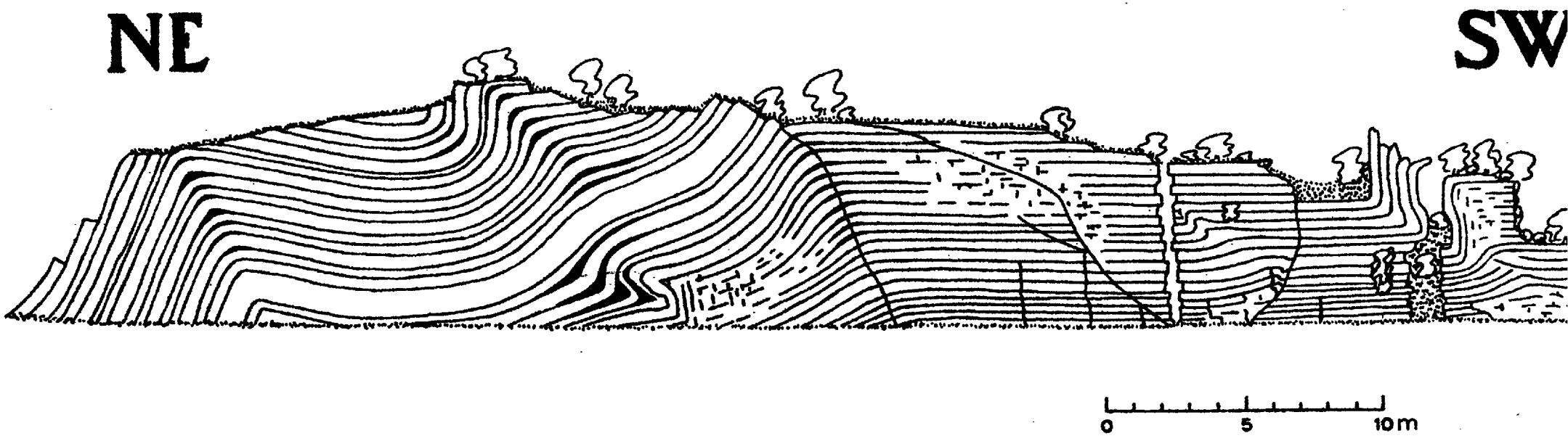


Plate 44.

PLATE 44.

Small-scale contortions in the Bedded Virieu bituminous shales, Lac d'Armaille (Ain).

to Ordonnaz (fig.37 & plate 43). These beds are folded out of harmony with the competent units above and below (respectively the Massive Virieu and Ambléon Limestones). The exposure itself exhibits disharmonic folding on a small scale, with thinly-bedded limestone contorted above and below a relatively competent, thicker bed (fig.37). These small-scale folds in the Oignon Beds occur on the north-eastern flank of the Molard Dedon-Colomieu anticline (map 2). Comparable structures have also been found on the south-western limb (map 2). Here the folds generally have a steep plunge.

The style of deformation affecting the Bedded Virieu Limestone varies according to the bedding thickness of the member. Strata in the Bedded Virieu Limestone normally measure from ½ to 1m. thick. These beds are in places contorted like the Oignon Beds below, for example on both flanks of the Molard Dedon-Colomieu anticline. More commonly however, the relatively thickly-bedded Lower Virieu Limestone is found to be unaffected by small-scale folds. Instead, it is infolded with the overlying Massive Virieu Limestone, which generally gives the main structure a box-shape. Locally, near lac d'Armaille, oil shales occur in the middle of the Bedded Virieu Limestone. These shales have behaved very incompetently, and have become intensely contorted (plate 44).

The Massive Virieu Limestone is almost invariably found folded into structures with a broad amplitude, for example in the Montagne d'Izieu (enclosure 4, sections I and

PLATE 45 A & B

PLATE 45. A & B.

A. Small-scale folds in Cerin Lithographic Stone above the Massive Virieu Limestone, Préveysieu (Ain).

B. Small-scale folds in Lithographic Stone below the Massive Virieu Limestone, Préveysieu (Ain).

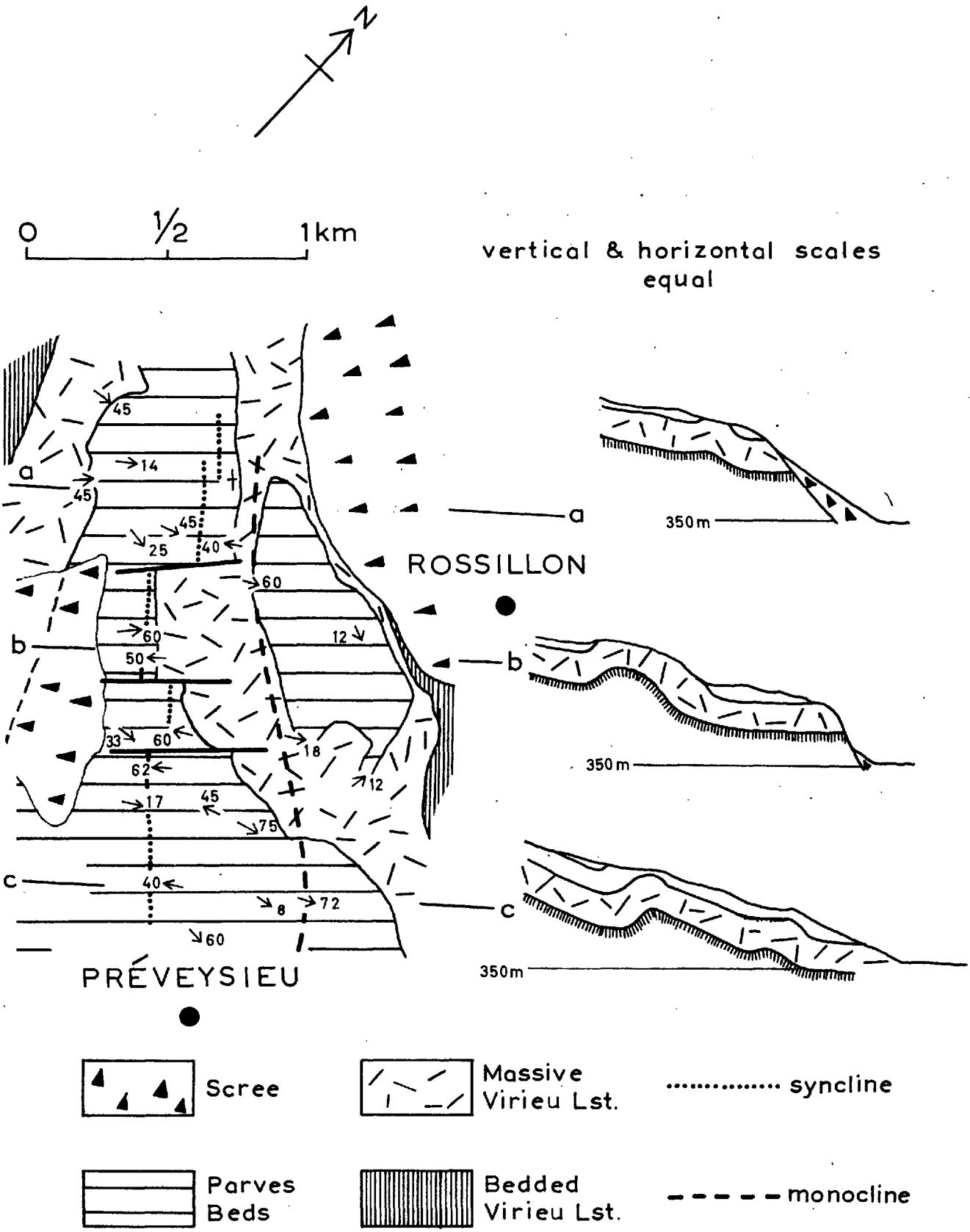
II), in the Montagne de Sérémond (plate 39), and in the Grand Colombier (fig.32). Small-scale folds are generally lacking since these result from movement along bedding planes, which are absent in the Massive Virieu Limestone. Instead the division is affected by a pronounced joint system, involving fractures in three almost mutually perpendicular directions. The passage of the Massive Virieu Limestone north-westwards into the Cerin Stone is accompanied by a marked change in reaction to deformation. The thinly-bedded lithographic stone is intensely contorted both above and below the Massive Virieu Limestone, over the north-eastern flank of the Molard Dedon-Colomieu fold (see plates 45 A & B).

The Parves Beds are commonly folded out of harmony with the underlying Massive Virieu Limestone. This is especially the case in the Préveysieu region (see enclosure 4, section IX). The structures here have amplitudes of about 200m. Many of them have two axial planes and are thus miniature boxfolds. The symmetry and south-easterly plunge to one of these minor folds, situated 1km. west of Contrevoz, is particularly well-seen from the air (see plate 38, F-G/14-15). Only one of the subsidiary folds involving the Parves Beds near Préveysieu has been traced down into the Massive Virieu Limestone (section X).

No small-scale structures have been seen in the ferruginous bioclastic calcarenites and marls of the Bourdeau Beds. However, the formation is believed to be less competent than the underlying Parves Beds, and the overlying Chambotte

FIG.38

SMALL AMPLITUDE FOLD IN THE MASSIVE VIRIEU LIMESTONE



Limestone. This is apparent in the Fier gorge through the Chambotte ridge (plate 2B). At the level of the Massive Virieu Limestone the Gros Foug-Chambotte anticline is a symmetrical, concentric fold with a single axial plane. Higher up, in the Chambotte Limestone, the fold is "boxed" having two axial planes. The marls of the Bourdeau Beds are therefore thought to have been squeezed between the competent units of the Chambotte and Massive Virieu Limestones.

It is interesting to note that the three competent units of the succession are the three reef limestones, the Ambléon Limestone, Massive Virieu Limestone and Chambotte Limestone. The incompetent units correspond mainly with the marls of the Cuzieu Beds, Chavoley Beds and Bourdeau Beds.

B. MINOR FOLD INVOLVING MASSIVE VIRIEU LIMESTONE.

In the south-eastern Jura, the Massive Virieu Limestone is a thick and competent unit, which controls the shapes of the main folds. The thinning of the member to the north-west (figs.25 & 28) is accompanied by evidence of a reduction in competency. In the Préveysieu region, the Massive Virieu Limestone (only 100m. thick) is involved in a small-amplitude anticline (map 1 & fig.38). Due to the absence of bedding in the Massive Virieu Limestone, the evidence for the existence of this fold comes mainly from the disposition of the overlying Parves Beds. The topography over the minor structure is very immature, and the core of the Virieu Limestone stands out as a prominent ridge. In places the juvenile topography was used to locate the position

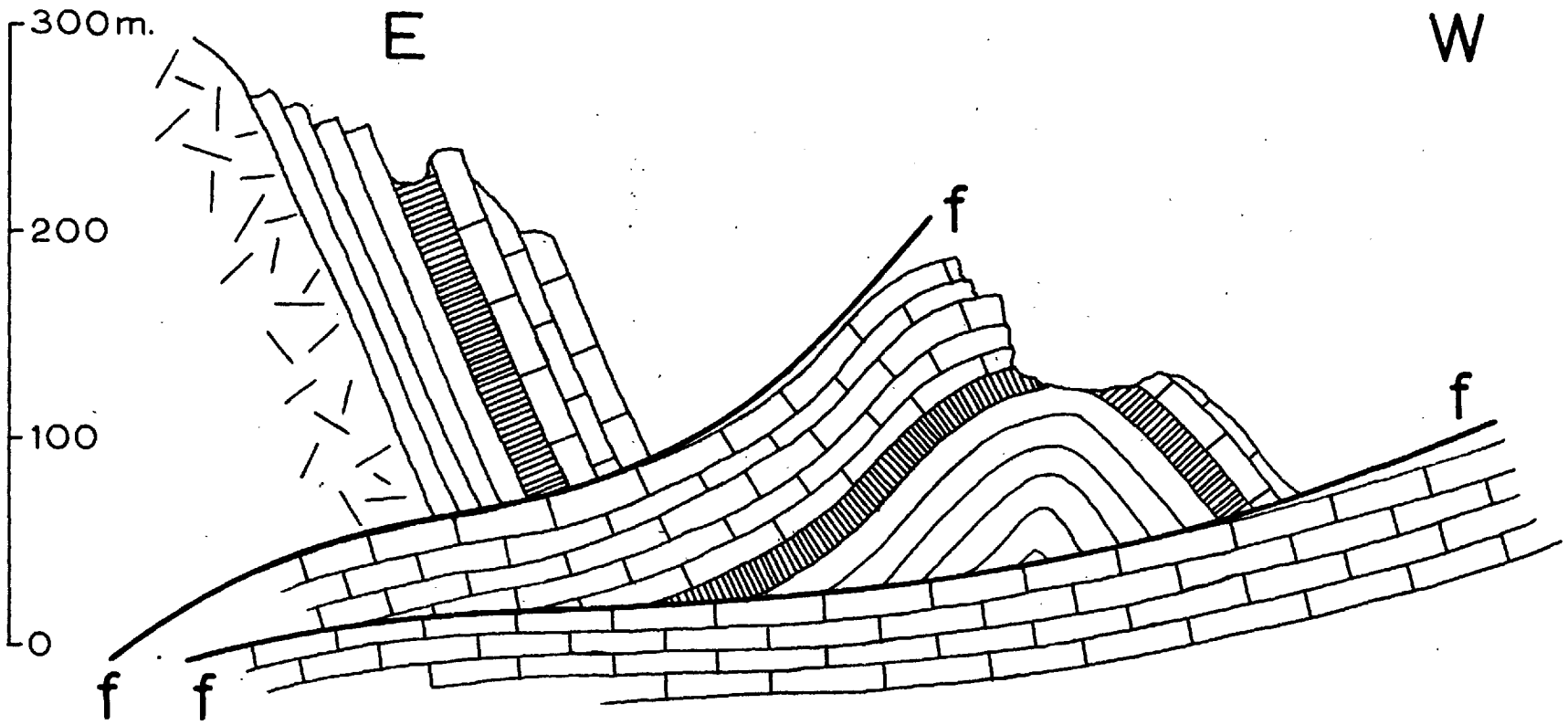
Plate 46

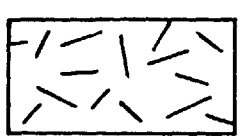
PLATE 46.

Montagne d'Izieu & the Crapéou-Izieu fault zone viewed from the Montagne de St.Benoît to the north-west. Photograph also illustrates the abrupt change in altitude from Haut- to Bas-Bugey in the south of the area mapped.

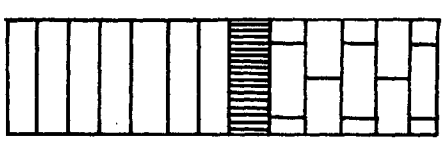
FIG.39

SCHEMATIC INTERPRETATION OF PART OF THE CRAPÉOU-IZIEU FAULT ZONE





MASSIVE VIRIEU LST.



L. M. U.
PARVES BEDS

of the north-eastern monocline of the structure (see fig.38, sections b).d). The minor fold, described above, is shown in relation to the Molard Dedon-Colomieu anticline in enclosure 4, section X.

C. CRAPÉOU-IZIEU FAULT ZONE IN NORTH FACE OF THE MONTAGNE d'IZIEU.

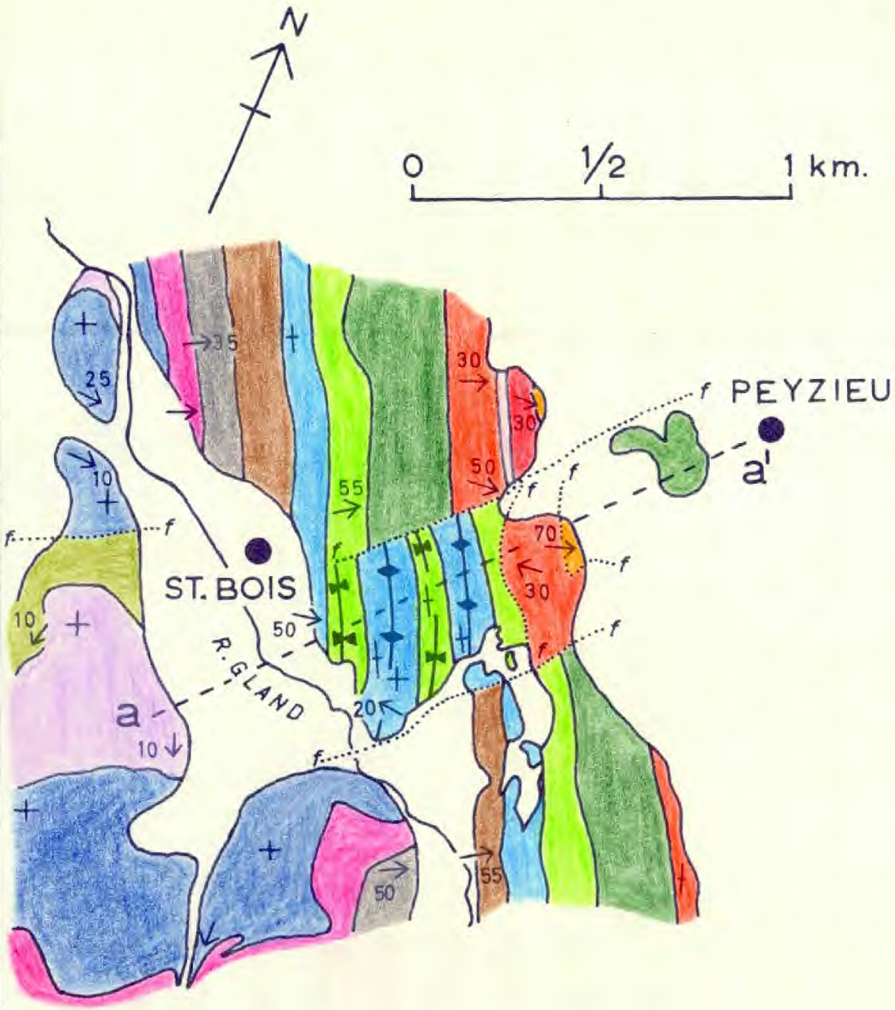
The structure of the Montagne d'Izieu is best seen from the Montagne de St.Benoît (map 2). Plate 46, photographed from this vantage point, shows, on the left, the gently dipping roof to the main Ambléon-Prémeyzel anticline, in the centre, the ridge representing its steep western limb and, on the right, the gentle eastern limb of the Tantainet-St.Benoît fold. Between the latter two features lies the Crapéou-Izieu fault zone. The structure here is indicated on maps 1 and 2, and enclosure 4 (section II). It is also shown schematically in relation to plate 46 in fig.39. The fault zone is represented by a small anticline in faulted contact with the Tantainet-St.Benoît anticline below and the Ambléon-Prémeyzel anticline above. Both these dislocations pass down into a single fault at the foot of the Montagne d'Izieu. The thrust between the subsidiary anticline and the St.Benoît fold is characterised by heavily slicken-sided brown marl, and it is believed that the ferruginous Middle Parves Beds here acted as a lubricant for the dislocation.

D. St.BOIS SHATTER ZONE.

North of St.Bois, the amplitude of the Ordonnaz-

FIG.40

ST. BOIS SHATTER ZONE



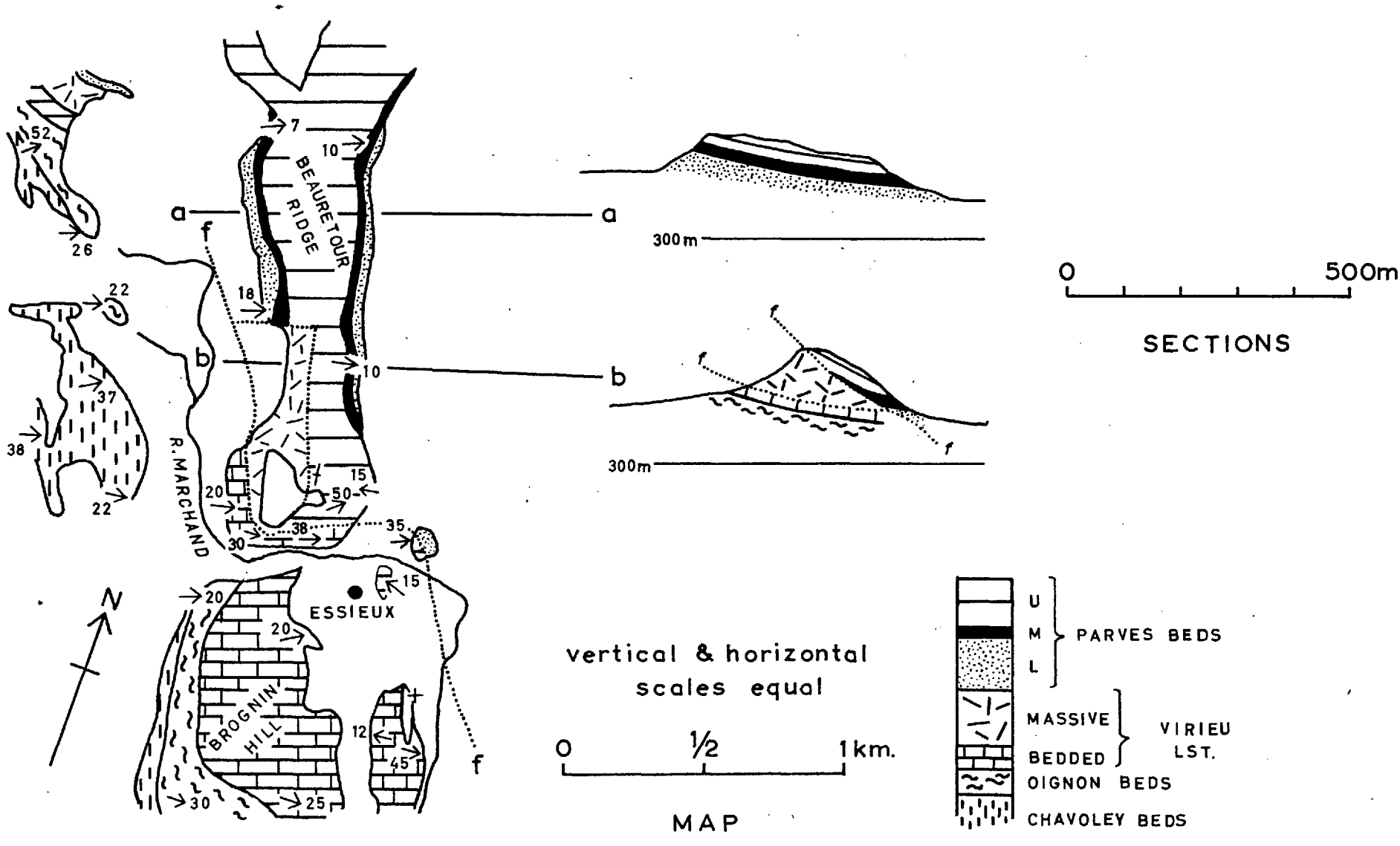
vertical &
horizontal
scales equal

key to formations on enclosure 4

Ambléon-Prémeyzel anticline decreases abruptly by ½km. This reduction in amplitude takes place between the confines of the St.Bois Shatter Zone, which lies between the villages of St.Bois and Peyzieu (maps 1 & 2). The shatter zone is bounded to the north-west and south-east by transverse faults. Between these, the Oignon Beds and Bedded Virieu Limestone are involved in a series of tight, almost isoclinal folds (see fig.40). Calcilutites and black breccia bands of the Lower Parves Beds are in contact with the Bedded Virieu Limestone in the north-east. Glauconitic marls of the Bourdeau Beds are found next to the Lower Parves Beds also in the north-east. Just west of Peyzieu, an isolated exposure of Massive Virieu Limestone is found. Hence, apart from the Oignon Beds and Bedded Virieu Limestone, there appears to be no stratigraphical continuity between the lithologies represented in the shatter zone. The outcrop of the Massive Virieu Limestone west of Peyzieu must belong to the eastern limb of the Ambléon-Prémeyzel anticline. It is possible that the Parves Beds of the St.Bois shatter zone were thrust over the Virieu Limestone, as indicated in fig.40 (section a). The transverse faults delineating the shatter zone have not been found west of the Gland alluvium. The north-western fault is known, in fact, to terminate in the axis of the westernmost syncline of the shatter belt (see fig.40). The small normal fault separating Cuzieu Flags from Middle Ambléon Limestone, west of St.Bois (map 1) is entirely unconnected with the shatter zone. Instead, it represents

FIG.41

PART OF THE BEAURETOUR — LAC D'ARMAILLE FAULT ZONE



the line, along which the main Ambléon-Prémeyzel anticline commences its south-easterly plunge.

E. BEAURETOUR-LAC d'ARMAILLE FAULT ZONE.

A complex zone of faults exists between the hill north of Essieux (the Beauretour ridge) and lac d'Armaille. Most of the dislocations here seem to be high angle reverse faults (enclosure 4, sections VI-VIII), though it has not been possible to prove this from the available exposure.

The structure of the Beauretour ridge itself is especially interesting since it involves both strike and transverse faults (fig.41). The ridge is well-seen from the Cross of Innimont (plate 40, H-I/11-14). A transverse fault undoubtedly separates the Massive Virieu Limestone, seen on the right-hand side of the field of view, from the distinctive double-cliff feature of the Parves Beds, seen on the left. The change in topography from the Massive Virieu Limestone to the Parves Beds is clearly apparent both from the east and west. However, as shown in fig.41, the Middle Parves marker band passes along almost the entire length of the eastern side of the ridge. This indicates that the transverse fault, seen so clearly from the Cross of Innimont in the west, does not cut across the whole ridge. Mapping shows the Massive Virieu Limestone to be overlain by steeply dipping Upper Parves Beds (fig.41 section b), which are contorted farther east. Below the Massive Virieu Limestone, the Bedded member is incomplete. It is believed that here the Massive Virieu Limestone exists as a faulted block between the Bedded

Virieu Limestone and Upper Parves Beds (fig.41, section b). A further transverse fault must occur along the valley of the river Marchand (fig.41), since the Massive Virieu Limestone of the Beauretour ridge strikes into Bedded Virieu Limestone of Brognin Hill, just south of the Marchand.

F. ROSSILLON-LA BURBANCHE FAULT.

Immediately south of the Ambérieu-Culoz cluse, the Molard Dedon-Colomieu fold is a symmetrical anticline with both limbs dipping at approximately 45° (enclosure 4, section X). The same structure is well-exposed in the north face of the cluse above la Burbanche (plate 41). Here the south-western limb is steep, with dips nearing the vertical, whilst the north-eastern limb dips gently at about 20°. This change in shape of the anticline over the narrow passage of the cluse is accompanied by a displacement of the axis of the fold, 600m. to the south-east (map 2). It is therefore believed that a tear fault, or series of faults exists along the cluse from Rossillon to la Burbanche.

PART V.

SPECIFIC LABORATORY STUDIES.

CHAPTER 18.

MINERALOGICAL DIFFERENTIATION BY STAINING TECHNIQUES.

A. GENERAL.

The dominant mineral in the Mesozoic succession of the Southern Jura is calcite, so that it became necessary to distinguish consistently this mineral from other carbonates occurring only in accessory quantities. The optical properties of carbonate minerals are all rather similar. However, reliable differentiation between these minerals may be effected if solutions can be found, which react distinctively with each of them.

B. CALCITE & ARAGONITE.

Aragonite is a metastable form of calcium carbonate. It is an important component of modern carbonate muds, oolites and molluscs. In these occurrences, the mineral exists either as minute crystals or slender fibres, so that differentiation on the basis of crystal form is unreliable. Aragonite is found fossil mainly in Caenozoic rocks, and to a lesser extent in Cretaceous strata. One of the most fundamental problems of diagenesis in carbonate sediments concerns the replacement of aragonite by calcite. Many of the rocks studied exhibit textures of calcite after aragonite, and it was considered important to determine whether any unaltered aragonite occurs in the youngest part of the exposed Mesozoic succession (Lower Cretaceous). Consequently polished hand

specimens and thin sections of rocks coming from the Middle Parves Beds to the Chambotte Limestone were treated with freshly prepared Feigl's solution (Feigl, 1958), when it became evident that no aragonite is present in the rocks studied. Boiling the same samples in 10% cobalt nitrate (Meigen's solution) failed to produce the characteristic pink stain for aragonite. This thus confirmed the results obtained with Feigl's solution. Both reagents differentiate calcite from aragonite on the principle that aragonite is very slightly more soluble than calcite.

C. CALCITE & DOLOMITE.

Whereas calcite dissolves in dilute hydrochloric acid, dolomite does not. Etching polished rock samples with dilute acid will therefore, in the absence of other minerals, indicate the distribution of dolomite and calcite. More reliable differentiation is attained by employing staining reagents. Many staining techniques, based upon the different reactions of dolomite and calcite to dilute hydrochloric acid, have been proposed for the distinction of these two minerals. Calcium ions, liberated from calcite by the acid, are allowed to react with a further reagent to form a coloured product. The present author has found the most reliable reagent for this purpose to be the organic dye-stuff, alizarin red S in dilute hydrochloric acid. Alizarin red S (sodium alizarin sulphonate) reacts with calcium ions to form the red pigment, calcium alizarin sulphonate. No ions are liberated

TABLE IV

STAINING REAGENTS	CALCITE			DOLOMITE		
Compositions are given in weights percent. Critical solution strengths are underlined.	Fe^{++} free	Fe^{++} poor	Fe^{++} rich	Fe^{++} free	$\frac{Fe^{++}}{Mg^{++}} < 1$	$\frac{Fe^{++}}{Mg^{++}} > 1$
	calcite *sensu stricto*	ferroan calcite		dolomite *sensu stricto*	ferroan dolomite	ankerite
0.2% hydrochloric acid 0.2% alizarin red S	red	red	red	not stained	not stained	not stained
0.2% hydrochloric acid 0.5%-1.0% potassium ferricyanide.	not stained	light blue	dark blue	not stained	light blue	dark blue
0.2% hydrochloric acid 0.2% alizarin red S 0.5%-1.0% potassium ferricyanide.	red	mauve	purple	not stained	light blue	dark blue

TABLE IV

from the dolomite, so this mineral remains unstained. The technique appears first to have been developed by Schwarz (1930, 1953). Reference to the use of alizarin red S in acid solution has subsequently been made by Feigl (1958), Friedmann (1959), Warne (1962) and Evamy (1963).

Table IV shows the composition of an alizarin red S reagent employed by the present author. The strength of hydrochloric acid used (0.2% by weight) is just below that which causes calcite to effervesce visibly. Adherence of gas bubbles to the surface being treated yields unreliable results. At the strength of hydrochloric acid quoted above approximately one minute is required to stain adequately thin sections or polished rock surfaces. More intense pigmentation, due to the production of a thicker layer of stain, results if the reagent is applied for longer periods. This is undesirable because desiccation cracks are likely to develop over the stained surface as this dries out.

Feigl (1958), Friedmann (1959), and Warne (1962) also advocated the use of alizarin red S in sodium hydroxide to differentiate dolomite from calcite. In strongly alkaline solution, magnesium ions in dolomite form the colloid magnesium hydroxide. The colloidal particles adsorb the alizarin dye so that the dolomite becomes stained a reddy-purple. The present author has found this technique extremely unreliable due to the common presence of impurities, which interfere with the differentiation. For example, clay minerals occur most commonly as colloidal particles, and

readily adsorb coloured dye-stuffs, so that clay-bearing limestones tend to stain a mottled reddy-purple in alkaline alizarin red S. Furthermore, calcite may contain an appreciable quantity of magnesium in its lattice. Such high magnesian calcite would also provide colloidal magnesium hydroxide in alkaline solution for the alizarin to stain. In addition, calcium ions from calcite yield calcium hydroxide in strong alkali. Although calcium hydroxide precipitates in particles with dimensions mainly above the colloidal range, the possibility of dye-stuffs becoming adsorbed to the precipitate is still quite strong. Due to all these interferences, the present author has found the differentiation between dolomite and calcite in alkaline alizarin red S to be rather diffuse and unreliable.

D. DETECTION OF FERROUS-IRON.

Calcite and dolomite may contain varying proportions of ferrous-iron. Palache, Berman and Frondel (1951) called ferrous-iron bearing calcite, ferroan calcite. They referred to ferrous-iron bearing dolomite as ferroan dolomite or ankerite, depending upon the ferrous-iron content of the dolomite. They considered ferrous-iron to form a substitution series for magnesium in dolomite. They divided this series where the $\frac{Mg^{++}}{Fe^{++}}$ ratio is unity. Thus where $Mg^{++} > Fe^{++}$ in dolomite, the variety was known as ferroan dolomite, and where $Mg^{++} < Fe^{++}$, it was termed ankerite.

It is known from classical chemistry that ferrous-iron reacts with potassium ferricyanide in dilute hydrochloric

acid to form the pigment, Turnbull's blue. Potassium ferricyanide solution made up in the proportions given in Table IV have been found suitable for detecting the distribution of ferrous-iron in either dolomite or calcite. It is reasonable to assume that the intensity of the stain, Turnbull's blue, is directly proportional to the concentration of ferrous-iron present.

The present author (Evamy, 1963) has combined the reagents of alizarin red S and potassium ferricyanide in a single solution, acidified with 0.2% by weight hydrochloric acid (Table IV). The concentration of both components in the combined reagent are the same as in their individual staining solutions. It has been found that the reactions due to alizarin red S and potassium ferricyanide in this single solution do not interfere. The distribution of colour due to each is the same as if the stains had been employed independently. Dolomite remains unstained by the alizarin red S component, but takes on a superficial stain of Turnbull's blue where ferrous-iron is present. The full range from unstained ferrous-iron free dolomite to deeply blue stained ankerite may thus be revealed by using this stain (Table IV). Calcite, free of ferrous-iron, is coloured a clear red by the alizarin red S operating alone; it is unaffected by any component of Turnbull's blue. Ferroan calcite takes on both stains (Table IV). It is coloured mauve (red component dominant) where ferrous-iron is poorly represented, and purple

Plates 47 & 48

PLATES 47 & 48.

Thin sections stained with alizarin red S & potassium ferricyanide in dil. HCl. Plane polarised light.

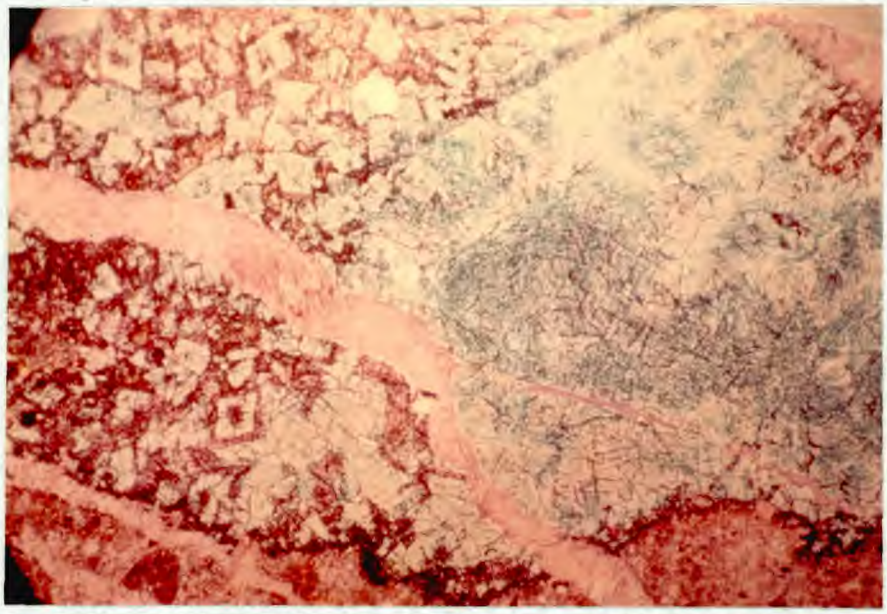


PLATE 47. Vug-infilling of coarsely-crystalline dolomite & calcite in fine-grained limestone. Lower reef horizon of Middle Ambléon Limestone at type section. Host rock (bottom right) appears reddy-mauve & is made up of mixed ferrous-iron free, and ferroan calcite. Main part of vug-infilling (right) is dolomite of varying ferrous-iron content. On the left, in the zone of weathering & dedolomitisation, rhombic zones of ferroan calcite & dolomite alternate. (X22).

PLATE 48. Cavity-filling of coarsely-crystalline calcite in fine-grained pellet limestone. Upper reef horizon of Middle Ambléon Limestone at type section. Cavity-filling crystals consist of alternating zones of ferrous-iron free calcite (light) & ferroan calcite (dark). X15.

(blue component dominant) where ferrous-iron is more concentrated. All transitions from clear red to deep purple are possible for calcite of increasing ferrous-iron content.

Photomicrographs of thin sections, which have been treated with the dual stain, are shown in plates 47 and 48.

Plate 47 shows a cavity-filling of carbonate minerals in a sample taken from the lower reef horizon of the Middle Ambléon Limestone (chapter 5). The fine-grained host rock (bottom right-hand corner of the photomicrograph) is stained a mottled red, mauve and purple. It consists of both ferrous-iron free calcite and ferroan calcite. The cavity-filling is mostly unstained by alizarin red S. In the top right-hand quarter of plate 47 a series of rhombohedral zones can be seen. These zones are each depicted in Turnbull's blue of uniform intensity. The successive rhombohedral outlines, however, are due to variations in intensity of the pigment from one zone to the next. The cavity is thus principally of ferrous-iron bearing dolomite. Certain crystals of this dolomite contain variable quantities of ferrous-iron. It is hence apparent that a crystal of ankerite, as defined by Palache, Berman and Frondel (1951) may well contain zones, ranging in composition from ferrous-iron free dolomite, via ferroan dolomite to ankerite. For this reason it is proposed that all dolomite containing any ferrous-iron should be termed ferroan dolomite. Ankerite <u>sensu stricto</u> ($CaCO_3 . FeCO_3$) is apparently unknown in nature.

Plate 48 exhibits a cavity-filling of coarse-grained calcite crystals. These crystals have all been stained by

the alizarin red S. However, certain crystallographic zones within them have also reacted to potassium ferricyanide, and thus appear dark. The crystals are hence partly of ferrous-iron free calcite and partly of ferroan calcite.

The cause of the variable iron content of the successive zones within the dolomite and calcite studied is not known. It can be seen (plate 48) that any one zone within a crystal may change its width according to crystallographic direction. This is clearly the expression of the differential rate of growth of calcite in these directions. However, irrespective of changes in width, the intensity of the stain due to the ferricyanide in any one zone does not vary. If the proportion of ferrous-iron incorporated in the calcite lattice at any one time was purely determined by the amount present in the pore fluids, the intensity of the stain should be greatest in those parts where the rate of crystal growth was slowest, i.e. where the zones are narrowest, and least in those directions where crystal growth was most rapid, i.e. where the zones are widest. It seems likely therefore that ferrous-iron was available in the pore fluids, in excess of the proportions taken into the lattice at any one time, and that one or more physico-chemical variables influenced the acceptance or otherwise of ferrous-iron into the lattice. Possible influences could have been confining pressure and temperature, which would both vary with depth of burial.

E. <u>DETECTION OF MAGNESIUM IN CALCITE.</u>

There are apparently no coloured compounds, in

which magnesium exists as a cation. For this reason no staining reagents are known for the detection of high-magnesium calcite in acid solution. Those authors, who propose an alkaline solution of alizarin red S to stain up dolomite, consider a weakly alkaline solution of this dye to be capable of staining high-magnesium calcite, but not dolomite. The unreliability of staining techniques, involving the principal of adsorption, have already been discussed in section C of this chapter.

High-magnesium calcite, found in modern echinoderms and calcareous algae, is unstable and reverts to calcite, free of magnesium with time. The magnesium thrown out is believed to be the source of magnesium in much dolomite. In the Mesozoic succession studied, dolomite occurs mainly in the bio-clastic calcarenites and reef limestones of the Ambléon Limestone, and in the reef complex of the Massive Virieu Limestone. There does therefore appear to be a relationship here between the occurrence of dolomite and the abundance of echinoderm and algal debris. Due to its instability, no significant proportion of high-magnesium calcite is believed to occur in the Mesozoic rocks of the Southern Jura.

F. DETECTION OF MANGANESE.

Manganese carbonate crystallises in the Hexagonal System like calcite and dolomite. It was thus considered possible that, like ferrous-iron, divalent manganese might occur in traces in the calcite and dolomite of the rocks studied, and that its distribution might prove interesting.

Feigl (1958) pointed out that manganous salts are oxidised in acetic acid to potassium permanganate, when treated with potassium periodate, as follows:-

$$\underset{\text{manganous salt}}{2Mn^{++}} + \underset{\text{periodate}}{5IO_4^{'}} + 3H_2O = \underset{\text{permanganate}}{2MnO_4^{'}} + 5IO_3^{'} + 6H^{+}$$

According to Feigl, large amounts of manganese may be directly detected by the purple permanganate colour. Smaller quantities are revealed by adding a solution of tetrabase (tetramethyl-diaminophenylmethane) in chloroform. An intense blue colour is formed due to an oxidation product of the tetra-base. This test was applied to several of the Mesozoic rocks of the area mapped. There was without doubt some positive reaction, but the distribution of stain was patchy and inconsistent as if once formed, the pigment had spread irregularly. Furthermore, the stain varied in colour, being blue in places and purple elsewhere. The reagents used were thus modified somewhat. Dilute hydrochloric acid was employed to liberate the manganese ions instead of acetic acid, and a solvent of carbon tetrachloride was used for the tetrabase. Under these conditions the stain took on a uniform purple colour, presumed to be due to potassium permanganate. The distribution of stain too, became more meaningful. Manganese appeared to occur in the fine-grained matrices of certain calcarenites and in the pore-fillings of echinoderm and polyzoan fragments. The reagent also stained the concentric and radial structure of ooliths, but was no-

where seen to affect the coarsely-crystalline calcite or dolomite of the rocks studied. Mr. M.C.Audley-Charles very kindly carried out a spectrographic analysis of a specimen of oolite from the Upper Ambléon Limestone, which had taken a positive stain for manganese. The bulk analysis showed the rock to contain approximately 0.02% by weight manganese.

The precise mechanism for the liberation, and staining of the manganese is not fully understood. It nevertheless seems reasonable to assume that manganese in the rock is oxidised to potassium permanganate, and that the tetrabase stabilises the stain in the presence of hydrochloric acid. Normally hydrochloric acid reacts with potassium permanganate to yield chlorine and manganese dichloride.

The purple pigment due to artificial staining was found to follow closely the distribution of iron-oxide in the rocks studied, especially in the radial and concentric structure of ooliths. It seems possible, therefore, that the iron and manganese here were deposited together, respectively as ferric hydroxide and manganese dioxide. This conflicts with the fact that the difference in redox potential between divalent iron and manganese generally causes the two elements to be segregated in the sedimentary cycle (Mason,1952), although they tend to occur together in minerals, not of sedimentary origin. It is probable, however, that the separation is incomplete, and that a small amount of manganese

dioxide is usually deposited with ferric hydroxide. It is believed that the staining reagents described above have detected such traces of manganese in the rocks studied. If this is the case, it is reasonable to conclude that the associated ferric oxide was originally deposited as the hydroxide, and that it is not the oxidation product of ferrous-iron, formerly in the calcite or dolomite of the rocks.

G. DETECTION OF CLAY MINERALS.

As has been pointed out in section C of this chapter, clay minerals generally occur in grains with colloidal dimensions. If therefore, a neutral solution of an organic dye, such as safranin or alizarin red S is applied to a rock containing clay minerals, the location of the clay will be shown up by the distribution of adsorbed red stain. This technique is well established and widely used. It is quite reliable when the reagent is employed in neutral solution. In alkaline solution, other colloids such as magnesium hydroxide interfere with the test, and in both alkaline and acid solution, certain of the clays coagulate to form large floccules, outside the colloidal range.

H. DETECTION OF FURTHER CATIONS.

Applications of staining techniques to the study of carbonate petrology are presented in chapters 19 and 20. These applications show that, if the distribution of trace cations in limestones can be exposed, they can be used to explain many limestone textures and to elucidate certain

cementation histories. It is suggested for future study, that limestones showing interesting textures should first be analysed spectrographically in order to determine the trace cations present. Staining techniques should then be developed to illustrate the distribution of these cations.

I. THE USE OF CELLULOSE PEELS WITH CHEMICAL STAINS.

It is well known that many of the grain-to-grain textures in carbonate rocks may be studied from cellulose peels. Polished hand specimens are etched in 0.2% hydrochloric acid for about 1 minute. They are then washed first in water and then in acetone. After allowing them to dry out, the etched surfaces are covered with fresh acetone. A sheet of cellulose is smoothed down on top of each surface, so that the formation of bubbles is prevented. The relief of the etched rock surface is preserved on the cellulose, which dissolves where relief is high, and concentrates in a solution of acetone where relief is low. The cellulose is allowed to dry out, preferably over-night, but in any event for at least 20 minutes, after which time most of the acetone will have evaporated. The sheet of cellulose is then peeled off, and examined with unpolarised or plane polarised light. All the stains, described in previous sections of this chapter, peel off satisfactorily on sheets of cellulose, except that for trace manganese. In this case the acetone appears to react in some way with the tetrabase, so that a smeared blue-purple stain results.

CHAPTER 19.

DEDOLOMITISATION.

A. GENERAL

Certain of the calcarenites and reef limestones of the Ambléon Limestone , and calcilutites of the Oignon Beds have been found to contain calcite, which has replaced dolomite. The replacement process is known as dedolomitisation.

The history of the use of the term "dedolomitisation" was reviewed by Shearman, Khouri and Taha (1961). The present author uses it, like them, in the sense in which it was originally applied by von Morlot (1848), and not in the metamorphic meaning of Teall (1903). Von Morlot had pointed out that the reaction of magnesium sulphate on calcite to form dolomite is theoretically in equilibrium with a reverse reaction of calcium sulphate on dolomite to give calcite. He termed the reverse process "dedolomitisation". The equation below indicates how the reaction might proceed.

$$CaSO_4 + MgCO_3.CaCO_3 \underset{\text{dolomitisation}}{\overset{\text{dedolomitisation}}{\rightleftharpoons}} 2CaCO_3 + MgSO_4$$

Three petrographic textures of dedolomitisation were described by Shearman, Khouri and Taha (op. cit.) from the Mesozoic limestones of the southern French Jura. Each appears to occur at a distinctly separate stratigraphical level. It is probable that the difference in texture is due to the contrasting sedimentary types, which exist at each of these levels. The textures described by Shearman, Khouri and Taha have been found at the same horizons in the area

mapped by the present author. In addition, however, two new replacement textures have been observed, occurring in the Ambléon Limestone (Evamy, 1963) and Oignon Beds. The stratigraphical column in the area thus exhibits a great variety of dedolomitisation textures.

Tatarskiy (1949) reported that dolomite in the Carboniferous of the Russian platform is superficially replaced by calcite. Borehole samples showed that at depth the dolomite is unaltered. Khvorova (1958) considered that salts, washed from the Lower Permian strata, had brought about this superficial dedolomitisation. Evidence in favour of von Morlot's mechanism for dedolomitisation comes from an observation by Tatarskiy that certain of the Russian dedolomitised limestones show a seasonal efflorescence of epsomite, which is washed away in the rainy season. As concluded by Tatarskiy, it would appear that dedolomitisation is here taking place at the present day. Shearman, Khouri and Taha (op. cit.) pointed out that calcium sulphate solutions, derived from the "Purbeckian" lagoono-lacustrine complex of the Jura, could have been available to bring about dedolomitisation, and that also suitable solutions could have been mobilised from the underlying Triassic evaporites. The present author agrees that the widespread replacement of dolomite by calcite at the horizons studied by Shearman, Khouri and Taha was probably caused by calcium sulphate solutions derived from Triassic or "Purbeckian" evaporites. The replacement textures, studied in detail by the present writer,

however, are believed to have been caused by the action of calcium or possibly iron sulphate solutions, derived locally from the oxidation of pyrite (Evamy, 1963).

B. THE DEDOLOMITISING AGENT.

Certain of the coarse bioclastic calcarenites of the Ambléon Limestone contain numerous aggregates of brassy yellow pyrite. These aggregates normally measure up to 2mm. across, whilst the individual crystals forming the aggregates are approximately 20 μ in size.

Some of the limestones studied, and in particular those of the Oignon Beds, exhibit blue hearts surrounded by buff envelopes (plate 22). The envelopes are believed to have resulted from the weathering of the rock along joint and bedding planes. Polished surfaces and thin sections of the blue hearts are seen to be riddled with tiny blue to black spots (8-35 μ across). Since these spots are not found in the outer buff envelopes, it seems likely that they cause the colour of the blue hearts. The fossiliferous limestones of the Chavoley Beds are also blue-hearted. Here the fauna is preserved in coarsely-crystalline pyrite. Small aggregates of pyrite also occur in the Oignon Beds. The association of blue-hearted limestone with pyrite has led the author to believe that the tiny blue spots in the Oignon Beds consist of finely-granular pyrite. This belief was later substantiated by the knowledge that the spots have apparently weathered to yield the oxidation products of

pyrite. The calcarenites of the Ambléon Limestone, which yield coarsely-crystalline aggregates of pyrite also show dark central cores, surrounded by buff envelopes. However, this is less noticeable than in the Oignon Beds.

Palache, Berman and Frondel (1944) pointed out that pyrite oxidises readily to the various iron sulphates, and then subsequently to limonite and finally to haematite, the end product of the reaction. The so-called "gossan" or ferruginous crust found on pyrite minerals is formed in this way. Sulphuric acid, generated in the oxidation process, is believed by these authors to play an important role in sulphate mineralisation elsewhere. The oxidation reaction of pyrite may be represented as follows:-

$$2\ FeS_2 + 4H_2O + 15\ [O] = Fe_2O_3 + H_2SO_4$$

In a calcareous medium, the free sulphuric acid would become neutralised to calcium sulphate. No doubt some ferrous sulphate would also be carried over in the reaction.

It is believed that weathering solutions, percolating along bedding and down joint planes, superficially oxidised the blue-hearted limestones of the succession. Granules of pyrite, formerly in the weathered envelopes, are thought to have become altered to finely-disseminated haematite, which could now cause the buff colour of these zones. Some of the coarser aggregates of pyrite persist in the outer buff envelopes, where they have a coating of haematite. Clearly these were only superficially oxidised. This was presumably because the finer granules had a greater surface

area per unit volume than the coarser aggregates. Consequently the oxidising agents had more intimate contact with the finer grains.

During the oxidation of pyrite by weathering, therefore, a reagent (calcium sulphate) was liberated which, according to von Morlot's equation, is suitable for bringing about dedolomitisation.

C. THE DOLOMITE AND "DEDOLOMITE".

At certain horizons, dolomite occurs in rocks which have central blue, and apparently pyritic cores, and outer buff envelopes. If dedolomitising solutions had been set free by the superficial oxidation of the pyrite, then the dolomite should be confined to the central unweathered zones, and textures of calcite after dolomite (or "dedolomite") should be found in the outer weathered envelopes. This is indeed the case.

The dual stain, described in chapter 18, has revealed much ferroan dolomite in the pyritic limestones of the Ambléon Limestone. The blue hearts of these limestones are dolomitised, whilst their buff envelopes display no dolomite. Transitions between the two zones are normally sharp. In certain cases, however, they are more fully represented. The cavity filling of ferroan dolomite, shown in plate 47, lies across the zone between weathered and unweathered regions of the rock. The right-hand side of plate 47 shows the unweathered part, containing unaltered ferroan dolomite. On the left-hand side, where the weathered zone

begins, is a region showing rhombic zones of ferroan calcite (red-mauve) within ferroan dolomite crystals (light blue). In addition to the mauve colour, artificially given by the staining reagent, the ferroan calcite is characterised by a natural, and heavy brown pigment of iron-oxide.

In completely weathered regions, whole crystals of iron-oxide stained calcite occur without any ferroan dolomite. These crystals of calcite resemble, in size, the ferroan dolomite crystals, characterising the unweathered rock. Both types of crystal exhibit undulose extinction. Where rhombic zones of calcite exist within ferroan dolomite, the extinction wave passes uninterruptedly through calcite and dolomite alike. The zones are thus in optical continuity. It appears, therefore, that either the ferroan dolomite is secondary to the iron-oxide stained calcite, or that this calcite has replaced the ferroan dolomite. The transitions from dolomite to calcite parallel the changes from pyritic, unweathered zones to haematite-bearing, weathered envelopes. These changes involve the liberation of calcium sulphate, a potential dedolomitising agent. The transitions are thus inferred to be due to dedolomitisation, rather than dolomitisation.

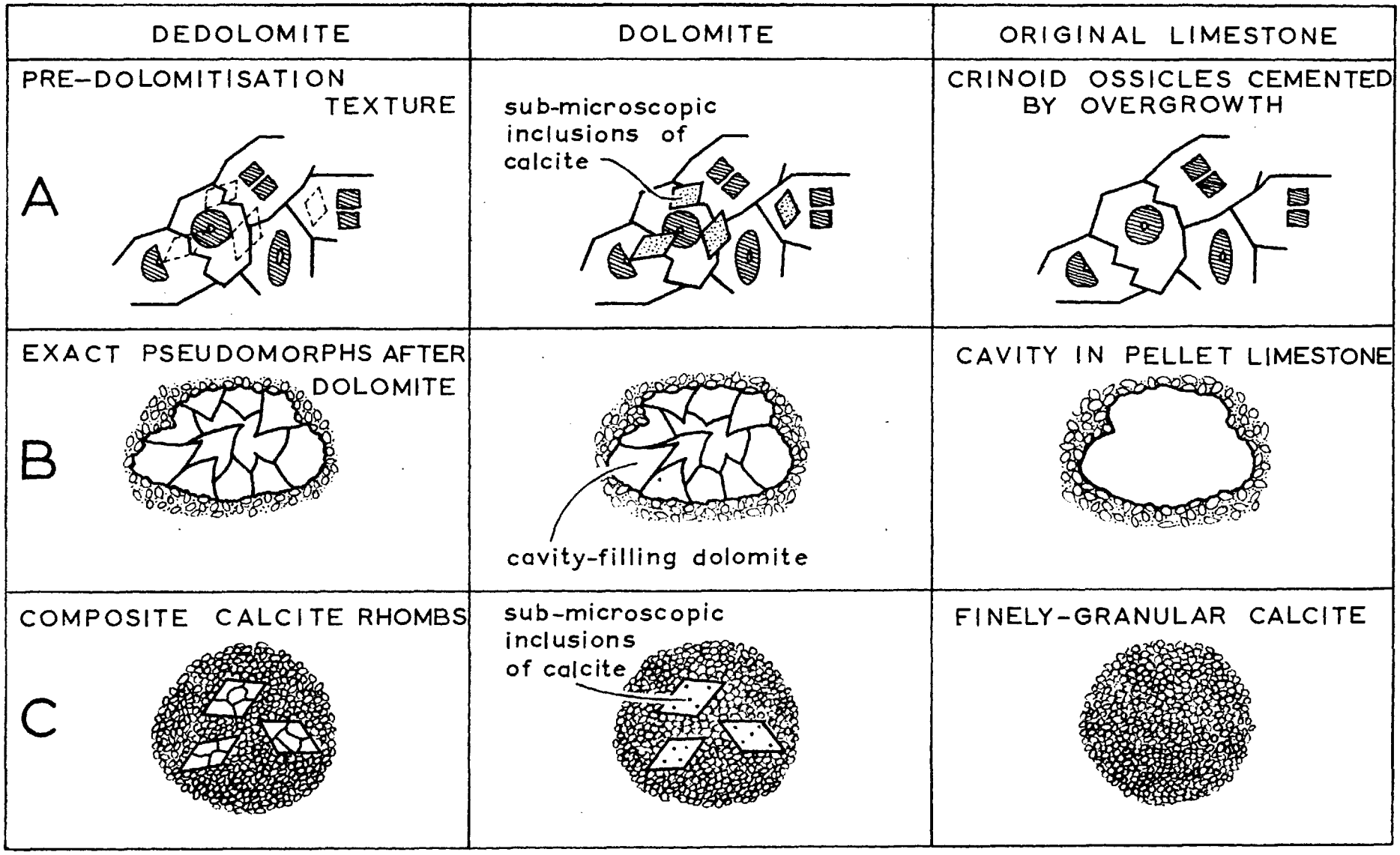
The superficial iron-oxide stain, which here characterises the calcite after ferroan dolomite, does not occur over unaltered ferroan dolomite, or other types of calcite. The distribution of the iron-oxide may be explained in terms of the replacement of ferroan dolomite by calcite.

The ionic radius of ferrous-iron lies between the ionic radii of calcium and magnesium, but nearer to that of magnesium. (Ca^{++}: 0.99Å; Fe^{++}: 0.74Å; Mg^{++}: 0.66Å; values after Ahrens,1952). It is hence reasonable to assume that ferrous-iron will substitute for magnesium ions in dolomite more readily than it will for calcium ions in calcite. Thus the concentration of ferrous-iron in dolomite may be in excess of the amount required to saturate a calcite lattice. During dedolomitisation, this excess of ferrous iron would be ejected and, under certain physico-chemical conditions, would be readily precipitated as colloidal ferric hydroxide. The ferric hydroxide would dehydrate to form iron-oxide, which would then permeate the cleavages of the crystals of the new generation of calcite (Evamy, 1963).

Dolomite rhombs have been found in some of the blue-hearted limestones of the Oignon Beds (chapter 8). Where dolomitised at all, these limestones exhibit dolomitised blue hearts. The buff envelopes too are commonly dolomitised. In a number of specimens, however, just the blue hearts exhibit dolomite. Never have the buff envelopes been seen preferentially dolomitised. It is believed that the same parallelism exists here, between pyrite oxidation and dedolomitisation, as found in the Ambléon Limestone. In the examples where dolomite is confined to the central blue hearts of the Oignon Beds, no obvious replacement textures have been seen in the outer buff envelopes. The change from dolomite to calcite nevertheless appears to be one of de-

FIG. 42

TEXTURES OF DEDOLOMITE RELATED SCHEMATICALLY TO THOSE OF DOLOMITE AND OF THE ORIGINAL LIMESTONE



dolomitisation, since a narrow transition zone exists involving the original rhombs in all stages of peripheral corosion. The replacement calcite is indistinguishable from the undolomitised calcilutite of the Oignon Beds, and it is for this reason that there is an apparent absence of any replacement textures. In this case, therefore, dedolomitisation seems to have regenerated the pre-dolomitisation texture of the limestone.

D. POSSIBLE ORIGIN OF DEDOLOMITISATION TEXTURES.

(i) Introduction.

The two contrasting textures of "dedolomite", described in section C of this chapter, are believed to have resulted from the reaction between dolomite and the same reagent (calcium sulphate), liberated from the rock in the same way (oxidation of pyrite in a calcareous medium). The texture of "dedolomite" thus appears not to be related to the chemistry of the dedolomitising agent.

The textures of "dedolomite" described by Shearman, Khouri and Taha (1961), and by the present author appear to fall into three groups (see fig.42). These are:-

(a) "dedolomites", which exhibit pre-dolomitisation textures of the limestone.

(b) "dedolomites", which are the exact pseudomorphs of the earlier dolomite.

(c) "dedolomites", which appear as composite calcite rhombohedra.

It is considered that these textural groups are

related firstly, to the pre-dolomitisation texture of the limestone (where present), and secondly to the intensity of the rock's subsequent dolomitisation.

If a rock specimen is stated to exhibit a transition from calcite to dolomite, it is inferred that a gradual increase in the proportion of dolomite rhombs, from 0-100%, has been observed. Generally, all dolomite rhombohedra involved in any one transition zone appear to have approximately the same dimensions. The size of the rhombs is not, for example, seen to increase progressively as the rock becomes more heavily dolomitised.

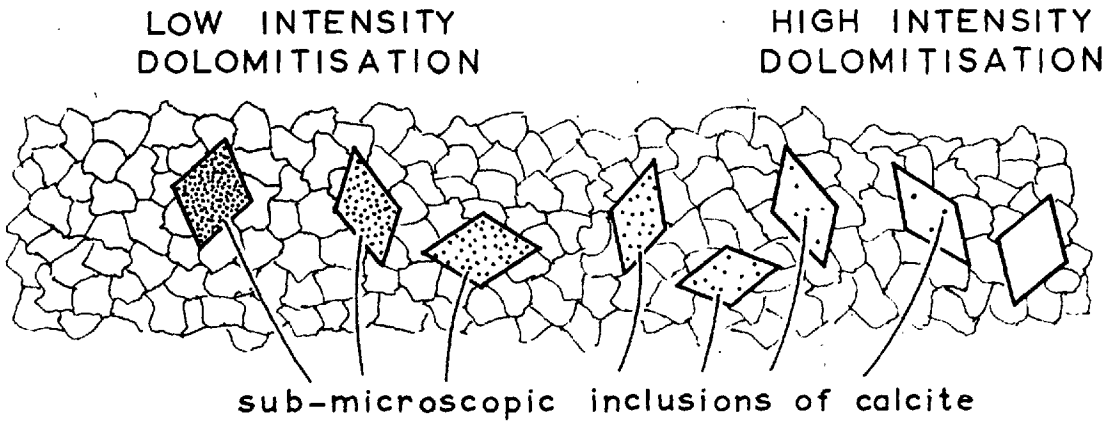
Whereas transitions involving the change from calcitic to dolomitic limestones are common, no transitions are known to show the development of dolomite rhombohedra. These are generally believed to represent small volumes in the rock, where the mineral dolomite exists to the absolute exclusion of calcite. Since a rhomb does not gradually increase in size in dolomitisation transitions, the formation of the rhombic crystal boundaries to dolomite must occur very suddenly. If these crystal boundaries immediately enclose 100% of the mineral dolomite, then the process of dolomitisation must take place in a series of jerks, rather than in the smooth way characteristic of normal chemical reaction.

(ii) <u>Development of dolomite rhombohedra.</u>

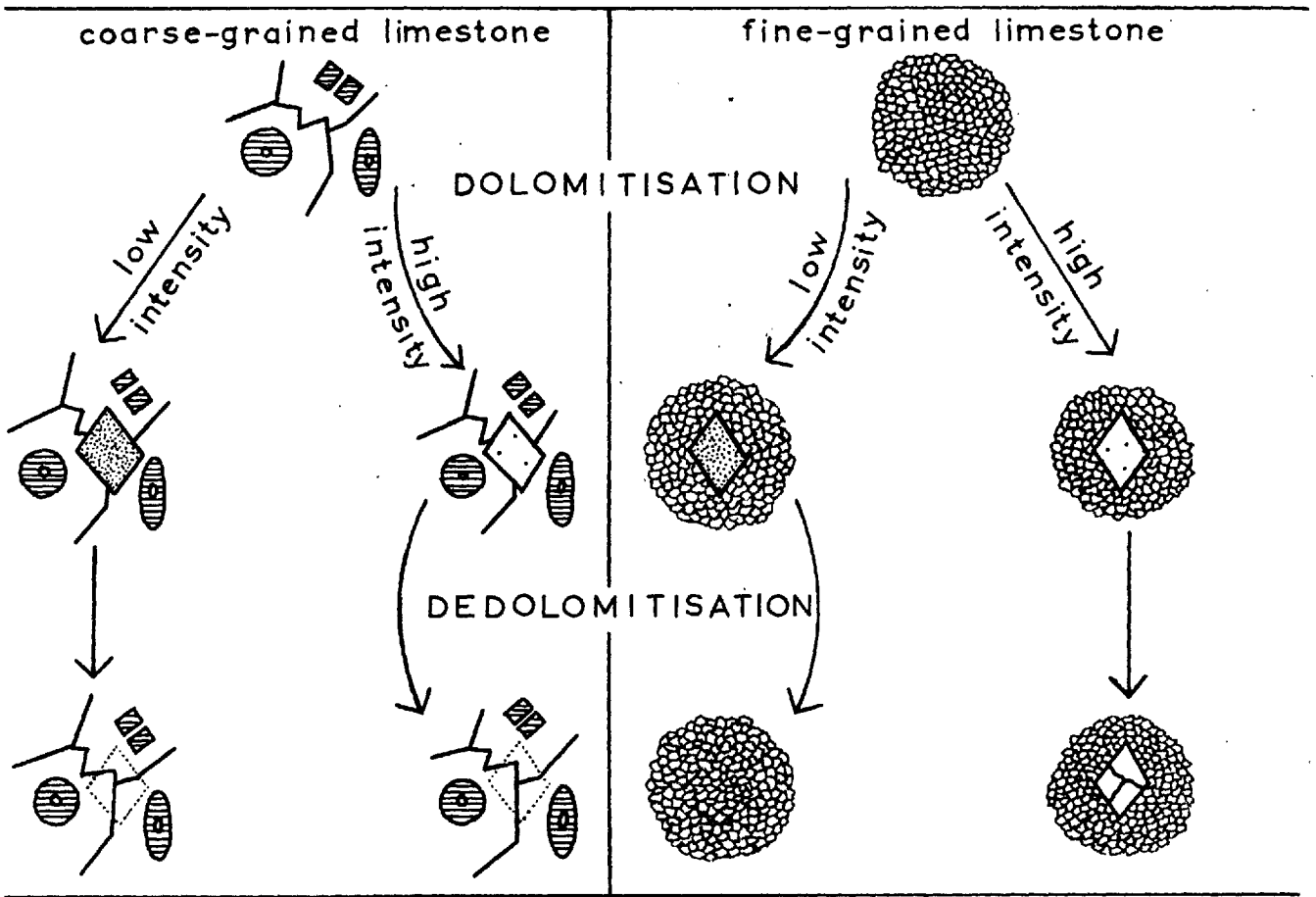
It is proposed here that there might be a complete transition from 100% calcite to 100% dolomite in the formation of a single dolomite rhombohedron (see fig.43A). This hypo-

FIG. 43

A TRANSITION FROM CALCITE TO DOLOMITE (HYPOTHETICAL)



B DEDOLOMITE TEXTURES RELATED TO ORIGINAL GRAIN-SIZE & INTENSITY OF SUBSEQUENT DOLOMITISATION



regeneration of the pre-dolomitisation texture

production of composite calcite rhombs

thesis is made principally in order to explain the various textures of "dedolomite" found in the southern French Jura.

An initial stage in the development of a "dolomite" rhomb could be the local, but partial replacement of the original calcite grains in the limestone by the mineral dolomite. Dolomite is crystalloblastic, and normally exists in euhedral rhombic crystals. It is suggested that dolomite, only partially replacing calcite, may immediately take on rhombic crystallographic boundaries. Such rhombs could consist predominantly of calcite, disposed as minute, sub-microscopic inclusions within the dolomite lattice (fig.43A). Further replacement of calcite by dolomite could take place at the margins of the inclusions and could gradually reduce their number within the dolomitic rhombs. Ultimately the replacement could altogether eliminate the calcite nuclei, so that rhombohedra containing 100% dolomite are produced. The term "intensity of dolomitisation" is here chosen to indicate the ratio of dolomite to calcite, existing in a given dolomitic rhombohedron (fig.43A). Low intensity dolomitisation suggests the presence of abundant calcite inclusions within the dolomite lattice, whilst high intensity dolomitisation indicates that the mineral dolomite exists almost to the entire exclusion of calcite within a given rhomb.

At any stage in the complete dolomitisation of a specific rhomb, the inclusions of calcite in the dolomite lattice are considered to have a uniform distribution. At the commencement of dolomitisation, it is probable that each

calcite grain in the original limestone is represented by a number of these minute inclusions (fig.43A). The actual number of inclusions, derived from each former particle of calcite, depends upon the grain size of the original limestone. The coarser the particle size, for a given intensity of dolomitisation, the greater would be the number of inclusions derived from each original grain. In some cases, the original limestone might have been so fine-grained that only a single inclusion of calcite could be derived from each former calcite particle. Here the replacing dolomite could have initially acted as a mere cement, poikilitically enclosing the former calcite grains. It is significant, in this connection, that certain textures of "dedolomite", described by Shearman, Khouri and Taha (op. cit.) apparently resulted from a precisely analogous mechanism. These authors showed fine-grained dolomite rhombs to have been poikilitically cemented by larger anhedral calcite crystals. The cementing calcite is demonstrated by them to have encroached marginally upon the dolomite rhombs, ultimately entirely replacing them.

(iii) The dedolomitisation textures explained.

The possible origin of the three textural groups of "dedolomite" may now be analysed in terms of the hypothesis that a full transition exists in the development of a single dolomite rhombohedron.

(a) Pre-dolomitisation texture.

The calcite inclusions, suggested to occur within many dolomites, could well act as centres of crystallisation for a new generation of calcite, brought about by dedolomitisation. These inclusions, or nuclei have the lattice orientations of the calcite grains in the original limestone. If each grain of the former limestone is represented by at least one calcite inclusion in the subsequently formed dolomite lattice, then dedolomitisation could regenerate the pre-dolomitisation texture of the rock (see fig.42A). It is clear from fig.43B that the likelihood of the pre-dolomitisation texture being regenerated, is directly proportional to the grain size of the original rock, and indirectly proportional to the "intensity of dolomitisation". The regeneration of the pre-dolomitisation texture in the fine-grained Oignon Beds thus indicates very "low intensity dolomitisation". It should, therefore, be possible, for future study, to test the hypothesis by determining whether the Ca /Mg ratio of the dolomite in the Oignon Beds is unusually high.

(b) Exact pseudomorphs of the earlier dolomite.

Clearly a pre-dolomitisation texture could have had little influence over the production of exact pseudomorphs of calcite after dolomite. It is hence believed that the connection between the original and subsequent generations of calcite must either never have existed, or have been severed during dolomitisation. This indicates:

Primary dolomitisation in either, which case there would have

been no pre-dolomitisation texture.

or,

Dolomitisation after a mineral, other than calcite, for example aragonite.

or,

Maximum intensity dolomitisation after calcite, in which case all relics of the former limestone texture would have been removed.

It has been indicated that the ferroan dolomite crystals of the Ambléon Limestone have the same size and undulose extinction as the crystals of "dedolomite". Here, therefore, dedolomitisation has yielded exact pseudomorphs after the earlier dolomite. The ferroan dolomite of the Ambléon Limestone seems to have infilled former cavities in the rocks (plate 47), and is in a sense primary dolomite. It is believed that for this reason there was no regeneration of a former limestone texture during dedolomitisation (see fig.42B).

(c) Composite calcite rhombohedra.

The "intensity of dolomitisation" may have reduced the number of calcite inclusions in a rhomb, so that not every original calcite grain is represented, (fig.42C). The inclusions remaining would thus have a wider separation than if all the original grains had been represented. During dedolomitisation, the replacement calcite would grow in lattice continuity with the inclusions, and would produce a coarser mosaic than the original, pre-dolomitisation texture of lime-

Plates 49 & 50.

PLATES 49 & 50.

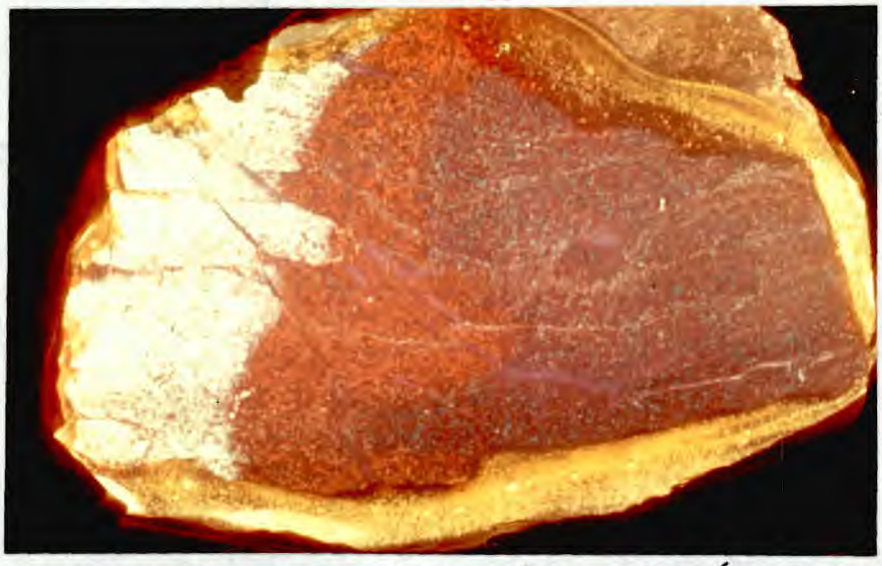


PLATE 49. Chert-bearing calcarenite, Lower Ambléon Limestone at type section. Hand specimen stained with alizarin red S & potassium ferricyanide in dil. HCl. Host rock (right) contains ferroan dolomite (stained blue). This is separated from the chert (left) by a narrow zone of coarsely-crystalline calcite with a natural & heavy brown stain of iron-oxide. Reflected light. (X 2 1/3).

PLATE 50. Sequence of thinly-bedded dolomite (about 4m). capped by a thicker bed of calcilutite, Lower Parves Beds, Rossillon (Ain). Joint in bed of calcilutite passes down into a wide fissure in the bedded dolomite. Next to the fissure, the dolomite has been replaced by calcite.

stone. Thus the sites of former dolomite rhombs would become occupied by composite calcite rhombohedra, such as were illustrated by Shearman, Khouri and Taha (op. cit).

E. SILICIFICATION AND DEDOLOMITISATION.

The "dedolomites", described in section C of this chapter have resulted from the oxidation of pyrite caused by weathering. In the rocks exhibiting "dedolomite" in the Ambléon Limestone, an earlier phase of dedolomitisation, associated with silicification, can often be recognised.

Chert nodules are common at certain levels in the Ambléon Limestone. Over thin, or polished sections of these rocks, silicified and unsilicified areas are observed to be separated by narrow transitions, measuring 1.5mm. or less across (plate 49). The host rocks often contain ferroan dolomite and pyrite, but these minerals occur neither in the cherts, nor within a narrow band (5-16mm), immediately surrounding the silicified zones. The zone enclosing the chert is characterised by coarsely-crystalline, and haematite-stained calcite (plate 49). Calcite with these characteristics has already been recognised as the product of dedolomitisation of ferroan dolomite. Outside the "dedolomite" envelopes come areas bearing unaltered ferroan dolomite and pyrite. In plate 49 the ferroan dolomite of the bulk of the rock is stained blue by the dual stain, described in chapter 18.

In thin section many of those rocks are seen to contain detrital quartz, disposed in cross-laminations. In the chert nodules, sponge spicules appear to be aligned

parallel to these foreset laminae. Sponge spicules are absent in the unsilicified zones. It appears that the spicules were deposited as detrital grains throughout the sediments. It seems that subsequently they were removed from the zones, not occupied by chert. It is probable that the silica was taken into solution by the connate waters. It is interesting that the locations of the chert nodules were apparently pre-determined, for in these zones alone are the siliceous sponge spicules preserved.

Sulphuric acid, liberated during the oxidation of pyrite, is considered to have been the active dedolomitising agent in the rocks of the Ambléon Limestone. Centres of oxidation, the origins of which remain uncertain, are thought to have existed in the zones now occupied by chert nodules. The sulphuric acid generated was probably never isolated, since it was able to become neutralised immediately by dissolving calcite. However, the pH in the original oxidation centres is considered to have been lowered sufficiently to precipitate much of the silica, re-distributed from the original sediment by the connate waters. Whence it is proposed that carbonate was removed in solution, whilst silica was physico-chemically precipitated to form the chert nodule. The outer margin of the chert nodule represents the limit of complete solution of carbonate. Beyond this, any sulphuric acid generated was entirely neutralised to calcium sulphate.

Unlike calcite, dolomite is unstable in the presence of calcium sulphate solutions, and undergoes dedolomitisation

until the sulphate is dissipated. Thus an envelope of "dedolomite" surrounds the chert nodule, separating it from the main part of the rock, where unaltered pyrite and dolomite co-exist (see plate 49). The fact that the active dedolomitising agent, presumed to be calcium sulphate, has no effect on calcite may be demonstrated in the field. Plate 50 shows part of the sequence of bedded, fine-grained dolomites and calcilutites, found in the Lower Parves Beds near Rossillon. In the photograph, a bed of calcilutite is seen capping a band of dolomite. Joints in the calcilutite pass down into relatively wide fissures, which have opened out into the dolomite. The rock adjacent to these fissures is entirely dedolomitised. Farther away laterally, full transitions may be found into unaltered fine-grained dolomite. Here it appears that dedolomitising solutions passed along original planes of weakness in the rocks, that is down joints and along bedding planes. Where in contact with dolomite, chemical reaction took place and the planes of weakness were widened. Since calcite is stable to such reagents however, the joints through the calcilutites remained unaffected.

The complete solution of dolomite by sulphuric acid may be represented by the following equation:-

$$2H_2SO_4 + MgCO_3 . CaCO_3 = MgSO_4 + 2H_2CO_3 + CaSO_4$$

The above reaction is considered to proceed in two distinct stages.

(i) Dedolomitisation.

$$CaSO_4 + MgCO_3 . CaCO_3 = MgSO_4 + 2\ CaCO_3$$

(ii) Calcite Solution.

$$CaCO_3 + H_2SO_4 = H_2CO_3 + CaSO_4$$

Calcite, the insoluble product of equation (i) is attacked by sulphuric acid following equation (ii). The calcium sulphate yielded is available for further dedolomitisation according to equation (i).

In the rocks studied, the solution of dolomite is considered to have progressed by way of an outer front of dedolomitisation, followed by a wave of calcite solution and physico-chemical precipitation of silica. These fronts of chemical change are represented in the rocks respectively by the narrow zone of "dedolomite" and by silicified nodules themselves (plate 49). Thus it appears that dedolomitisation is a transitory phase in the mechanism, whereby sulphuric acid dissolves dolomite.

CHAPTER 20.

ON THE DEVELOPMENT OF OVERGROWTHS FROM ECHINODERM FRAGMENTS. 1.

A. INTRODUCTION.

A study of the calcarenites of the Ambléon Limestone (chapter 5) has yielded important information concerning the cementation of echinoderm debris by calcite.

The separation and fragmentation of the calcitic structures of echinoderms provides the most consistently identifiable skeletal component of the bioclastic limestones. This ease of recognition, both in hand specimen and thin section, rests largely on the fact that each fragment is characteristically preserved as a single crystal of calcite.

Echinoderm debris may occur in two contrasting types of limestones. In the one, it appears to have accumulated, often with other skeletal fragments and ooliths etc., to form carbonate sand, free of any interstitial fine-grained materials. These various components have been subsequently cemented together by a coarsely-crystalline mosaic of calcite.

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1. The author would like to record special thanks to Mr. D.J.Shearman for his many stimulating ideas and general encouragement while this topic was being investigated, and also for his assistance in preparing the manuscript of this chapter. Some of the findings presented here have already been demonstrated to the Geological Society of London (Evamy & Shearman, 1962) and it is hoped that the contribution will be published in full in due course.

In the other, the skeletal fragments etc., are set in a groundmass of microcrystalline calcite. In both these settings the echinoderm fragments may each be surrounded by a rim of calcite which is in optical continuity with the host fragment. In the first, there is little doubt that the overgrowths grew freely out into open pore-spaces and can be described as a true cement. There has been some uncertainty about the origin of the overgrowths in the second type of limestone. Bathurst (1958), describing Dinantian limestones from Northern England, interpreted them as having been produced by the replacement of the fine-grained matrix. He suggested that the replacement took place by the solid-state process of grain growth. In the area studied by the present author, the mixed bioclastic and oolitic calcarenites at the top of the Ambléon Limestone contain echinoderm debris with overgrowths embedded in a fine-grained matrix. These overgrowths are shown not to have had a replacement origin, but to have formed during an early phase of cementation. It is demonstrated that the matrix here was not a primary component of the rock, but was introduced into the pore-spaces subsequent to the early phase of cementation.

Although the overgrowths around echinoderm debris are apparently simple structures, they have had, in the rocks described, complex diagenetic histories. These complexities have been made apparent by the identification of iron-bearing and iron-free zones within the calcite of the overgrowths by the use of staining techniques. It will be demonstrated that the crystallographic orientation of the calcite of an echino-

derm fragment, in relation to its morphology, plays an important role during the development of the overgrowth. For this reason a brief review of the orientation of the calcite in echinoderms is necessary before the main discussion on the cementation of echinoderm debris.

B. CRYSTALLOGRAPHY OF ECHINODERM DEBRIS.

Echinoderms stand apart from all other groups of organisms which secrete calcium carbonate in the make-up of their skeletal structures. Each plate, spine and ossicle consists of a single, relatively large, crystal of calcite which in life is sponge-like, being ramified by a network of minute canals.

Cayeux (1916 & 1935) gave useful and comprehensive reviews of the crystallographic and morphological features of most of the classes of the phylum. Sorby (1879) appears to have been the first to observe that the principal crystallographic axis of the calcite of each skeletal element is symmetrically related to its morphology. He found that the c- crystal axis was approximately coincident with the long axes of echinoid spines, and in the specimens studied by him, perpendicular to the surface of the plates. Amongst subsequent work on echinoderm crystal orientation, Raup (1959) made a detailed study of Recent and fossil regular echinoids. He found that in these, the c- crystal axes are either parallel to, or normal to the surfaces of the plates of the test. The only exceptions which he found occurred in two species of regular echinoids which show an ontogenetic variation in the

orientation of the calcite of the coronal plates. In the calcarenites of the Ambléon Limestone, which are the subject of the present study, crinoid ossicles have their c- crystallographic axes parallel to the vertical morphological axes. On the basis of the information available, it seems that in the majority of instances at least, the principal crystallographic axis of any echinoderm skeletal element is geometrically simply related to its morphology.

Although echinoderm fragments can easily be recognised in general terms in thin section studies, ossicles can consistently be identified, because they are normally preserved relatively intact (Cayeux, 1916 & 1935). Many crinoidal limestones show cross-bedding, suggesting deposition in environments of strong current action. Ossicles may show evidence of abrasion, and many have calcareous encrustations on their articulating surfaces. These features suggest that a relatively long interval of time may elapse between dis-articulation and final burial. The ability of ossicles to resist fragmentation no doubt results from the combination of their low effective density and shape (Sorby, 1908). Because of this tendency to retain their original form, it is not difficult in thin section studies to determine their morphological and crystallographic orientations relative to the plane of the thin section. The morphological orientation can be determined by observations on the shape of the outline of the ossicle, the shape of the trace of the central canal, and the pattern shown by the network of minor canals. The critical vertical

and transverse sections can usually be identified with absolute confidence, but the orientation of oblique sections can only be assessed in general, but nevertheless, useful terms. The direction of sections through echinoid spines can similarly often be determined, but those through plates of tests and calyces are commonly difficult to assess.

C. CEMENTATION BY OVERGROWTH.

(i) General.

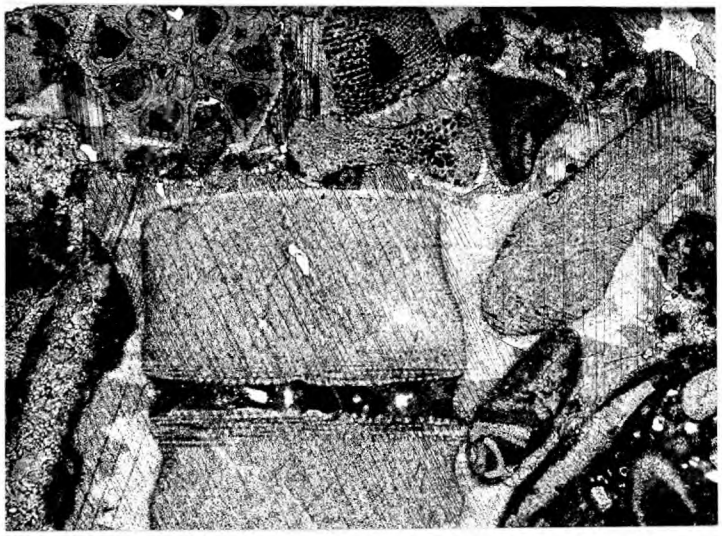
It has long been known that cementation around echinoderm debris is usually achieved by enlargement of the calcite crystals of the original fragments. This appears to have been observed first in hand specimen as early as 1826 by Hessel. In thin section the lattice continuity between the crystal of the detrital fragment and its overgrowth is shown by the fact that under crossed polars they extinguish as a single entity.

Cementation in lattice continuity involves not only the development of the overgrowth, but also in many cases, the infilling of the canals. In some fragments no trace of the canal system can be seen, and it is reasonable to suppose that in these, the canal walls were clean and free from impurities. Similarly, where the surface of the fragment was also clean, little distinction can be made between the original fragment and the overgrowth. Usually, however, impurities outline part of the canal system or parts of the surface of the fragment. These impurities may occur as minute dark specks of uncertain origin, whilst in some rocks the canal system may be

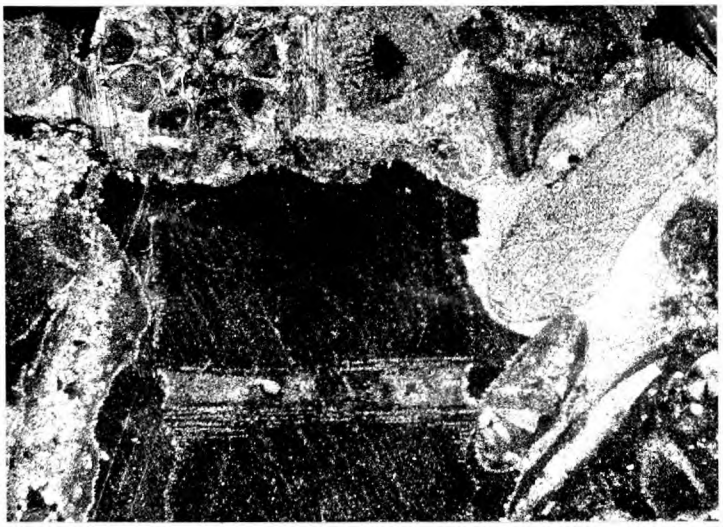
Plate 51

PLATE 51 A & B.

Crinoidal limestone from Bioclastic Calcarenite Sequence of Middle Ambléon Limestone at type section. Thin section stained with alizarin red S & potassium ferricyanide in dil.HCl.(X40).



A. Plane polarised light: Minor canals of ossicles partially filled with microcrystalline calcite. Inner iron-free zones of overgrowths (light) are wide & serrated away from articulating surfaces of ossicles; they are narrow&of constant width parallel to the lateral margins of the host grains.

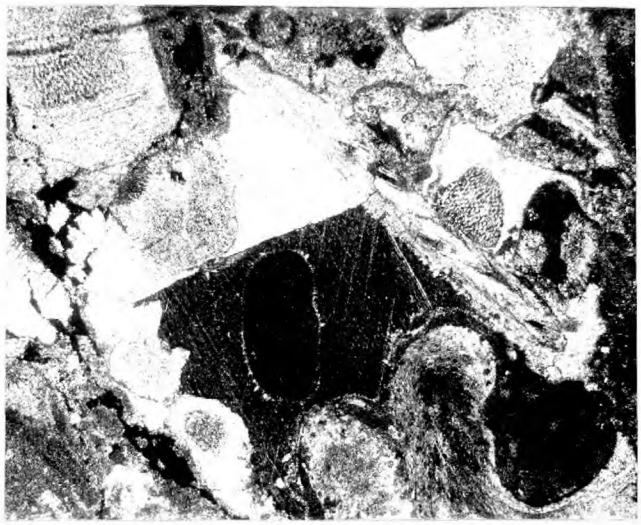


B. Crossed polars: Fringes of minute calcite crystals surrounding ossicles best seen when host is extinguished. This is because the interference colours of the minute crystals stand out best against a dark background. Compromise boundary between overgrowths is in part serrated and in part simple, according to directions of growth from host ossicles.

be clearly defined by an infilling of glauconite, ferric oxides or occasionally chalcedony. In the rocks studied, the most common canal infilling is a mosaic of very fine-grained calcite. This becomes most apparent by its interference colours when the calcite of the fragment is brought to a position of extinction under crossed polars. Characteristically this fine-grained infilling does not extend throughout the whole of the canal system. In vertical sections through ossicles (see plates 51 & 53) it commonly occurs infilling the canals near the upper and lower surfaces, and extends to greater depths along some canals than along others. This distribution suggests that it is an infilling of microcrystalline carbonate mud introduced from outside, and not a growth of a polycrystalline mosaic precipitated within the canals. Where this fine-grained infilling to the canals occurs, the outline of the fragment is usually delineated by a narrow fringe of minute calcite crystals (plate 52) which is enclosed within the overgrowth. It can often be seen that the fringe is not continuous all around the fragment, but that it only occurs where the canal entrances are filled with calcite mud. The crystals of the fringe have grown out from this poly-crystalline surface, whereas the large crystal of the overgrowth has grown out from the intervening clean surfaces of the fragment, which generally occur between the canals. Occasionally particles of calcite mud or irregular patches of fine-grained calcite, reminiscent of organic encrustations, have adhered to the surface of the fragments (plate 53).

Plate 52.

PLATE 52.



Crinoidal limestone from Bioclastic Calcarenite Sequence of Middle Ambléon Limestone at type section. Thin section unstained. Echinoderm fragment at extinction is seen to be rimmed by minute calcite crystals which are completely enclosed by an overgrowth in optical continuity with the host. A variety of different types of compromise boundaries between overgrowths are to be seen, straight, curved and serrated. Crossed polars, (X30).

Unless these completely invest the surface they do not inhibit the formation of the overgrowth.

(ii) Boundaries between overgrowths.

When seen in thin section the boundaries between the crystals of adjacent overgrowths are variable in outline. The traces of the boundaries may be long and straight, saw-toothed or occasionally curved (plate 52). Often the trace of a boundary between two overgrowths changes along its length, being straight in one part, but serrated or curved in another (plate 51B). It is difficult at first sight to see the cause of the various types of boundaries, but it will be shown later that they are related to the crystallographic and morphological orientation of the adjacent fragments.

(iii) Poikilitic cementation.

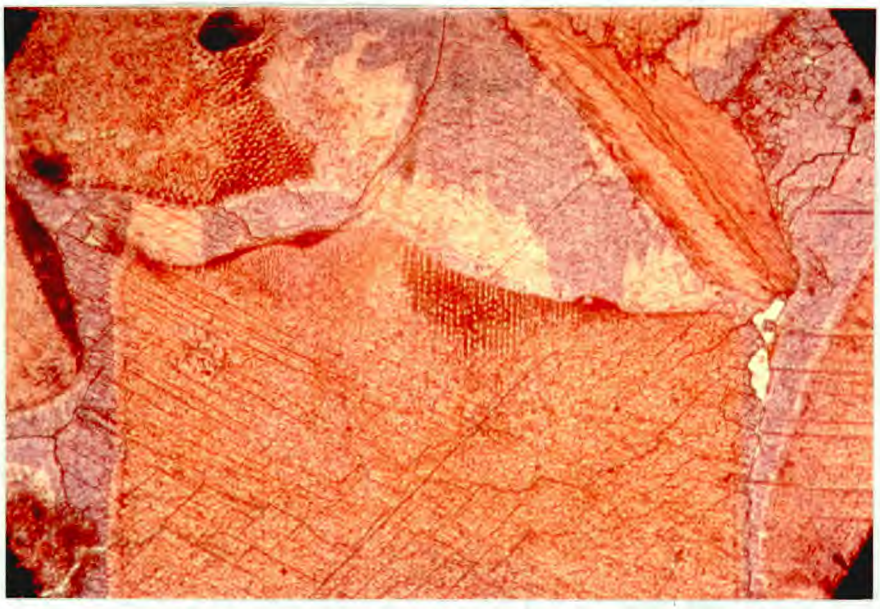
Where echinoderm debris is mixed with other skeletal fragments and ooliths or pellets etc., the overgrowths from the echinoderm fragments are often relatively large and appear to have swamped the polycrystalline pore-filling mosaic which developed around the other detrital components. Occasionally, the overgrowths are so large that they tend to enclose neighbouring polycrystalline fragments and their fringing cement in an incipient poikilitic manner (plate 56).

(iv) Variable ferrous-iron content of overgrowths.

Calcite may carry small amounts of ferrous-iron substituted for calcium in its lattice. Iron-bearing and iron-free calcites may be identified by immersing thin sections in a weakly acid solution of potassium ferricyanide (chapter 18)

Plate 53.

PLATE 53.



Crinoidal limestone from Bioclastic Calcarenite Sequence of Middle Ambléon Limestone at type section. Thin section stained with alizarin red S & potassium ferricyanide in dil. HCl. Iron-free calcite appears red; ferroan calcite is mauve (see Table IV). A near vertical section through an ossicle is shown. System of minor canals only seen clearly where canals are filled with fine-grained calcite. Inner iron-free zone of overgrowth serrated & wide over the articulating surface of the ossicle, narrow & simple over the lateral margins, & absent where the surface is encrusted with fine-grained calcite. Outer iron-bearing zone of overgrowth encloses encrustations. Plane polarised light (X55).

Plate 54

PLATE 54.

Crinoidal limestone from Bioclastic Calcarenite Sequence of Middle Ambléon Limestone at type section. Thin section stained with potassium ferricyanide in dil.HCl. Iron-free calcite is unstained & appears white; ferroan calcite is blue (see Table IV). A near-vertical section through an ossicle is shown. The overgrowth is divided into two main zones, an inner iron-free zone & an outer iron-bearing zone; The iron-bearing part of the overgrowth is not of uniform composition, but consists of a succession of light & dark stained zones. The multiple terminations to these zones simplify in number away from the articulating surface of the ossicle.
Plane polarised light, (X75).

In the Ambléon Limestone, the calcite of overgrowths reacts to the potassium ferricyanide solution by taking on a stain of Turnbull's blue. In most cases, the calcite of the echinoderm fragments and of the inner parts of the overgrowth remain unstained, i.e. they consist of iron-free calcite. The outer part of each overgrowth, however, shows a succession of zones of varying iron content. It is reasonable to suppose that the outlines of these zones represent the shapes of the overgrowth at the various stages in their development. In section D. of this chapter, overgrowths are described which have had their development arrested during cementation. The shapes of these overgrowths correspond closely to the shapes of the iron-bearing and iron-free zones of the fully developed overgrowths.

In vertical sections (plate 5A & fig. 46), the zones in the overgrowth are strongly serrated where they have grown out from the articulating surfaces, that is in the c-crystal direction. The axes of the serrations are normal to the basal plane of each ossicle and parallel to its principal crystallo axis. Around the sides of the same ossicles, the zones are straight. They lie parallel to the sides of the ossicles and are at the same time parallel to the principal crystal axis. The width of any one zone varies with its direction:- parallel to the sides of the ossicles the zones are narrow, but above and below the ossicle, where the zones are zig-zag in outline, they are much wider. This is clearly the result of variation in the rate of growth of calcite with crystallographic direction.

Plates 55 & 56

PLATES 55 & 56

Oolitic calcarenite, Upper Ambléon Limestone, Veyrin Hill (Ain). Thin sections stained with potassium ferricyanide in dil. HCl. Overgrowths to echinoderm fragments poikilitically enclose adjacent grains. Extent of overgrowth crystals seen by continuity of cleavages, twinning, & zoning depicted by staining. Plane polarised light, (X70).

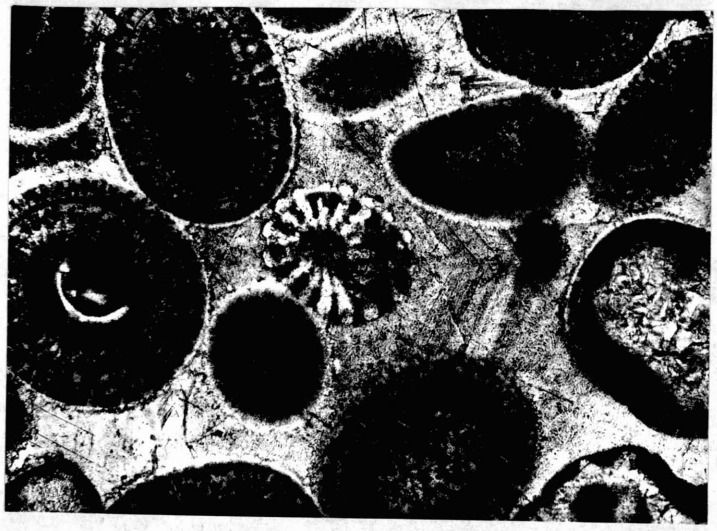


PLATE 55. Perfect basal section through an echinoid spine. Microcrystalline calcite fills radial pattern of canals. Inner iron-free zone (light), grown from clean surfaces between canals, appears as discrete spires with prismatic terminations. The later iron-bearing zones (dark) have adopted hexagonal outlines & enclose neighbouring ooliths.

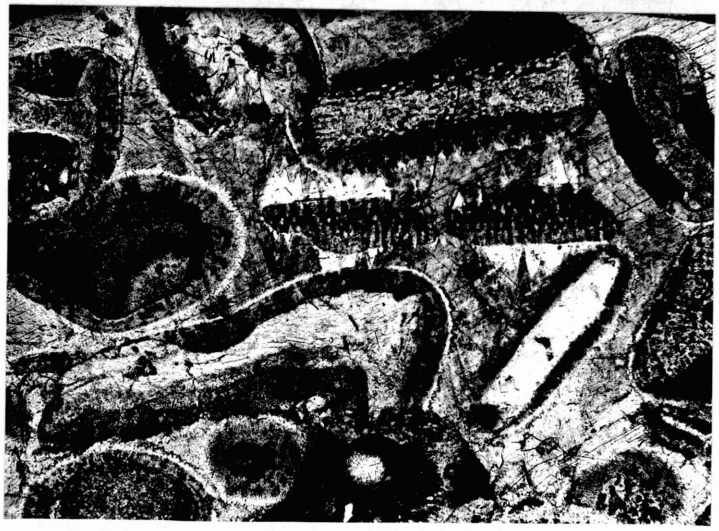


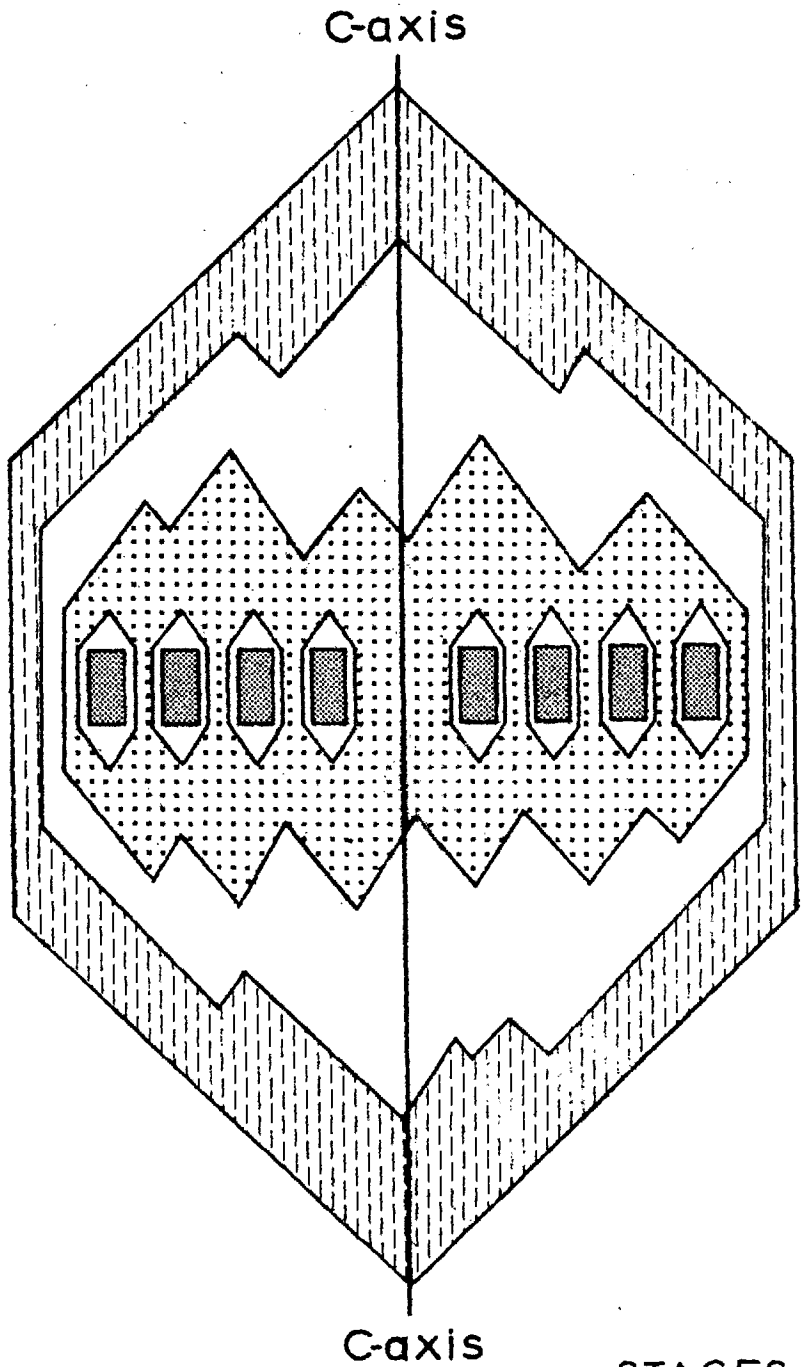
PLATE 56. Vertical section through an ossicle. Canals infilled with microcrystalline calcite. Inner iron-free zone extremely narrow, & locally exists as minute discrete spires arising from the upper & lower surfaces between canals.

Basal sections through the echinoderm fragments show a much simpler pattern of zoning in the overgrowths (plate 55) and fig. 47). The innermost zones characteristically follow the outlines of ossicles. They are circular or elliptical, depending upon the morphology of the species. Traced outwards through the overgrowth, the successive zones take on a hexagonal outline, first with curved sides and ultimately with straight sides identical to the hexagonal outline of a basal section through a prismatic crystal of calcite. Each of these basal sections through ossicles gives a well-centred conoscope image, and is therefore parallel to the basal plane of the calcite crystal. The changes in shape of the zones outward through the overgrowth show clearly the evolution of hexagonal prism faces from the cylindrical "crystal" of the calcite of the ossicle.

The presence of hexagonal zones in basal sections through overgrowths leaves no doubt that while the overgrowths were developing, they were gradually taking on a prismatic crystal habit. The zig-zag outlines of the zones growing out from the upper and lower surfaces of the ossicles must represent multiple terminations in the c- crystal direction. At first sight these present something of an anomaly. However, in all vertical sections, the multiple terminations are seen to become reduced in number outwards away from the host ossicle, (plates 54 & 58). It seems likely therefore, that if the pore-spaces had been sufficiently large to allow outward simplification to proceed to completion, the multi-

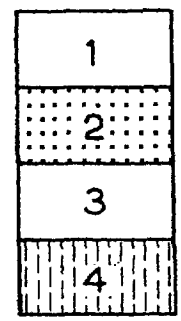
FIG. 44

SCHEMATIC REPRESENTATION OF THE STAGES OF OVERGROWTH DEVELOPMENT ON AN ECHINODERM FRAGMENT



ECHINODERM FRAGMENT

STAGES OF OVERGROWTH



plicity of terminations would pass outwards into a single termination (see fig. 44). Measurements of the traces of the interfacial angles to the terminations suggest that they are of the dog's tooth spar type. Although the terminations are seen to simplify outwards through the iron-bearing part of the overgrowth, no evidence normally exists of the evolution of the multiple terminations in the iron-free inner part. However, it is reasonable to suppose that if they could be identified in this iron-free zone, they would be seen to become more numerous inwards, and have their maximum complexity at the surfaces of the host ossicles. Consequently it is at the surface of the ossicles that one must look for their origin. Articulating surfaces of ossicles are perforated by the multitude of entrances to the network of internal canals. The multiplicity of terminations must clearly result from crystal growth out from this perforated surface. This is best illustrated diagrammatically, and fig. 44 shows the suggested evolution of the terminations from an ossicle, uncontaminated by microcrystalline calcite. A few specimens were found which provided confirmation of this suggested origin. In one of these specimens (plate 56) an overgrowth around a fragment showed an exceptionally narrow iron-free zone, which locally exists only as minute discrete spires arising from the surface between canal openings.

The diverse and apparently confusing arrangements of zones around oblique sections through ossicles are readily explained once the pattern shown by vertical and basal sec-

FIG. 45

RELATIONSHIP BETWEEN LONGITUDINAL AND OBLIQUE SECTIONS THROUGH OVERGROWTHS

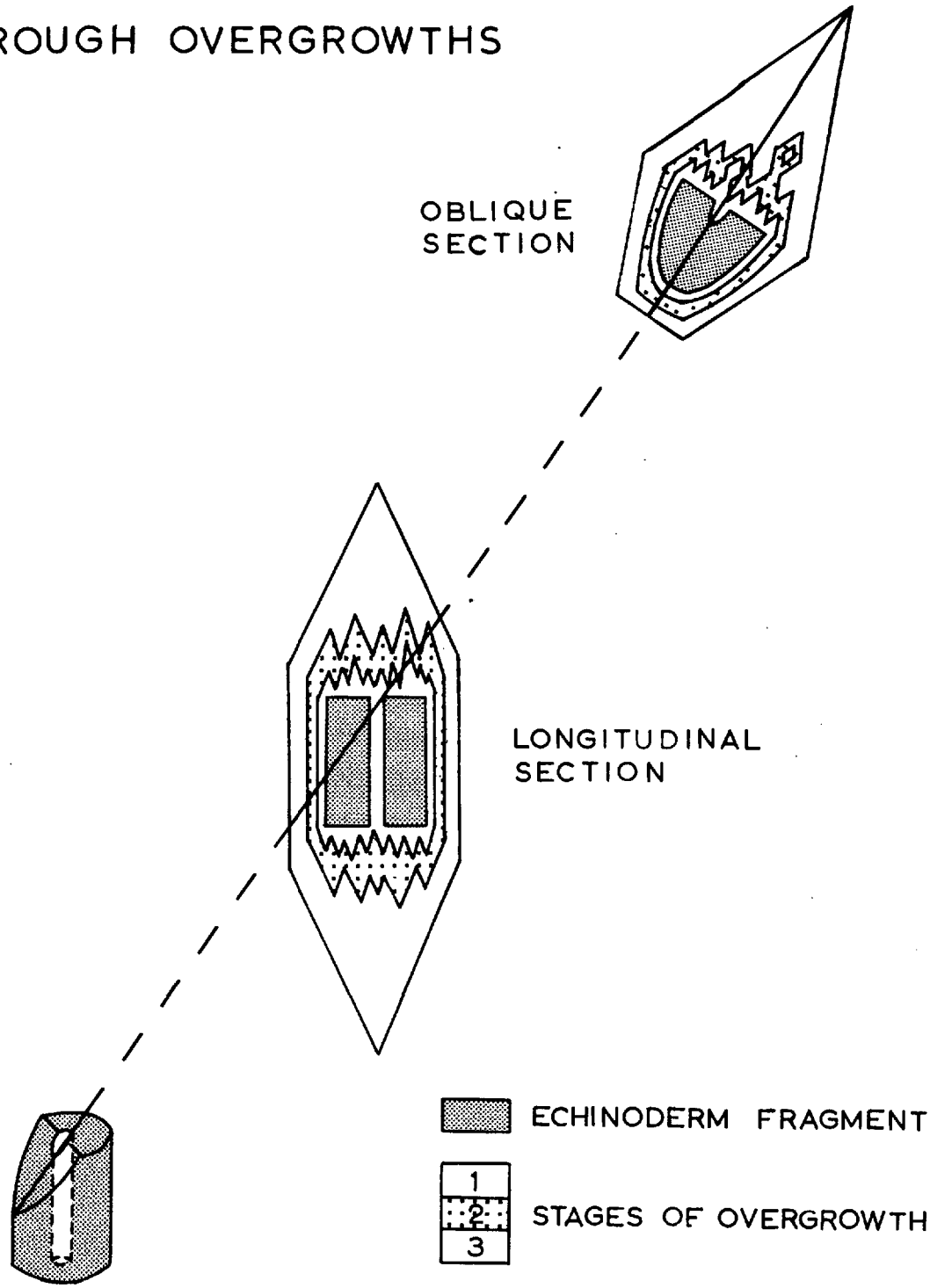
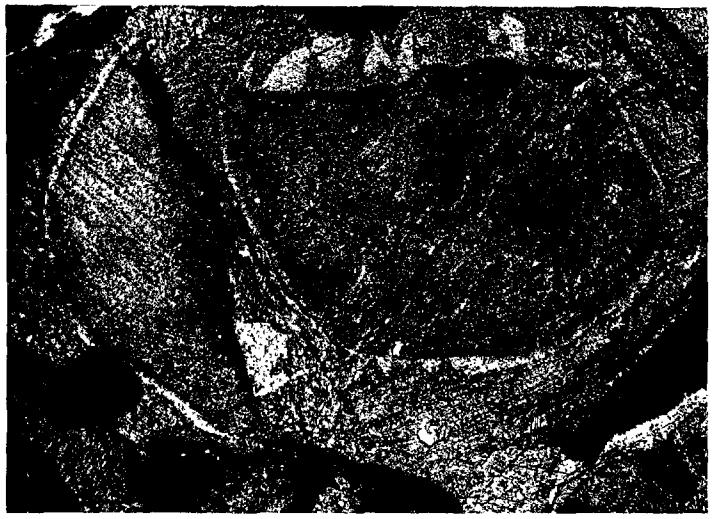


Plate 57.

PLATE 57.



Crinoidal limestone from Bioclastic Calcarenite Sequence of Middle Ambleon Limestone at type section. Thin section stained with alizarin red S & potassium ferricyanide in dil. HCl. Two oblique sections through ossicles shown with the characteristic elliptical traces of the central & minor canals. The articulating surfaces of the ossicles (straight) are somewhat encrusted by microcrystalline calcite. Inner iron-free zones of overgrowths (light) are narrow & of uniform width around lateral margins of ossicles (curved). The islands of iron-free calcite floating in ferroan calcite (dark) away from the articulating surfaces are a feature of sections through the tops of discrete spires.
Plane polarised light, (X35).

tions is understood (fig. 45). An interesting feature shown by some oblique sections, is the presence of islands of the earlier zones, and especially the iron-free part of the overgrowth, floating within the later iron-bearing zones (plate 57 & fig. 45).

(v) Influence of surface encrustation.

Patches of very fine-grained calcite occur as surface encrustations on many echinoderm fragments. Unless these completely invest the fragment they do not inhibit the formation of an overgrowth, but become enclosed within it. Encrustations occurring on the articulating surfaces of ossicles have a profound effect on the arrangement of the iron-bearing and iron-free zones (plate 53). However, encrustations on the sides of ossicles do not appear to affect the pattern of zoning. These contrasted effects are considered by D.J.Shearman (personal communication) to be in part an expression of the different rates of growth of calcite crystals in the various crystallographic directions.

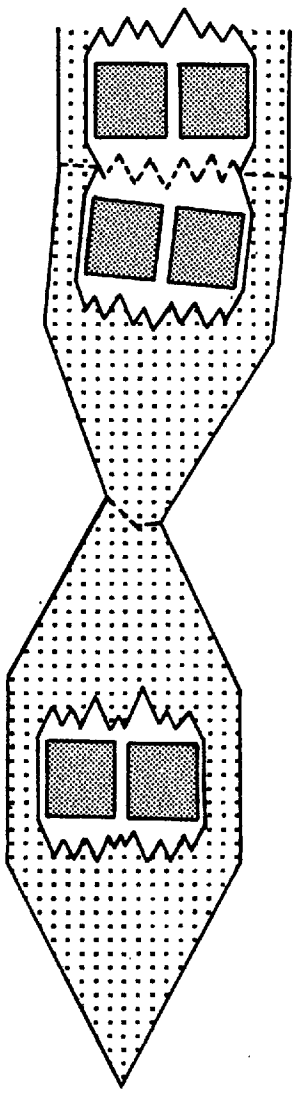
(vi) Reconsideration of boundaries between overgrowths.

The causes for the diverse types of boundaries developed between adjacent overgrowths, which present problems in studies made on unstained thin sections, are now easily resolved. Firstly, it is clear that the boundaries are not crystal faces, but are compromise boundaries, (Buckley, 1951; Bathurst, 1958). This is shown by the fact that in the majority of cases the traces of the boundaries are not parallel to the iron-bearing zones of the overgrowths, but

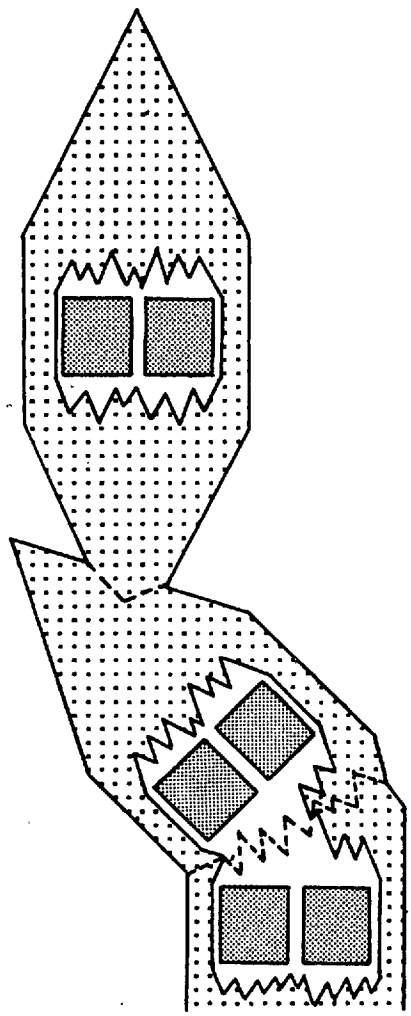
FIG. 46

SCHEMATIC REPRESENTATION OF SOME TYPICAL BOUNDARIES BETWEEN OVERGROWTHS

a). c-axes almost coincident



b). c-axes appreciably inclined



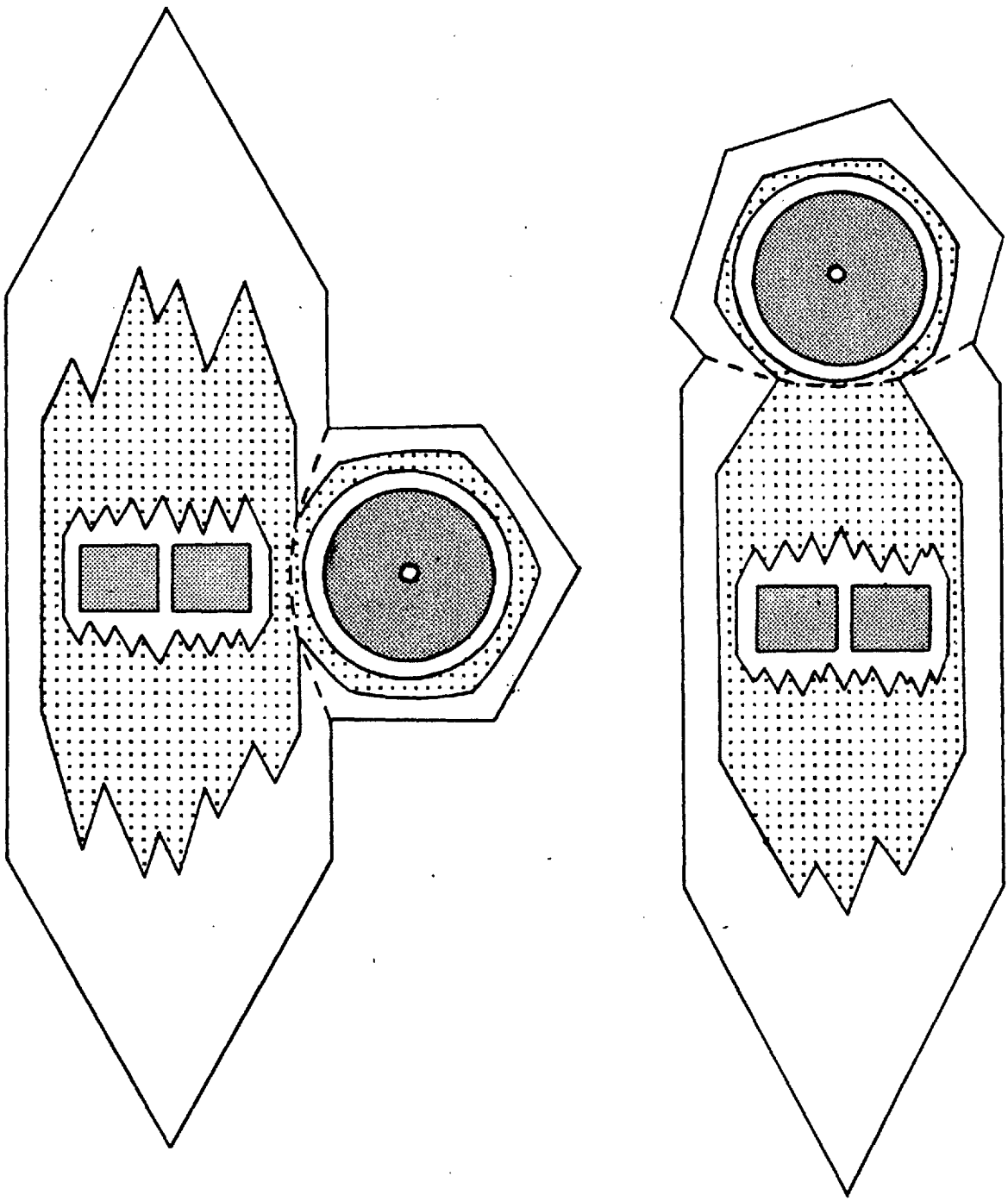
ECHINODERM FRAGMENT

1 / 2 STAGES OF OVERGROWTH

---- BOUNDARY BETWEEN OVERGROWTHS

FIG. 47

DEVELOPMENT OF CURVED BOUNDARIES BETWEEN OVERGROWTHS



ECHINODERM FRAGMENT

1
2
3
STAGES OF OVERGROWTH

BOUNDARY BETWEEN OVERGROWTHS

instead, transgress them. In the light of what is now known of the changes in shape, which occur during the development of overgrowths around echinoderm fragments, it is evident that the outline of the boundary between two overgrowths will depend principally upon two factors:- (a) the morphological and crystallographic orientations of the fragments, and (b) their distance apart. Figs. 46 and 47 illustrate the origin of some of the diverse types of boundaries which may occur. Fig. 46 illustrates the situation where the c- crystal axes of two ossicles are inclined in such a way that the terminations of the crystals of the overgrowth advance towards one another. If the ossicles are relatively far apart, simplification of the terminations is achieved before the advancing crystal faces meet and the compromise boundaries are relatively simple ones. Where two ossicles occur with the same relative orientation but much closer together, simplification of the terminations is not achieved, and the multiple terminations of the two crystals advance on one another. The compromise boundary between them must necessarily be strongly serrated. Plate 51B illustrates an example of this phenomenon. Gently curved boundaries may form against overgrowths around circular and elliptical basal sections of ossicles (fig. 47). Plate 51B shows the way in which the boundary between two overgrowths may exhibit different outlines in different crystallographic directions.

Boundaries between overgrowths are best seen when the crystallographic orientations of the adjacent overgrowths

Plate 58.

PLATE 58.

Crinoidal limestone from Bioclastic Calcarenite Sequence of Middle Ambléon Limestone at type section. Thin section stained with potassium ferricyanide in dil. HCl. Two ossicles are shown, each with an independent overgrowth. This is demonstrated by the zoning of Turnbull's blue (dark) which shows a reduction in the number of spires away from the articulating surfaces of the ossicles. Both ossicles & their overgrowths have a common crystallographic orientation, indicated by the continuity of cleavage & twinning traces. No boundary can be detected between the two overgrowths under crossed polars. Plane polarised light (X30).

are oblique to one another (plate 51B). Under these circumstances the difference in relief between the calcite crystal of each overgrowth shows up the boundary between them. Furthermore, under crossed polars, the crystals extinguish at different angles. If the adjacent overgrowths have a parallel orientation, the boundaries between them are indiscernible. For example, in plate 58 , two host ossicles are seen with overgrowths showing a complex series of zones near the surfaces of the ossicles. However, no boundary is seen between the overgrowths, since there is no difference in relief between the calcite of each. Twinning and cleavage traces are found to pass undeviatingly from one overgrowth to the other and, under crossed polars, both overgrowths appear to be in optical continuity. Similarly, boundaries between adjacent spires, found in early phases of overgrowth development (fig. 44), are not seen due to the parallel crystallographic orientation of all the spires.

(vii). <u>Relative ages of the different phases of cementation.</u>

In the majority of specimens studied, the overgrowths show a clearly defined, essentially iron-free inner zone succeeded outwards by iron-bearing calcite with zones of varying iron concentration (plate 54).

In the same specimens, these two broad phases are represented in the granular cement, associated with polycrystalline shell debris and with ooliths. These granular cementation mosaics commonly resolve themselves into

Plates 59 & 60

PLATES 59 & 60.

PLATE 59. Mechanically compacted oolite, Upper Ambléon Limestone, Veyrin Hill (Ain). Thin section stained with potassium ferricyanide in dil. HCl. Ooliths are shown with their outer layers sprung apart. A fringe of iron-free polycrystalline calcite occurs on the outer surfaces of the deformed layers but does not line the cavities produced by the compaction. These are filled by ferroan calcite belonging to the overgrowth of the ossicle in the centre of the field of view. Plane polarised light (X80).

PLATE 60. Oolitic calcarenite, uppermost Ambléon Limestone, Appregnin (Ain). Thin section stained with potassium ferricyanide in dil. HCl. Near-vertical section through an ossicle shown. Pattern of zoning seen within overgrowth follows closely the outline of the overgrowth against the fine-grained groundmass. Overgrowth wide & serrated away from articulating surfaces, narrow & uniform over the lateral margins, & absent where the ossicle is encrusted. Plane polarised light, (X30).

two parts in terms of crystal size. Each of the polycrystalline detrital components is surrounded by a narrow fringe of small crystals, and this passes outwards abruptly into a more coarsely crystalline mosaic which fills the centres of the original pore-spaces. These mosaics do not show the progressive increase in crystal size, which characterises the granular cement of the drusy mosaic described by Bathurst (1958), but are more akin to the mosaics observed by Graf & Lamar (1950). Thin sections which have been stained to differentiate iron-free from iron-bearing calcite show that the fringes of small crystals which surround the polycrystalline components are iron-free, but the coarsely-crystalline mosaics of the central parts of the pore-fillings are predominantly iron-bearing. In some of the more oolitic limestones, the ooliths show deformation due apparently to compaction. The outermost layers of many of the ooliths are sprung apart, or are partially spalled off (plate 59). The fine-grained, iron-free calcite cement occurs only on the outer surfaces of these spalled-off layers. It does not line the cavities and spaces produced by the deformation, which are occupied exclusively by the more coarsely crystalline iron-bearing calcite. Quite clearly, the iron-free phase of calcite cement pre-dated the deformation of the ooliths. It appears likely that the deformation occurred before the commencement of the deposition of the iron-bearing phase of calcite cement. If this interpretation is correct, there must have been a clearly defined interval of time between the two phases of cementation.

The two phases are also represented in the calcite after aragonitic skeletal fragments. These present many complexities. The former hollows are coated inside and out by narrow fringes of iron-free calcite crystals, while the centre of each is occupied by more coarsely-crystalline iron-bearing calcite. In the Ambléon Limestone the skeletal aragonite appears to have gone into solution early during, if not completely before the iron-free phase of cementation. This left weakened shell fragments, many of which suffered deformation and compaction. As in the case of the ooliths, this deformation post-dated the early iron-free calcite and pre-dated the iron-bearing phase.

D. OVERGROWTHS IN A FINE-GRAINED MATRIX.

(i) General petrological evidence.

Cayeux (1935) described limestones from the "Toarcien" of May (north-west France) in which echinoderm debris with overgrowths occur scattered in a groundmass of fine-grained calcite. He noted that the overgrowths were often serrated along one side or along two opposite sides. Bathurst (1958) found similar outgrowths in some of the Dinantian limestones of Northern England, and the same phenomenon occurs in the uppermost Ambléon Limestone of the area mapped.

In thin sections of these uppermost Ambléon calcarenites, the different parts of the outline to any one overgrowth are highly variable. As Cayeux observed for rocks of this type, the overgrowths may show a succession of spires

Plates 61 & 62

PLATES 61 & 62.

Oolitic calcarenite, uppermost Ambléon Limestone, Appregnin (Ain).

PLATE 61. Perfect cross-section through an echinoid spine & its overgrowth. The outline of the overgrowth against the fine-grained groundmass is quasi-hexagonal. Plane polarised light (X75).

PLATE 62. Oblique section through an ossicle & its overgrowth. On the left, is the narrow part of the overgrowth away from the lateral margins of the ossicle - on the right, is the wide growth out from an articulating surface. The oblique section has cut through the tops of several discrete spires, & has yielded islands of overgrowth in the fine-grained groundmass. Plane polarised light, (X35).

along one side, or along two sides opposite to one another (plates 60& 62). Where serrations occur along two opposite sides the section is cut parallel to, or only slightly oblique to the c- crystal axis. Basal or near basal sections do not show spires, but instead exhibit near-circular or quasi-hexagonal outlines (plates 61). Hexagonal sides which are curved represent transitional stages in the development of the hexagonal prism of calcite from a cylinder of the crystal. Certain oblique sections may show serrations along one side only. An interesting example of the effects of an oblique section is shown in plate 62 . In this, isolated blebs of calcite, in optical continuity with the overgrowth, occur apparently floating in the groundmass a short distance beyond the main body of the overgrowth. This superficially anomalous distribution of calcite forming the overgrowth is readily understood by reference to fig. 45 .

Study of specimens collected during the first long field season showed:-

(a) that the overgrowths are restricted in size. Their outlines (plates 60 & 62) are closely similar to the arrangement of iron-bearing and iron-free zones observed in the overgrowths, which grew freely into intergranular pore-spaces (compare with plates 53 & 57 in Section C).

(b) that when the thin sections are treated with acidified potassium ferricyanide, iron-bearing and iron-free zones can be identified within the calcite of the overgrowths (plate 60).

(c) that a narrow fringe of calcite crystals surrounds ooliths and polycrystalline skeletal debris and separates them from the matrix. This fringe is similar in all respects to that developed during the first phase of cementation of the rocks discussed earlier (compare plates 60 & 56).

(d) that the frequency of grain contacts, as seen in thin sections, indicates that the coarse bioclastic fragments and ooliths form a rigid framework. There is no evidence to suggest that these components are "floating" in the matrix.

(e) that encrustations and patches of calcite mud occur locally on the surfaces of many of the echinoderm fragments (plate 60). Both the fabric of the calcite of the matrix and of the encrustations appear superficially similar although they differ slightly in grain size. The overgrowths extend freely into the matrix on either side of the encrustations but they do not appear on those parts of the surfaces where the encrustations occur. In this way the overgrowths in fine-grained matrices resemble closely the form of the early iron-free parts of the overgrowth which developed into open pore-spaces (compare plates 60 & 53).

On the basis of the information available, two explanations for the origin of the overgrowths in the fine-grained matrix were possible:-

(a) that the matrix was a primary depositional component. If this was so, then the overgrowths must have formed by replacement. However, the presence of iron-bearing and iron-free zones within the lattice of the overgrowths is not

consistent with the suggestion made by Bathurst (1958) that such overgrowths result from a solid-state process of grain growth. If they are a replacement, solutions must have played a role.

(b) that the overgrowths are a true void-filling cement, and are the equivalents of the first phase of cementation of the rocks described earlier. If this is so, then the matrix was introduced subsequently, during diagenesis.

Insufficient evidence was available to resolve the two alternatives. Hence the field relationships of the rocks were re-studied and a further suite of specimens collected during the second long field season. The additional petrological evidence accumulated is presented in the following paragraphs.

(ii) Additional petrological evidence.

The specimens containing echinoderm debris with overgrowths in a groundmass of fine-grained calcite occur in the cross-bedded, bioclastic and oolitic calcarenites of the uppermost 5-6 cm. of the Ambléon Limestone (chapter 5), immediately below the contact with the Chanaz Beds (plate 16). Lower down, but within the same unit of the Ambléon Limestone the calcarenites are cemented by coarsely-crystalline, pore-filling calcite. A very narrow transition zone (about 3-4 cm. wide) exists between the uppermost part of the unit, with the matrix, and the underlying part, fully cemented by sparry calcite. Thin sections cut from this zone indicate a post-depositional age for the matrix. This corroborates the

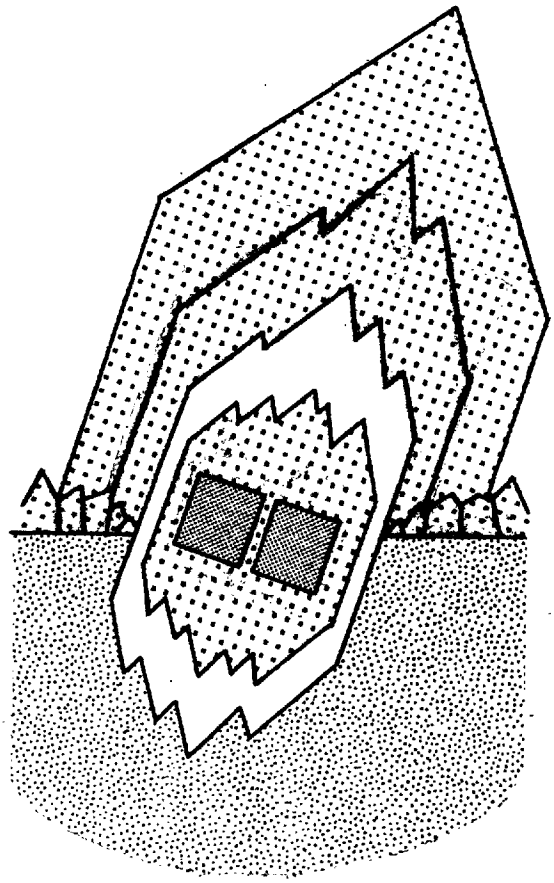
deductions made in chapter 5 from the field evidence (see page 138). Furthermore, thin sections from the transition zone at the top of the Ambléon Limestone demonstrate the relative ages of the matrix and the overgrowths.

Typical thin sections of the transition zone show that the pore-spaces are in part occupied by fine-grained calcite, and in part by cavity-filling mosaics of calcite crystals. The amount of fine-grained material decreases downwards and the entire transition can be seen within the width of one normal sized thin section. Where the pore-spaces are only partially infilled by the fine-grained internal sediment, the upper surfaces of the infilling are level and consistently face upwards (plate 19). "Umbrella" effects are produced by many of the skeletal fragments. All these features confirm the subsequent age of the matrix.

Where the overgrowths are entirely embedded in fine-grained calcite in the uppermost part of the bed, they show only two principal zones (plate 60):- an iron-bearing inner zone, followed by an iron-free zone. In places within the transition zone, where the pore-spaces are only partly filled by internal sediment, echinoderm fragments occur which are in part embedded in the fine-grained material, and which are in part project up into what were former voids, above the internal sediment. This is best illustrated diagrammatically and fig. 48 shows a combination of the salient features about these overgrowths, accumulated from a number of examples in the transition zone. For comparison, a photomicrograph of an

FIG. 48

SCHEMATIC REPRESENTATION OF AN OVERGROWTH PARTIALLY EMBEDDED IN A FINE-GRAINED MATRIX



ECHINODERM FRAGMENT

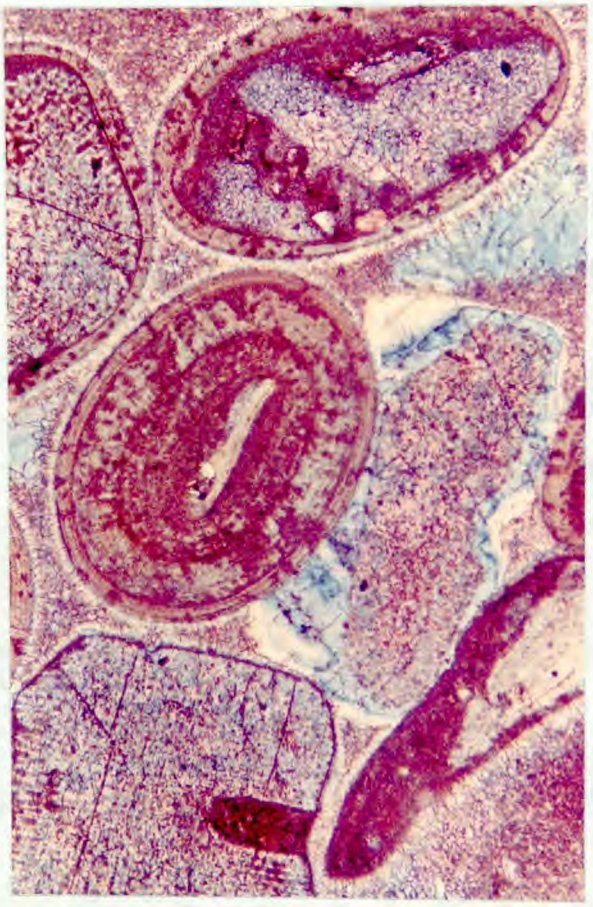
FINE-GRAINED SEDIMENT

FERROUS-IRON FREE CALCITE

FERROUS-IRON BEARING CALCITE

Plate 63.

PLATE 63



Oolitic calcarenite, uppermost Ambléon Limestone, Appregnin (Ain). Thin section stained with potassium ferricyanide in dil. HCl. Ferrous-iron free calcite is unstained & appears white. Ferroan calcite is stained blue. Intergranular pore-spaces partially filled by microcrystalline calcite & in part cemented by coarsely-crystalline calcite. The fine-grained calcite in the partly filled pore-space (right) has an upper level surface. The overgrowth to the ossicle in the centre of the field of view continues out & fills the former cavity above this level surface. Fringes of polycrystalline cement are seen around ooliths & pseudo-ooliths, except where these grains are in contact with the echinoderm overgrowth. Plane polarised light, (X80).

actual overgrowth in this position is shown in plate 63. Where in contact with the fine-grained groundmass, overgrowth development is seen to have been arrested towards the end of the iron-free zone. Above the level of the internal sediment, however, an additional outer, iron-bearing zone is represented. In plate 63, this zone fills the greater part of the cavity above the level of the internal sediment. The fact that this calcite is part of the overgrowth is shown by the continuity of cleavages and twinning from the undoubted overgrowth into the cavity-filling. Furthermore, a succession of subsidiary zones can be seen in the cavity-filling, continuing out from the iron-free part of the overgrowth. Finally, both areas of the thin section are found to extinguish as a single entity under crossed polars. The more fully developed succession of zones, where overgrowth development has been unrestricted by the internal sediment, is comparable to that found in the lower part of the unit where fine-grained matrix is lacking.

The accumulated evidence summarised in fig. 48, suggests that the internal sediment entered the system at the end of the iron-free zone. Where matrix material came into direct contact with the overgrowth, further development was inhibited. In the void above the level of the internal sediment, however, cementation continued. The overgrowth competed for the available space with the polycrystalline spar, growing from the upper surface of the internal sediment. The

crystals of the fringe closest to the ossicle were invaded first. They were thus not given the opportunity to grow very large. Those further away were able to attain a greater size before becoming swamped by the more rapidly[1] developing overgrowth.

The petrographic evidence leaves little doubt that the overgrowths enclosed in the fine-grained matrix are not of replacement origin, but are an early phase of cement. The matrix is believed to have been introduced from above, later.

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1. It is quite clear from plate 63 that the monocrystalline overgrowths did develop faster than polycrystalline cement:- Firstly, the relatively wide, finner iron-bearing and iron-free zones of the echinoderm overgrowth are represented as extremely narrow zones in the polycrystalline cement around the ooliths and pseudo-ooliths of the rock. Secondly, in places where the echinoderm overgrowth touches these oolithic grains, the polycrystalline rim of cement is notably absent, or only rudimentary. This indicates that the overgrowth had reached the adjacent grains almost before polycrystalline cementation had started. It appears therefore, that the force of crystallisation from the relatively large monocrystalline echinoderm fragments was much greater than from the finer-grained, polycrystalline oolithic jackets.

APPENDIX.

The purpose of this Appendix is to indicate how the data used in fig.15 was obtained, and to tabulate this data for reference (Table V).

Point count analyses were made of thin sections taken from each different lithology represented in the Lower Ambléon Limestone at the type section. The reference number of each sample analysed is indicated on fig.15 and Table V. Where a certain lithology is repeated several times up the column, generally only one sample was analysed. The reference numbers of such samples appear in brackets in fig.15, where they refer to repetitions and without brackets where they indicate the actual rock analysed.

Many of the hand specimens collected, and thin sections cut show small-scale cross-laminations. Commonly these laminations are made up of different components. For example in the limestones of the Cuzieu Flags, laminations of detrital quartz alternate with thin bands of bioclastic calcarenite. In LAn3 also, thin bands of oolite alternate with laminations of coarse-grained bioclastics. It was impracticable to represent these rapid differences in composition exactly on the graphs shown in fig.15. Nevertheless, it was desirable that the compositions of each type of lamination should be included in the graphs. Consequently the units of laminated rocks were arbitrarily divided into two parts, A & B (see fig.15), each

part representing the average composition of one type of lamination.

The alternation of thinly-bedded limestone and shale in Cu 1 (fig.12) was difficult to represent on the graphs of fig.15. Consequently the total thickness of shale was considered as an entity on its own (reference No.1.), and likewise with the limestone (reference No.2.). The shales of the Cuzieu Flags are strongly silicified so that the only consistently recognisable detrital component is the quartz (see fig.15 & Table V).

The Lower Ambléon Limestone at the type section is generally well-exposed (see fig.14). The small parts of the succession, which are covered in the Cuzieu Flags and LAn3, can reasonably be supposed to be similar to the adjacent parts of the column, as indicated in fig.15. The only significant gap in the succession occurs near the base of LAn1, where the rock types involved are difficult to assess.

The point count analyses involved the identification and recording of the components, which occur at a number of points regularly distributed over the surfaces of the thin sections studied. As indicated by Barringer (1954), these points represent the line intersections of an imaginary grid, laid upon the thin sections. During the course of point counting, each intersection was optically sampled under the microscope. The analyses were made as representative as possible by arranging to have the imaginary grid system

covering the entire thin section in each case. The number of points counted per thin section was generally about 1000. However, it was commonly not possible to count so many points for the different laminations in the banded strata. The coarse bioclastic calcarenites of the succession, with their well-mixed skeletal debris, were subjected to more exact analyses. This was done in order to study the hydrodynamic properties of the grains in relation to their size and shape. Insufficient data has so far been accumulated to draw conclusions on this subject, other than those presented in chapter 5.

The analytical errors inherent in the method of point counting have been discussed by Barringer (1954). As can be imagined, the error for any one component, decreases as the number of points counted increases; also, for a given number of points counted, there is greatest accuracy in determining the percentage of the most prominent component, and least accuracy for estimating the percentage of the accessory constituents.

TABLE V

DATA OF POINT COUNT ANALYSES.

Reference No. 1.

Shales of the Cuzieu Flags (Average analysis of 4 thin sections).

	Total No. of points counted.	Detrital quartz		Sponge spicules		Others.	
		No.	%	No.	%	No.	%
	1461	159	10.9	251	17.2	1051	71.9
	1170	113	9.6	226	19.2	831	71.2
	1376	113	8.2	250	18.2	1013	73.6
	1404	114	8.1	224	16.0	1066	75.9
Average	5411	499	9.2	951	17.6	3961	73.2

Ref: No.	Total No. of points counted.	Detrital quartz.		Ooliths.		Pellets		Echinoderm debris		Brachiopod mollusc debris.		Polyzoan debris.		Lithic fragments.		Foraminifera.		Calcilutite.		Sparry calcite.		Others.	
		No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
2 A	4947	755	15.2	-	-	398	8.0	269	5.4	908	18.3	-	-	-	-	250	5.0	235	4.7	2107	42.6	25	0.8
B	3152	233	7.4	-	-	246	7.8	201	6.3	735	23.3	-	-	-	-	190	6.0	182	5.8	1349	42.8	18	0.6
3 A	591	200	33.8	-	-	21	3.6	26	4.4	81	13.7	-	-	-	-	10	1.7	8	1.4	245	41.4	-	-
B	96	6	6.2	-	-	5	5.2	4	4.2	18	18.8	-	-	-	-	-	-	1	1.4	62	64.6	-	-
4	1121	2	0.2	-	-	11	1.0	181	16.2	296	26.4	198	17.7	36	3.2	3	0.3	3	0.3	391	34.7	-	-
5	673	287	42.7	34	[illegible]	34	5.0	37	5.5	155	23.0	30	4.5	-	-	6	0.9	62	9.2	62	9.2	-	-
6	330	27	8.2	-	-	39	11.8	18	5.4	45	13.7	-	-	-	-	6	1.8	6	1.8	170	51.5	19	5.8
7	567	260	45.9	-	-	20	3.5	9	1.6	61	10.7	-	-	-	-	-	-	95	16.7	122	21.6	-	-
8	919	260	29.9	-	-	25	2.7	49	5.2	75	7.9	-	-	-	-	12	1.3	29	3.2	469	49.8	-	-
9	1023	22	2.15	-	-	11	1.1	130	12.8	231	22.6	186	18.1	2	0.2	9	0.9	57	5.6	375	36.6	-	-
10 A	1645	46	2.8	-	-	120	7.3	108	6.6	567	34.4	174	10.6	47	2.9	37	2.2	41	2.5	478	29.1	27	1.6
B	442	39	8.8	-	-	81	18.3	23	5.2	85	19.3	-	-	-	-	27	6.1	27	6.1	160	36.2	-	-
11	334	164	49.2	-	-	15	4.5	5	1.5	28	8.4	-	-	-	-	-	-	55	16.5	67	20.0	-	-

Ref: No.	Total No. of points counted	Detrital quartz.		Ooliths		Pellets		Echinoderm debris		Brachiopod-mollusc debris		Polyzoan debris		Lithic fragments		Foraminifera		Calcilutite		Sparry calcite		Others	
		No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
12	1301	28	2.2	-	-	27	2.8	167	12.8	375	28.8	189	14.5	31	2.4	7	0.6	94	7.2	374	28.7	-	-
13	1329	9	0.7	-	-	35	2.6	53	4.0	394	29.8	185	13.9	27	2.0	35	2.6	70	5.3	520	39.1	-	-
14	431	-	-	63	14.7	40	9.3	38	8.8	126	29.2	-	-	-	-	10	2.3	7	1.6	147	34.0	-	-
15	1613	7	0.4	-	-	38	2.4	344	21.3	308	19.1	410	25.4	20	1.2	9	0.6	90	5.6	382	23.7	5	0.3
16	1477	-	-	-	-	30	2.0	251	17.0	394	26.7	200	13.5	37	2.5	8	0.5	34	2.3	523	35.5	-	-
17	1652	4	0.2	-	-	37	2.2	257	15.6	486	29.4	253	15.3	40	2.4	19	1.2	37	2.2	519	31.5	-	-
18	1703	2	0.1	6	0.4	33	1.9	489	28.7	459	26.9	73	4.3	49	2.9	-	-	81	4.8	503	29.5	8	0.5
19	1182	34	2.9	3	0.3	23	1.9	395	53.7	125	10.5	10	0.8	13	1.1	2	0.2	70	5.9	268	22.7	-	-
20 A	431	29	6.7	63	14.6	52	12.1	36	8.4	37	8.6	-	-	-	-	1	0.2	21	4.9	192	44.5	-	-
20 B	424	-	-	57	13.4	28	6.7	170	40.0	20	4.7	-	-	22	5.2	-	-	-	-	127	30.0	-	-
21	504	46	9.1	34	6.7	78	15.5	18	3.6	80	15.9	-	-	-	-	-	-	47	9.3	188	37.3	13	2.6
22 A	475	-	-	241	50.7	8	1.7	66	13.9	12	2.5	-	-	-	-	-	-	-	-	148	31.2	-	-
22 B	411	4	1.0	65	15.8	28	6.8	155	37.7	52	12.7	-	-	10	2.4	2	0.5	-	-	95	23.1	-	-
23 A	426	19	4.5	140	32.8	75	17.6	34	8.0	44	10.3	-	-	-	-	-	-	-	-	112	26.3	2	0.5
23 B	133	-	-	24	18.0	8	6.0	51	38.4	9	6.8	-	-	-	-	-	-	-	-	40	30.1	1	0.7
24 A	420	-	-	151	36.0	14	3.3	81	19.3	29	6.9	14	3.3	-	-	-	-	-	-	129	30.7	2	0.5
24 B	497	-	-	80	16.1	8	1.6	215	43.3	32	6.4	10	2.0	-	-	-	-	-	-	148	29.8	4	0.8
25 A	629	13	2.3	292	46.4	60	9.6	65	10.3	15	2.4	-	-	-	-	-	-	-	-	184	29.0	-	-
25 B	1029	-	-	110	10.7	75	7.3	389	37.9	75	7.3	37	3.6	5	0.5	-	-	-	-	337	32.7	-	-
26	441	24	5.4	43	9.8	45	10.2	122	27.7	73	16.6	11	2.4	5	1.1	3	0.7	4	0.9	111	25.2	-	-
27	1694	15	0.9	75	4.4	34	2.0	387	22.8	481	28.4	147	8.7	54	3.2	20	1.2	167	9.9	314	18.5	-	-
28	1611	10	0.6	4	0.3	83	5.2	496	30.7	253	15.7	288	17.8	56	3.5	25	1.6	72	4.5	324	20.1	-	-

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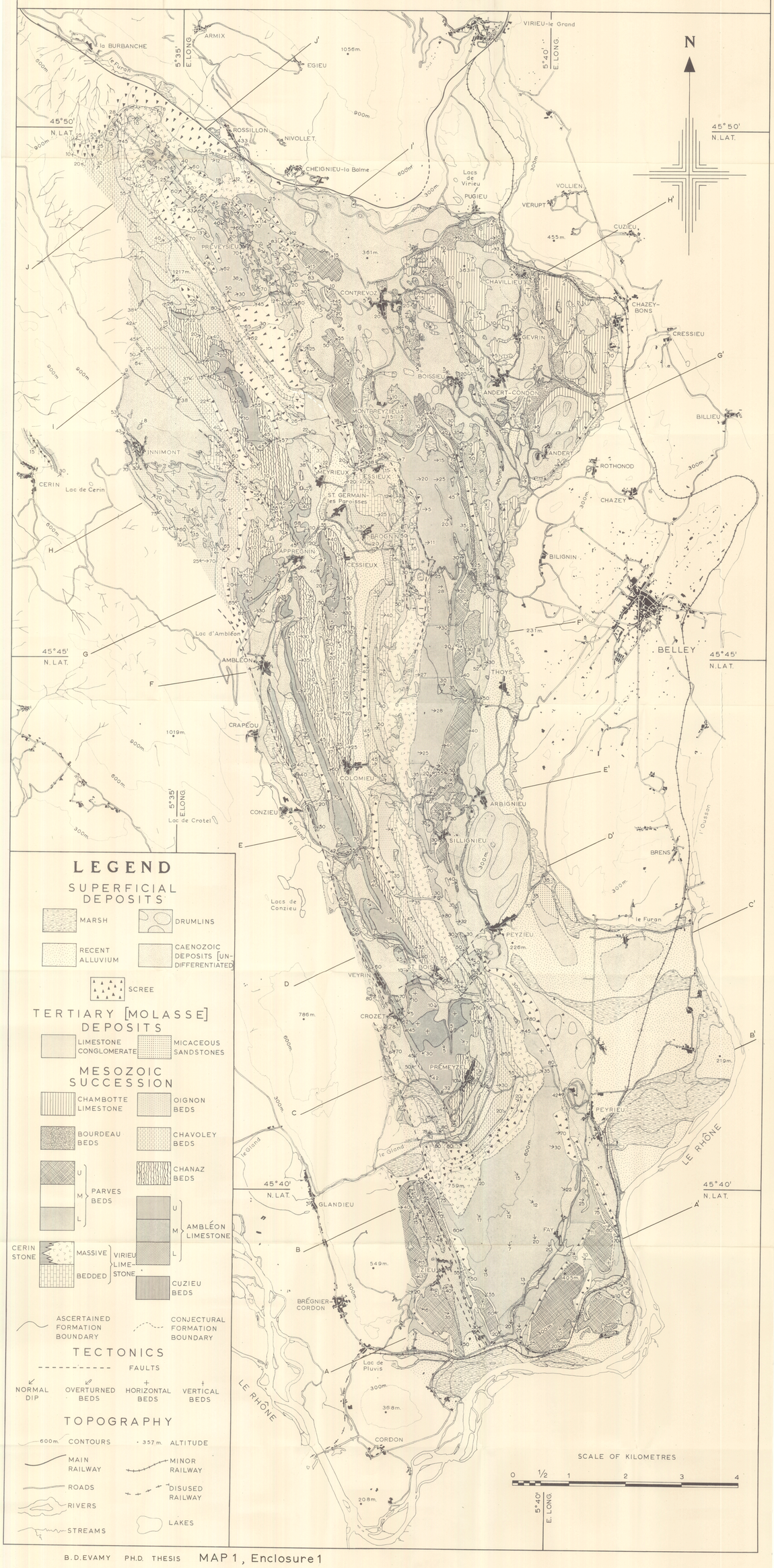
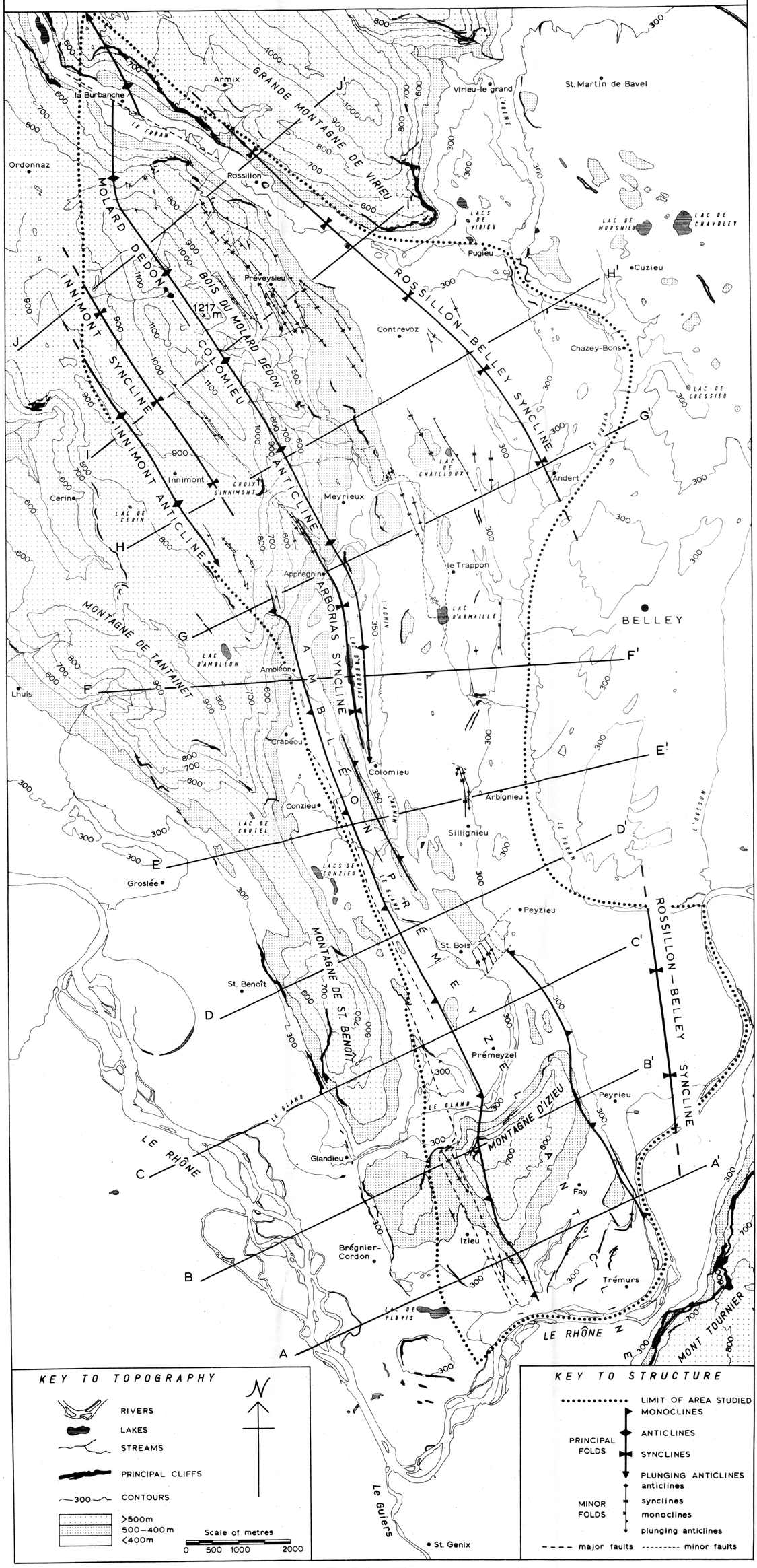
GEOLOGICAL MAP OF PART OF THE FRENCH JURA WEST OF BELLEY [AIN]

by B.D.Evamy



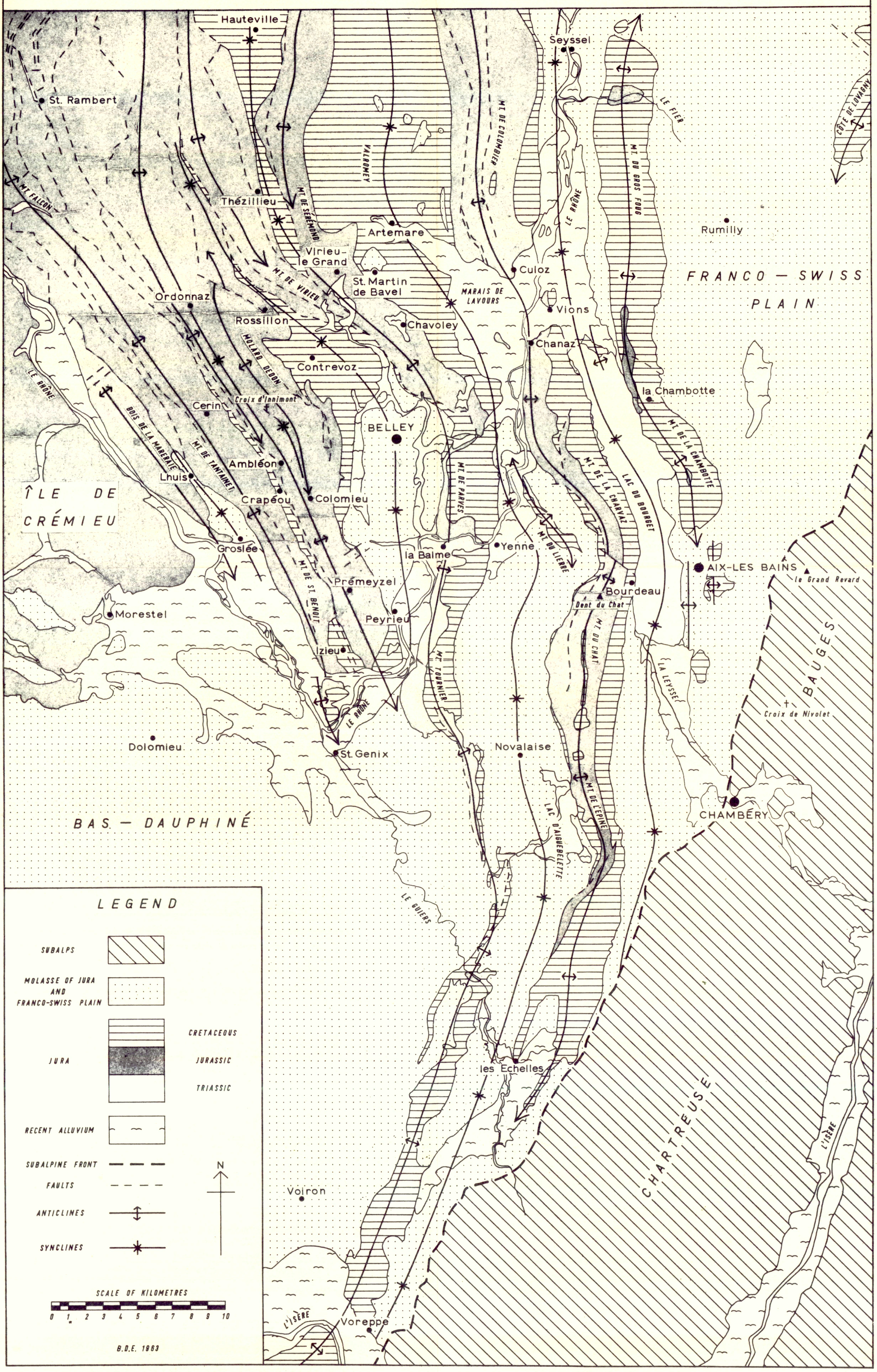
B.D.EVAMY PH.D. THESIS MAP 1, Enclosure 1

STRUCTURE OF PART OF THE SOUTHERN FRENCH JURA by B. D. Evamy



B.D.EVAMY PH.D THESIS MAP 2, Enclosure 2

STRUCTURAL MAP OF THE SOUTHERN FRENCH JURA



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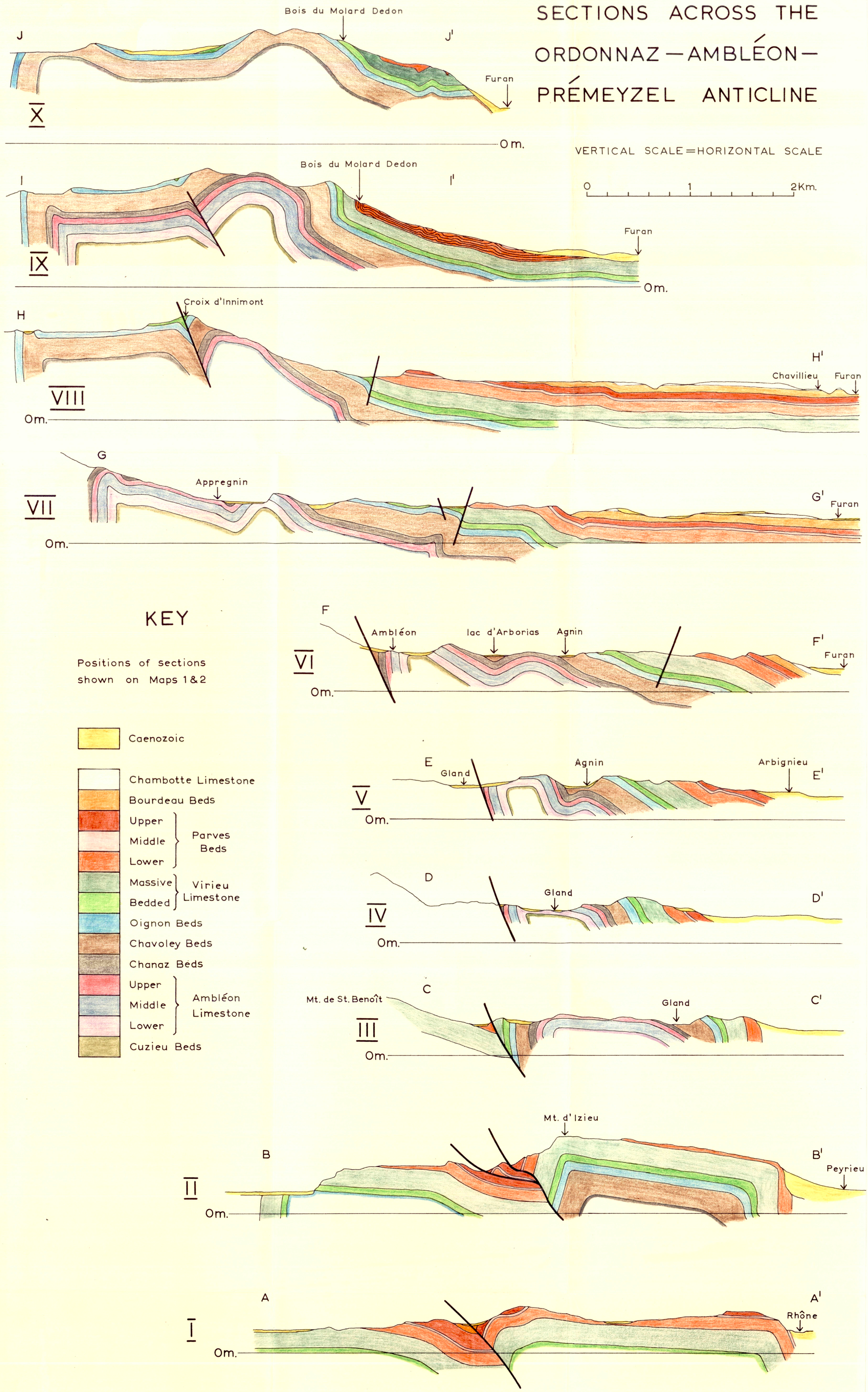
MAP 3, Enclosure 3

SECTIONS ACROSS THE ORDONNAZ—AMBLÉON—PRÉMEYZEL ANTICLINE

VERTICAL SCALE = HORIZONTAL SCALE

0 1 2Km.



KEY

Positions of sections shown on Maps 1 & 2

- Caenozoic
- Chambotte Limestone
- Bourdeau Beds
- Parves Beds: Upper, Middle, Lower
- Virieu Limestone: Massive, Bedded
- Oignon Beds
- Chavoley Beds
- Chanaz Beds
- Ambléon Limestone: Upper, Middle, Lower
- Cuzieu Beds

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Enclosure 4