

THE GEOLOGY OF PORTUGUESE TIMOR

BY

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ABSTRACT

This thesis is an account of the stratigraphy and structure of Portuguese Timor (an area of 16,000 sq. km.) supported by four geological maps (1:100,000).

Twenty four formations are distinguished, four of which are allochthonous. The autochthonous formations range in age from Lower Permian to Recent, and make up a section of 8000 metres thickness. Of the allochthonous formations one is pre-Permian, two are Permian, and the other a mid-Miocene gravity slide deposit. The lithology and petrography of each formation is described, the fauna and flora recorded, and the environment of deposition discussed.

As limestones are the predominant rock type in Timor special attention has been paid to limestone petrography.

Five separate periods of folding are recognised, two of which, the Timorean and the Ramelauean, were of major importance and accompanied by large scale overthrusting. Two unconformities in the Lower Tertiary are recognised but no associated folding can be distinguished. Immediately following both the Timorean and Ramelauean orogenies there was a period of uplift: the Dartollu Uplift and Soro Uplift respectively. Thirty five folds are defined and described.

Results of a gravity survey are presented as Bouguer Anomaly maps (1:100,000). The significance of the gravity anomalies is discussed throughout the text.

The geological history of Portuguese Timor is described, and in broad terms an attempt is made to correlate

events in eastern Timor with those in western Timor, the other islands of the Indonesian Archipelago, New Guinea and northern Australia. A regional tectonic sequence emerges. A palaeogeographic history of the Archipelago and northern Australia from the Permian to the end of the Mesozoic is briefly attempted.

The petroleum seepages, thermal springs and mud volcanoes of Portuguese Timor are described and discussed.

Detailed geochemical analyses of some Cretaceous cherts, radiolarites and ferromanganiferous sedimentary rocks are described and their origin discussed in the Appendixes.

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B

C

D

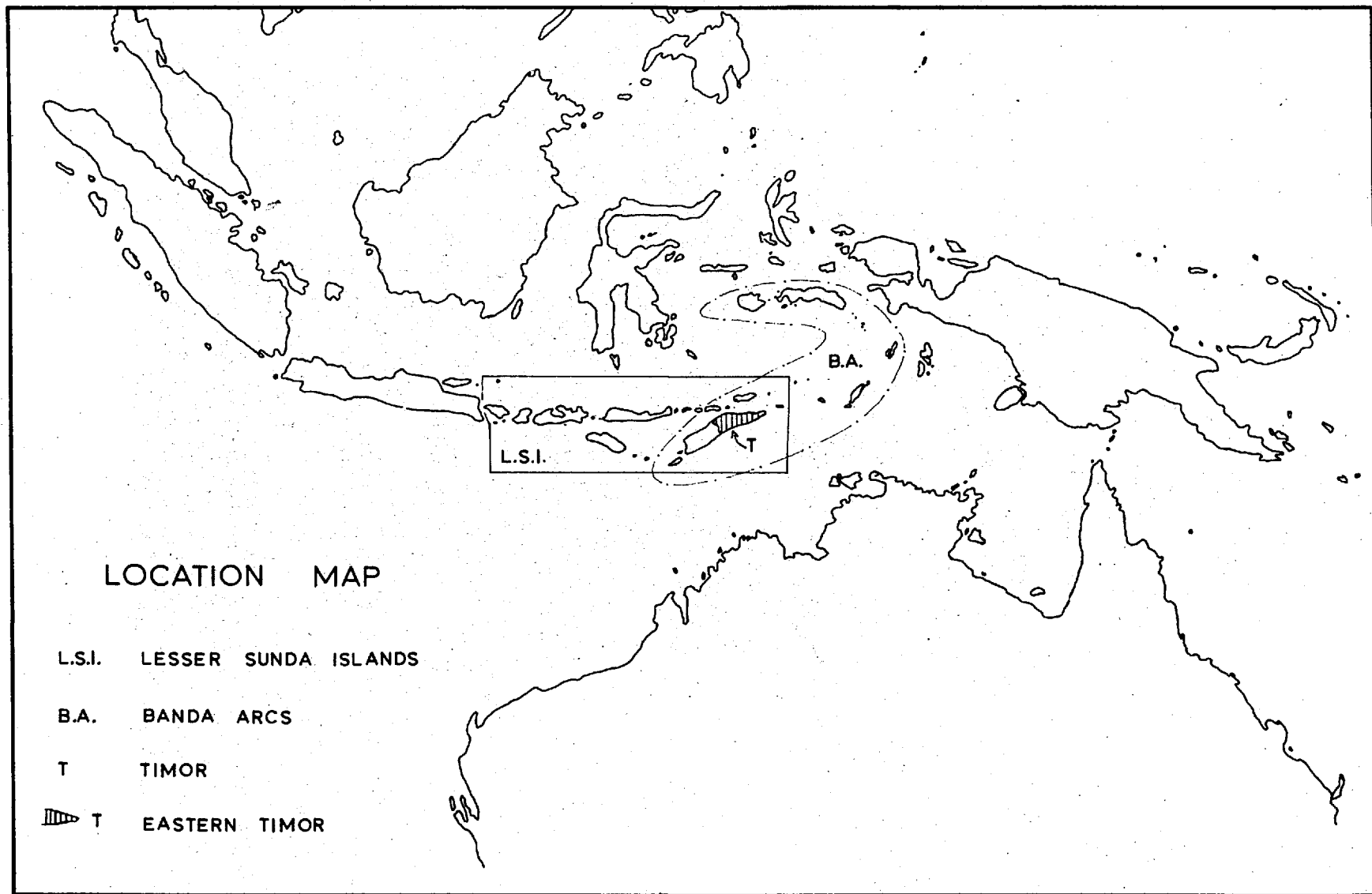


Fig. 1

CHAPTER I

INTRODUCTION

a). REGIONAL SETTING.

The island of Timor (figure 1) is the largest of the Lesser Sunda Islands which form the south-eastern part of the Indonesian Archipelago. Timor is about 365 kilometres long and 100 kilometres at its greatest width. It is divided politically between Portugal and Indonesia. Portuguese Timor consists of the eastern half of Timor, together with the enclave of Ocussi in western Timor, and the two small islands of Atauro and Jaco. This report deals with all of Portuguese Timor except Ocussi and the island of Atauro, that is with the eastern half of Timor and Jaco Island, an area of about 16,000 sq. kilometres. In this report the expression "eastern Timor" refers to this region as defined above, whose western limits are the rivers Masin, Tafara, Malibara and Talaoe.

Timor forms part of the Banda Arcs, (figure 1 & enclosure 15) being the largest island of the outer arc. The non-volcanic Outer Banda Arc comprises the islands of Rotti, Timor, Letti, Tanimbar, Kai, Ceram (Serang), Buru, and Buton (Butung). The south-eastern part of Celebes (Sulawesi) is sometimes regarded as part of this major unit.

The Banda Arcs are situated between the Sahul Shelf of Australia and New Guinea in the east and south, and the Sunda Shelf of S.E. Asia in the west and north (enclosure 15). This region has been characterised by crustal instability since the end of the Cretaceous.

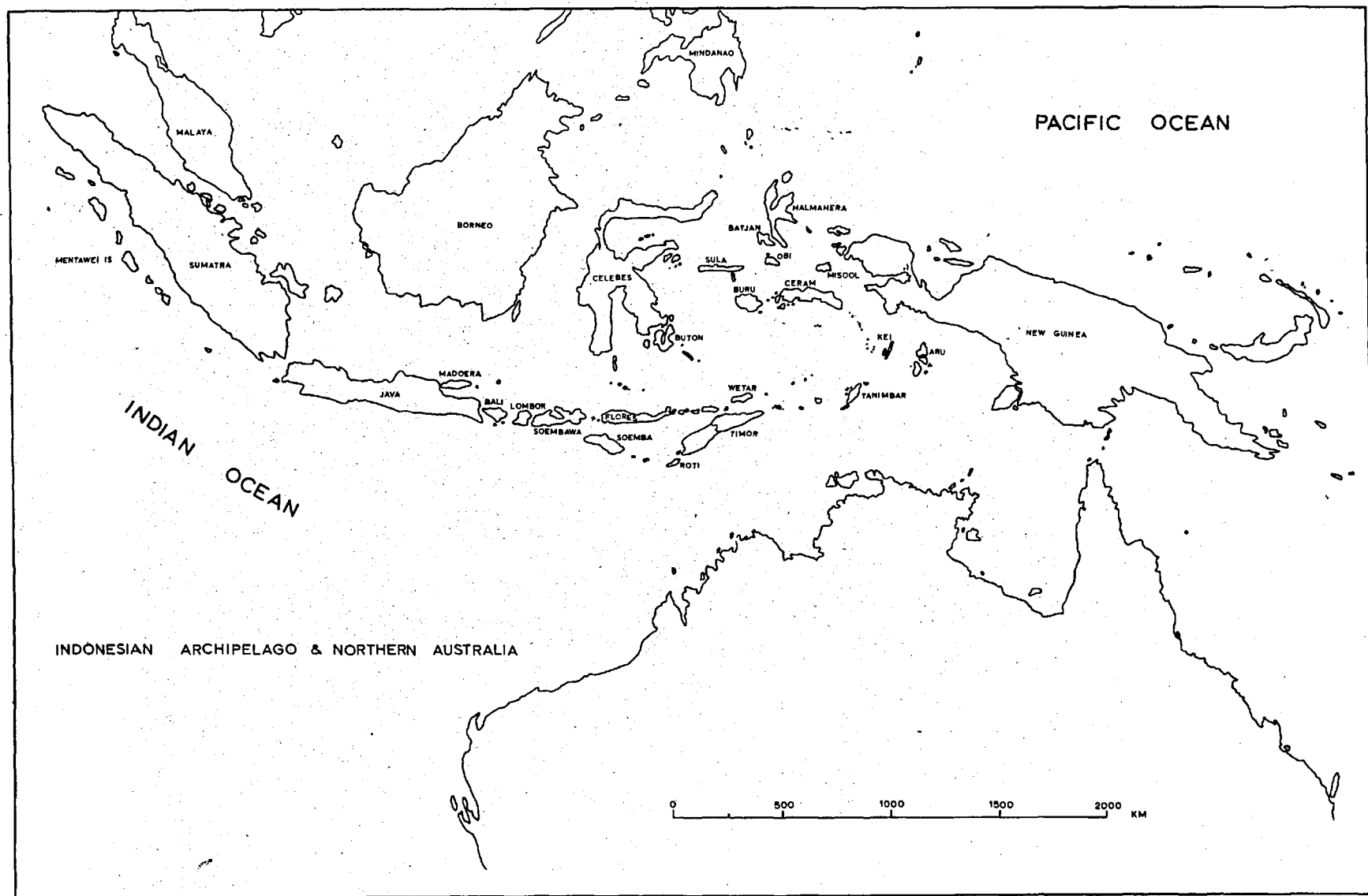


Fig. 2

The present position of Timor as a mountainous island bordered by deep-sea troughs with strong gravity anomalies augurs the continuance of labile conditions.

Since the end of Permian times the majority of sedimentary rocks formed on the site of Timor have been limestones. Relatively little terrigenous detrital material has been transported into this area since the end of the Permian. This observation suggests that Timor has probably been separated by large seas from the continents of Asia and Australia since the end of Permian times. There is no pre-Permian record in Timor.

b). OUTLINE OF GEOLOGICAL HISTORY.

The oldest autochthonous rocks in eastern Timor, the Atahoc Formation and the Cribas Formation, are of Permian age. They exhibit many features of deltaic sediments, and it is probable that these sediments, that are more than 1000 metres thick, were built out from the continental shelf of Australia. The Lower Triassic is probably absent throughout eastern Timor (it is reduced to 2 metres in western Timor); an unconformity separates the Middle & Upper Triassic from the Permian. Sedimentation probably continued in most of eastern Timor from the Middle Triassic to Middle Jurassic, resulting in 2000 metres of limestone (mostly calcilutites) and shales. During the Triassic limestones largely predominated; in the Jurassic shales were the principal deposit with quartz arenites increasing in importance towards the top. These sediments were probably deposited in a shallow shelf environment, which the impoverished benthonic fauna suggests may have been restricted. The region was

TABLE OF ROCK - STRATIGRAPHIC UNITS

AUTOCHTHONOUS UNITS							ALLOCHTHONOUS UNITS						
AGE	STRUCTURAL EVENT	FORMATION NAME	THICKNESS METRES	LITHOLOGY & FOSSILS	FACIES	PETROLEUM PROSPECTS	AGE	FORMATION NAME	TIME OF OVERTHRUSTING	THICKNESS METRES	LITHOLOGY AND FOSSILS	FACIES	
RECENT & PLEISTOCENE	UPLIFT	SUAI FORMATION	1000	GRAVELS, SANDS, SILTS, MUDS, MARLS; INTERDIGITATED FORAMINIFERA, MOLLUSCS, ECHINODERMS, CORALS.	LITTORAL & EPINERITIC	POSSIBLE SOURCE & RESERVOIR BEDS							
		POROS LIMESTONE	20	HARD, BEDDED, ALGAL LIMESTONE; GASTROPODS	LACUSTRINE								
		BAUCAU LIMESTONE	100	MASSIVE (FRINGING) CORAL REEF, CALCIRUDITES, CALCARENITES, QUARTZ ARENITES.	LITTORAL								
		AINARO GRAVELS	1000	CONGLOMERATES, GRAVELS, SANDS.	ALLUVIAL MOLASSE								
UPPER PLEISTOCENE - UPPER PLEISTOCENE	LATE PLEISTOCENE FOLDING	SEKETO BLOCK CLAY	20	EXOTIC BLOCKS, PEBBLY MUDSTONE, MARLS, FORAMINIFERA.	NERITIC : SUBMARINE SLUMPS	SOURCE BEDS & SDST. RESERVOIRS : OIL SEEPS. POSSIBLE STRATIGRAPHIC & ANTICLINAL TRAPS							
	Tgh	DILOR CONGLOMERATE	300	CROSS BEDDED CONGLOMERATES, SANDS, SILTS, RARE MUDS : LENTICULAR. FORAMINIFERA	EPINERITIC MARINE DELTAIC								
	Tg	LARI GUTI LIMESTONE	75	FRINGING CORAL BIOLITHITES, CALCARENITES	LITTORAL								
	Tgh	VIQUEQUE FORMATION	700	BASAL CONGLOMERATES, SANDST., SILTSTS, MUDST, MARLS, CHALKS: LENTICULAR & GRADED BEDDING RICHLY FORAMINIFERAL. MOLLUSCS, CORALS.	LITTORAL, NERITIC MOLASSE								
MIDDLE MIOCENE	Tf	MID-MIOCENE OROGENIC CLIMAX FOLDING, OVERTHRUSTS, HUGE GRAVITY SLIDES					MIDDLE MIOCENE	Tf	BOBONARO SCALY CLAY	EMPLACED DURING Tf AS A SUBMARINE GRAVITY SLIDE	2000+	SCALY BENTONITIC CLAY MATRIX WITH NUMEROUS EXOTIC BLOCKS. DERIVED AND INDIGENOUS FORAMINIFERA	WILDFLYSCH
LOWER MIOCENE	Te	ALIAMBATA LIMESTONE	50	CALCILUTITES EXTREMELY RICH IN PELAGIC FORAMS.	INFRANERITIC ?								
	Te	CABLAC LIMESTONE	600	CALCIRUDITES, CALCARENITES (SOME OOLITIC), CALCILUTITES: DOLOMITISED. FORAMS, CALC ALGAE	BAHAMITE								
OLIGOCENE	Tcd	UNCONFORMITY	BARIQUE FORMATION	300	DACITIC & BASIC TUFFS, PUMICE, BASIC LAVAS(PILLOWS), CONGLOMERATES, RARE QTZ. ARENITES: FORAMINIFERA	MARINE							
MID. & UPPER EOCENE	Tab	UNCONFORMITY	DARTOLLU LIMESTONE	100	DENSE BIOCALCARENITES: CALC. ALGAE, FORAMS	OFF-REEF							
L. EOCENE	Ta		SEICAL FORMATION	100?	RADIOLARITES, CALCARENITES, Fe/Mn CEMENT. FORAMS	INFRANERITIC							
LOWER EOCENE TO DANIAN		LOWER EOCENE OROGENIC CLIMAX FOLDING, OVERTHRUSTS.											
MAESTRICHTIAN TO CAMPANIAN		UNCONFORMITY	BOROLALO LIMESTONE	200	CALCILUTITES, BIOCALCARENITES, CHERT. FORAMS	INFRANERITIC OR BATHYAL	MAESTRICHTIAN TO CAMPANIAN		BOROLALO LIMESTONE	Tf	50	CALCILUTITES, BIOCALCARENITES, FORAMINIFERA	INFRANERITIC OR BATHYAL
MAESTRICHTIAN TO APTIAN		UNCONFORMITY	WAI BUA FORMATION	500	RADIOLARITES, CHERTS, CALCILUTITES RICH IN RADIOLARIA & FORAMS., RADIOLARIAN SHALES MANGANIFEROUS SHALES & NODULES. GRADED ARENITES	INFRANERITIC OR BATHYAL							
MIDDLE JURASSIC TO NORIAN			WAI LULI FORMATION	1000	MOSTLY SHALES WITH CALCILUTITES & MARLS. RED & GREEN SHALES, CONGLOMERATES, QTZ. ARENITES, CALCARENITES, OOLITES. AMMONITES, BELEMNITES	NERITIC							BITUMINOUS SHALES. POROUS ARENITES
NORIAN TO LADINIAN		UNCONFORMITY	AITUTU FORMATION	1000	MOSTLY MASSIVE & BEDDED RADIOLARIAN CALCILUTITES WITH THIN INTERBEDDED SHALES. CONGLOMERATES & CALCARENITES LOCALLY. HALOBIA INDEX FOSSIL. AMMONITES VERY RARE.	NERITIC							HIGHLY BITUMINOUS LSTS. & SHALES. OIL & GAS SEEPS. DOLOMITISATION. POSS. CALCARENITE RESVRS
UPPER PERMIAN			CRIBAS FORMATION	500	MICACEOUS SHALES & SILTSTONES WITH QUARTZ ARENITES, CALCILUTITES, CALC. NODULES: PELECYPODS & FORAMINIFERA	FLYSCH NERITIC	MIDDLE PERMIAN		MAUBISSE FORMATION	Tf	900	CALCIRUDITES, CALCARENITES, QTZ. ARENITES, TUFFS, LAVAS: VERY RICH REEF FAUNA	LITTORAL & EPINERITIC
LOWER PERMIAN			ATAHOC FORMATION	600	QUARTZITES, BLACK SHALES, SILTY SHALES, CALCILUTITES, CALC. NODULES: AMMONITES	FLYSCH NERITIC	PROBABLY PERMIAN		AILEU FORMATION	Tf	1000+	SHALES, PHYLLITES, SLATES, META-ERUPTIVES : PELECYPODS	INFRANERITIC OR BATHYAL
							PROBABLY PRE-PERMIAN		LOLOTOI COMPLEX	LOWER EOCENE Ta	600?	LOW GRADE REGIONALLY METAMORPHOSED SEDIMENTARY AND ERUPTIVE ROCKS. NO FAUNA	METAMORPHIC COMPLEX

M. G. Aubrey-Charles. June, 1964.

stable throughout most of this period.

The absence of the upper part of the Jurassic and the lower part of the Cretaceous is due to the orogenic phase which occurred during this time interval. The Cretaceous Wai Bua Formation ~~forms~~ a particularly characteristic suite of cherts, radiolarites, radiolarian shales and highly foraminiferal limestones. Manganese nodules are found in this formation. These sedimentary rocks, that range from Aptian to Maestrichtian in age, probably accumulated far from any land mass in a deeper-neritic or bathyal environment.

A major orogenic phase occurred between the end of Maestrichtian and the opening of the Middle Eocene. The results of this orogeny were the major folding with complex superficial crenulations of all the Permian and Mesozoic strata, and the emplacement (by overthrusting or gliding) of large sheets of regionally metamorphosed sedimentary and eruptive rocks called the Lolotoi Complex.

The preservation of a few remnants of Middle & Upper Eocene neritic limestones, the Dartollu Limestone, indicate that one of the consequences of the Lower Eocene orogeny was the shallowing of the Timor region in contrast to the deep water conditions of the Cretaceous. During the Oligocene large parts of eastern Timor were covered by lavas and tuffs deposited in a shallow marine environment. The base of these eruptives (Barique Formation) is a strong unconformity, often marked by a coarse conglomerate. It seems probable that these Oligocene eruptives resulted from the relaxation of the compressional orogenic forces that had reached a climax

in the Lower Eocene.

The Lower Miocene saw the development of the Cablac Limestone, a typical bahaman-type deposit that probably covered most of the central and northern parts of eastern Timor. The area of the present south coast was occupied by much deeper water that received concentrations of pelagic Foraminifera and relatively little carbonate mud (the Aliambata Limestone).

The mid-Miocene was a period of orogenic catastrophe that resulted in the folding of the Cablac Limestone and all older formations, and the overthrusting of huge sheets of Permian strata with much smaller sheets of Cretaceous rocks. This overthrusting was accompanied by the emplacement of enormous submarine slides of a Wildflysch-type deposit 2000 metres thick called the Bobonaro Scaly Clay. This formation, that bears a strong resemblance to the Argille scagliosa of the northern Apennines, was, like the overthrust sheets, derived from the region north of Timor. The base of the Bobonaro Scaly Clay is everywhere a violent unconformity.

The Upper Miocene & Pliocene rocks form a marine molasse facies about 1000 metres thick called the Viqueque Formation. These arenites, marls and clays resulted from the emergence of Timor from the sea during this period.

In late Pliocene times there was another orogenic phase that produced relatively gentle folds in the Bobonaro Scaly Clay and the Viqueque Formation. The older and harder rocks, against which these two soft formations were folded, responded to this tectonic phase mainly by

block faulting.

The subsequent history of Timor has been the continued uplift of the island throughout Pleistocene and Recent times without any folding. These epeirogenic movements have resulted in the coral reefs, that fringed much of the shore during the Pleistocene & Recent, forming a series of terraces from present sea level up to 500 metres. The molasse-type sedimentation of the Viqueque Formation has also continued to the present day. South of the mountainous spine and foothills of the island a wide coastal plain has been developed locally. The composition of these coastal plain sediments is comparable to that of the Viqueque Formation.

c). GEOGRAPHY.

The region described in this report (enclosures 1A, 1B, 1C & 1D) is the eastern half of the island of Timor, that is all of Portuguese Timor except Ocussi and Atauro. It is an area about 365 kilometres long and 100 kilometres at its greatest width, amounting to 16,000 sqr. kilometres. The western part of Timor was formerly administered by the Dutch, it now forms part of the Republic of Indonesia.

Topography:

A wide diversity of topography is seen within the eastern half of Timor (enclosure 4). There is a central mountain range that rises to over 3000 metres. This range is highly dissected due to the island having been elevated rapidly since the Upper Miocene. From the central range many side spurs and ridges are developed.

Most of the rivers run north and south, and have short steep courses to the sea except in places on the south coast where they cross a wide coastal plain. Five main morphological regions can be recognised: -

i) The north west region:

This is almost entirely mountainous, much of the area being above 1000 metres. Most of the mountains are composed of Permian rocks that in the north have been regionally metamorphosed. The high terrain has produced a subsequent drainage pattern where the rivers flow between the longitudinal (generally E-W) ridges, and develop as consequents where they break through the ridges in a few gorges.

There are a few coastal flats, but generally along this part of the north coast the mountains rise abruptly from the sea (plates 1B, 48A).

An anomalous feature in this otherwise mountainous area is the Maliana Plain, (enclosures 1A, 3AB), which is really an intermontagne valley filled with the Viqueque Formation overlain with Pleistocene and Recent alluvium. The Maliana Plain is probably a graben filled with the late Tertiary and Quaternary sediments mentioned above.

ii) The central divide:

This is more rugged than the north-west region due to two factors; namely a much greater proportion of hard eruptive rocks, and the presence of the resistant Cablac Limestone capping many mountain peaks. These precipitous caps give rise to some of the most spectacular scenery in Timor, and characterise the central ranges (plates 2D,

28D, 47A).

The central area has the greatest elevation and reaches its highest point in Tata Mai Lau (3200 metres) of the Ramelau Range, which is composed of one large klippe of Permian eruptives and limestones called the Maubisse Formation. Excepting the Cablac Limestone peaks, in the area east of Laclubar the mountains tend to become lower and less rugged as the eruptive rocks give way to the Mesozoic formations. The metamorphic and eruptive rocks of the Lacluta and Barique regions form conspicuous mountains surrounded by hills of Mesozoic strata.

The high rugged peaks of the central mountains about Ossu, and to the east of Ossu, are formed of Cablac Limestone. The most dramatic features are Mt. Bibiliu, Mt. Wai Nete (Mundo Perdido), Mt. Lari Tame, and above all the magnificent Mt. Mata Bia that rises to over 2300 metres. Unlike many of the eruptive rocks these limestones always support a heavy growth of large trees.

An exceptional feature in the central mountains is the Legumau Range in the east. This is a large klippe of Permian limestones and eruptives of the Maubisse Formation.

Drainage from the central divide is both to the north and south coasts, through steep narrow gorges, until in the foothills, of Mesozoic and Tertiary formations, where the rivers sometimes develop a spread of alluvium (plates 4A, 4B). The principal watershed of eastern Timor has an approximate north-east - south-west trend,

that is parallel to the trend of the island.

iii) The southern slopes:

The area south of the north-west mountains and the central divide is made up of rugged hills that rise to about 700 metres and have a deeply incised drainage pattern. This zone is formed almost entirely of hard resistant Mesozoic strata with a covering of softer Tertiary and Quaternary formations. Generally the Tertiary and Quaternary deposits form the lower and more southern hills. Landslides are a common feature of this region (plate 2C).

iv) The Baucau and Lospalos Plateaus:

These are two remarkable limestone plateaus in the north-east and eastern regions respectively. The Baucau Plateau is about 400 metres above sea level, and the Lospalos Plateau about 500 metres. Both carry a light grass and thin tree cover (plates 2A, 42A). They exhibit well developed sink-hole and karst topography (plate 2B), with terra rossa. Underground rivers occur in the Lospalos Plateau. Both plateaus are formed of Pleistocene and Recent coral reefs (the Baucau Limestone), and were obviously at one time more extensive than they are today; erosional remnants being common.

v) The coastal plains:

There is very little development of coastal plain on the north side of the island, except towards the eastern end where there is a narrow strip covered with skeletal carbonate sands. On the southern side of the island there is very little coastal plain east of Beaco, but west from Beaco almost to Betano a savannah up to 12 kilometres wide

is developed. West of Betano the savannah is found locally all the way to the River Masin (and beyond), but is usually not more than 6 kilometres wide.

These five main types of morphology have numerous interesting minor variations that will not be described here. While there is a general relationship between morphology and the larger stratigraphic units such as Mesozoic, Tertiary and Quaternary formations, in detail very few specific formations have consistent characteristic morphological expression.

Climate:

The climate is tropical, warm and humid. Rainfall is seasonal. The wet season is December to March on the north side of the island, and December to July on the south. The other months are remarkably dry. In general during the wet season most rain falls between 1100 hours to 1600 hours. There is a fairly regular diurnal temperature variation with a maximum about 1400 hours and a minimum about 0600 hours. Four climatic zones are distinguished:

- i) north coast:
hot & dry, with estimated rainfall of 50 - 110 cms.,
mean temperature of 26 degrees Centigrade.
- ii) south coast:
hot & moist, with an estimated rainfall of 160 - 270
cms., and a mean temperature of 24 degrees Centigrade.

- iii) interior up to 1350 metres:
intermediate zone, estimated rainfall of 140 - 270 cms., and a mean temperature of less than 21 degrees Centigrade.
- iv) interior above 1350 metres:
cool zone, estimated rainfall about 320 cms., more evenly distributed than the other zones, a mean temperature relatively low for these latitudes.

The south coast has a wider temperature range than the north, the highest recorded temperature in the south being 41.4 degrees Centigrade.

Vegetation:

The vegetation of the region is much lighter than would be expected at these latitudes, due to the relatively low rainfall and exceptionally dry conditions between the monsoons. The range of vegetation is wide, varying from semi-desert scrub to tropical rain forest. The coastal strip frequently carries mangrove swamps and rain forest. In the foothills there is not much rain forest. Much of the foothill region is covered by either a park-like vegetation of grass with large stands of Eucalypts and Cassurinas and very little undergrowth, as is found over much of the Tertiary rocks, or a mixture of thorny scrub and large trees such as are commonly found on the Viqueque Formation. Higher parts of the foothills are sometimes covered by grassy slopes with a few small scattered trees and shrubs. This type of vegetation is commonly found on the Aitutu Formation and Wai Luli Formation. Many of the limestone mountains over 1350 metres support a dense forest of large trees.

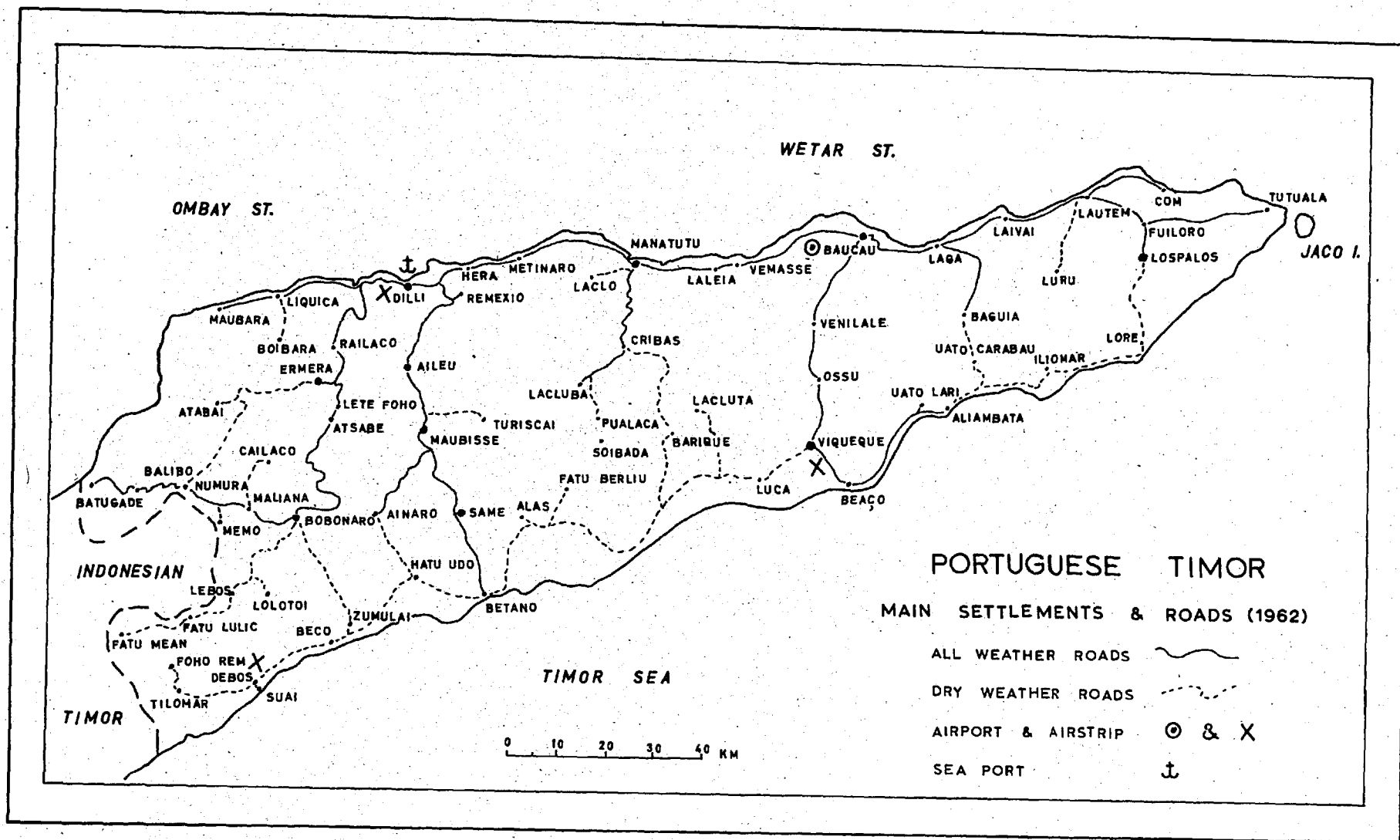


Fig. 3

Communications:

All connecting roads in eastern Timor are unsealed and only metalled in parts, although in general those on the north side of the island have been well macadamized. The north coast road and those leading to the principal settlements in the mountains are negotiable by four-wheeled drive vehicles throughout the year (figure 3), except when major rivers are in spate. The south coast track is open throughout the dry season but closed from January to July. Portuguese Timor is well served by minor tracks open to four-wheeled-drive vehicles throughout the dry season. During the monsoon (December to July) the roads that connect the north and south coasts often become impassable. Most of these roads become tortuous tracks south of the principal watershed which in the wet season are hazardous.

Several airstrips useful for light aircraft are maintained. Dilly the capital has a good harbour whose facilities are being developed. A number of anchorages are present along the north coast, but the south coast where there is usually a high surf and swell, offers little shelter to shipping. Tank landing craft have been employed by Timor Oil Ltd. to move heavy equipment such as drilling rigs from place to place on the south coast.

Timor is well served with paths and tracks for horse and foot. The Timor pony is a sure footed animal that can be used as a pack-horse with much advantage by the field geologist. The numerous foot paths and generally light vegetation greatly facilitate field mapping.

People and produce:

The total population of eastern Timor is about 500,000 of which the great majority are Timorese. European Portuguese, Indians, and Chinese make up the rest of the community. The Timorese have no written records and their origins are obscure. There are many languages, and local communities are based on language. Throughout both Portuguese and Indonesian Timor the lingua franca is Tetum, a primitive form of Malay. Unlike most people of the Archipelago the Timorese are not Muslims.

The Timorese are entirely agricultural, their main produce being maize, rice, copra, coffee, rubber and tobacco. A little oil is produced from the more important of the many oil seepages and is consumed locally. Small deposits of gold, chromium and manganese are known.

Although it is possible to live on the local produce, the itinerant field geologist is better advised to depend mainly on imported preserved foods supplemented by local fruit and vegetables. These stores can be carried by Timorese porters and in the more open country by horses.

d). HISTORY OF EXPLORATION.

Probably the first geological study of eastern Timor was made by Hirschi (1907) who made two traverses across the island. He recognised that the island was structurally complex, and found palaeontological evidence for the presence of Permian, Triassic, Jurassic as well as Tertiary strata.

The next investigator was F. Weber who in 1910 - 1911 made a reconnaissance for an oil company. He never published his findings, but some were later published by Umbgrove (1935), and by Wanner (1956).

In 1936 geologists of the Allied Mining Corporation made a geological reconnaissance and studied the mining prospects of eastern Timor under the direction of S.F. Wittouck. A geological report with a geological sketch map and some detailed maps and sections were published privately by the Allied Mining Corporation (Wittouck, 1937).

A geological reconnaissance of the eastern part of eastern Timor was made during 1947-1948 by E.P. Escher and H.R. Grunau on behalf of Companhia Ultramarina do Petroleo (Lisboa) which belonged to the B.P.M. division of the Royal Dutch/Shell Petroleum Co.. A regional gravity survey of part of this area was also made at the same time by G. de Snoo on behalf of the same Company. Some geological results of this work have been published by Grunau (1953, 1956, 1957a and 1957b). The gravity data has been discussed by Teixeira (1952) in a paper dealing with the stratigraphy and structure of Portuguese Timor.

From May to November 1955 R. Gageonnet & M. Lemoine made a reconnaissance of Portuguese Timor for the Portuguese Government. They published their findings in a number of papers: Gageonnet & Lemoine (1957a, 1957b, 1957c, 1957d and 1958); Gageonnet, Lemoine & Trumpy (1959); Lemoine (1959).

Timor Oil Ltd., under the direction of their geological consultant Dr. W.F. Schneeberger began the

exploration of eastern Timor in 1956. The first important geological field work was that of I.B. Freytag, who in an unpublished report (dated 1959), dealing with his reconnaissance of part of central southern Portuguese Timor, proposed a revised Tertiary stratigraphy and doubted the presence of any major overthrusting in Portuguese Timor. This contradicted the concepts of earlier workers such as Grunau (1957a), Gageonnet & Lemoine (1957b, 1957c and 1958), and Lemoine (1959), who described complex overthrust tectonics and regarded Portuguese Timor as being largely composed of allochthonous formations in the form of greatly fragmented overthrust slices.

The present work is based on the results of a systematic mapping programme of all of eastern Timor by the writer alone, commenced early in 1959 and continued with interruptions until the end of 1961. Supplementing and supporting this field work are many palaeontological reports whose authors are listed in the acknowledgements. Various petrological and some geochemical studies of the stratigraphic column have been made by the writer during a research programme at Imperial College, London, begun in 1962. The results of these studies have been incorporated in this report.

The reliability of the field mapping is indicated in figure 4, which shows that the southern 2/3 of the region (i.e. the area covered by aerial photographs which have permitted preparation of base topographic maps on a scale of 1: 40,000) has been mapped in semi-detail. The best base topographic maps available for the rest of the area are on a scale of 1: 100,000; this dictated the practical scale of mapping in this area as 1: 100,000.

The scarcity of recorded dips and strikes in the pre-Tertiary formations does not reflect either frequency of outcrop or observation, but results from the extreme local variability of dip and strike in these rocks, caused by the complexity of minor folds and faults that characterise the pre-Tertiary formations. To record all the observed dips and strikes is possible only on maps having a scale of 1: 20,000 or better; to be selective in recording on a scale of 1: 100,000 can be highly misleading. The compromise presented in the maps accompanying this thesis (enclosures 1A,1B,1C,1D) is regarded as only partially satisfactory.

The gravity data included in this report is based on surveys with a Worden gravimeter conducted by the writer in 1959 and 1960, and on other surveys supervised by him in 1961. Incorporated in the Bouguer Anomaly maps (encls: 2B,2C,2D) is the data given by Teixeira (1952).

The petrography is based on a study of 3000 rock samples representative of the whole exposed column. From these samples 700 thin sections were cut and studied in detail.

Geochemical analyses of major and trace elements of some selected Cretaceous rocks have been made; these are reported on in the Appendixes I & II of this thesis.

Subsurface data from Tinor is scanty. In 1900 Elliott and Co. sunk a well in the Alianbata district to about 140 metres but no log or samples are known. In 1914 an Australian rig reached 170 metres in the Mete-Hou district for which no geological record is available.

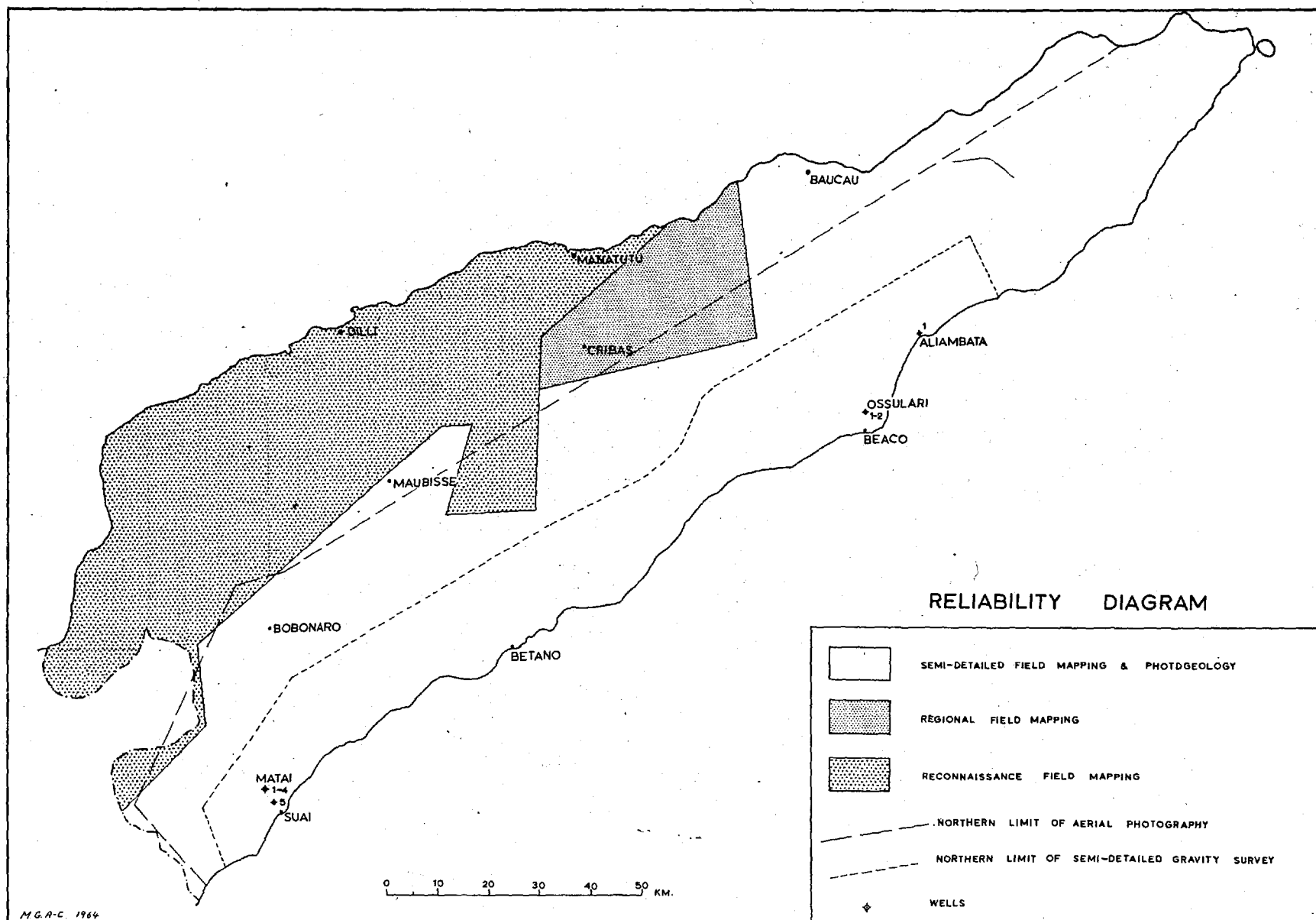


Fig. 4

In 1926-1928 a well was drilled to 270 metres at Aliambata. No samples are available but a driller's log of little value was published by Allied Mining Corporation (Wittouck, 1937).

Timor Oil Ltd. in 1957 drilled a well Aliambata No. 1 to 1355 metres. The section (as interpreted by W.F. Schneeberger in an unpublished report dated 1961) is discussed in the section dealing with the stratigraphy of Borolalo Limestone. Other wells drilled by Timor Oil Ltd. are Ossulari No. 1 which reached 2249 metres, Ossulari No. 1A to 1533 metres, Matai No. 1 which reached 673 metres, Matai No. 2 to 845 metres, Matai No. 3 to 320 metres, Matai No. 4 to 567 metres, Matai No. 5 to 1529 metres. The position of these wells is shewn in enclosure 1B. The section encountered in these wells are described in the section on the stratigraphy of the Viqueque Formation. Apart from these eight wells drilled with the Brewster 65 rig, the portable Edeco E 1000 drill has provided useful information from several Tertiary formations from slim hole core-drilling programmes in the areas about the Viqueque Anticline and the Matai Anticline.

The most recent field work in eastern Timor is that of Leme (1963) who investigated part of the area east of Mt. Mata Bia (enclosure 1D). Leme (1963) makes extensive use of the unpublished reports and maps of the present writer (dated 1961) which were available to him in Lisbon. In the mapping of the Tertiary formations of this region there is close agreement between Leme (1963) and the unpublished maps of the writer (dated 1962) that were also available to him in Lisbon, what differences there are

between the mapping of Leme (1963) and this present thesis seem to be due largely to the greater detail of the latter. There is some considerable disparity between the mapping of the pre-Tertiary by Leme (1963) and the revised work of the writer (this thesis). These differences are probably due to the present work not being available to Dr. Leme as well as a reflection of the greater detail of the present work. It is this much greater detail of the present study that makes elaborate comparison with the work of Grunau (op.cit.), Gageonnet & Lemoine (op.cit.), and Leme (op.cit.) inappropriate, but where there are important distinctions in interpretation or observation they are discussed in their pertinent context.

e.) PHOTOGEOLOGY.

It is understood that before the last war Royal Dutch/Shell Petroleum Co. (BPM) produced vertical aerial photographs covering the eastern part of eastern Timor, and that during the war the USAAF made some oblique aerial photographs of some trimetrogon runs.

In 1957 vertical aerial photographs affording stereoscopic coverage of the southern 2/3 of the area of eastern Timor (figure 4) were produced for Timor Oil Ltd. The photographs were taken with a six-inch focal length lens, and have a scale of approximately 1: 40,000. With the exception of a few runs most of these photographs were taken through a light haze which has reduced the clarity of the photographs, so that the quality of the photography is probably slightly below average.

These photographs were used to prepare controlled

planimetric maps having a scale of 1: 40,000 on stable film using a transverse Mercator projection by Adastral Airways Pty. Ltd., Sydney. This company produced by reduction another series of planimetric maps having a scale of 1: 100,000, that is the same scale as the maps that cover the area of eastern Timor not covered by the aerial photographs.

Detailed photogeological study of Timor is difficult because the surface distribution of the rock formations is complex, and in plan has a patchwork chaotic appearance. Other important impediments are the absence of marker horizons in most formations, the bedding of many formations is not evinced in the photographs, and the lack of well developed photo-characters of several of the formations. The situation is of course **aggravated** by the complexity of the tectonics. Despite these difficulties study of the photographs has permitted geological analysis that facilitated the mapping as the following remarks demonstrate:

The Baucau Limestone:

Generally dark toned, with hummocky topography, heavy vegetation, quite often stratified, always horizontal or very low dips.

Viqueque Formation:

Characteristically light toned with a relatively smooth surface. Often exhibits very well developed stratification. Vegetation generally light. This Formation and its contacts are usually identifiable on photographs.

Bobonaro Scaly Clay:

Generally light to medium toned, characteristic hummocky topography, exhibits some limited stratification locally (which can never be identified on the ground). It has a soft homogeneous appearance except for the 'hummocks' which are obviously composed of much harder rocks (these 'hummocks' are large exotic blocks derived from various older formations). Vegetation is variable but generally light. Locally this formation can be identified confidently on the photographs, but its contacts are generally very hard to define, particularly the contacts with the Aitutu and Wai Luli formations. Similar difficulties are often experienced on the ground where outcrops are scarce.

Cablac Limestone:

Dark toned, rugged, high topography, with a heavy growth of large trees. Stratification rarely seen. Despite these strong characters this formation cannot be distinguished on the aerial photographs from either the Borolalo Limestone or the massive limestones of the Aitutu Formation in the Serricutti Range.

Barique Formation:

Dark toned with a heavy growth of large trees. Stratification exhibited locally. This formation is generally very difficult to separate from the Lolotoi Complex on the aerial photographs.

Borolalo Limestone:

Dark toned, rugged, high topography, heavy growth of large trees. Poorly exhibited stratification, Indistinguishable from the Cablac Limestone.

Wai Bua Formation:

Poorly expressed, lacking any distinctive characters, variable in tone and vegetation. Some limited stratification visible locally.

Wai Luli Formation:

Poorly expressed, variable tone and vegetation which may be generalised as medium to light. Topography suggests both soft and resistant strata present. Weakly expressed stratification except rarely.

Aitututu Formation:

Medium toned, vegetation generally light to very light, relatively smooth surface. Topography characterised by rugged prominent escarpments. Stratification poorly expressed except locally and along escarpments. The Aitututu Anticline is exceptionally well expressed on the photographs.

Cribas Formation and the Atahoc Formation:

Medium toned, variable vegetation. Topography variable and stratification only rarely exhibited.

Maubisse Formation:

Dark toned, very heavy vegetation of large trees, high topography, rugged, some well expressed stratification locally. This formation that is readily identified on the aerial photographs is always allochthonous in eastern Timor.

Lolotoi Complex:

Dark toned, rugged usually high topography, supports a heavy vegetation. Some limited stratification expressed locally. It is difficult to distinguish the Lolotoi Complex from the Barique Formation on the aerial photographs.

The geological maps that accompany this report (enclosures 1A,1B,1C,1D) were prepared by first plotting on to the aerial photographs in the field the observations made in the field. This information was subsequently transferred to the base planimetric maps. Photogeological maps on the same scale were also produced and composite maps were finally produced.

f.) LIMESTONE NOMENCLATURE

The classification applied to all the limestones of eastern Timor is based very largely on the system by Folk (1959) with modifications based mainly on suggestions of Wolf (1961) and Stauffer (1962).

Three compositional end members are recognised, they are defined as follows:

I. Terrigenous constituents:

All materials derived from erosion of source lands outside the basin of deposition, and transported as solids to the sediment.

II. Orthochemical constituents:

Normal precipitates shewing little or no evidence of transportation.

III. Allochemical constituents:

Discrete particles that originated within the basin of deposition.

is

The classification according to grain size^{is} from the scheme proposed by Folk (1959). The grain size limits for each group given by Folk are adopted here because his arguments in support of them are regarded as appropriate to the various limestones from Timor.

Some notes on the compositional end members are offered below:

I. Terrigenous constituents.

A very wide variety of terrigenous constituents are found in the various limestones, but there is usually a suite characteristic of each formation. In the calcirudites and calcarenites the following clasts are common:

quartz grains, chert grains, volcanic detritus, rock fragments of formations older than the host formation, various iron oxides, glauconite, heavy minerals and clay minerals. The last three are not very common. In the calcilutites the only common terrigenous constituents are

clay minerals and quartz grains.

II. Orthochemical constituents.

Three orthochemical constituents of importance are involved, they are microcrystalline calcite, sparry calcite and diagenetic minerals.

1. Microcrystalline calcite.

This type of calcite forms a mud (lutite) whose constituent grains are generally considered (Folk, 1959 and Stauffer, 1962) to be less than 0.004 mm. in diameter. The controversy over the origin of microcrystalline calcite as being precipitated initially as aragonite or calcite will not be discussed here. It is difficult, as Folk (1959) observed, to be definite about the upper grain size limit between microcrystalline calcite and sparry calcite cement. The distinction between them is important because of the generic inference that most microcrystalline calcite is precipitated from solution by chemical or biochemical agencies (Maslov, 1961), whereas sparry calcite usually forms a chemical precipitate that acts as a pore filling cement (Bathurst, 1958 and Folk, 1959) being deposited on to the free surfaces of allochems, or else by recrystallisation of microcrystalline calcite to sparry calcite. A grain size limit of universal application seems to be unsuitable, and it must be admitted that the best solution at present seems to be a partly subjective

interpretation based on texture and a particular size limit for each formation. This problem has been discussed recently by Stauffer (1962) who refers to the work of Folk (1959), Sander (1951) and others. For rocks of eastern Timor the size limit chosen is 0.008 mm.

2. Sparry calcite.

This was defined by Stauffer (1962) as "calcite deposited on free surfaces from solution". This type of calcite generally has grain diameters greater than 0.01 mm., and less than 0.2 mm. The pore filling cement has been described by Bathurst (1958) as having three principal habits: granular cement, drusy growth and rim cementation. These are all commonly recognised in the limestones from eastern Timor.

3. Diagenetic minerals.

The principal diagenetic mineral is recrystallised calcite. This was defined by Stauffer (1962) as "calcite which has occupied its present space by taking the place of another mineral or a different form of the same mineral". It is not always easy to be sure whether some sparite was precipitated as sparite or was formed by recrystallisation from microcrystalline calcite. This problem of distinction has been discussed by Bathurst (1958) and (1959) and Stauffer (1962) who give a number of criteria for distinguishing between them. Other commonly occurring diagenetic minerals are dolomite, chalcedony, and pyrite. In studying

the Timor limestones it was found that there is a grade of calcite that falls between sparry calcite and microcrystalline calcite, it usually falls into the grain size range of 0.06 to 0.008 mm.; this is termed microsparite. This term as employed here does not imply recrystallisation.

III. Allochemical constituents.

There are four main types of allochem that occur most frequently:

1. Intracrasts.

Intracrasts have been well defined by Folk (1959). A very wide variety of intracrasts are found in the Cablac Limestone, in the other formations they are not common.

2. Oolites.

Both oolites and superficial oolites as defined by Illing (1954) are particularly common in the Cablac Limestone, in the other formations they are rare. In the Cablac Limestone a considerable variety of structure and texture is seen in the oolites.

3. Pellets.

The term pellet is applied here in the sense defined by Folk (1959) with the modification that the size range quoted by Folk (of 0.15 to 0.03 mm. with a common size of 0.08 to 0.04 mm.) is extended to cover the range 4.0 to 0.03 mm.

It is found that most of the pellets smaller than 0.1 mm. form clots of microcrystalline calcite and give rise to a texture that Cayeux (1935) called "structure grumeleuse".

4. Skeletal fragments.

The skeletal fragments vary according to the age of the formation. In the Cablac Limestone the principal fossil debris is composed of calcareous algae, Foraminifera, bryozoans, echinoids, molluscs and sponges. The classification used here is based upon the principal type of allochem present, and the nature of the matrix or cement in which the allochems are held. The size of the allochems (irrespective of the grain size or nature of the cement or matrix) is indicated by using the appropriate term arenite or rudite; no allochems of lutite grade were recognised.

THE LIMESTONE CLASSIFICATION SCHEME:

1. Allochemical limestones (i.e. those limestones containing more than 10% allochems). - See Table II.
2. Orthochemical limestones (i.e. those limestones containing less than 10% allochems).
There are two main types of orthochemical limestones:
 - (i) Micrites. Microcrystalline calcite forms more than 90% of this type.

TABLE II

1. Allochemical limestones (i.e. those limestones containing more than 10% allochems).

Sparry Calcite	Microcrystalline Calcite	Microcrystalline Calcite	Sparry Calcite
Predominant allochem	ROCK NAME *	ROCK NAME	Average size of allochems
Intraclasts	Intrasparudite **	Intramicrodite	Rudite
Intraclasts	Intraspararenite	Intramicroarenite	Arenite
Pellets	Pelsparudite	Pelmicrodite	Rudite
Pellets	Pelspararenite	Pelmicroarenite	Arenite
Oolites	---	---	Rudite ***
Oolites	Oospararenite	Oomicroarenite	Arenite
Skeletal	Biosparudite	Biomicrodite	Rudite
Skeletal	Biospararenite	Biomicroarenite	Arenite

NOTES:

- * The term 'dismicrite' (see orthochemical limestone classification below) is employed in place of micrite or sparite where the majority of the matrix-cement is microsparite.
- ** An unusual variety of this type is found in the Cablac Limestone and is termed 'polymict intracalcirudite'. They are termed polymict because they contain a variety of terrigenous clasts as well as intraclasts in the sense employed by Folk (1959). The term 'intracalcirudite' is introduced to distinguish this group of calcirudites that contain little or no cement or matrix between the clasts.
- *** There no oolites of rudite grade.

- (ii) Dismicrites. Microsparite forms more than 50% of the micrite matrix.

When allochems are presented (up to a maximum of 10%) the appropriate term may be used as with the allochemical limestones e.g. oomicrite, biodismicrite, etc..

3. Dolostone, dolomite and dolomitic limestones.

In this work the word 'dolomite' refers only to the mineral dolomite. The word 'dolostone' (Shrock, 1948) is used for rocks in which dolomite forms 50% or more of the total volume. The term 'dolomitic limestone' is applied to limestones containing less than 50% of the mineral dolomite.

Since the purpose of this classification is to provide a schematic analysis that facilitates ~~their~~ study, a highly complex scheme would not be pertinent to the present recognisance survey. Hence a simplified version of Folk's (1959) system that provides a practical method of classifying the various limestones found in eastern Timor is employed. Clearly the above scheme does not allow for all varieties, such as variations between proportions of allochemical to orthochemical constituents. A method of including this detail was described by Wolf (1961). Similarly the proportions between various allochems present in one rock are not detailed, such a scheme has been described by Folk (1959). Other variations could also be built into this classification as required.

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PLATE 1

A. View from the central mountains looking towards the Lacluta klippe (a).

- (a) - Lolotoi Complex klippe, Mt. Aitana.
- (d) - South limb of Cribas Anticline (eastern
plunge).
- (e) - Barique Formation
- (o) - Cablac Limestone, Mt. Bibiliu
- (v) - Viqueque Formation of Dilor Syncline
- (n) - North coast
- (s) - South coast

B. North coast west of Manatutu, the Aileu Formation.

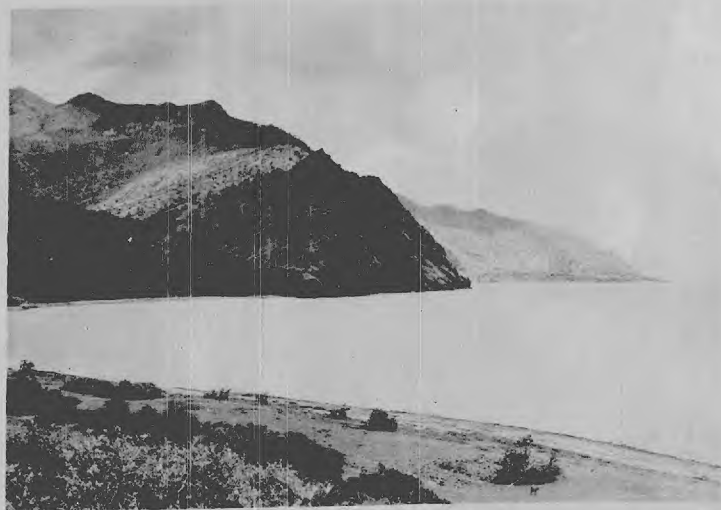


PLATE 2

- A. Baucau Plateau - Karst topography in the Baucau Limestone.
- B. Mt. Mata Bia - west face fault scarp.
- (n) - Cablac Limestone
- (o) - Bobonaro Scaly Clay
- C. Lospalos Plateau - looking south-east. Poros Limestone in the foreground, the distant hills are Aitutu Formation.
- D. Landslide south of Bobonaro.



PLATE 3

A. Alluvial terrace north of Same

- (n) - Barique Formation
- (o) - Ainaro Gravels

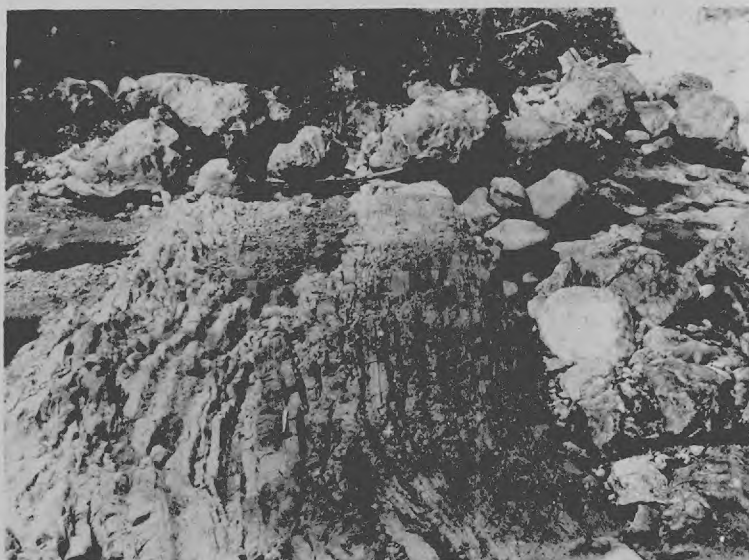
B. Bazol Anticline - looking west.

- (n) - Klippe of Lolotoi Complex
- (o) - Cribas Formation
- (p) - River Bazol coincident with axial plane
trace of the anticline.



PLATE 4

- A. River Cua with outcropping limestones of the Aitutu Formation. Typical features of upper reaches of rivers in eastern Timor.
- B. River Wai Luli - looking north. Typical braided streams of the foothills and south coast plains. Hummocky hills in middle distance are Bobonaro Scaly Clay.



CHAPTER II

STRATIGRAPHY

INTRODUCTION

The oldest dated rocks in eastern Timor are Lower Permian, the metamorphic rocks of uncertain age are interpreted as probably pre-Permian. With the exception of two important breaks and a number of minor but widespread unconformities (affecting all of eastern Timor) from Permian times onwards sedimentation was fairly continuous to the Recent. Some formations are entirely allochthonous in eastern Timor.

The present work attempts a complete revision of the stratigraphic column involving the definition of many new formations, revision of the limits of others and their re-positioning in the time sequence. All field mapping and stratigraphic subdivisions were based on rock-stratigraphic units. Fossils collected from these various units and identified by specialists have provided the time control. In this account the recommendations of the Australian Code of Stratigraphic Nomenclature (4th Edition, 1964) are followed as closely as possible.

Grunau (1953) recognised that some rocks of eastern Timor were tectonically allochthonous and divided the formations into an autochthonous and an allochthonous complex. Gageonnet & Lemoine (1958) followed Grunau (1953) in this procedure. The confusions of these and earlier workers over which formations are allochthonous are dispelled; the large majority of the formations are now recognised as autochthonous. Four separate formations are realised as completely allochthonous: the Lolotoi

Complex, Aileu Formation, Maubisse Formation and the Bobonaro Scaly Clay. Of these the Bobonaro Scaly Clay is distinct in that it was emplaced in Timor as a submarine gravity slide. Unlike all the other allochthonous formations it does not rest on a thrust plane. The Bobonaro Scaly Clay is exposed over a larger area than any other formation yet such is its peculiar nature that it was not recognised by Grunau (1953, 1956, 1957a, 1957b) or by Gageonnet & Lemoine (1958). It was the failure to recognise this formation that led to the misconception of multiple thrust planes, allochthonous "Fatu Limestone", and the "Bibiliu Series" of the earlier workers.

Because the Bobonaro Scaly Clay is nearly always present below the autochthonous rocks younger than Middle Miocene, and because it was emplaced by sedimentological rather than tectonic processes it is described in this thesis in the autochthonous sequence rather than with the allochthonous formations.

The rock-stratigraphic units are listed in the table I and a generalised stratigraphic column for eastern Timor is shown in enclosure 5.

The biostratigraphic subdivision of the Tertiary is based on Foraminifera, and expressed in the letter classification of van der Vlerk & Umbgrove (1927) - revised by van der Vlerk (1955). The subdivisions Ta, b, c, d, e, f, g, h, are considered to be time stratigraphic units. The problem of Tertiary stratigraphic correlation and the use of the letter classification have been recently discussed by Eames et al. (1962).

In the account of the stratigraphy which follows all the autochthonous formations are considered first.

ATAHOC FORMATION

SUMMARY

The Atahoc Formation is the oldest (Lower Permian) exposed autochthonous stratigraphic unit in eastern Timor. It is found only in two inliers; the Cribas Anticline and the Loi Quero Anticline. The Atahoc Formation, is about 600 metres thick. The formation, that is a flysch-type facies, consists mainly of shales and interbedded quartz sandstones with numerous calcareous nodules. The environment in which it was deposited was probably a relatively shallow shelf sea.

INTRODUCTION

Autochthonous Permian rocks were first recognised in eastern Timor by Grunau (1953) from the Cribas Anticline and the Loi Quero region. Gageonnet & Lemoine (1958) followed Grunau (1956) in calling these rocks the Cribas Series. Recent work by the present writer has shewn that autochthonous Permian strata occur in four other widely separated areas (figure 5). Gageonnet & Lemoine (1958) subdivided their Cribas Series into an upper and a lower

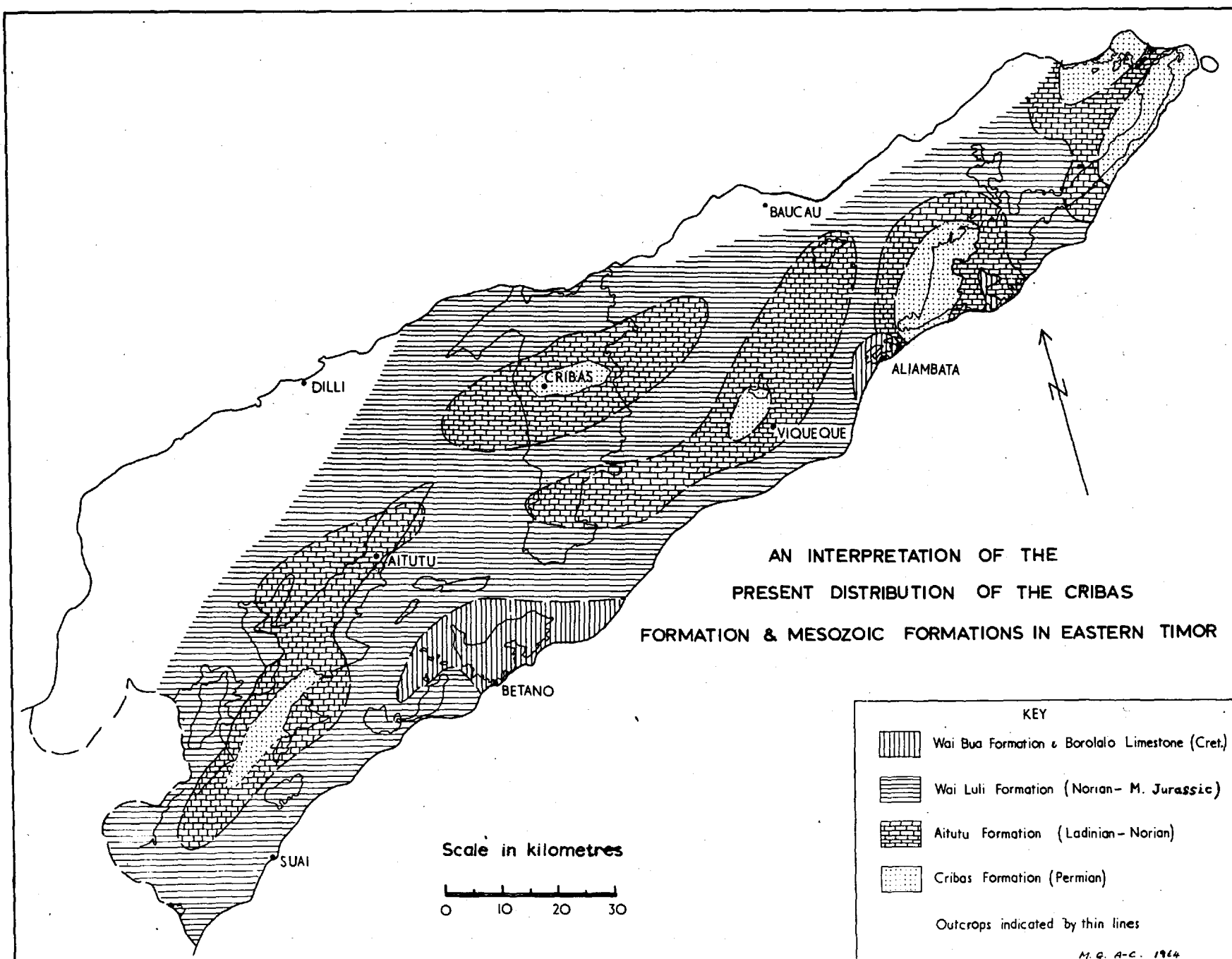


Fig. 5

part. In this report these two parts are elevated to the 'rank' of formation. The lower part is called the Atahoc Formation and the upper part the Cribas Formation. Gageonnet & Lemoine (1958) described a type section for their Cribas Series from the Cribas Anticline. Their type section serves for both the Atahoc and Cribas Formations.

The Atahoc Formation is known only from the core of the Cribas Anticline and the Loi Quero Anticline, where it is conformable below the Cribas Formation.

The type locality for the Atahoc Formation is the exposed core of the Cribas Anticline in the banks of rivers Akraun (north of the village Atahoc), Sumasse (about Cribas village), and Tuquete (north of the village of the same name). Here in the type locality the lowest exposed part of the Atahoc Formation is a hard, unfossiliferous, pink and grey coloured massive quartz sandstone (plate 5C) with some thin black shale intercalations. Just north of Cribas village large cliffs of this sandstone are well exposed.

Above this unfossiliferous sandstone the succession is mainly hard black silty shales with numerous calcareous nodules and some thin limestone beds that may be followed as marker horizons. These limestones are beige, grey and red coloured, usually fossiliferous containing debris of crinoids, trilobites (rare), cephalopods, corals and bryozoa. A few very thin cherts are interbedded with the limestones. Thin beds of hard micaceous quartz sandstone are also developed, particularly towards the top of this Formation. The top of the Atahoc Formation is taken arbitrarily as the top of the amygdaloidal basalt that forms a good marker horizon. It varies between 3 and 7

metres thick, and is red and greenish in colour. Immediately below this basalt red shales and a red limestone bed containing the trilobite Phillipsia occur. The type section which is estimated to be about 600 metres thick is illustrated in enclosure 6.

Outside the type locality the Atahoc Formation is found only in the vicinity of Loi Quero village (enclosures 1C & 1D). Here the Formation consists of a series of hard grey slates that weather to a rusty colour, and pink and grey hard massive quartz sandstones shewing traces of fine laminations and cross bedding. No fossils have been found in these beds, but lithologically they resemble the Atahoc Formation of the Cribas Anticline. Furthermore they are overlain by the Cribas Formation with apparant conformity. The thickness of the Atahoc Formation at Loi Quero is estimated to be about 600 metres. Exposure here is patchy due to the partial erosion of the Pleistocene raised coral reefs revealing the inlier.

LITHOLOGY & PETROGRAPHY

The bulk of the Formation is composed of hard black shales and silty shales. Finely laminated and monotonous in appearance these shales have not been studied. Incorporated in these shales are numerous calcareous nodules, and clay-ironstone nodules. Some thin limestones form marker beds within the shales. Massive quartz sandstones form the lowest exposed lithology. Other beds of quartz sandstones and siltstones are interbedded with the shales.

Quartzites and other non-carbonate arenites.

The non-carbonate arenites range in grain size from medium sandstones to siltstones; very-fine-sandstone predominate. Most of these arenities are very poorly sorted and have a clay-silt matrix, but some of the quartz sandstones have virtually no matrix and no cement. The detrital grains of these rocks are composed of about 95% quartz, they are generally angular or subangular. Fresh plagioclase grains form less than 5% of most arenites, and tourmaline grains that are usually rounded or subrounded make up about 1% of the volume of detritus. Mica is a highly variable constituent.

Most of these arenites have a clay matrix comprising more than 5% of the rock and fall into Folk's (1954) immature sandstone - orthoquartzite category. A few have patches of sparry calcite cement, and occasionally a quartz arenite has a sparry calcite cement throughout. Some arenites have a granular patchy siderite cement. Many of the finer grade sandstones and siltstones have well developed microlenticular bedding in which microlenticles of fine sand interdigitate with silt or mud grade.

Diagenesis has affected these rocks in a number of ways: (1) pressure solution between quartz grains is variable (plate 5A); (2) corrosion of the quartz grains by the clay matrix; (3) corrosion of quartz grains by the calcite cement; (4) dolomitisation of some of the sandstones, this is rarely seen but where it occurs the dolomite is usually ferroan.

Bedded Limestones

The individual limestone beds are seldom more than 10 cm thick. They are mostly pink and grey but a few are dark red. Typically they are hard and dense. Most of the bedded limestones are calcarenites with a micrite matrix, but locally the original matrix seems to have altered to microspar. A few limestone beds are calcilutites with some scattered skeletal fragments.

The calcarenites (strictly biomicarenites) are remarkably uniform in composition whether they come from the Cribas or Loi Quero inliers. The allochems are fragments of corals, bryozoans, crinoids, molluscs and brachiopods with numerous siliceous Foraminifera. Some contain plagioclase crystals which have become largely altered to a granular mosaic of calcite. Pyrite is commonly present in small quantities. The micrite matrix is usually fine and dense.

Very little diagenesis is observed except silicification and the formation of chert nodules. These chert nodules are not common. They usually contain dolomite rhombs which are sometimes zoned. The dolomite is usually ferroan. Also present in the cherts are relic calcite structures in various stages of replacement by silica. The cherts themselves are frequently cut by veins of sparry calcite (plate 5D).

Calcareous nodules.

The calcareous nodules and the clay-ironstone nodules that are very common in the shales vary in size (maximum

diameter) from about 25 cm to 2 cm. The calcareous nodules generally have a regular shape, while the clay-ironstone nodules are commonly torpedo shaped or irregular with tubercle-like excrescences. The clay-ironstone nodules have a rusty brown coloured rind and a blue-grey cortex. All the nodules are very fine grained and very rarely contain fossil fragments.

STRATIGRAPHIC POSITION

The Atahoc Formation is the oldest exposed group of autochthonous rocks in eastern Timor. It is overlain conformably by the Cribas Formation, the contact between them being chosen arbitrarily at the top of the basaltic flow in the Sumasse River section south of Cribas. In the Loi Quero region the boundary selected between the two formations is at the base of the lowest red shales. The age of the Atahoc Formation is determined as Lower Permian on the basis of its sparse fauna. The fauna has been studied by Grunau (1953, 1955 & 1956), and Gageonnet & Lemoine (1958), and the following have been recorded:

Stachaeoceras cf. timorense (Haniel)

Metalegoceras sp.

Popanoceras timorense Haniel

Parallegoceras sp.

? Phillipsia sp.

This fauna has been compared by Grunau (1956) with that of the Somohole Beds in western Timor whose age is Sakmarian.

ENVIRONMENT

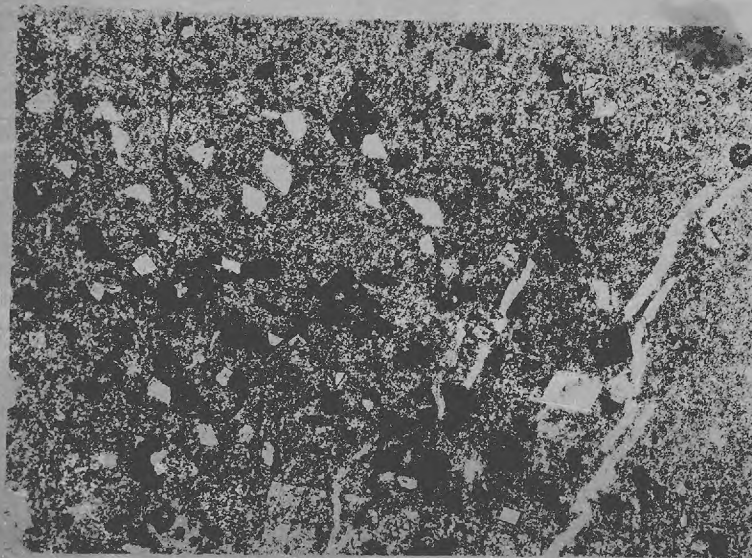
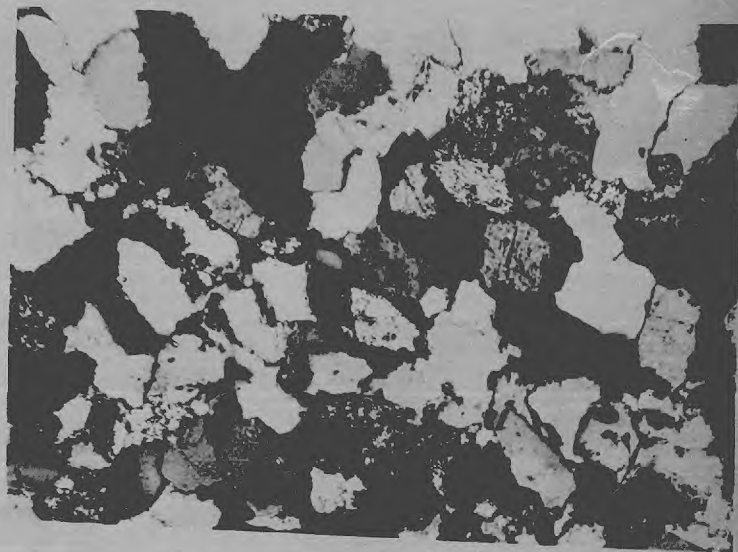
The Atahoc Formation is a monotonous sequence of shales and silty shales with interbedded siltstones, sandstones and occasional limestones. This group of rocks meets most of the requirements of flysch as defined by Kuenen (1958, p.329) except that graded bedding is not commonly seen in the Atahoc Formation. Likewise most of Tercier's (1947, p.168) requirements are fulfilled, and many of those of Sujkowski (1957) and Trumphy (1960). Tercier (1947) considers that flysch sedimentation is not restricted to any particular depth zone but could take place along any steep slopes from coastal environments to great depths.

Similarly the sedimentary structures in these rocks, particularly the current ripple laminations, that are very common in the arenites, have been described from a wide range of modern sedimentary environments; e.g. deep-sea (Menard, 1952), tidal mudflats (van Straaten, 1959) and rivers (Shantser, 1951). What they do indicate is deposition under quiet traction conditions. The fossils found in this Formation - ammonoids, gastropods, pelecypods, crinoids, bryozoans, corals, and trilobites indicate little beyond a marine environment. The poorly sorted nature of the non-carbonate arenites suggests deposition under quiet traction conditions. The biomicarenites that suggest shallow water deposition also point to weak traction currents.

The calcareous concretions that are common in the shales may indicate stagnant conditions (Weeks, 1953). The associated black shales frequently containing pyrite accord with this idea.

PLATE 3

- A. Atahoc Formation - quartz arenite shewing pressure solution (nicols crossed, x 150).
- B. Cribas Formation - sedimentary slumped horizon; note rounded boulder of limestone (near hammer) in slumped shale layer.
- C. Atahoc Formation - quartz arenite in the southern limb of the Cribas Anticline.
- D. Atahoc Formation - chert with dolomite partly replaced. (crossed nicols x 25).



The evidence available does not permit a satisfactory interpretation of the environment in which this Formation was deposited. What does emerge is that the sequence is marine, that bottom currents were probably weak and conditions may have become stagnant locally. The presence of calcarenites and the accompanying fauna suggest but do not prove that conditions were relatively shallow.

CRIBAS FORMATION

SUMMARY

The Cribas Formation consists of a flysch facies of about 500 metres thickness. Principal lithologies are shales with interbedded quartz sandstones and limestones. The age of the formation is probably Upper Permian. The Cribas Formation occurs in six inliers in eastern Timor, in four of which it forms the oldest exposed autochthonous rocks and in the other two it is underlain conformably by the Atahoc Formation. The Cribas Formation was probably deposited in a shallow shelf sea.

INTRODUCTION

The Cribas Formation is equivalent to the upper part of the Cribas Series described by Grunau (1956) and by Gageonnet & Lemoine (1958) from the Cribas Anticline. These earlier workers recognised these rocks only from the

Cribas Anticline and the Loi Quero inlier. They are now known from four other inliers (figure 5).

The type locality for this Formation is the section in the River Sumasse, where it cuts through the Cribas Anticline, south of Cribas village. The type section, estimated to be about 500 metres thick, is illustrated in enclosure 6. The base of the Formation consists of a sequence of black and blue-grey brittle shales and micaceous shales with finely micaceous siltstones and greenish fine grade quartz sandstones. Some of these arenites are rich in the pelecypod Atomodesma. Calcareous nodules and clay-ironstone nodules are common in these shales. The shales are finely to very finely laminated, and locally red and green varieties are developed. Bedded limestones are rare in this part of the section, where they do occur they resemble those of the Atahoc Formation being biomicarenites and calcilutites. Higher up the section calcareous nodules become less common, but cone-in-cone and clay-ironstone nodules occur frequently. Towards the top of the formation the non-carbonate arenites become rare and limestones increase in importance and marly horizons make a notable contribution. The limestones are hard and dense, mostly blue-grey and black.

Outside the type locality the Cribas Formation outcrops in the Bazol Anticline, the Viqueque inlier, the Aliambata Anticline, the Loi Quero Anticline and the Veru Anticline. In all these areas the composition of the Formation is remarkably similar and the maximum thickness about 500 metres. The detailed succession in these other inliers has not been worked out because minor folding and faulting has been severe and fossils are extremely rare.

It may be that the various red shale horizons could be used as markers.

Lavas and tuffs make minor contributions to the Formation in the most of the inliers.

LITHOLOGY & PETROGRAPHY

The principal lithologies found in the Cribas Formation are - shale, silty shale, quartz arenites, calcilutites, marls, cone-in-cone, calcareous nodules, clay-ironstone nodules, lavas and tuffs. The characteristics of these various rock types are described briefly below.

Shales and silty shales.

Shales and silty shales make up the bulk of the Formation wherever it is exposed. The shales are generally black or blue-grey with local developments of green and red shales.

They are interbedded with thin quartz siltstones and sandstones that are usually micaceous, as well as with occasional thin limestones (plates 8B,8D). In most of the inliers some sections of the shales have clearly been involved in large sedimentary slump movements. Three such structures are illustrated in the plates: 5B,6A,6C.

Quartz arenites.

Grain sizes in the sandstones and siltstones range from medium sandstone to fine siltstone. Most of the

arenites are poorly sorted and fall into the very-fine-sandstone category (plate 9A).

Quartz generally angular or subangular always predominates forming more than 95% of the detrital elements. Fresh plagioclase is usually present but never forms more than 5%. Mica though variable is generally an important constituent (plate 7B). Of the heavy minerals only tourmaline is present in most samples, but it never forms more than 1%. Ilmenite, leucoxene, magnetite, hematite and pyrite occur occasionally, usually in very small quantities. The only lithic detrital particles recognised are quartz-mica-schists of very fine grain size and cherts. These lithic fragments are not present in all arenites, and never form more than 2%.

These quartz arenites fall into two categories on the basis of their having either a fine silt-clay matrix or a calcite cement. The large majority have a silt-clay matrix (plates 6B,6D). These poorly sorted arenites are characterised by two types of sedimentary structures: current ripple lamination (marked by microlenticular bedding as seen in plate 6D), and burrowing features. Some of these muddy sandstones have a patchy sparry calcite cement. The calcite cemented quartz sandstones and siltstones frequently exhibit lustre mottling due to the poikilitic texture of the calcite cement. Some of the sparry calcite cements are ferroan (plates 7A,8C).

In these quartz arenites two types of diagenesis are noted: corrosion of the quartz grains by either the calcite cement or the clay matrix, and pressure solution between the quartz grains. The extent to which these processes

have affected different rocks in the Formation is variable, some arenites shew no trace of either process.

Fossils are very rare in these rocks, but local concentration of the pelecypods Atomodesma and Pterinea do occur. Occasionally fragments of crinoids, bryozoans, corals and molluscs are seen. Very poorly preserved plant remains and lignite are common in these arenites.

Calcilutites.

The calcilutites generally form beds less than 50 cms. thick. They are typically hard with a subconchoidal fracture. Most of them are blue-grey or beige but a few pink, green and less commonly red limestones occur. Most of the calcilutites contain about 1 percent disseminated pyrite. Sparry calcite filled veins usually cut these limestones. Most are composed of a fine dense micrite but some appear to have largely recrystallised to microspar. Organic remains of four kinds are found: crinoid and molluscan fragments, burrowing structures ("Worm tubes"), siliceous Foraminifera (plate 8A) and bituminous grains.

Some of the calcilutites are probably radiolarian (plates 7C,7D). They contain globular structures now composed of clear sparry calcite (usually ferroan calcite in contrast to the iron-free calcite of the matrix). As no radiolarian structures composed of silica have been preserved it is not possible to confirm their origin, but the writer has seen Triassic limestones of the Aitututu Formation in which siliceous radiolarian skeletons have been partially replaced and filled as well as wholly replaced and filled in the same thin section; they

resembled these structures quite closely (compare plates 7C & 7D with the Triassic limestones plate 12A & 12B).

Siliceous Foraminifera are common in these calcilutites, and ostracods are quite common (plate 8A).

Dolomitisation is rare, and wherever it is seen takes the form of scattered small rhombs of dolomite (occasionally zoned) in the micrite. Silicification has not been observed in these rocks. Small angular quartz grains occur in some of the calcilutites.

Marls.

Marls are relatively uncommon in the succession, they are thinly bedded, and are distinguished by their light grey colour and platy fracture. They are composed of fine grained mixtures of micrite and clay. Pyrite is commonly associated with them in small quantities. Micro-lenticular bedding is seen in thin sections because it is marked by reddish brown bituminous matter in stringers. Some of the marls have scattered quartz grains and mica amounting to about 30 percent of the total volume.

Cone-in-cone.

Cone-in-cone calcite structures are common in the upper part of the Formation. These structures occur in thin calcite layers within the shales and are usually but not always associated with extremely thin layers of lumachelle and bituminous lumachelle. The associated sparry calcite cement is usually ferroan.

The original calcite of the cone-in-cone is iron-free. The thin veins of sparry calcite that commonly cut the structures are often ferroan. Thin veins of quartz also cut the cone-in-cone and may be seen to have replaced the calcite of the cones. Micronodules of chert are commonly found in the cones. It is of interest that the conical structures seem to exert some control over the distribution of the chert.

Clay-ironstone nodules.

Although calcareous nodules are common only in the lower part of the Formation, the clay-ironstone varieties occur throughout the section. The strictly calcareous nodules are composed of very fine micrite and usually contain no recognisable fossils beyond the occasional crinoid fragment. The clay-ironstone nodules are usually composed of a very fine mud. They have a rind that is rusty and flakey when weathered whilst the core is generally blue-grey. Irregular in shape, and usually less than 25 cms largest diameter, their surface commonly has small tubercle-like excrescences.

In thin section they often shew discrete siderite crystals, a few quartz grains, and limonite grains, pyrite, and a little chert. Fossils are either absent or present as rare fragments. Ostracods are present occasionally.

Eruptive rocks.

Both lava flows and tuffs make rare contributions to the Cribas Formation. Frequently they are associated with red shales and thin red limestones. The flows are

basaltic but vary considerably in texture, some being highly porphyritic. All the inliers with the exception of the Viqueque inlier contain eruptives. In outcrop the tuffs usually weather very badly, and are rapidly eroded, decomposition preventing fresh samples being collected. The tuffs in the Tualo Creek are rich in the pelecypod Atomodesma, indicating they are shallow marine deposits.

STRATIGRAPHIC POSITION

In the type locality and in the Loi Quero inlier the Cribas Formation overlies the Atahoc Formation conformably, in the other inliers, where the Cribas Formation is exposed, it is the oldest autochthonous formation. The age of the Cribas Formation has been determined as Upper Permian (probably lower Upper Permian) on the basis of the fauna.

In the type locality the problem of the contact between the Cribas Formation and the overlying limestones and shales of the Aitutu Formation (Ladinian to Norian) is difficult to resolve because there is no clear lithological break. Tectonic dislocation in this region has been severe, so that the presence of complex folding and faulting, and the absence of any good index fossils (only a few poorly preserved pelecypods are found in the upper part of the Cribas Formation) the boundary is taken at the first horizon that contains Halobia, the index fossil for the Triassic in Timor. Elsewhere in eastern Timor the contact between the Cribas Formation and the overlying Aitutu Formation is clear and pronounced. Outside the type locality of the Cribas Anticline the contact between the two formations appears to be unconformable, the whole of the Lower Triassic and probably the Middle Triassic missing. In the

Cribas Anticline it must be admitted that the Lower Triassic might be present. In western Timor the Lower Triassic, represented by a cephalopod facies, is reported to be complete in 2 metres thickness (Umbgrove, 1938). It is interesting (but probably not significant) that a Lower Triassic (Scythian) ammonite Dinarites hirschii Wanner was collected by Hirschi from the ejected blocks of the mud volcano at Bibiluto (south of Viqueque). The blocks derived from this mud volcano are exotic blocks in the Bobonaro Scaly Clay (a mid-Miocene gravity slide deposit discussed later).

All the inliers except the Bazol Anticline and the Viqueque inlier have yielded the Permian pelecypods, identified by J.M. Dickins & S.K. Swarko of the Bureau of Mineral Resources in Canberra Australia (personal communication, 1961) -

Atomodesma exerata Beyrich
Atomodesma variabile Wanner

Grunau (1956 & 1957) reported another pelecypod from the Cribas Anticline and the Loi Quero Anticline:
Merismopteria cf. macroptera (Morris).

The Bazol Anticline has yielded the following Foraminifera identified by D.J. Belford of the Bureau of Mineral Resources Canberra Australia (personal communications, 1960 & 1961):

Textularia sp.

Trepilopsis sp.

Geinitzina triangularis Chapman & Howchin

Fronidularia sp.

Nodosaria sp.

Lagenidae

A very similar limestone (an exotic block in the Bobonaro Scaly Clay) yielded the following Foraminifera and Radiolaria etc:

Cornuspira sp.

Dentalina sp.

Fronidularia sp. aff. F. woodwardii Howchin

Geinitzini triangularis Chapman & Howchin

Nodosaria sp. aff. N. postcarbonica Spandel

Radiolaria:

Cenosphaera sp.

Acanthosphaera sp.

Dictyonitra sp.

Rhapolodictyum sp.

Ostracoda:

Bairdia spp.

Other fossils that occur in the Cribas Formation are crinoids, brachiopods, gastropods and bryozoa, but they are always fragmentary and indeterminate. Cephalopods are notably absent from this formation.

It is only the Viqueque inlier in which the Cribas Formation cannot be confirmed by the fauna as Permian because the ostracods and Foraminifera found in these beds are not diagnostic. It is on the basis of comparable lithology that the rocks in the River Cua section are identified as belonging to the Cribas Formation (micaceous shales, silty shales, with thin siltstone and limestone beds).

ENVIRONMENT.

With the exception of the lignite and plant remains all the fossil material in the Cribas Formation is of marine origin, and there is nothing to suggest that the whole Formation was not deposited in a marine environment. The poorly sorted nature of the arenites together with the current ripple marks, burrowing structures, the presence of lignite, plant remains and the pelecypod Atomodesma suggest the environment of deposition may have been fairly shallow water not far from land. However, it must be admitted that the current ripple laminations and burrowing structures of themselves do not indicate shallow water or near shore conditions; they have been described from a wide range of modern sedimentary environments (Menard, 1952; Van Straaten, 1959 & Shantser, 1951). The Cribas Formation consists of a monotonous series of shales, siltstones, sandstones and occasional limestone (plates 8B, 8D) that fits most definitions of flysch reasonably well (e.g. Tercier, 1947; Sujkowski, 1957; Kuenen, 1959 and Trumphy, 1960). Flysch-like sediments seem to be developed in a wide range of marine environments (Tercier, 1947).

One important feature of this Formation is the presence of large scale sedimentary slump structures (see plates 5B,6A,6C). That such slumping can occur in deep geosynclinal sediments is well known, that it also occurs in shallow water on gentle submarine slopes was shewn by Kuenen (1948) for the Carboniferous rocks of Pembrokeshire. The description of these rocks from Pembrokeshire recalls many features of the Cribas Formation. It is tempting to suggest that the Cribas Formation (and the Atahoc Formation) may represent pro-delta shelf deposits, and delta slope beds, but Taylor (1963) in dealing with the Wealden delta has ~~continued~~ argued against interpreting ancient sediments as deltaic unless "at least 3 of the 4 principal environments can be recognised".

The presence of calcareous nodules in black occasionally pyritic shales may indicate (Weeks, 1951) that stagnant conditions developed locally.

The angularity of the quartz grains and the presence of brilliantly fresh plagioclase in the arenites of the Cribas Formation suggest that these sandstones are first cycle deposits. The composition of these arenites also suggests they were derived from acid igneous rocks, Furthermore the brilliant freshness of the plagioclase grains suggests they were eroded from their source under a rigorous climate (Barton, 1961; Pettijohn, 1957, p.127). Palaeogeographic considerations (discussed in more detail later in the chapter on the Geological History) suggest the most likely source area for much of the detritus of the Cribas Formation is the area to the south, that is the area now occupied by the Sahul Shelf.

PLATE 6

- A. Cribas Formation - slumped shales in the Bazol Anticline.
- B. Cribas Formation - quartz arenite with siltv clay matrix.
- C. Cribas Formation - slumped horizon, note slump folded limestone beds near the feet of standing figure.
- D. Cribas Formation - quartz arenite with silt clay matrix shewing microlenticular bedding (x20).

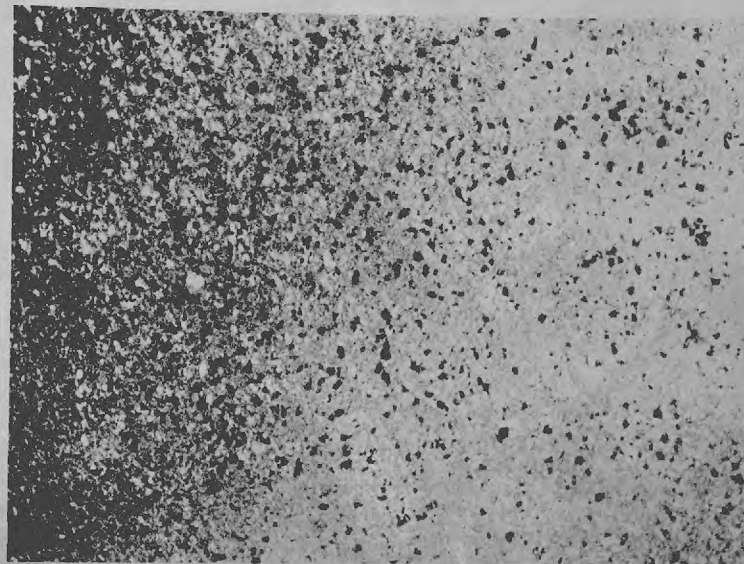
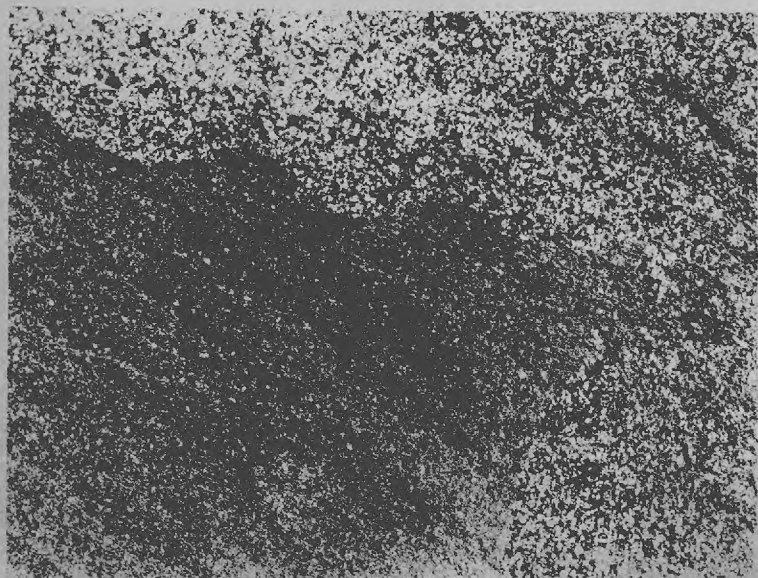


PLATE 7

- A. Cribas Formation - quartz arenite with mixed calcite and clay cement (x 25).
- B. Cribas Formation - quartz arenite with calcite cement. Note biotite and fresh plagioclase grains (x 150).
- C. Cribas Formation - calcilutite with sparry calcite filled ostracod and radiolarians (x 20).
- D. Cribas Formation - marl with sparry calcite filled radiolarians (x 25).

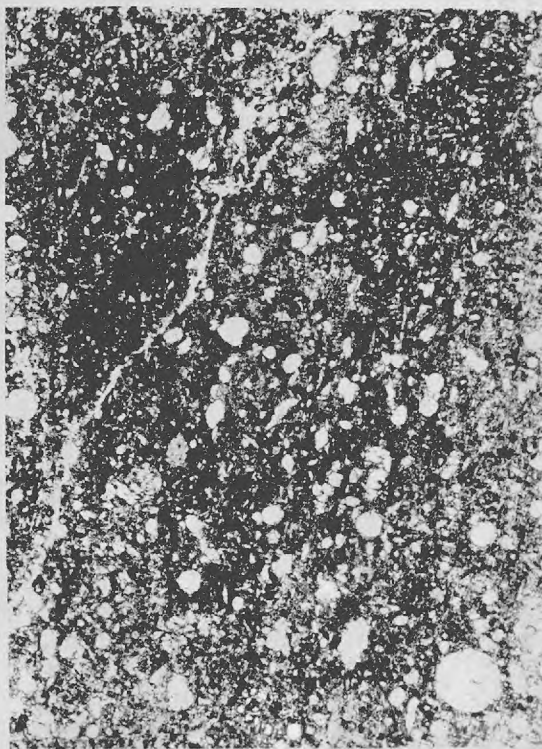
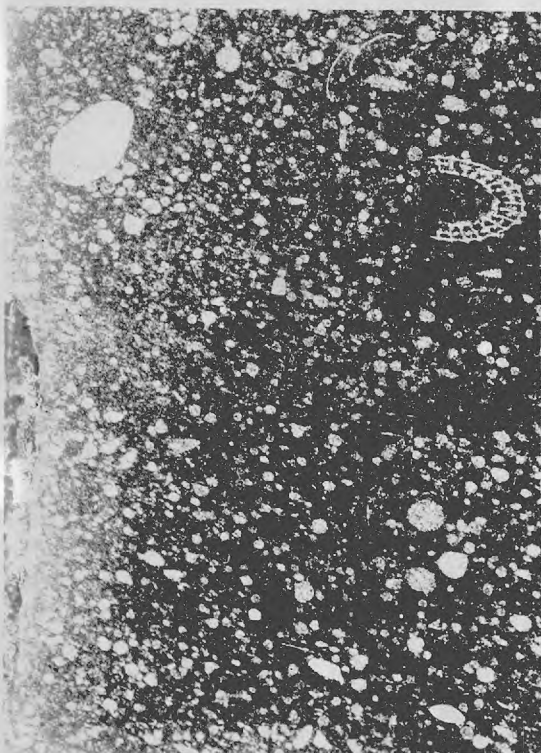
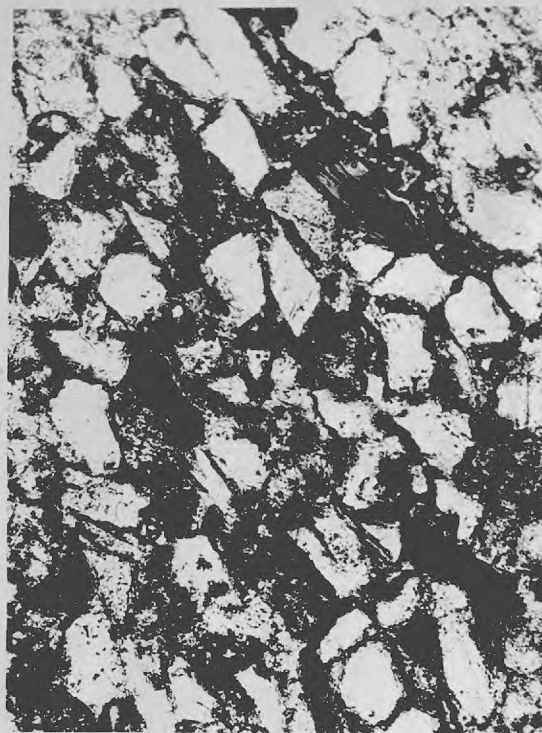
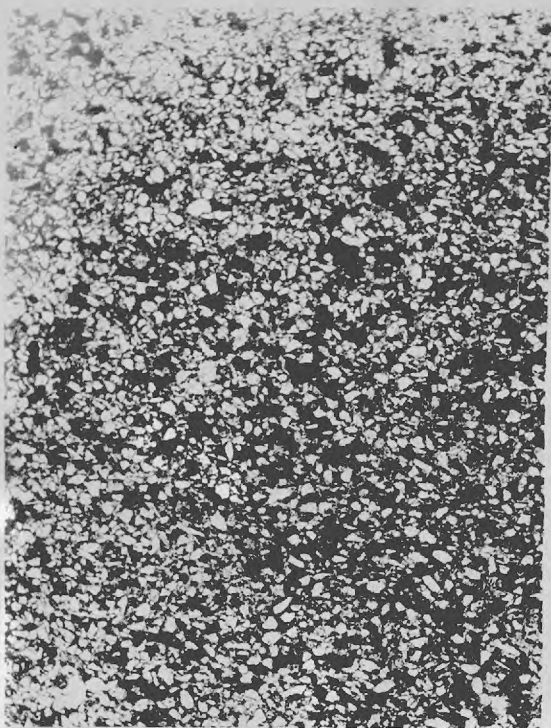


PLATE 8

- A. Cribas Formation - biomicarenite with siliceous Foraminifera and echinoderms (x 20).
- B. Cribas Formation - typical shale - silty shale sequence with thin interbedded calcilutites. Recent alluvium at top. Bazol Anticline.
- C. Cribas Formation - quartz arenite with micrite clasts and fossil fragments. Sparry calcite cement (x 20).
- D. Cribas Formation - typical shale - silty shale sequence with thin interbedded limestones from the Aliambata Anticline.

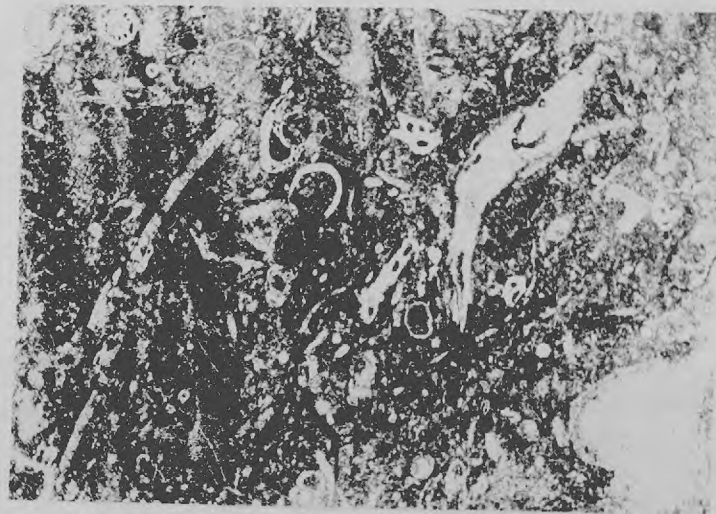
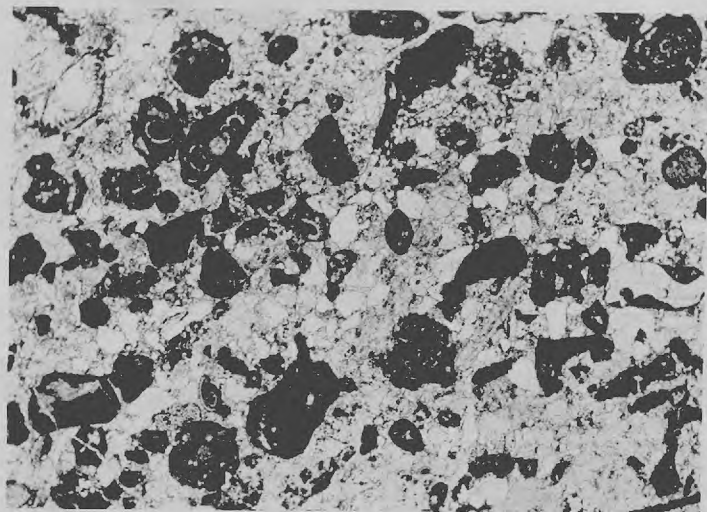
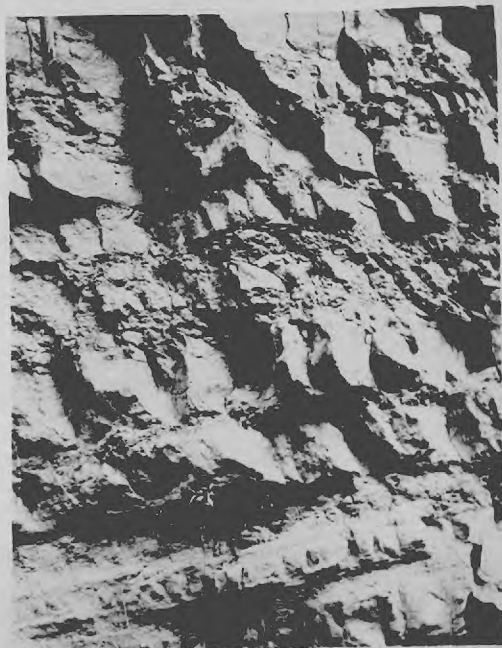
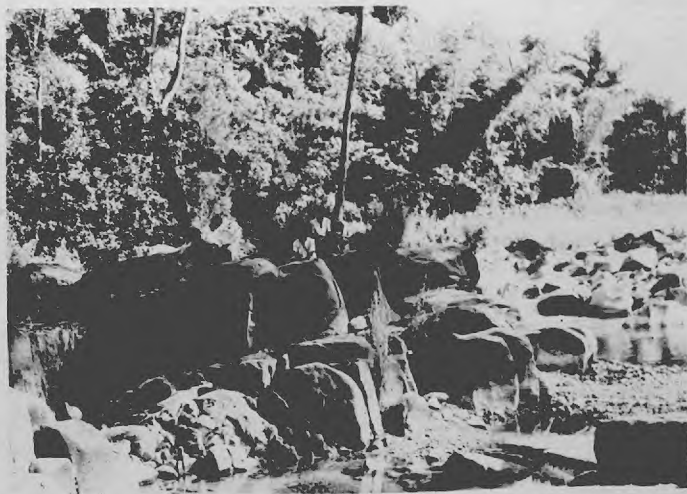


PLATE 9

- A. Cribas Formation - quartz arenite from the Veru Anticline.
- B. Cribas Formation - quartz arenites and tuffs.
- C. Cribas Formation - shales and interbedded quartz arenites.
- D. Aitutua Formation - near Tutuala looking south towards the Serricutti Range,
(n) - Aitutua Formation.



It is significant that the area from which the fresh plagioclase grains were derived was adjacent to the region known to have been glaciated during the Permian (David, 1950).

AITUTU FORMATION

SUMMARY

About 2000 metres of marine sedimentary rocks form a continuous succession from the Ladinian (locally Carnian) through to the Middle Jurassic. These rocks are divided into two formations. A predominantly limestone facies, the Aitututu Formation, principally of Upper Triassic age is overlain by the Wai Luli Formation composed largely of shales with arenites of mainly Jurassic age. The Aitututu Formation is about 1000 metres thick, its fauna is poor and restricted. The Aitututu Formation was probably deposited in shallow water under conditions that were frequently highly saline and anaerobic.

INTRODUCTION

According to van Bemmelen (1949) the Triassic and Jurassic rocks of eastern Timor are mainly shales and sandstones of a flysch facies; but he stated that no Triassic or Jurassic fossils have been found. Grunau (1953) reported about 2000 metres of "autochthonous Triassic" which he described briefly as occurring in two facies; a radiolarian limestone facies with Halobia and Monotis, and a shale-sandstone facies. He also recorded the presence of Jurassic marls. Gageonnet & Lemoine (1958) followed Grunau (1953) in recognising two facies of their "Complexe Triasico - Jurassique", namely a limestone facies with Halobia and radiolarians, and a flysch facies of interbedded shales and sandstones. They also suggested a three-fold stratigraphic grouping into Lower Flysch, Limestone Series, and Upper Flysch, they did not map, however, these three units separately but grouped them all together as Mesozoic. It is important to mention here that large areas of eastern Timor were mapped by Grunau (1953) and by Gageonnet & Lemoine (1958) as autochthonous Mesozoic (Triassic and Jurassic) that in reality are outcrops of a Middle Miocene gravity slide pebbly mudstone deposit, containing huge exotic blocks of Mesozoic and other rocks. This "wildflysch" deposit is defined and described above as the Bobonaro Scaly Clay. Failure to distinguish between in situ Mesozoic rocks and exotic members of the Bobonaro Scaly Clay has caused much misunderstanding of the Timor Mesozoic.

Having distinguished the in situ Mesozoic from the exotic blocks (not always an easy exercise) the next impediment a stratigrapher has to overcome is the

exceptionally poor fauna of the Triassic and Jurassic strata. Halobia serves as the index fossil for the Triassic, but it is relatively rare, being found only at widely spaced intervals. Brachiopods are confined to a very few local occurrences. Ammonites are sporadic, very rare, and generally too poorly preserved for identification. The Jurassic rocks have an equally impoverished fauna; ammonites and belemnites occur rarely. There is seldom any opportunity to follow a particular horizon in the field because of the intense minor folding and faulting that has affected all the Mesozoic rocks of eastern Timor (plates 21B, 51C, 51D, 52A). Clearly the Triassic and Jurassic rocks do not lend themselves readily to detailed stratigraphic study. It has not been possible to determine properly measured detailed sections, although the general succession has been worked out and is shewn in enclosure 7.

The type locality for the Aitutu Formation is the large Aitutu Anticline between Maubisse and Samé (enclosure 1A). Here the Formation is very well exposed but the detailed succession has not been established because of the complex minor tectonic structure. The stratigraphic columns in enclosure 7 are generalised. In the type locality the base of the Formation is only seen at the western end of the anticline. Here (enclosure 1B) in the three creeks: Il Belis, Batzolor & Boie Teu the Cribas Formation is overlain with strong unconformity by argillites, ~~marls~~ and calcilutites of the Tallibelis Member of the Aitutu Formation. This Member is described at the end of this section. In the type locality the succession above the Tallibelis Member consists predominantly of dense, **very** fine-grained,

radiolarian calcilutites shewing a wide variety of bedding thickness. Interbedded locally are thin developments of shales and calcareous shales. It is quite common to find 50 metres of limestone without any interbedded shale.

The distribution of the Aitutu Formation in eastern Timor is shewn in figure 5. This map shews the distribution of surface outcrops and interprets the subsurface distribution. The evidence for this interpretation is largely structural, it is discussed later in the chapter dealing with tectonics. Enclosure 7 shews stratigraphic columns through the Aitutu Formation in the principal structures where it occurs.

The character of the Aitutu Formation is very consistent throughout eastern Timor, it is easily identified in the field. The hard radiolarian calcilutites that dominate the lithology from prominent rugged escarpments, and generally support only a light vegetation (plates 11C, 51A, 51B). These features are well expressed in the aerial photographs.

The thickness of the Aitutu Formation is estimated in the type locality to be about 1000 metres. This value is approximate because tectonic complications have not permitted precise measuring of sections. The thickness of the Aitutu Formation in other parts of eastern Timor seems to be of a similar magnitude.

LITHOLOGY & PETROGRAPHY.

The Aitutu Formation consists of about 80 percent calcilutites, 15 percent shales and calcareous shales, and

about 5 percent calcarenites, lunachelles, quartz arenites, radiolarites and highly bituminous rocks.

Calcilutites.

Most of the calcilutites are hard, very fine grained lithographic-type limestones. Their weathered surfaces are generally pale grey or cream coloured, whilst the fresh broken surfaces are mostly pale blue-grey, white, cream and less commonly green, rarely pink. The calcilutites are always massive in the sense of McKee & Weir (1953). The style of bedding of these calcilutites is variable (plates 10A, 10B, 10C, 10D, 11A, 11B, 11C). These three main types may be termed thick, thick-bedded (McKee & Weir, 1953), and masonry-type. Shales are found interbedded in varying proportions with these limestones, such that these calcilutites are found up to 50 metres thick without intervening shales. Where shales or calcareous shales do occur they usually form thin or very thin beds (frequently less than 2 cm.).

Since these calcilutites form such an important fraction of this extensively exposed formation 75 thin sections were prepared and studied. Nearly all are composed of a very fine grained dense micrite (which is iron-free calcite), in which internal moulds of Radiolaria composed of sparry calcite (frequently ferroan calcite), forming either a drusy or granular mosaic, are commonly present. The proportion of Radiolaria (nearly always calcite moulds) present varies from less than 1 percent to more than 75 percent of the volume (plates 12A, 12B). Siliceous aggregated Foraminifera are often present but make a negligible contribution to rock volume. Long thin

shreds of a pelecypod, probably Halobia, are a common but volumetrically unimportant constituent (plate 12B). Crinoid ossicles, ostracods, Inoceramus-like prisms, ammonoids, gastropods and brachiopods are all very rarely seen in these calcilutites.

Most of the calcilutites contain less than 5 percent insoluble residue. Occasionally silt size quartz grains and water-clear very small feldspar laths are found. It is notable that the marls (as defined by Pettijohn, 1957) interbedded with the calcilutites are generally slightly silty and laminated in contrast to the more homogeneous massive calcilutites.

An exceptionally rare feature of these rocks is the clotted texture (plate 12C) or what Cayeux (1935) called 'structure grumeleuse'. Regrettably these Aitututu rocks do not resolve the problem whether this texture is the result of post-depositional diagenesis or whether the clots represent primary discrete aggregates. Environmentally it may be significant that an extremely similar 'microfacies' occurs in the Lower Miocene Cablac Limestone which is known to be a bahaman-type deposit (cf. plate 45D).

An important sedimentary feature of these calcilutites is the presence of burrowing structures. There are present two main types that are responsible for the prominent mottling of some of the limestones and marls; one may be compared with Chondrites, this has a fine branching tubular structure (plate 17C), and the other probably results from the activity of much larger organism, having tube diameters varying between 0.5 and 1.5 cm. Occasionally

this larger type which resembles Scalarituba Weller (in Häntzchel, 1962) has branches, generally these tubes and their branches transect the beddingplanes perpendicularly or at very steep angles (plate 17A). Similar trace fossils have been studied by Seilacher (1953), and the Chondrites structures have been discussed in detail by Simpson (1957). Hallam (1960, fig. 16, plate 2) illustrated Chondrites from the Blue Lias Limestones and marls of Dorset, where it causes conspicuous mottling, that appear to be identical with those of the Aitutu Formation of eastern Timor. In hand specimen these burrowing structures are always of darker colour than the surrounding matrix, whether calcilutite or marl; in thin section these dark spots are seen to be caused by finely disseminated carbonaceous matter, perhaps due to mucous or excreta.

Diagenetic changes within the calcilutites appear to have been relatively few. Dolomitisation is extremely rare, and where it occurs it takes the form of very small scattered rhombs. The most prominent change is the dissolution of siliceous skeletal structures, particularly Radiolaria and sponge spicules, and their replacement by sparry calcite (usually ferroan). The evidence for this process having taken place is clearly evinced by the illustrations in plate 12D), where a siliceous sponge spicule, with its central canal visible, has had its apical portion replaced by a granular mosaic of ferroan sparry calcite. Similarly, plates 12A, 12B are examples of calcilutites in which Radiolaria have been replaced and filled by sparry calcite. Sometimes the calcite takes the form of a drusy mosaic suggesting that the Radiolaria were dissolved leaving a void to be filled by calcite

producing an internal mould. Frequently the delicate parts of the skeleton such as the spines (plate 12A) are now composed of a granular mosaic of calcite; this suggests a replacement process, since the preservation of voids resulting from the dissolution of such fine structures as radiolarian spines is highly unlikely. Confirmation of this replacement process is found in the radiolarites composed of opaline and chalcedonic silica, in which some of the radiolaria are seen to consist of a granular mosaic of ferroan sparry calcite. A number of workers have suggested that most sedimentary chert originated by diagenetic dissolution of the siliceous skeletons of diatoms, Radiolaria and sponge spicules which was later precipitated as chert (Branlette, 1946; Krauskopf, 1956; Siever, 1957; and Siever, 1962). The present writer, after detailed geochemical and petrological study of the Cretaceous cherts and radiolarites of eastern Timor (see Appendix I), arrived at the same conclusion for those rocks. It is therefore most interesting to have this process recorded also throughout the Aitututu Formation, particularly since relatively little chert is found in this Formation. It is estimated that about 10 percent of the Aitututu Formation consists of calcilutites that originally consisted of about 50 percent Radiolaria (by volume); this would amount to a considerable quantity of silica. As the detailed structure of the Radiolaria is commonly preserved in calcite, it seems highly probable that the dissolution of the silica occurred very early in the history of the sediment, certainly before compaction. Thus the possibility must not be overlooked that much of the dissolved silica may have passed quickly back into circulation in the sea, providing the material for another generation of Radiolaria.

The cause of the diagenetic dissolution of silica

and its replacement by calcite is generally considered to be due to conditions of high pH (i.e. above pH9, although this can be modified to some degree by pressure - temperature variations). This has been discussed by Correns (1950); Krauskopf (1956 & 1959); Okamoto et al. (1957); Siever (1957); Walker (1960 & 1962).

Pyrite is common in the calcilutites. It takes the form of very thin lenticular veins parallel to the bedding, and as blebs. One notable type of pyrite consists of aggregates of small discrete spheres. Pyrite in limestones is widely considered to result from anaerobic changes in organic matter. In this context it may be significant that the pyrite in the calcilutites of the Aitututu Formation is commonest in those containing terrigenous detritus such as clay and silt. It may be that this association is due to the detritus being the source of the iron, since sea water normally contains extremely low iron concentrations (cf. Evany, 1963).

Recrystallisation of the micrite of these calcilutites is extremely rare, they are mostly composed of very fine, dense, calcite mud. Very occasionally a calcilutite identified in hand specimen is revealed under the microscope to be composed of microsparite. The texture of this microsparite, which has a very regular grain size (of about 6 microns) is an interlocking granular mosaic. The work of Bathurst (1958 & 1959), Voll (1960), and Shoji & Folk (1964) suggests that these coarser calcilutites were probably originally composed of micrite that has altered diagenetically to microspar by the process of grain growth.

Stylolites are rare in the calcilutites of the Aitutu Formation. Other limestone formations in eastern Timor (e.g. the Upper Cretaceous Borolalo Limestone and the Lower Miocene Cablac Limestone) are characterised by the prevalence of stylolites. One explanation of this difference may be that whereas in general the limestones of the Aitutu Formation have responded to tectonic stress by folding, the other limestones, in which stylolites are common, have behaved in a more brittle manner, and are broken by many faults. This brittle response may be related to the absence of interbedded shales.

Calcarenites.

The calcarenites are usually thin bedded, with fine cross laminations visible on their weathered surfaces. Their freshly broken surfaces are mostly dark blue or black, and weather a light ochreous colour. A considerable variety of calcarenites are present in this Formation. The principal types are biospararenites, pelspararenites, oospararenites, and biomicarenites. A particular kind of biomicarenite (viz. lumachelles) forms a characteristic 'microfacies'. A feature of all these calcarenites is the great variety of diagenetic processes that have affected them. The calcilutites, it will be recalled, have been very little altered. Whether this difference is a function of porosity, or of the variety of allochemical constituents is uncertain. The concentration of bituminous matter in some calcarenites certainly suggests a relationship with porosity. The principal types of calcarenite are discussed below.

Biospararenites: Two types are recognised; those containing mixed skeletal allochems, and those composed almost entirely of Halobia (i.e. the lumachelles).

The most common allochems in the mixed type of biospararenite are oolites, pellets, fragments of Bryozoa, molluscs, crinoids, brachiopods and ostracods (plates 13A, 13B, 13C, 14A). Intraclasts of micrite and pelmicarenites are sometimes present (plate 13C). Terrigenous clasts are quartz, always angular and poorly sorted, mica, blue tourmaline and rare clay wisps. The sparry calcite cement takes the form of a granular mosaic, it is frequently ferroan in composition. Apart from the cementation, four types of diagenesis have altered these rocks; (1) dissolution of aragonitic skeletal structures with subsequent infilling of voids by drusy mosaics of sparry calcite, (2) dolomitisation (3) silicification and (4) pyritisation. Usually it is skeletal structures such as those of brachiopods, crinoids and pelecypods that have been attacked. Ferroan dolomite as small scattered rhombs replaces these allochems locally, where it is often associated with chert in such relationships that it is difficult to determine the order of alteration (plate 13C). Pyrite is also found replacing these skeletal fragments, its other mode of occurrence is as isolated grains. Pyrite is an important constituent of these arenites, sometimes forming about 5 percent of their volume. These mixed allochem biospararenites are found in all the major structures of eastern Timor, they are particularly well developed in the Aliambata region.

Lumachelles: These are a particular type of biospararenite that forms a highly characteristic 'microfacies' of the Aitutu Formation, being found at many horizons throughout the Formation in all parts of eastern Timor. In the hand

specimen they are readily divisible into two types:

(a) the white and cream coloured lumachelles that appear to consist entirely of tightly packed shells of Halobia, and (b) dark blue or black bituminous lumachelles that usually but not always have shaly partings.

The white, non-bituminous (type 'a') lumachelles usually have a sparry calcite cement shewing granular mosaic (plate 13D), but sometimes, such as under the concave fragments of Halobia, umbrella drusy mosaic is developed (plates 12B, 14B). This type of lumachell seldom contains any dolomite or bitumen. These calcarenites grade into the other (type 'b') in which the Halobias are so densely packed together that what little sparry calcite cement is present has a drusy mosaic; this variety commonly contains a little micrite. It is also characterised by being dolomitised (usually 15 percent - 20 percent dolomite) and being thoroughly impregnated with bitumen. The bitumen surrounds the Halobia shells and is present as thin films between the calcite grains of the micrite and sparry cement. A more bituminous variety of type 'b' consists of Halobia, dolomite and bitumen (plate 16). These bituminous, dolomitised, shell beds have a shaly appearance when weathered, so that in the field they are generally mistaken for bituminous shales although they contain no clay. One feature of these rocks is that the sparry calcite cement is always highly ferroan. Some of the bituminous lumachelles contain siliceous Foraminifera, calcitic internal moulds and replacements of Radiolaria.

A very rare diagenetic change in the lumachelles is silicification; in the form of layers of chert replacing selectively and locally all of the original rock. It is

It is seen that the Halobias were replaced by the chert before the calcite cement or micrite matrix (plate 13D). The occurrence of a zone of limonite grains in the zone of partial replacement by chert (plate 13D) probably represents the residue of iron oxide after the ferroan calcite of the totally replaced zone had gone into solution.

Oospararenites: These are known from all parts of eastern Timor although they occur rarely in the Aitutu succession. They are particularly well developed at Aliambata and north of Pualaca. The oospararenites always contain calcitic skeletal allochems, and calcareous algae are generally well represented. Most of the oolites have quartz nuclei. Some oolites have a concentric structure in the jacket, whilst others have only a coarse radial structure. The non-carbonate grains include quartz (always present), quartzites, cherts and very fresh feldspar laths. Where dolomitisation has altered these rocks it has usually attacked the skeletal fragments, particularly the crinoids and calcareous algae, rather than the oolites. The cement is sparry calcite (usually ferroan) in the form of a granular mosaic (plates 13A, 13B).

Pelspararenites: Like the oospararenites these are rare in the Aitutu Formation. They consist mainly of allochems of dark dense micrite pellets in a sparry calcite cement having a granular mosaic. Other allochems present are skeletal fragments such as crinoids, brachiopods, bryozoans and pelecypods. Siliceous Foraminifera are generally present. The only terrigenous constituent is mica.

Biomicarenites: Biomicarenites make up by far the largest proportion of the calcarenites, and shew a wide variety of

composition. Three main types are recognised, based on allochemical composition: Halobia - biomicarenites; coral-biomicarenites; and mixed allochem-biomicarenites; each type is discussed below.

Halobia - biomicarenites: These are composed of the very thin shells of Halobia & fragments of the same, embedded in a dense matrix of micrite. The shells and fragments are always aligned parallel to the bedding except where they have been disturbed by burrowing organisms. The micrite matrix often contains ostracods and internal calcite moulds of Radiolaria as well as a few siliceous Foraminifera. Less commonly a few fragments of crinoids are present. This type of biomicarenite is illustrated in plates 12B, 14B. Very rarely, micrite aggregates or clots (cf. 'structure grumeleuse' of Cayeux, 1935) are present.

Usually a little sparry calcite granular mosaic is present at the Halobia - micrite interface. Sometimes a little sparry calcite forms a drusy mosaic where the curved shape of the shell preserved a void (umbrella) in the sediment (plate 12B). Dolomitisation of the micrite matrix by small scattered rhombs amounting to about 5 percent - 10 percent of the rock volume is quite common. Where chert is developed (rarely) it is always the Halobia fragments that have been replaced. Bitumen forms intergranular films in the micrite of some of these rocks.

Corals - biomicarenites: These rocks, which consist of fragments of colonial corals in a micrite matrix, are very rare. The coral allochems are (usually exclusive) & generally form about 25 percent - 45 percent of rock volume. The matrix is dense micrite sometimes mixed with

a little clay.

Mixed allochem - biomicarenites: This type is particularly well developed around Tutuala, at the eastern end of the island and at Aliambata. The Tutuala variety ammonites, gastropods, pelecypods, brachiopods, crinoids, bryozoans and siliceous Foraminifera. The matrix is a dense micrite (plate 14C). The rock weathers to a dark red colour, and the weathered surface shows in relief the dense packing of the well preserved fossils. Large intraclasts of micrite are also present. This facies is a basal conglomerate. Diagenetic changes have been slight and few. Some of the allochems have been replaced by opaline silica. The Aliambata type is illustrated in plate 14D.

Dolostones: These are extremely rare in the Aitutua Formation, and where they occur they are often associated with bituminous calcarenites. The Aitutua dolostones weather to a yellow colour and have a sandy appearance in hand specimen. In thin section they are found to be composed of a granular mosaic of interlocking dolomite rhombs, many of which are zoned (plate 15A). This texture has been described by Cayeux (1935) as 'dolomie grenue'. No relic structure has been seen in these rocks.

Quartz arenites: Another very rare rock type in the Aitutua Formation is the quartz arenite, of which there are two kinds; (a) those with a sparry calcite cement, frequently with poikilitic texture producing lustre mottling, (plate 15B) and (b) those with a silt - clay matrix (plate 15C). The arenites with a calcite cement are generally yellow or reddish in colour, whilst the others are grey and black.

The arenites with a silt-clay matrix have very well preserved burrowing structures (plate 17B). The quartz arenites are generally cross laminated, and many are very finely bedded. The quartz arenites having a calcite cement are always found interbedded with calcarenites, while those with a silt-clay matrix are interbedded with shales, calcareous shales and marls. All the quartz arenites are medium sandstones to siltstones. The quartz grains are always poorly sorted and angular to very angular. Very fresh to slightly altered feldspars (both orthoclase and plagioclase) are present in small quantities (1 percent-2 percent). Blue tourmaline occurs as small rounded grains, hornblende, ilmenite and magnetite being the only heavy minerals present (in insignificant amounts). Lithic grains such as chert, quartzite and a fine grained quartz-mica schist are usually present but seldom from more than 2 percent of the rock. Mica in the form of tiny flakes is present in very small quantity in the calcite cemented arenites, but in those having a clay-silt matrix mica makes a much more important contribution. Fragments of crinoids, calcareous algae; brachiopods, pelecypods and oolites are present in some of the arenites.

An important feature of most of the quartz arenites that have a clay-silt matrix is the presence of woody fragments, leaf cuticle, pollen and spores. These plant remains are concentrated in certain laminae. Many of these arenites contain about 2 percent - 5 percent plant material.

Clay shales: The clay shales of the Aitututu Formation have not been studied in any detail, so nothing is known of their mineralogy. Many of them are calcareous due to

the presence of micrite and (or) calcitic moulds of Radiolaria.

Radiolarites: Radiolarites occur very rarely and sporadically throughout the Formation, usually associated with interbedded sequences of thin calcilutites and shales. They are green, hard, finely laminated and form beds about 10 - 15 cm thick. In thin section they are seen to be composed of densely packed Radiolaria with a few Foraminifera. The Radiolaria are usually now chalcedony but some beds are still opaline. A fine mixture of clay and micrite forms a dense matrix. Plate 15D illustrates a typical Aitutu radiolarite.

STRATIGRAPHIC POSITION.

Wherever the base of the Aitutu Formation or the Tallibelis Member (discussed later) is seen it appears to be unconformable on the Cribas Formation (of Permian age). In most localities the lowest beds of the Aitutu Formation have yielded only Halobia - type pelecypods that indicate an Upper Triassic (Carnian-Norian) age. In the Cribas Anticline, however, two localities have yielded Daonella cf. D.indica Bittner (Grunau, 1956) and Daonella pichleri var. timorensis Krumbeck (Skwarko, personal communication 1961) that indicate a Ladinian age. The apparent absence of any Lower Triassic fauna (except in exotic blocks of limestone present in the Bobonaro Scaly Clay which is a mid-Miocene deposit), together with the unconformity suggest that the Lower Triassic is absent from eastern Timor. It is significant that in western Timor the whole of the Lower Triassic is said to be only 2 metres thick (Umbgrove, 1938). One of the problems in eastern Timor

is to determine how much of the basal Aitututu Formation is Ladinian. The paucity of the fauna together with the very few outcrops of the basal part of the Aitututu Formation prevent a satisfactory solution. Locally at least the Ladinian is known to be absent, as for instance at Tutuala (enclosure 1D) where the coarse highly fossiliferous basal conglomerate contains a rich ammonoid fauna of Carnian age. This conglomerate contains the following ammonoids determined by Dr. M.K. Howarth (personal communication 1963):

Placites meridianus (Welter)

Pinacoceras sp.

Parathisbites scaphitiformis (Hauer)

Phormedites sp.

Arcestes malayicus Welter

Arcestes spp.

Proarcestes hanieli Welter

Tropites sp.

Paratropites cf. sellai (Mojsisovics)

Hoplotropites sp.

Discophyllites sp.

"Orthoceras" sp.

Clydonautilus biangularis Mojsisovics

Also present in this Carnian conglomerate are brachiopods identified by Dr. D.V. Ager (personal communication 1964) as Austriellula pirum (Bittner); and the pelecypod Halobia cf. H. cassiana (Mojsisovics) identified by ^{Dr.} L.R. Cox (personal communication 1963). Grunau (1965) reported Lovcenipora sp. and Misolia from the same locality. The numerous gastropods, bryozoans and Foraminifera in the conglomerate have not been

studied.

The base of the Aitutu Formation in the Bazol Anticline (enclosure 3AB) is distinguished as the Tallibelis Member. It is dated as Norian on the basis of Cochloceras sp. found in Il Belis Creek east of Bobonaro and identified by Dr. M.K. Howarth (personal communication, 1963).

The presence of the pelecypods Halobia cf. H. comata Bittner and cf. H. cassiana through most of the Aitutu Formation indicate that most of it is Carnian - Norian in age. These are the only fossils in this Formation that can be termed common.

The top of the Aitutu Formation is everywhere conformable below the Wai Luli Formation, the base of which can be dated by ammonites as Lower Jurassic. Thus the maximum time range of the Aitutu Formation is Ladinian to Norian inclusive. In a number of places the top of the Aitutu Formation has been independently confirmed as Norian on the basis of ammonites, e.g. in the Aitutu Anticline, the top of the Aitutu Formation has yielded Halorites sp. and Arcestes sp. Grunau (1956) reported Arcestes sunaicus Welter from near Pualaca. Gageonnet & Lemoine (1958) reported Halorites sp. and Cladiscites sp. indicating a Carnian - Norian age in loose boulders near Aliambata.

In the Aliambata Anticline brachiopods identified by Dr. D.V. Ager (personal communication, 1964) as "Halorella" nimassica Krumbeck occur with Halobia cf. H. comata Bittner of Upper Triassic age. But Ager (1964) has shewn

that this is not in fact a Halorella, and has made this species the type of a new genus: - Timorhynchia nimassica.

The quartz arenites, particularly those with a clay-silt matrix, frequently contain Myalina sp., numerous plant fragments pollen and spores. The following pollen and spores have been determined by Dr. M. Muir (personal communication, 1965) from one sample: -

Simplicisporites virgatus Leschik

Camerosporites sp.

Alisporites sp.

Illinites sp.

Lueckisporites sp.

Platysaccus sp.

Jugasporites (Pityosporites) sp.

Podocarpoid pollen

Granulatisporites sp.

Calamospora tener

cf. Ricciisporites

Dr. Muir commented on this flora

"The presence of the above species suggests strongly that the age of this sample is Upper Triassic (probably Keuper). The assemblages are very similar to the Triassic assemblages from the Alps, at Neuwelt and at the type localities of the Karnian and Upper Triassic and Rhaetic in Austria (Leschik, 1955 and Klaus, 1960).

They differ very strongly from all Upper Triassic assemblages described from Australia. The reason for this difference is that the Upper Triassic of the Alps

probably represents the pollen derived from an upland flora, while the Australian assemblages represent a lowland flora. It seems possible that the assemblage of pollen grains and spores derived from an upland flora will be best represented in marine rocks, and this is certainly the case in the Austrian assemblages described by Klaus (1960)."

ENVIRONMENT.

The micro- and macrofauna leave no doubt that the Aitututu Formation is completely marine. The problems of environment are best considered in relation to each principal lithofacies.

The calcilutites and interbedded shales:

These rocks account for about 95 percent of the Aitututu Formation, of which 80 percent are calcilutites, since the formation is about 1000 metres thick this means about 800 metres of calcilutites. In order for such a thickness of fine calcite (or aragonite) mud to have been deposited, conditions must have been quiet with an absence of strong bottom currents. The preservation of the delicate skeletons of Radiolaria (that are a characteristic of these calcilutites) supports this view. The only common macrofossils are the very thin shelled pelecypods Halobia that are frequently found well preserved although their valves are generally separate. Under high energy conditions such thin shells would be rapidly broken up. Jefferies & Minton (in press) suggest that Halobia was probably nekto-planktonic.

The high purity of most of the calcilutites (less than 5 percent insoluble material) indicates that very little terrigenous material was entering this area for most of the time. This accords with the absence of strong currents necessary to transport the terrigenous detritus, although it does not, of course, prove the absence of such currents.

The origin of the calcite mud, which may originally have been aragonite, by analogy with the formation today of calcium carbonate muds in the Persian Gulf (Wells & Illing, 1964) and the Bahamas (Cloud, 1962, p. 19-22), may be ascribed to inorganic precipitation of CaCO_3 from sea water due to the activity of plankton, probably acting as catalysts by lowering the pH of the sea water by such processes as photosynthesis. Prolific radiolarian and Diatom biota are present in many of the calcilutites. Such organisms flourish today in clear seas, free from detritus, but in which nutrients such as nitrates and phosphates are available. The presence of the thin beds of radiolarites, found occasionally interbedded with shales, may indicate that the muddying of the seas produced an unsuitable environment for the plankton. Hallam (1964) discussing the origin of the calcium carbonate muds that formed much of the Blue Lias (a formation that in many respects is remarkably similar to the Aitututu Formation) suggests that most was precipitated as calcite by bacteria, as has been suggested for the muds of the central parts of the Black Sea (Archangelsky, 1927; Caspers, 1957), and he claims, is supported by the experiments of Lalou (1957). Hallam (1964) admits the possibility that aragonite muds were formed in shallow water and swept into deeper water to add to CaCO_3 being deposited. The importance of

bacteria as agents of CaCO_3 precipitation in the Aitututu Formation is unknown, but this must not be overlooked since pyrite is found throughout the Aitututu Formation, which may be the result of sulphate-reducing and denitrifying bacteria, that are said to precipitate CaCO_3 in the Black Sea.

Whereas the calcilutites of the Aitututu Formation contain a microfauna, the macrofauna is impoverished. Brachiopods have not been found in the calcilutites, crinoids are known only as isolated rare ossicles, only Halobia is common, and this is thought by Jefferies & Minton (in press) to be a nekto-planktonic species. Ammonites are extremely rare. The only indication of a benthos are the burrowing structures of "Chondrites" and "Scalarituba". These observations suggest that conditions were unfavourable for benthonic organisms, particularly the shelled animals. One explanation for the poor and restricted fauna is that bottom conditions have been stagnant. Support for this comes from the frequency of pyrite and the development of highly bituminous limestones at a number of horizons, demonstrating that anaerobic environments were established (cf. Bitterli, 1963). The presence of gypsiferous shales in the north flank of the Cribas Anticline may indicate that salinities were locally abnormally high. In a closed stagnant basin like the Black Sea, high salinities and anaerobic conditions on the bottom would prohibit the development of a shelly bottom fauna while permitting the development of planktonic organisms.

The depth of water in which these calcilutites were deposited is very difficult to interpret in the absence of

a benthos. It may be inferred from the presence of interbedded calcarenites containing oolites, calcareous algae, and other reef debris that conditions were neritic and possibly epineritic. The occurrence of quartz arenites rich in plant remains and burrowing structures that possibly represent deltaic deposits interbedded in the Aitututu Formation support a neritic or epineritic environment for the calcilutites.

Whether the appearance of shales interbedded irregularly with the calcilutites is the result of tectonic, climatic or other changes is unknown.

The calcarenites:

The calcarenites consisting of mixed skeletal fragments and oolites may be compared with similar deposits forming on the Bahama Banks (Illing, 1954) and in the Persian Gulf (Houboult, 1957) today. Invoking uniformitarianism it is inferred that the Aitututu calcarenites were deposited in very shallow, clear, warm water with a high energy environment. The sparry calcite cement accords with this (Folk, 1959). The mixed quartz and calcareous skeletal sands indicate currents transporting the terrigenous constituents from a source outside the basin of deposition.

Lumachelles:

Most of the Aitututu lumachelles consist of closely packed disarticulated shells of Halobia. Similar coquinas often form very thin units at master bedding planes as well as the thicker more important shell beds. Whether

these shell beds (of both types) are the result of currents winnowing the shells, or whether the sudden death of the Halobia, or a reduced rate of sedimentation of the CaCO_3 mud is uncertain.

The quartz arenites:

Many of these sandstones and siltstones contain much much plant material such as leaf cuticle, pollen and spores. They are finely laminated and contain numerous large burrowing structures. Myalina is quite common in these rocks. Although it is dangerous to infer deltaic environments on such slim evidence (Taylor, 1963) these arenites have much in common with modern delta sediments.

Simmary of the environment of the Aitututu Formation:

There is a fairly convincing pattern of evidence from the Formation as a whole that it accumulated in a shallow marine environment. There is much to suggest that the bulk of the Formation was formed in a closed basin in which bottom conditions were unfavourable for the development of shelly organisms due possibly to an anaerobic and highly saline environment brought about by the absence of circulation and bottom currents. The development of the calcarenites suggests that, in the presence of high energy waters, reef organisms flourished. The presence of the quartz arenites possibly indicate tectonic disturbance of the basin margins.

TALLIBELIS MEMBER

SUMMARY

The Tallibelis Member of the Aitututu Formation consists of about 150 metres of mainly mudstones and marls. It is known only from three small creeks that drain the north limb of the Bazol Anticline, where the Tallibelis Member is unconformable on the Cribas Formation (enclosure 1B). Small shell banks of poorly preserved brachiopods, pelecypods, gastropods and ammonites are present and date the Member as Norian. The shelly fauna indicates a shallow marine environment.

INTRODUCTION

The type locality for the Tallibelis Member is the upper reaches of the Il Belis Creek, north of the village of Tallibelis (about 6 km. S.E. of Bobonaro). Here about 150 metres of well bedded purple and dark blue mudstones, marls and some thin limestones rest unconformably on the Cribas Formation.

Outside the type locality this Member is known only from the upper reaches of the nearby creeks Batzulor and Bele Teu where the lithology and thicknesses are the same (enclosures 1B, 3 AB & 7).

LITHOLOGY & PETROGRAPHY

The Tallibelis Member is readily distinguished from the rest of the Aitututu Formation by its dark colours, the presence of mudstones and marls and the absence of

radiolarian limestones. The shell banks of mixed fossils, characteristic of this Member, are not found in the Aitutua Formation.

Mudstones.

This term is used to describe rocks of clay grade (and clay minerals) without fissility. Dark coloured, purple, mauve and blue-grey, they are interbedded with marls and thin calcilutites. In places the mudstones contain poorly preserved decorticated shelly fossils.

Marls.

Like the mudstones these are dark coloured and poorly laminated. They contain small shell banks about 3 metres wide and 10 cms high. The shells are poorly preserved, nearly all of them being decorticated. Mostly pelecypods, some gastropods, brachiopods and ammonites are also present. Nearly all the fossils collected have been described as indeterminable, because of their poor preservation. Most of the fossils are small. Disseminated pyrite is quite common in these marls.

Calcilutites.

Thin bedded calcilutites without radiolarians are interbedded with the marls and mudstones. They are composed of micrite with occasional fragments of crinoids and molluscs.

PLATE 10

- A. Aitutu Formation - radiolarian calcilutite with
 unusual surface features from
 the Aitutu Anticline.

- B. Aitutu Formation - characteristic masonry-type
 bedding from the Aliambata
 Anticline.

- C. Aitutu Formation - radiolarian calcilutite from
 the Aitutu Anticline.

- D. Aitutu Formation - calcilutite with interbedded
 calcarenite.



PLATE 11

- A. Aitutu Formation - radiolarian calcilutites with
 nodular bedding from the Aliambata
 Anticline.

- B. Aitutu Formation - radiolarian calcilutites and
 interbedded shales from the
 Cribas Anticline.

- C. Aitutu Formation - typical calcilutites.

- D. Bazol Anticline - note the strong regional dip
 of the limestones of the
 Aitutu Formation.

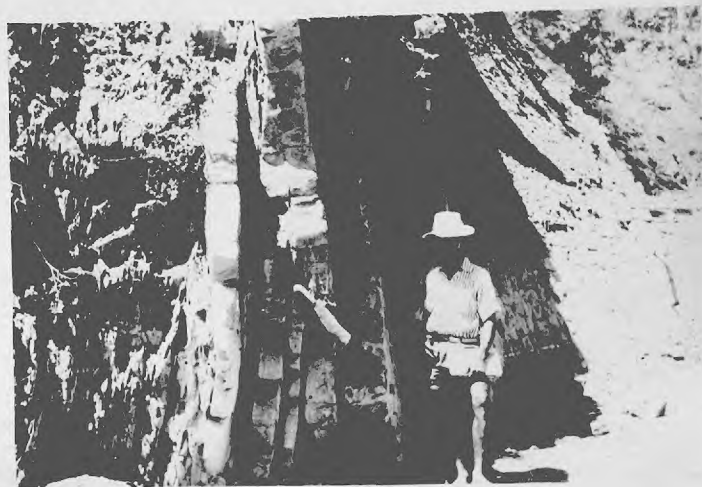
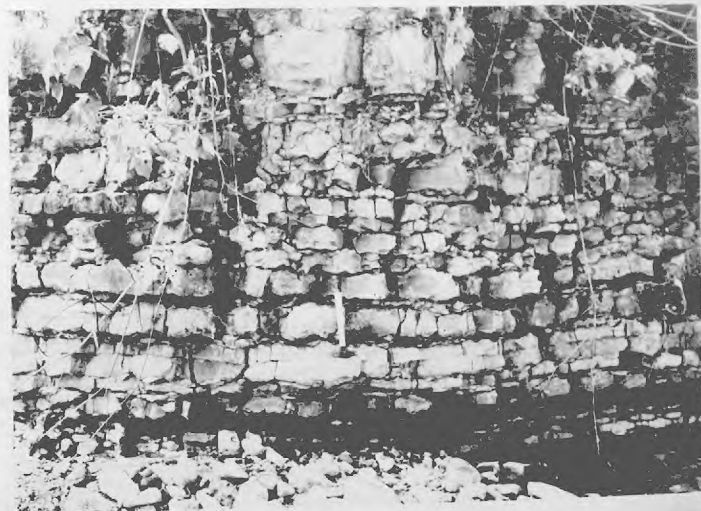


PLATE 12

- A. Aitututu Formation - radiolarian calcilutite. Note radiolarian skeletons including the delicate spines have been entirely replaced by sparry calcite and filled with a drusy mosaic of sparry calcite (x 50).
- B. Aitututu Formation - calcilutite rich in radiolarians now replaced and filled by sparry calcite. Thin filaments of Halobia making umbrella effect with the drusy calcite beneath the shell indicating the original orientation of deposition (x 25).
- C. Aitututu Formation⁵ - calcilutite with 'structure grumeleuse' texture (x 25).
- D. Aitututu Formation - siliceous sponge spicule (note central canal) partly replaced by ferroan calcite (x 150).

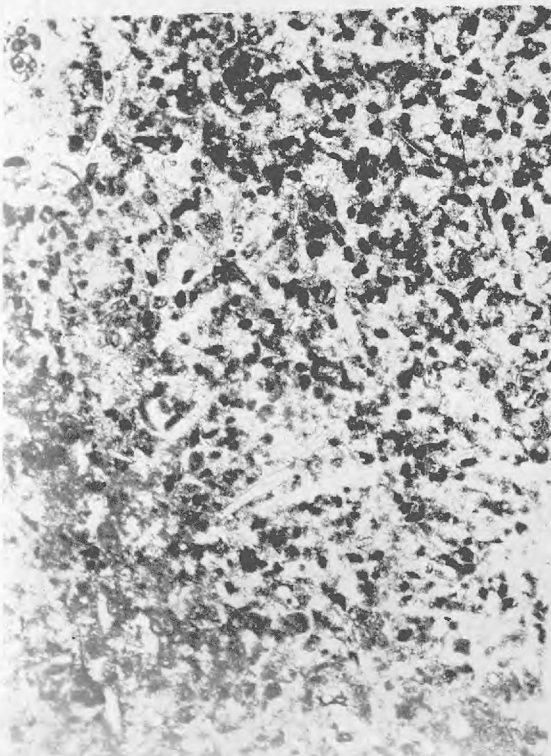
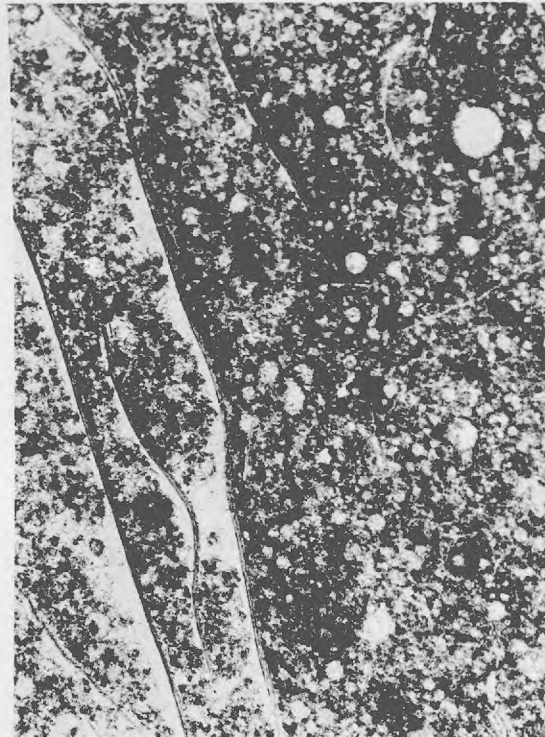
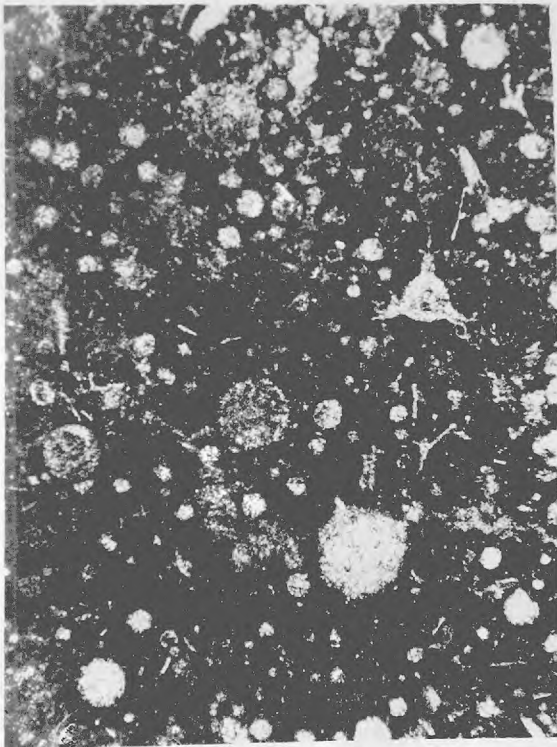


PLATE 13

- A. Aitututu Formation - biospararenite, note thick micrite jackets on the allochems, and the 'ghost' of dissolved shell filled with drusy mosaic (x 20).
- B. Aitututu Formation - Biospararenite, note oolites with quartz nuclei and the thick micrite jackets (x 20).
- C. Aitututu Formation - biospararenite, allochems of Halobia, echinoderms, and a large micrite clast. Note the small globule of opaline silica (white, near micrite clast) containing small rhombs of ferroan dolomite (x 20).
- D. Aitututu Formation - biospararenite, lumachelle of Halobia. The top left corner replaced by opaline silica. The black grains are limonite (x 25).

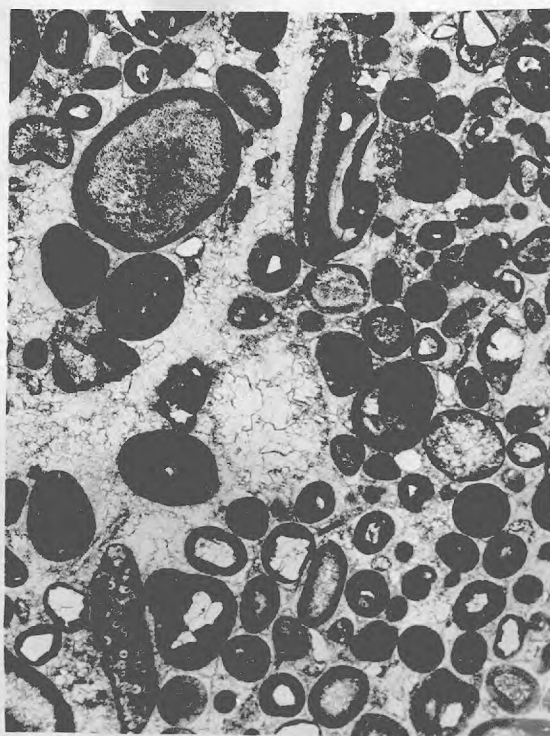
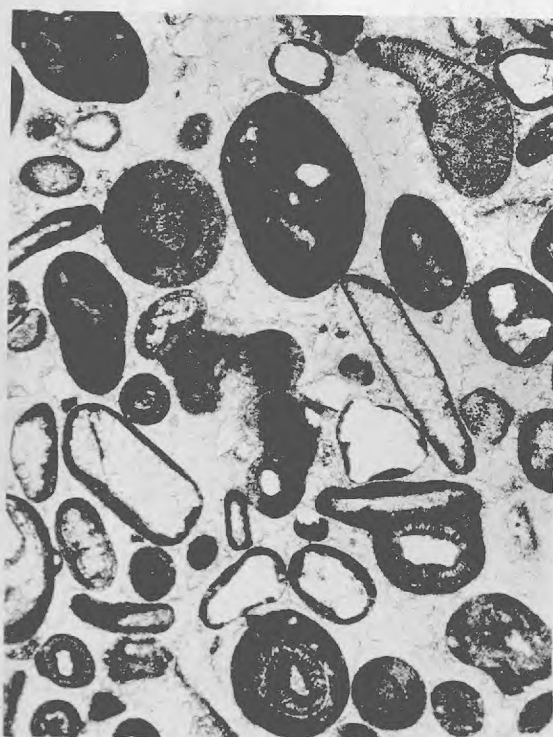
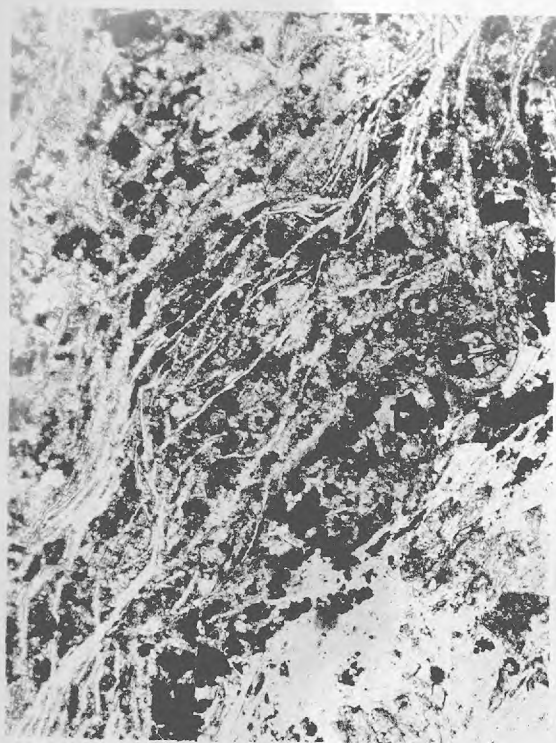


PLATE 14

- A. Aitututu Formation - biospararenite. The top right hand side has been replaced by opaline silica (dark area), partial replacement (light band). In the bottom left corner only the allochems have been replaced. Note transecting (later) calcite veins (x 20).
- B. Aitututu Formation - boundary between two beds:
(i) - biomicarenite with thin filaments of Halobia and
(ii) - biosparenite of mixed allochems. Transecting (later) calcite veins (x 20).
- C. Aitututu Formation - biomicarenite of mixed allochems: gastropods, echinoderms, brachiopods, pelecypods and ammonoids (x 20).
- D. Aitututu Formation - biomicarenite with mixed allochems. Note the thick micrite jackets on some allochems, and the 'level bubble' structure (x 20).

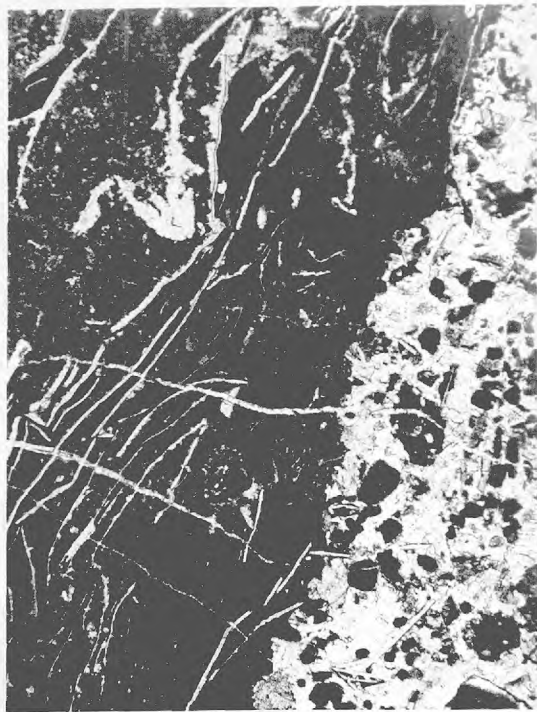


PLATE 15

- A. Aitututu Formation - dolostone with zoned rhombs (x 50).
- B. Aitututu Formation - quartz arenite with sparry calcite cement. Note strong radial texture of the oolites (x 50).
- C. Aitututu Formation - quartz arenite with clay-silt matrix. Note extreme angularity of the quartz grains, and presence of some lithic grains (e.g. quartzite) (x 25).
- D. Aitututu Formation - radiolarite (x 20).

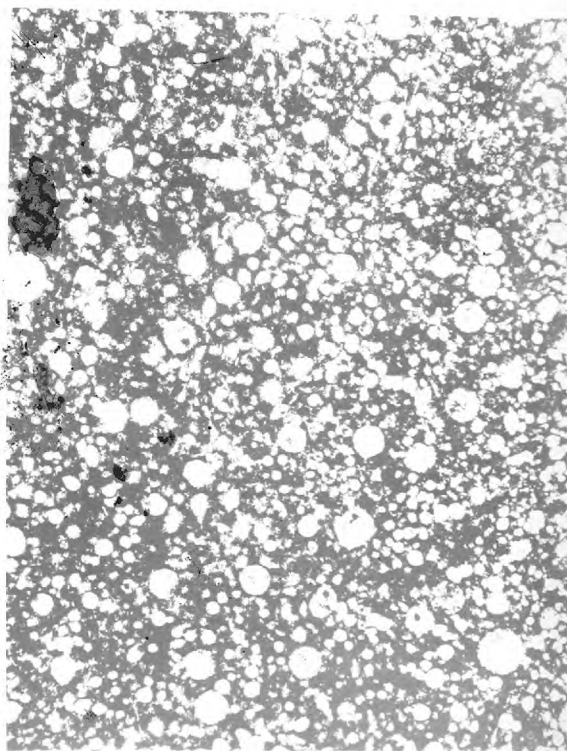
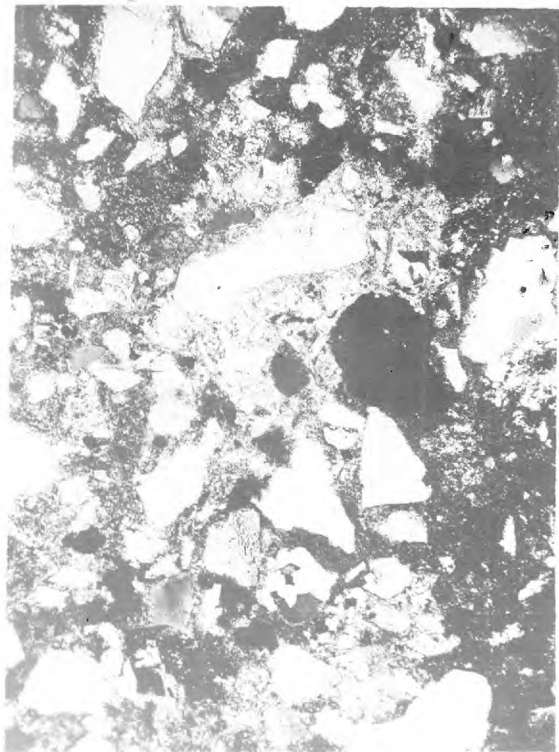
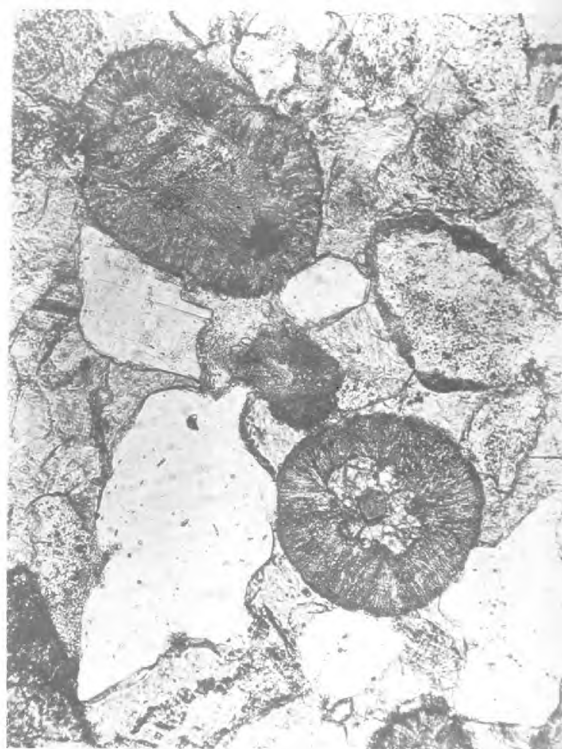
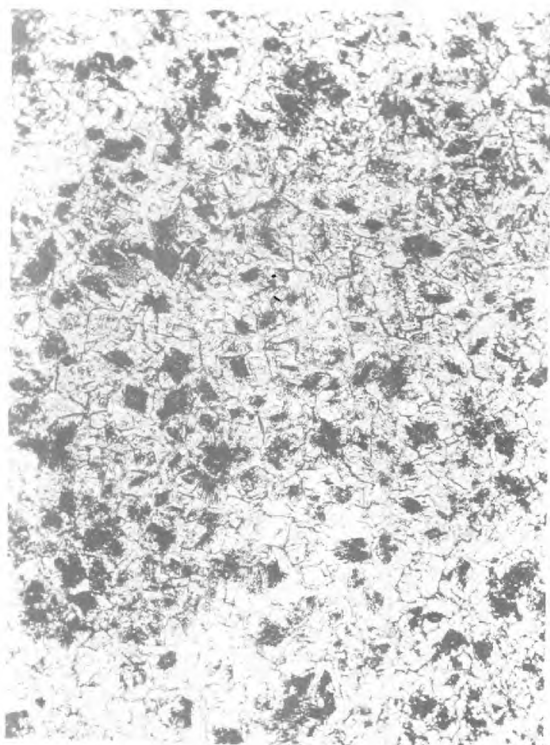


PLATE 16

Aitututu Formation - lumachelle of Halobia with bitumen (black), Note the dolomitisation by numerous small rhombs, and the presence of small pyrite crystals (black) (x 20).

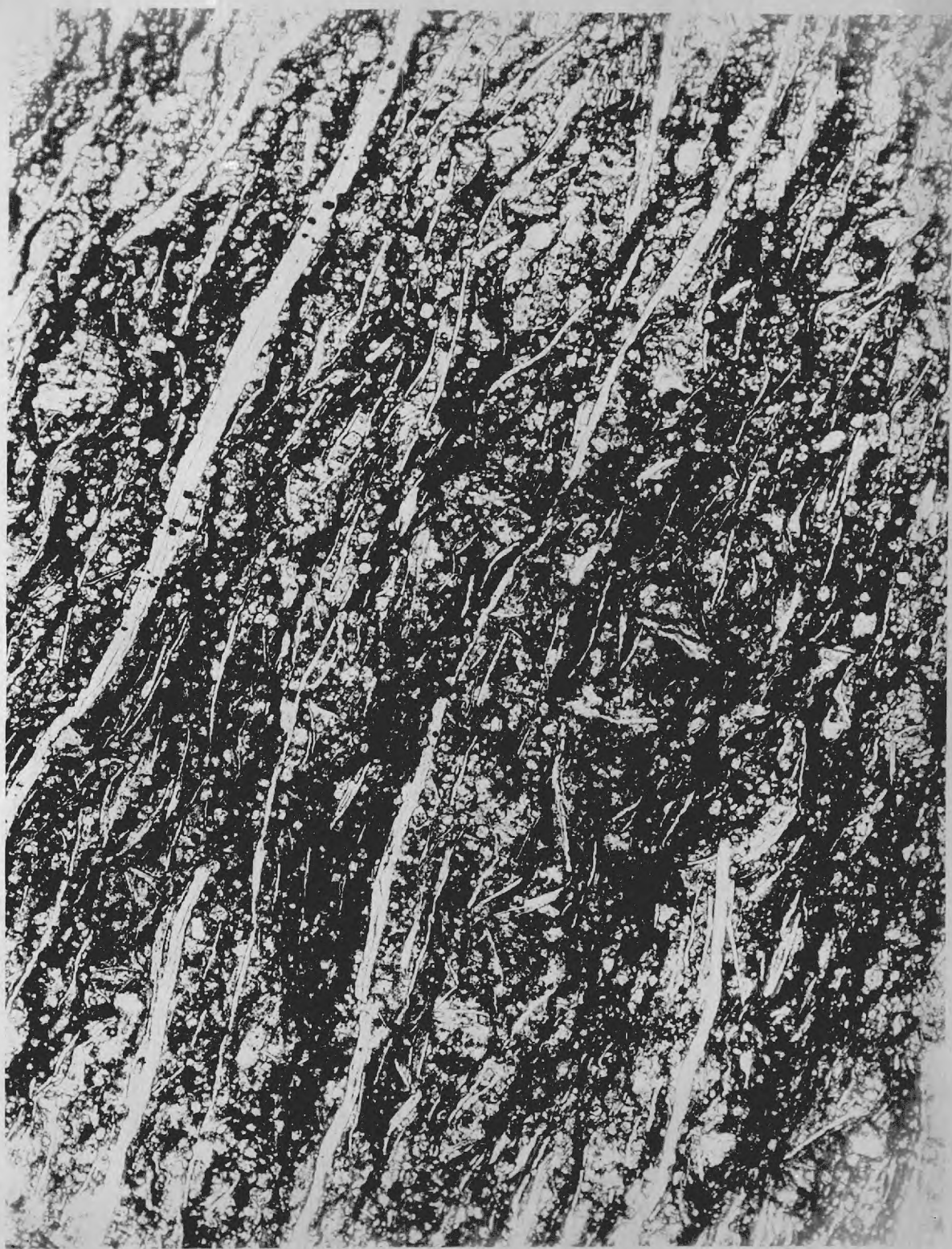
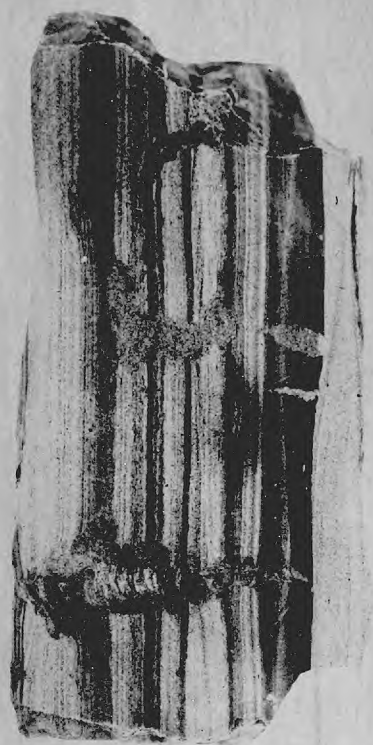


PLATE 17

- A. Aitututu Formation - burrowing structures cf.
Scalarituba in calcilutite.
- B. Aitututu Formation - burrowing structures in cross
bedded quartz arenite with silt-
clay matrix.
- C. Aitututu Formation - burrowing structures cf.
Chondrites in calcilutite.
- D. Wai Luli Formation- sedimentary slump structures
in calcilutite.



STRATIGRAPHIC POSITION

The Tallibelis Member overlies the Cribas Formation unconformably although the actual contact is not exposed. The Tallibelis Member has been dated as Norian by Dr. M.K. Howarth (personal communication, 1963) on the basis of Cochloceras sp. from the shell bank material of the Il Belis Creek, (near Tallibelis).

Overlying the Tallibelis Member conformably are the radiolarian limestones of the Aitututu Formation also dated as Norian.

ENVIRONMENT

The presence of the shelly fauna indicates a shallow marine environment, while the fine grain size of the mudstones, marls and calcilutites suggests the absence of strong bottom currents.

WAI LULI FORMATION

SUMMARY

The Wai Luli Formation consists of about 1000 metres of shales, marls, limestones and quartz arenites. The quartz arenites and silts becoming more important towards

the top of the Formation. The Wai Luli Formation is conformable on the Aitututu Formation. It ranges in age from Novian to Middle Jurassic. The fauna is poor and restricted. The Formation was probably deposited in a shallow sea under conditions that were sometimes highly saline and anaerobic.

INTRODUCTION

The type locality for this Formation is the valley of the River Wai Luli where it follows the strike of the Aitututu Anticline. The Formation is well exposed in the sides of the valley. Detailed stratigraphic sections have not been worked out because of the complexity of the minor folds and faults, but the general succession in the type locality has been established (enclosure 7). Here the base of the Formation consists of well bedded spotted blue-grey marls and limestones with ammonites. The spots are very characteristic, being a much darker colour than the matrix; they are burrowing structures like Chondrites and Scalarituba (plates 17C & 18D). Above these spotted marls and limestones a succession of micaceous shales with thin interbedded calcilutites follows. These thin limestones become less common up the section, and give way to shales with quartz arenites. At the top of the exposed section coarse conglomerates appear interbedded with quartz arenites, calcarenites and micaceous shales.

Outside the type locality the main features of this succession are preserved. The series of spotted marls and limestones is found at the base of the Formation wherever the base is seen. Above these marls and limestones the Formation is everywhere represented mainly

by monotonous shales with interbedded quartz arenites and thin limestones. The distribution of the Wai Luli Formation may be seen in figure 5, and some general stratigraphic sections are illustrated in enclosure 7.

The thickness of the Formation is difficult to estimate in the absence of detailed measured sections, but in the type locality it is probably about 800 metres, and elsewhere it probably achieves a thickness of about 1000 metres.

LITHOLOGY & PETROGRAPHY

Shales probably form about 70 percent of the Wai Luli Formation, the other principal rock types being marls, calcilutites, calcarenites, quartz arenites and coarse polymict conglomerates.

Shales:

Most shales are dark blue or black when fresh, their weathered surfaces being buff or yellowish. A few sections of red and green shales are developed locally (plate 19A, 19B). Most of the blue-black shales are finely micaceous. Much of the shale is calcareous due to the presence of micrite. Pyrite in small amounts is common in the shales. Plant remains, mainly, leaf cuticle, pollen and spores, are found throughout the section, concentrated at certain horizons.

On the north flank of the Cribas Anticline in the region between Manatutu and Laleia a series of blue and red shales, gypsum and gypsiferous shales with rare salt

pseudomorphs are found with some calcilutites exhibiting an extreme degree of plastic deformation (plate 17D). The deformed calcilutites are possibly the result of large volume changes in the sediments due to chemical reactions of the anhydrite - water - gypsum system. Associated with these shales and calcilutites are calcarenites and quartz arenites.

Silty shales:

Silty shales are quite common in this Formation; they are usually micaceous and often calcareous due to the presence of micrite. The silt fraction is composed mainly of quartz with about 5 percent fresh feldspar and 5 percent quartzose lithic fragments. These silty shales are sometimes rich in plant remains and poorly preserved pelecypods such as Myalina and pectinids.

Calcilutites:

The calcilutites become less frequent higher up the section and are rare throughout much of the Formation. They are mostly dark blue or grey in colour although cream, green and pink varieties are common (plates 19C, 19D). They are generally composed of a fine dense micrite in which Radiolaria and Foraminifera make important contributions, with rare fragments of molluscs and crinoids. Some calcilutites contain very small, scattered quartz grains.

The calcilutites frequently display dark-coloured spots representing the burrowing structures of "Chondrites" and "Scalarituba". Other macrofossils are very rare, but

locally Halobia- like pelecypods become relatively common, belemnites occur only very occasionally.

Marls:

The marls from a very important marker unit at the base of the Formation where they are interbedded with calcilutites. They weather to a characteristic pale blue-grey colour and typically are spotted due to the burrowing structures being a darker colour (plates 17C & 18A). They have a characteristic splintery fracture and contain a poorly preserved fauna of ammonites among which some have been identified.

Higher up the section marls occur mainly as thinly bedded shaly marls.

Calcarenites:

Calcarenites are relatively rare and seem to be almost restricted to the upper part of the Formation. They are typically dark blue-grey on freshly broken surfaces, where crinoid ossicles are usually visible. The weathered surfaces, often a buff colour, are usually etched, thus revealing the detrital nature of the limestone. Individual beds are seldom more than 2 metres thick although some are 5 metres. Fine cross bedding is common. In thin section it is found that the sparry calcite cement is usually ferroan and forms a granular mosaic. Most of the calcarenites contain an important fraction of quartz grains as well as a variety of intraclasts (plates 20A, 20C). The commonest allochems are algal pisolites, algal encrusted fragments, oolites and fragments of crinoids,

holothurians, brachiopods and molluscs. A feature of the oolites is the presence of many tiny quartz grains in the jacket of the oolite where they are arranged in concentric layers (plate 20B). Similar oolite jackets have been described from the Great Salt Lake Utah (Eardley, 1938).

The sorting of the constituent grains is poor. The quartz grains, whose contribution varies from 10 percent to 50 percent of all clasts, are poorly sorted, usually very angular and of low sphericity. Other terrigenous grains commonly present are quartzites, chert and a fine quartz-mica-schist. Feldspar grains generally form about 2 percent of the non-carbonate fraction. They are usually very fresh or slightly altered; both orthoclase and plagioclase being present.

Intraclasts make a notable contribution to these rocks; the most commonly occurring intraclasts are pelmicarenites, calcilutites and pelspararenites (plates 20A, 20C).

The principal diagenetic changes found in these calcarenites are the exsolution of aragonitic fragments with subsequent filling of the voids by a sparry calcite often having a drusy mosaic, and pyritisation. The pyrite has usually selectively replaced the oolites and algal structures.

Quartz arenites:

The quartz arenites become more important towards the upper part of the Formation. Beds vary in thickness from a few centimetres to 10 metres. Burrowing

structures are extremely common, cross bedding is the rule and ripple marks are found locally. The coarsest quartz arenites found are medium grade and the finest are fine siltstones. The commonest are fine sandstones. Most of the arenites are pale to dark yellow in colour and weather to an ochreous brown. There are two main types of quartz arenites; those with a calcite cement, and those with a clay-silt matrix. Plant remains are very common and well preserved in those with a clay-silt matrix (plate 20D).

The mineral composition of the two types of arenites is very similar. Generally about 90 percent of the detrital grains are quartz with about 5 percent feldspar (orthoclase and plagioclase). Mica, tourmaline, and the lithic fragments chert, quartzite and quartz-mica-schist make up the remainder of the rock. Mica is always much more important in those arenites with a clay-silt matrix. The feldspar is generally very fresh or slightly altered. Oolites and calcareous skeletal fragments make an occasional contribution.

The quartz of most of the arenites is poorly sorted, angular and of low sphericity, but the coarser sandstones (medium grade) are generally better sorted and shew more rounding.

The sparry calcite is generally ferroan and forms a granular mosaic which often has developed into poikilitic texture.

Pyrite is usually present and forms tiny lenticles parallel to the bedding, as well as large grains and clusters of tiny grains.

Polymict conglomerates:

Coarse conglomerates containing pebbles (some very well rounded) up to 25 cm in diameter are found towards the top of the Formation at a number of localities. They are particularly well developed in the Aitutu Anticline near to Mt. Cablac. The conglomerates are always associated with quartz arenites, calcarenites and micaceous shales. The upper and lower bedding contacts are quite normal and they shew no evidence of being slumps. They are regarded as normally interbedded rudites representing very high energy shallow water conditions.

Most of the pebbles in the conglomerate are either hard calcilutites or calcarenites closely resembling those of the Aitutu Formation. Many of the pebbles and larger clasts are encrusted with blue-green thread calcareous algae. Other clasts include algal pisolites, calcareous algal fragments, oolites, poorly sorted angular quartz grains (medium sand to silt grade) and altered feldspars. A sparry calcite cement forming a granular mosaic binds the various clasts together. These conglomerates are illustrated in plate 18B.

STRATIGRAPHIC POSITION

The Wai Luli Formation is everywhere conformable upon the Aitutu Formation. It is overlain everywhere unconformably by rocks of Cretaceous or younger age. The lowest part of the Wai Luli Formation, namely the spotted marls and limestones, have yielded the Lower Jurassic ammonites Arnioceras sp. at the type locality. The marls

on the southern limb of the Cribas Anticline have yielded the Toarcian ammonite Dactylioceras cf. D. braunianum (d'Orbigny). Thus the base of the Wai Luli Formation is established as Lower Jurassic (Toarcian) locally at least. In other places, for example the northern limb of the Aliambata Anticline and the northern limb of the Bazol Anticline, the Wai Luli Formation contains Halobia which suggests that here the Formation extends down into the Upper Triassic (Norian).

The upper part of the Wai Luli Formation is difficult to date precisely but the youngest fossils found so far are the belemnites from the Aliambata area (Belemnopsis sp.) which were identified by Dr. M.K. Haworth (personal communication, 1964), who commented that they probably indicate Middle or Upper Jurassic age. Because of the unconformity at the top of the Wai Luli Formation and the absence of any definite Upper Jurassic fossils it seems probable that the youngest part of the Formation is Middle Jurassic.

Other fossils found in the Wai Luli Formation include:

Pecten ?n. sp.

Myalina sp.

Misolea sp.

Two ammonites reported from the South Lacro region by Grunau (1956) were: Arietites sp. and ? Oxynoticeras sp. and later (1957) he reported Aucella sp. and Lima brouweri Krumbeck from the Aliambata region.

Mr. G.F. Elliott (personal communication, 1965) has identified "myxophytes (blue-green thread algae) in two samples," and commented that one sample "is a little like *Sphaerocodium*", but this has no age-significance.

One arenite sample rich in leaf cuticle was studied by Dr. M. Muir (personal communication, 1965) who commented that the sample "yielded abundant Ginkgoalean-type cuticles. The spores present were undiagnostic bisaccate spores, but were sufficiently abundant that the absence of the characteristically Permo-Trias striate pollen grains is significant. The sample is likely to be Jurassic in age from the presence of: -

Alisporites sp., Pityosporites sp., Cycadopites sp. and cf. Exesipollenites sp.

Dr. Muir regarded this leaf cuticle as drifted material.

ENVIRONMENT

The Wai Luli Formation is entirely marine. The fauna which is poor, restricted, sporadically distributed and generally poorly preserved, does not permit much to be said about the depth of water in which most of the formation accumulated. The presence of calcarenites with algal pisolites, oolites and skeletal sands, by analogy with modern deposits forming in the Bahamas (Illing, 1954) and the Persian Gulf (Houboult, 1957) indicate very shallow water conditions. The coarse polymict conglomerates with well rounded pebble clasts covered by algal growths also indicate shallow water with high energy

conditions. The increasing frequency with which these shallow water indicators appear towards the top of the Formation may be interpreted as pointing to deeper water conditions in the lower part of the Formation. Other facts that suggest the basin of deposition was shallow are the presence of gypsum, salt pseudomorphs, prolific plant remains and possibly the red shales. The much burrowed quartz arenites (and calcilutites and marls) accord with but do not prove a shallow water environment. Perhaps the most important indication of shallow water is the presence of calcareous algae (Johnson, 1961).

The presence of gypsum does not prove that this was an evaporitic zone because gypsum can be precipitated in marine environments such as the mangrove swamps of New Caledonia (Avis, 1953).

The only common benthonic fossil remains are the burrowing structures of "Chondrites" and "Scalarituba". The poverty of shelly fossils may be significant, especially in the presence of pyrite, bituminous horizons and gypsum, that may indicate anaerobic bottom conditions, that were possibly also highly saline. A closed stagnant basin would be an explanation of these sediments.

Thus it appears that the environment of deposition of the Wai Luli Formation may not have been widely different from that of the Aitututu Formation. Yet the lithologies of the two formations are very different, for while the Aitututu Formation is characterised by the lack of terrigenous material, the Wai Luli is predominantly a clay formation. Whether this difference reflects changes in the amount of erosion in the source area, alteration in

PLATE 18

- A. Wai Luli Formation- burrowing structures cf.
 Scalarituba in basal marls.

- B. Wai Luli Formation- intraformational conglomerate,
 note the algal coatings of
 many clasts.



PLATE 19

- A. Wai Luli Formation - shales with thin limestones and marls.
- B. Wai Luli Formation - interbedded limestones and shales near Manatutu.
- C. Wai Luli Formation - multicoloured shales, grey, green, red and purple.
- D. Wai Luli Formation - shales with slumped limestone bodies.

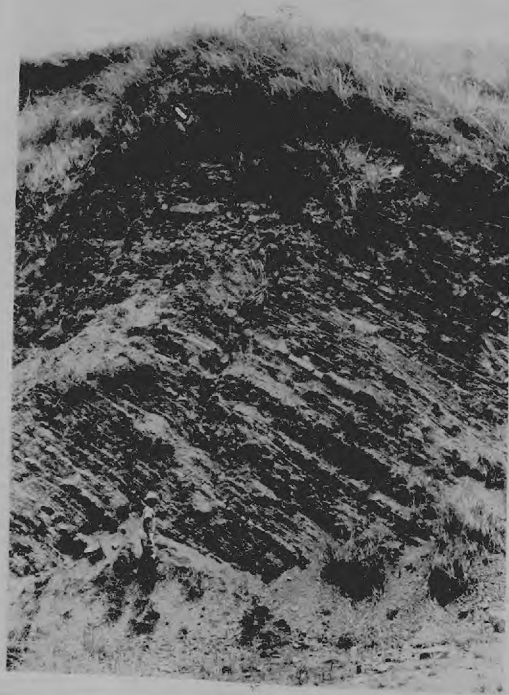
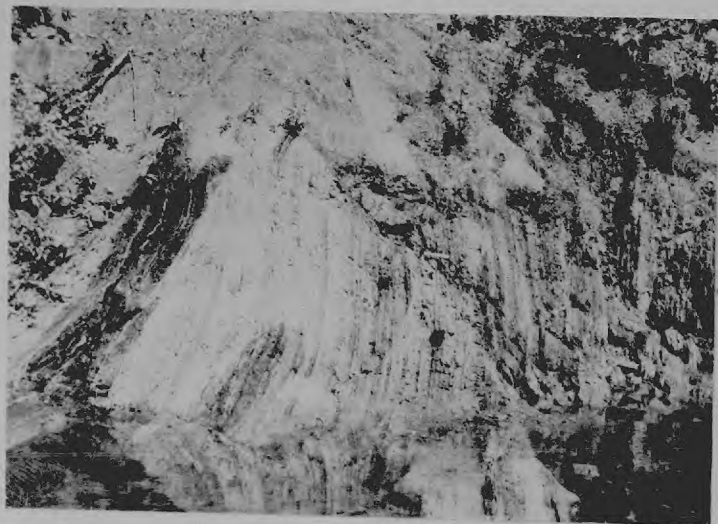


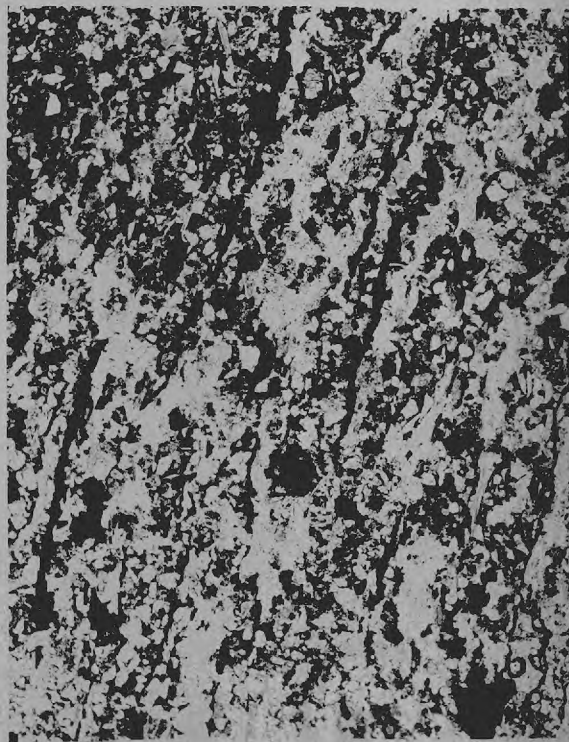
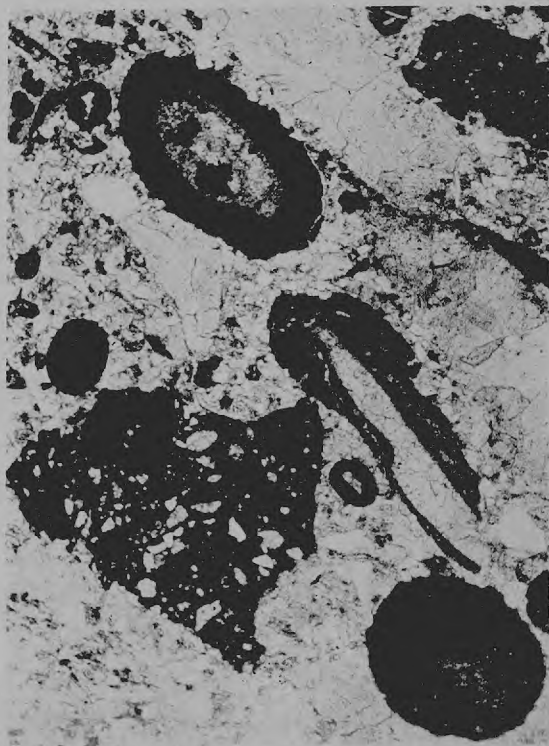
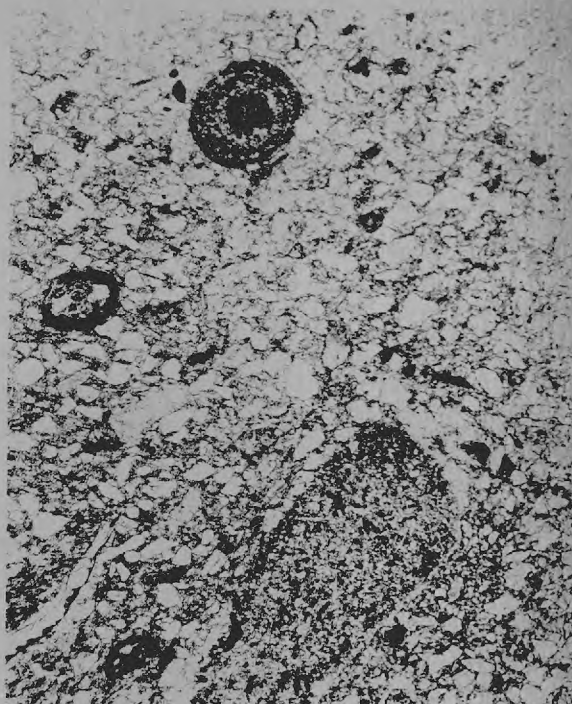
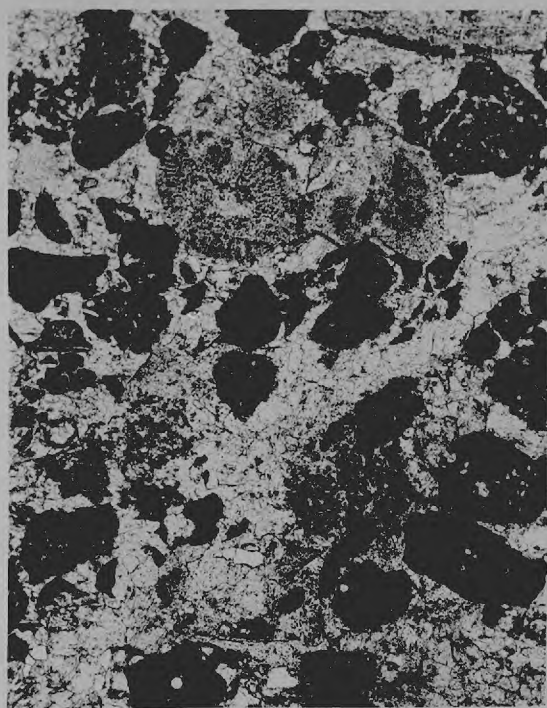
PLATE 20

- A. Wai Luli Formation - calcarenite with sparry calcite cement. Note oolites, micrite clasts and small quartz grains. (x 20).

- B. Wai Luli Formation - quartz arenite with oolites and calcite skeletal fragments in sparry calcite cement. Note very small quartz grains arranged in the oolite jacket (x 20).

- C. Wai Luli Formation - calcarenite with considerable quartz. Note the algal pisolites and the thick micrite jackets (algal ?) and large clast of silty calcarenite (x 20).

- D. Wai Luli Formation - quartz arenite with silt-clay matrix. Note the large leaf cuticles (x 20).



depth of water in the basin of deposition or structural changes removing what had been an effective barrier to transport of terrigenous detritus during the Upper Triassic, is unknown. What does seem important is that the basal marls of the Wai Luli Formation may represent a transition from the 'pure' carbonate environment of the Aitutu to the clay shales of the Wai Luli. Another important factor is that both formations are composed of more than 80 percent of lutite grade material which suggests persistence of quiet water deposition, until towards the top of the Wai Luli Formations where arenites become quite common and conglomerates appear, probably due to considerable shallowing.

WAI BUA FORMATION

SUMMARY

The Cretaceous succession in eastern Timor begins with the Lower Albian and ends with the Danian. There are two distinct facies, the Wai Bua Formation is confined to the east and the other the Borolato Limestone to the west. The western facies consists predominantly of radiolarian marls, shales and cherts with radiolarites, whilst in the east pelagic limestones predominate. Manganese nodules and manganiferous bedded rocks are found in the Wai Bua Formation. The environment of the Wai Bua was almost

certainly bathyal and a long way from any landmass.

INTRODUCTION

All the autochthonous Cretaceous rocks of eastern Timor are confined to the south coast. They are divided into two formations. The Wai Bua Formation is a siliceous facies consisting of radiolarian shales, radiolarites and cherts. It outcrops only in the region about Betano. The other Cretaceous formation is a pelagic limestone facies that is here named the Borolalo Limestone, and outcrops near Aliambata and further east. Geographically these two facies are now separated by about 130 km. in which there are no Cretaceous rocks exposed.

Earlier workers such as Grunau (1953) and Gageonnet & Lemoine (1958) placed the rocks of the Wai Bua Formation in the Bibiliu Series. This was a "sack" name that recent work has shewn to include Cretaceous, Eocene and Upper Miocene sedimentary rocks of four different facies and involving three major unconformities. It is therefore suggested that the term Bibiliu Series is now dropped. These earlier workers did not differentiate between in-situ Cretaceous rocks and the large exotic blocks of Cretaceous formations (plate 21A) in the Bobonaro Scaly Clay (an Upper Miocene block clay). I.B. Freytag, in an unpublished report to Timor Oil Ltd. in 1959, was the first to recognise that these Cretaceous rocks formed an important unit.

The type locality for the Wai Bua Formation is near the village of Wai Bua (9°07'S, 125°45'E). On the track from Betano leading to this village is exposed a succession

of friable radiolarites, and in the nearby River Maran is a larger section (15 metres) of radiolarian shales and marls. Exposures of this formation are almost confined to the cirque of hills north of Betano (plate 21C), and between the rivers Sui and South Lacro (an area of about 65 sq. km.). Sections are found principally in the creeks draining these hills, in particular in the rivers Leto and Cela. West of the River Sui, in an unnamed tributary of the River Bisumata is a section 60 metres thick. A few other scattered exposures in creeks just west of the River Sui complete the surface distribution of the autochthonous Wai Bua Formation. Exotic blocks of this Formation are found almost wherever the Bobonaro Scaly Clay outcrops.

The elucidation of the detailed stratigraphic succession is hampered by two factors: the intermittent scattered distribution of outcrops that seldom expose sections more than 20 metres thick, and the intense folding and faulting that has dislocated these brittle rocks. Because of the fragmental field evidence, the stratigraphic column shown in enclosure 8 is necessarily generalised. The Wai Bua Formation is estimated to be approximately 500 metres thick.

LITHOLOGY AND PETROGRAPHY.

Bedded cherts.

These are thinly bedded, and coloured walnut brown, yellow, red and dark olive green. Petrographically there are two main varieties: those with radiolarian skeletons and those without. The radiolarian cherts are typical and the cherts without radiolarians exceptional in this

succession. The radiolarian cherts are largely composed of chalcedonic silica. The radiolarian skeletons occur as relics, seen in thin section as circular or elliptical areas (plate 22A), filled with radiating fibrochalcedony or granular chalcedony, that have a different fibre pattern or grain size from the chalcedony of the matrix. Some of the radiolarian cherts contain relics of sponge spicules, and rare calcite fragments of what were probably Foraminifera. The presence of Foraminifera is reflected in the chemical analyses; two cherts containing Foraminifera remains had a CaO content greater than 1 percent.

The matrix of these cherts shews various chalcedonic textures. Following Smith (1960) these can be described as: cryptocrystalline, granular pin-point and fibrochalcedony. Where fibrochalcedony occurs in the matrix it is confined to very small patches of short fibres.

Bedded cherts without radiolarian skeletons are dark red in colour. Chemically they may be distinguished from the radiolarian cherts by having a much higher Fe_2O_3 content and much lower CaO. In thin section (plate 23C) they are characterised by areas of reddish brown isotropic 'mineral' that are surrounded by chalcedony with relics of colloform bands. Taliaferro and Hudson (1943) in an account of the chert and manganese association in the Coast Ranges of California state that both iron and manganese oxides can enter into SiO_2 gel in variable quantities and produce a homogeneous isotropic substance having many of the properties of opaline chert. It seems likely that the brown isotropic substance present in these cherts with high Fe_2O_3 originated in this way. Where the brown isotropic material has crystallised to chalcedony the Fe_2O_3 has been

expelled as small red, translucent grains, probably hematite.

This group of cherts exhibits a very wide variety of chalcedonic textures. Both granular and fibro- chalcedony are represented in considerable variety. The granular chalcedony ranges from almost cryptocrystalline to a coarse mosaic of idiomorphic quartz crystals (0.4 mm. diam.). These larger forms are present in a drusy mosaic where grains increase in size centripetally (plate 22B). The fibrochalcedony shews even greater variety, following the terminology of Smith (1960) chain-structures, and spherulitic textures in various sizes can be recognised. Polygonal spherulites are also present.

Chert nodules.

Occasional chert nodules are found in the marls and limestones of this Formation. They are typically black with a white rind, and generally not more than 20 cm. in diameter.

In thin section replacement textures are clearly discernible (plate 22C) with relics of Foraminifera and calcareous matrix preserved within the chalcedonic matrix. Radiolarian skeletons and sponge spicules are usually seen. Some of the nodular cherts consist of opaline not chalcedonic silica. Chalcedony where present has a microgranular or cryptogranular texture. The mode of replacement is seen to have been selective. Frequently scattered through a limestone are radiolarian relics (now chalcedony) and Foraminifera filled with chalcedony although the shell remains in whole or part.

The chemical analysis of one replacement chert nodule (after removing the rind) was found to contain 85 percent SiO_2 and 14 percent CaCO_3 .

Radiolarites.

The term 'radiolarite' as used in this essay is applied to rocks composed very largely of the remains of Radiolaria, and in which clay and foraminiferal debris are present in varying amounts. The Radiolaria of these Timor radiolarites are frequently composed of opaline silica but some have crystallised to chalcedony. The Radiolaria are occasionally very well preserved. The amount of clay present varies from 6 to 40 percent. Those radiolarites (the majority) with a clay content of less than 15 percent are extremely porous. These more porous varieties are very similar to modern radiolarian earths; they are friable, soft and have a dry earthy feel. They are pale grey, white, cream and pink coloured, and have a brittle splintery fracture. They are readily distinguished from the cherts which are hard, dense, dark coloured, translucent, vitreous rocks with a conchoidal fracture.

Some of the radiolarites contain traces of Foraminifera (plate 22D), but only one of the twenty four analysed contained more than 5 percent CaCO_3 , and more than half of the samples contained less than 1 percent CaCO_3 .

Bituminous matter is sometimes present as a dark brown and amber coloured material filling and staining the Radiolaria and their debris. Tiny quartz grains are sometimes present, usually in those radiolarites in which clay is an important constituent.

One of the features of the radiolarites is the fine bedding and microbedding in which individual layers are about 1mm. thick (plate 22D). This layering is often due to the primary separation of radiolarian debris into one horizon and Foraminifera and clay into an adjacent horizon. Other radiolarites that contain little clay consist of little else than radiolarian skeletons (plate 23A).

Of twenty four radiolarites analysed only three contained less than 83 percent SiO_2 . The chemical composition of these rocks is discussed in the Appendix I.

Radiolarian shales.

These are thinly bedded shales and siliceous mudstones having unusual pastel colours: pink, red, orange, pale-coffee and a few chocolate coloured beds. These colours are not weathering effects but are the colour of the freshly broken rocks. Brittle splintery fractures are characteristic. There is on commonly repeated sequence of orange and grey coloured shales in which the layers of one colour are between 3 and 1 cm. thick, and the microlayers within these coloured units frequently less than 1 mm. One section 6.5. metres thick consisting of these alternating coloured units only was measured along the River Cela (plates 21B and 21D).

Radiolarian marls.

The distinction between the radiolarian shales and marls is arbitrary since the shales grade into the marls by increase in the proportion of Foraminifera. They generally form beds about 10 cm. or less. They have

pastel colours similar to the shales and mudstones, and break with a brittle, blocky fracture.

Clays.

A number of bright coloured clays are interbedded with the shales and marls. These clays shew the results of considerable squeezing and flowing between the more resistant adjacent rocks.

Limestones.

Two very different kinds of limestone are present. One is a biocalcarenite, essentially composed of Foraminifera and their debris together with a varying proportion of Radiolaria. The other is a calcilutite consisting mainly of micrite with some scattered Foraminifera and Radiolaria.

The biocalcarenites form cream coloured beds seldom thicker than 15 cm. that are typically microbedded with layers frequently less than 5 mm. thick. The variations between the layers is mainly produced by different proportions of Foraminifera and Radiolaria. Clay forms less than 10 percent (by weight) and quartz is present only as rare very small grains. Some calcite cementation has taken place between the grains, and the foraminiferal cavities are frequently filled with a drusy mosaic.

The calcilutites generally form thicker beds which could be termed massive. This particular type of limestone resembles closely the typical Borolalo Limestone to be discussed later. These limestones are pink coloured with chocolate coloured stylolites. The calcilutites are

composed largely of micrite with scattered Foraminifera in varying proportions. Clay is very variable ranging from less than 1 percent up to 35 percent. This upper value is the limit, given by Pettijohn (1957), between limestone and marl.

Graded arenites.

A number of graded arenite units have been found interbedded with the radiolarites and radiolarian shales and marls. The coarsest layers would be medium sands on the Wentworth (1922) scale, and are about 30 cm. thick. Cross bedding is a feature of these beds. The coarse arenites consist very largely of rounded and subrounded grains of calcilutites, cherts, quartz, with Foraminifera, Radiolaria and Inoceramus fragments. The quartz grains are much larger than the tiny grains found in the radiolarites. A little clay is present. The coarser arenite beds grade upwards into siltstones and mudstones. The graded beds have pastel colours as is typical of the whole Formation. The siltstones are always much thicker than the coarser beds being about 1 metre thick. The photomicrograph in plate 23B illustrates part of the coarser arenite.

Manganese nodules and ferromanganiferous rocks.

The petrography and chemistry of these deposits are discussed in detail in the Appendix II. Manganese nodules, pyrolusite shales, pyrolusite siliceous shales, and pyrolusite-rich slabs occur as very rare units in the general succession interbedded with the radiolarian shales, marls and radiolarites. Shaly rocks composed largely of

ferric oxide, silica and calcium carbonate form rare sequences about 2 to 3 metres thick. With these ferriferous shales pyrolusite-rich layers are intimately interbedded.

STRATIGRAPHIC POSITION

The base of the Wai Bua Formation is never seen. It seems probable that the Wai Bua Formation rests unconformably upon either Jurassic or Triassic strata. It is overlain unconformably by various Upper Miocene sedimentary formations (enclosure 3C).

The Foraminifera and Radiolaria in the Wai Bua Formation indicate that the oldest strata exposed are of Aptian or Lower Albian age. The presence of microfossils indicating Cenomanian, Turonian, Senonian and Maestrichtian ages suggests, in the absence of any evidence to the contrary, that sedimentation continued at least until Maestrichtian times without serious interruption. There is some suggestion that the Cenomanian may be represented by only a 15 metre thick succession. This implies a somewhat condensed sequence; but in view of the tectonic dislocations and absence of any detailed study this has not been confirmed.

The following Radiolaria have been identified in a radiolarite from the Betano area by Dr. I. Crespin & Dr. D.J. Belford (in an unpublished report dated 1959):

Cenosphaera cf. immanis Tan

Dorysphaera

Spongotripus

Sphaerostylus

Dictyomitra sp. A

Dictyomitra sp. B

Rapolastrum

Porodiscus

Cenellipsis sp.

Ellpisoxphus cf. rugosus Tan

Eycritidrum cf. brouweri Tan

Lithomitra cf. pseudopenguis Tan

Cenosphaera sp. A

Dr. Crespín and Dr. Belford commented that this fauna indicates a Lower Cretaceous (Albian) age. Some of these forms are comparable with species from the Gearle Siltstone and Windalin Radiolarite of the Carnarvon Basin, West Australia. They commented that "it is most probable that these radiolarites of Portuguese Timor are equivalent in age to the Lower Cretaceous radiolarian beds of northern Australia, where the age has been determined by the presence of zonal Foraminifera and mega-fossils".

The following micropalaeontologists have identified foraminiferal assemblages indicating that Cenomanian, Turonian and Senonian (up to Maestrichtian) stages are probably represented: Dr. I. Crespín and Dr. D.J. Belford (unpublished report dated 1959) Dr. F.T. Banner (personal communication, 1963), and Mr. D.J. Carter (personal communication, 1964). The Foraminifera identified are:

Rotalipora brotzeni (Sigal)

Planomalina buxtorfi (Gandolfi)

Rotalipora cushmani (Morrow)

Rotalipora reicheli (Mornod)

<u>Praeglobotruncana stephani stephani</u>	(Gandolfi)
<u>Globotruncana lapparanti lapparanti</u>	Bolli
<u>Globotruncana lapparanti</u> subsp. nov.	
<u>Globotruncana</u> sp.	
<u>Pseudogumbelina</u> sp. cf. <u>P. striata</u>	(Ehrenberg)
? <u>Pseudotextularia</u> sp.	
<u>Rotalipora</u> sp. cf. <u>R. appenninica</u>	(Renz)
<u>Rugoglobigerina rugosa rugosa</u>	Plummer
<u>Rugoglobigerina rugosa</u> cf. <u>R. rotundata</u>	Bronniman
<u>Globotruncana contusa patelliformis</u>	Gandolfi
<u>Hedbergella</u> spp.	
<u>Heterohelix globulosa</u>	(Ehrenberg)
<u>Gublerina</u> sp.	
<u>Globotruncana spinea</u>	Kikoine
<u>Globotruncana rosetta</u>	(Carsey)
<u>Globotruncana stuarti</u>	(De Lapparent)

ENVIRONMENT

The fauna of the Formation implies deposition in an open sea, but does not help much in defining the bathymetry. There is a reasonable likelihood that conditions were those of an open basin having a depth of about 200 metres or more.

The frequency of microbedding, the absence of coarse clastics (except in graded sequences, where they suggest the agency of turbidity currents), the presence of manganese nodules and pyrolusite-rich shales all suggest a bathyal environment far from a landmass. Petrographic and chemical evidence imply that very little detrital material of terrigenous origin entered the basin in which the Formation was deposited. Petrographic and chemical

studies demonstrate that there was no important contribution from volcanic material to these shales, radiolarites, cherts or ferromanganiferous rocks, and that the cherts and radiolarites originated as radiolarian ooze. These conclusions accord with a bathyal environment far from land.

Ericson et al. (1961), in discussing sediments deposited far from land, considered that "the occurrence of digging structures, more or less visible may thus be taken as a characteristic of normal pelagic deposits. The lack of such structures indicates abnormal conditions, probably a very high rate of deposition". If this conclusion is valid it can be applied to the Wai Bua Formation where no digging or burrowing structures have been observed.

The presence in the succession of beds of limestone argues (by analogy with modern seas) against conditions having been abyssal. However as Bezrukov (1963) pointed out dissolution of CaCO_3 in the deep-sea is principally due to the action of cold waters rich in CO_2 . Such waters result from the presence of polar ice caps, that are generally believed not to have existed in Cretaceous times. In the absence of such cold CO_2 -rich waters circulating on the ocean floors CaCO_3 would perhaps be stable at greater depths.

In western (formerly Dutch) Timor the Cretaceous rocks have been studied by Molengraaff (1916, and 1922) and Brouwer (1925). Red clay-shales, with manganese nodules, sharks teeth, fish remains and other bones have been reported. Radiolarian shales and limestones rich in Globotruncana are also described. The chemistry of the

PLATE 21

- A. Wai Bua Formation - characteristic bedding of
 radiolarites, cherts and
 radiolarian shales. Note complex
 minor folding. This is an
 exotic block in the Bobonaro
 Scaly Clay.

- B. Wai Bua Formation - radiolarites and radiolarian
 shales.

- C. Wai Bua Formation - general view of Wai Bua region
 north of Betano shewing
 characteristic terrain and
 vegetation of this Formation.

- D. Wai Bua Formation - bedded cherts and radiolarian
 shales.

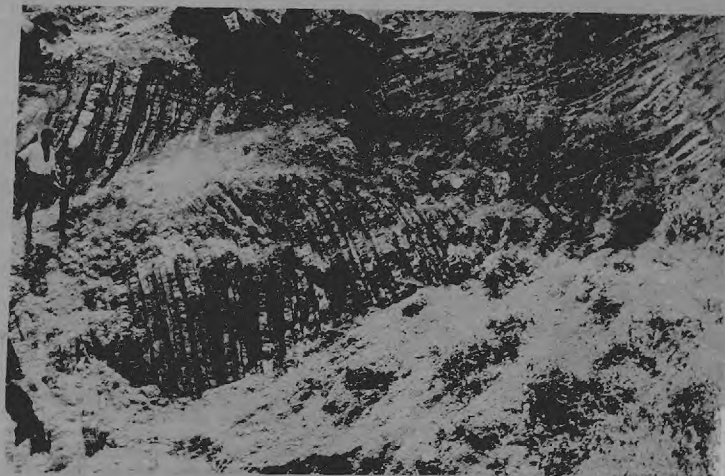


PLATE 22

- A. Wai Bua Formation - radiolarian chert now composed of chalcedony (x 35).
- B. Wai Bua Formation - bedded chert without radiolarian skeletons. Note drusy mosaic of chalcedony (x 60).
- C. Wai Bua Formation - chert nodules in calcilutites. Note the three stages of replacement of the limestone by chalcedony. The dark tone is an area of total replacement by chalcedony. In the lightest tone area (bottom of photo) only the Foraminifera have been replaced and filled by chalcedony (x 35).
- D. Wai Bua Formation - radiolarite composed almost entirely of radiolarian skeletons with a few Foraminifera, note the microbedding (x 20).

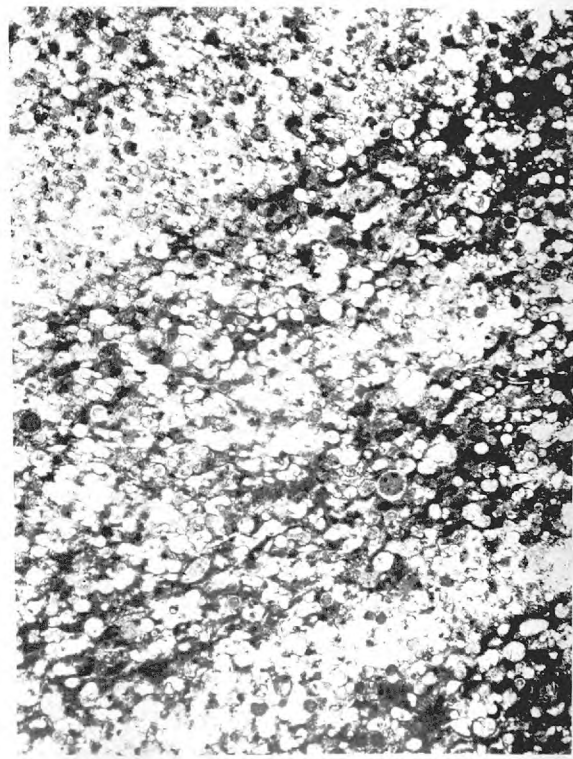
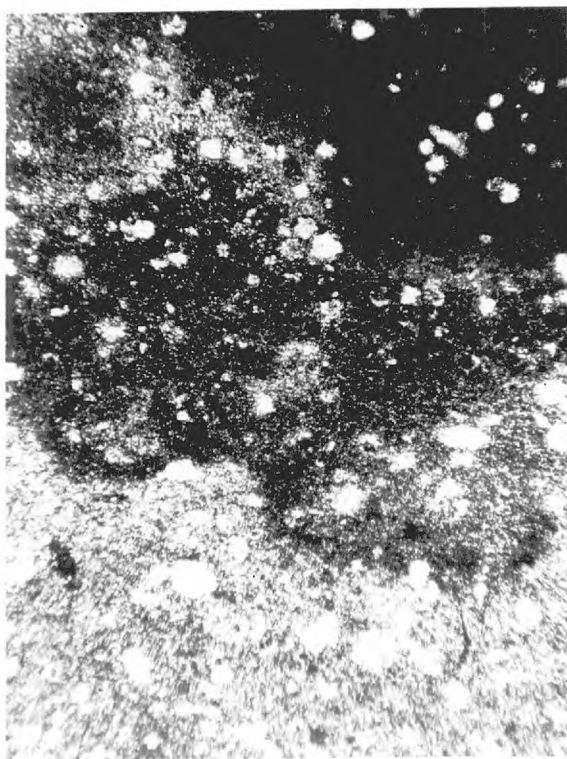
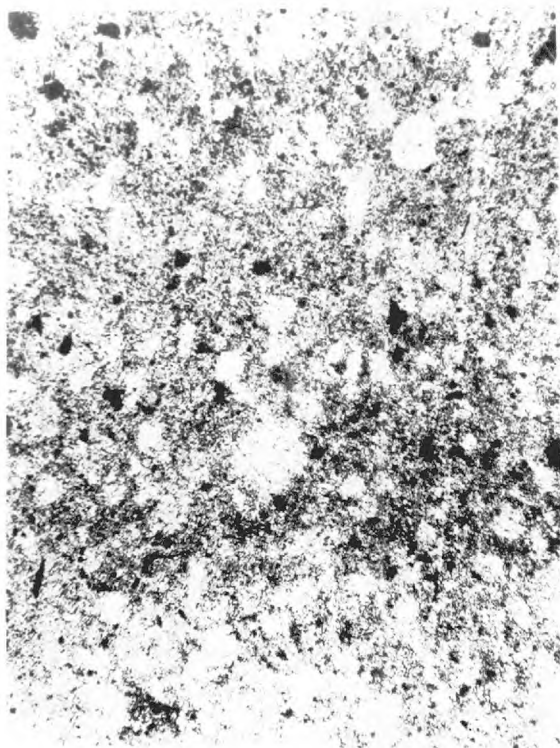
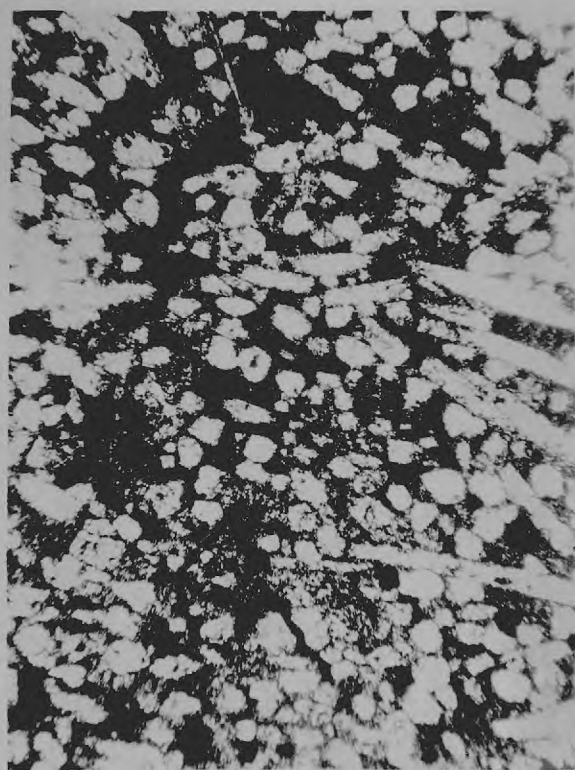
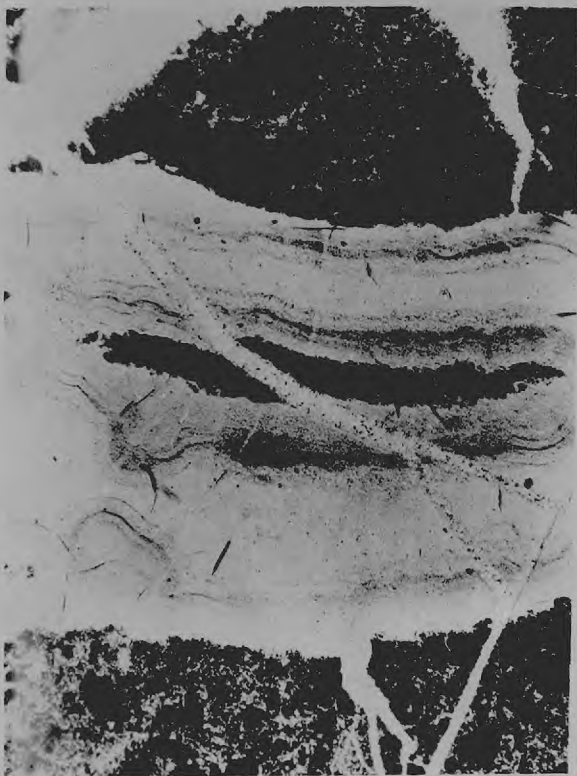
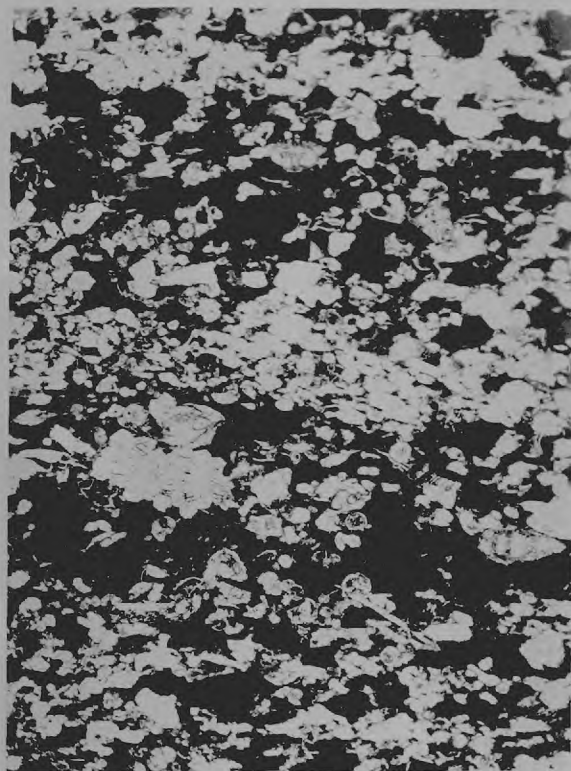
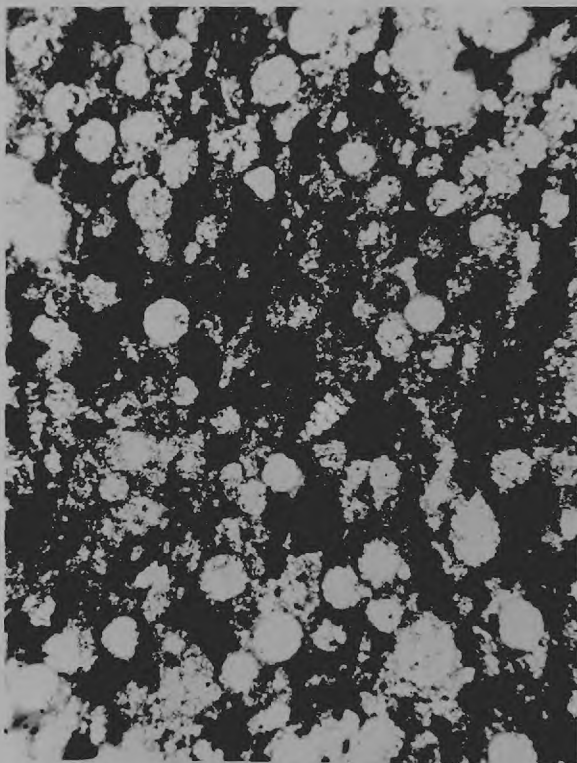


PLATE 23

- A. Wai Bua Formation - radiolarite composed of radiolarian skeletons and a little clay matrix (x 35).
- B. Wai Bua Formation - graded arenite with clay matrix. Note fragments of Inoceramus prisms and Foraminifera (x 35).
- C. Wai Bua Formation - bedded chert without radiolarian skeletons. Note colloform bands in chalcedony. The dark patches are due to a red-brown isotropic 'mineral' (x 60).
- D. Wai Bua Formation - Inoceramus-like fragments silicified by chalcedony (x 35).



red clay-shales and manganese nodules was studied by Molengraaff (1922) and El Wakeel and Riley (1961). These workers agree in considering these rocks analogous to modern bathyal and abyssal deposits.

The conclusion that the Wai Bua Formation was deposited far from land in a bathyal environment seems unavoidable, although the bathymetry cannot be defined precisely by the chemical and palaeontological work carried out to date. A more satisfactory conclusion can probably best be achieved by detailed study of the fauna.

BOROLALO LIMESTONE

SUMMARY

The Borolalo Limestone of Upper Cretaceous age is composed entirely of limestones, most of which are calcilutites. The succession, about 200 metres thick, outcrops only in the south-eastern part of eastern Timor. The fauna is mostly pelagic Foraminifera. The formation was probably deposited in a bathyal environment far from land.

INTRODUCTION

Previous workers (Grunau, 1957; and Gageonnet & Lemoine, 1958) included the limestones of Upper Cretaceous age in a "sack" group they called the Fatu Limestone. The Fatu Limestone included limestones of Triassic, Cretaceous, Eocene and Lower Miocene age, their common feature was their supposedly allochthonous nature. Several factors misled these workers into regarding these limestones as allochthonous; one was their failure to distinguish in situ strata from exotic blocks in a mid-Miocene gravity slide deposit (the Bobonaro Scaly Clay discussed later). The various members of this spurious grouping together of limestones of various ages have now been re-defined, and the term Fatu Limestone should now be abandoned.

The type locality for the Borolalo Limestone is the hill called Borolalo, north of the beacon on the beach at Aliambata ($8^{\circ} 46'S$, $126^{\circ} 36'E$). North of the beacon is a track that leads up the escarpment of the hill Borolalo. Along this track is exposed a section about 100 metres thick. The small creeks that drain this hill reveal a number of good sections. Further east in the region of Iliomar this formation gives to rugged hills with good exposures.

The lithology of the Borolalo Limestone shews little variation. Limestones and cherts are the only rock types recorded. This is essentially a succession of massive, dense limestones that form steep prominent escarpments and rugged hills. The limestones support a dense vegetation of large trees and may be delimited on the aerial photographs.

The succession is estimated to be about 200 metres thick. Apart from the few small outcrops of a similar limestone interbedded in the Wai Bua Formation near Betano, this formation is found in-situ only in the Aliambata and Iliomar districts. Like the Wai Bua Formation it is represented by numerous exotic blocks in the Bobonaro Scaly Clay. These blocks have in the past misled workers who failed to recognise their nature, and regarded them as klippen. Further misunderstanding has been caused by the occurrence in the central mountainous spine of eastern Timor of another hard massive limestone that supports a dense growth of large trees. This limestone, named by the present writer the Cablac Limestone is Lower Miocene in age. The Cablac Limestone contains derived Upper Cretaceous fragments and Foraminifera. This is further complicated by the presence of Borolalo Limestone overthrust slices sitting on the Cablac Limestone in a number of places e.g. Mt. Mata Bia (Grunau, 1957) and Mt. Wai Nete. This problem is even more confused by the Borolalo Limestone being overlain at Aliambata by a similar limestone facies of Lower Miocene age. It is of interest to recall here that in the eastern Celebes Upper Cretaceous sedimentary rocks are also overlain by a pelagic limestone of Lower Miocene age (van Bemmelen, 1949).

LITHOLOGY AND PETROGRAPHY

The Borolalo Limestone consists of massive or thickly bedded limestones. Generally they are pink with characteristically chocolate coloured stylolites. Cream and pale chocolate coloured limestones, in which large Foraminifera are visible in the hand specimen, form less important varieties. Interbedded, but less commonly seen,

is a pale yellow variety with a subconchoidal fracture and usually with dendritic manganese stains. This latter is a radiolarian limestone.

Cherts occur as black and red nodules, and less commonly as thin veins that cut bedding planes indiscriminately. The nodules are usually confined to particular horizons and vary in size from microscopic to 50 cm. in diameter. One interesting variety is a coquina cemented by chert. It is a pale pink with black layers due to pyrolusite. This rock is illustrated by a photomicrograph (plate 24A).

In thin section, two types of limestone are recognised: biocalcarenites which occur very rarely in the succession, and calcilutites that make up almost all of this formation.

Biocalcarenites.

These consist of pelecypod fragments cemented by chalcedonic silica. Two types of biocalcarenites are recognised. One type is composed of the calcite prisms of Inoceramus which are oriented parallel to the bedding planes. These calcite prisms are cemented by chalcedonic and opaline silica. Pyrolusite is concentrated at certain thin horizons within this type of biocalcarenite. Locally the chalcedony has replaced the calcite prisms leaving relic traces. This type of limestone is illustrated by the photomicrograph in plate 24A.

The other type of biocalcarenite is composed of long, thin, fine, arcuate fragments of a pelecypod such as

Pteria (Avicula). These fragments have been cemented by chalcedony (plate 24B). Very similar concentrations of thin fragments of a bivalve mollusc (cemented by calcite not chalcedony however) from the Middle Jurassic pelagic deposits of the western Mediterranean have been described by Colom (1955) in his study of pelagic sediments. In view of the pelagic character of the calcilutites of the Borolalo Limestone it seems probable that the thin beds of pelecypod debris introduced by some form of submarine current.

Calcilutites.

The calcilutites show considerable variation in the proportion of micrite to microfossils. Some thin sections contain no microfossils. The most common variety is composed of a very fine dense micrite through which there is a thin scatter of tiny Globigerinae sp. A few specimens were found to contain many small circular areas (globular) filled with clear calcite mosaics. These have possibly formed by the dissolution of aragonitic calcispheres that resulted in voids subsequently filled by a drusy mosaic of calcite. A number of calcilutites contain large pelagic Foraminifera that have their chambers filled with clear calcite drusy mosaic that contrasts with the typically dense micrite of the matrix (plate 24C). One type of calcilutite contains numerous Radiolaria and only a few Foraminifera. These radiolarian limestones quite often exhibit good chert replacement textures. A few samples have been found to contain many sponge spicules, but generally sponge remains are uncommon. Some calcilutite contain scattered prisms of Inoceramus (plate 24D).

STRATIGRAPHIC POSITION

At the type section near Aliambata the Borolalo Limestone is seen to rest unconformably on the Middle Jurassic shales of the Wai Luli Formation. The base of the Borolalo Limestone is dated as Upper Senonian on the basis of the Foraminifera. There is some suggestion that the youngest part of the succession may be Danian although no conclusive evidence for this has been found. The well Aliambata No. 1 drilled by Tinor Oil Ltd., in 1957 immediately north of the beach and below the escarpment reached 1277 metres before being abandoned. It was so beset with technical difficulties that no reliable record of the stratigraphy or palaeontology is available. It appears likely that most of the section drilled was Borolalo Limestone in a highly fractured condition. Multiple faulting is probably responsible for the thickness.

East of Aliambata in the Iliomar district the Borolalo Limestone is unconformable on the Upper Triassic Aitututu Formation.

In the type locality, the Borolalo Limestone is overlain by a pelagic limestone of Lower Miocene age. The contact is obscured by thick scree. Mention has already been made of the similar stratigraphic relationship in the eastern Celebes. At Aliambata and Iliomar the Borolalo Limestone is locally overlain unconformably by the Upper Miocene Bobonaro Scaly Clay.

The following Foraminifera from the Borolalo Limestone have been identified by Mr. D.J. Carter (personal

communication, 1964):

Globotruncana spinea Kikoine
Globotruncana stuarti (De Lapparent) .
Globotruncana rosetta (Carsey)
Globigerinea sp.
Hedbergella spp.
Heterohelix globulosa (Ehrenberg)

Mr. Carter considers that these forms probably indicate an Upper Senonian age.

ENVIRONMENT

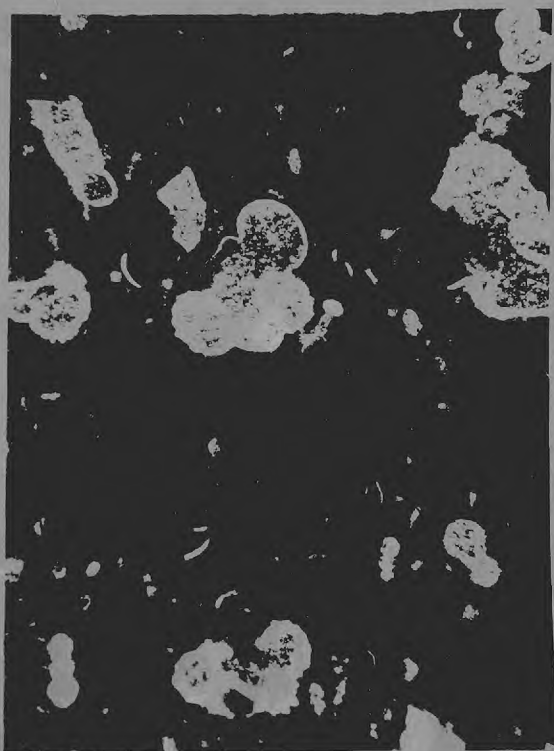
The fauna of the Borolalo Limestone is essentially pelagic. The very low proportion of clay and other land derived detritus indicate deposition far from land. Palaeogeographic evidence from Australia, New Guinea and the other inslands of the Indonesian archipelago supports the view that Timor during the Cretaceous was distant from any land area (figure 17).

The bathymetry of the Borolalo Limestone is difficult to estimate. The increase in the proportion of limestones in the Wai Bua Formation during the Senonian together with the development of the Borolalo Limestone facies in the east suggests that the sea covering the Timor region became shallower towards the end of the Cretaceous. The presence of neritic limestones of Eocene age in eastern Timor accords with the hypothesis.

The origin of the calcilutites (precipitated as a calcite or aragonite mud) presents a problem. Perhaps the

PLATE 24

- A. Borolalo Limestone - coquina replaced by chert.
Note fragments of molluscs and
Inoceramus all replaced by
chalcedony (x 20).
- B. Borolalo Limestone - biocalcarenite cemented by
chert. The thin calcite
artrate fragments of a pelecypod
? Pteria cemented by chalcedony.
Note porosity (x 60).
- C. Borolalo Limestone - calcilutite with large pelagic
Foraminifera whose chambers
are filled with drusy calcite
(x 35).
- D. Borolalo Limestone - calcilutite with scattered
Inoceramus prisms (x 35).



CaCO_3 was precipitated over shallow banks (Upper Cretaceous neritic limestones are reported from Misool by Van Bemmelen, 1949), and then swept off the banks by ocean currents into deeper water of the Timor region where it settled. In this way the Timor region covered by a sea of bathyal proportions could have received a supply of CaCO_3 mud that was originally precipitated elsewhere. In conclusion it must be said that the present study does not enable a precise bathymetry to be determined.

The absence of any pre-Senonian Cretaceous rocks below the Borolalo Limestone does not necessarily mean that this area was one of denudation during the pre-Senonian Cretaceous. Areas of non-deposition, such as current swept floors, are commonly found in modern bathyal and abyssal seas.

SEICAL FORMATION

SUMMARY

Exposed only in one very small area on the north coast are a group of radiolarites, radiolarian shales, cherts, foraminiferal limestones having a ferromanganiferous cement, and graded arenites. The thickness of these rocks is estimated to be about 100 metres. The oldest part of

the Formation is Albian, it appears to be separated by a diastem from the upper part which is Lower Eocene. There is considerable doubt as to whether these rocks are in situ or whether they are exotic blocks in the Bobonaro Scaly Clay.

INTRODUCTION

Grunau (1953) mapped these rocks as part of the Bibiliu Series. This practice was followed by Gageonnet & Lemoine (1958). As has been discussed elsewhere (see sections dealing with the Wai Bua Formation, and the Bobonaro Bobonaro Scaly Clay) this 'Bibiliu Series' was a "sack" term grouping together rocks ranging in age from Lower Cretaceous to Upper Miocene and incorporating four unconformities.

The Seical Formation is exposed only in a very small area about the mouth of the River Seical, which serves as the type locality. The Seical Formation is very similar lithologically to the Wai Bua Formation; it consists mainly of radiolarites, radiolarian shales, cherts, marls, some highly ferromanganiferous foraminiferal limestones and arenites. One feature that distinguishes the Seical Formation is the diastem between the Albian rocks and those of Eocene age. The Wai Bua Formation does not contain any such break in eastern Timor. However the Seical Formation has been so intensely dislocated by folds and faults that it has not been possible to determine the nature of this diastem that has been revealed only by micropalaeontology. In this connection it may be important to note that the Eocene rocks contain reworked Upper Cretaceous microfossils.

The base of the Seical Formation is not exposed, and the Formation is overlain unconformably by the Bobonaro Scaly Clay, which is a wildflysch-type of deposit of mid-Miocene age that contains large exotic blocks of various formations, including the Wai Bua Formation. Many of the exotic blocks of Wai Bua Formation are very similar to the rocks of the Seical Formation. The exceptionally chaotic nature of the outcrops of the Seical Formation, together with the apparent diastem from the Albian to Danian suggests that these rocks may be large exotic blocks within the Bobonaro Scaly Clay. The presence of the Bobonaro Scaly Clay cropping out around the exposures of the Seical Formation strengthens this suspicion. Caution is exercised however because of the absence of any exposures of the Bobonaro Scaly Clay within the region where the Seical Formation outcrops. This could be interpreted to mean that the Seical Formation here is one very large exotic block, or that it represents an overthrust slice (or slices) that achieved its present position during the mid-Miocene (Tf) orogeny when the allochthonous sheets of the Maubisse Formation and Borolalo Limestone were emplaced from the north (see later sections dealing with the Bobonaro Scaly Clay and the allochthonous formations). As there is no proof that the Seical Formation is composed either of exotic blocks or overthrust strata it is placed tentatively but doubtfully in the autochthonous stratigraphic sequence.

The exceptional disorder of the beds of this Formation prevent any determination of the detailed stratigraphic succession of the type locality.

LITHOLOGY & PETROGRAPHY.

Radiolarites:

The radiolarites of this formation are extremely similar to those of the Wai Bua Formation. Typically pastel coloured, friable, soft, with a brittle fracture, they are composed predominantly of the skeletons of radiolarians with admixtures of Foraminifera and clay.

Radiolarian shales:

These laminated brittle shales are very similar to those of the Wai Bua Formation.

Cherts:

The pale cream and black, thinly bedded cherts are rich in radiolarians. These cherts are now all composed of chalcedonic silica.

Ferromanganiferous limestones:

A few thinly laminated strata are composed of the tests of Foraminifera with some small angular quartz grains, and a cement of limonite, pyrolusite, and a mixture of them both. The composition of the cement of adjacent laminae show considerable changes which are reflected in the various shales of reddish brown and black. The plate 25C illustrates a thin section of a foraminiferal limestone having a pyrolusite cement. The chemistry of these rocks is discussed in Appendix II.

Arenites:

One feature of this Formation is the unusual arenites. These arenites like the ferromanganiferous limestones are Eocene in age but contain reworked Upper Cretaceous Foraminifera. The arenites are largely mixed in composition: quartz grains, Foraminifera, molluscan fragments, echinoid fragments, rare spores, and some lithic grains. Many of the arenites are quite well sorted (plate 25A), but some are poorly sorted (plate 25D).

These arenites are generally finely cross laminated, and quite often shew graded bedding.

STRATIGRAPHIC POSITION

The uncertainty about the autochthonous position of this Formation has been discussed in the introduction. The principal difficulty is that there is some evidence to suggest that this Formation may consist of several very large exotic blocks (more than 500 metres long) of the Wai Bua Formation that are part of the Bobonaro Scaly Caly, which is a wildflysch-type deposit of mid-Miocene (Tf) age, but that because the base of the Seical Formation is not exposed there is also the possibility that this Formation is tectonically allochthonous, having been overthrust to its present position during the mid-Miocene (Tf) orogeny. In the absence of unequivocal evidence this Formation is tentatively considered to be in situ.

The age of the radiolarites and interbedded radiolarian shales and cherts has been determined as "probably top Lower Cretaceous", i.e. Upper Albian, by

Dr. I. Crespin (in an unpublished report dated 1961) on the basis of comparable assemblage of radiolarians of that age in the Lower Gearle Siltstone, Carnarvon Basin, West Australia. The Radiolaria in the Seical Formation have been identified as:

Acanthosphaera sp.
Astrophacus sp.
Cenosphaera cf. immanis Tan
Eusyringium cf. pseudopenguis Tan
Lithostrobus sp.
Melitosphaera sp. aff. M. diversipora (Tan)
Sphaerophyle cf. nova Tan
Stylocapsa spp.
Stylosphaera sp.
cf. Stauralastrum sp.
Trigonactura (Trigonastinum) sp.

The ferromanganiferous limestones and arenites have been dated as Eocene, and one sample as Ta (Middle Eocene) on the basis of the Foraminifera. Reworked Foraminifera of Upper Cretaceous (Cenomanian-Turonian) age are present in these limestones. The following have been determined by Dr. C.G. Adams (personal communication, 1964).

? Aktinocyclus sp.
Alveolina sp.
Discocyclus sp.
Nummulites cf. javanus Verbeek
Globigerina sp.
Globorotalia sp.
Rotalids, and a small orbitoid.

Together with the following derived Upper Cretaceous forms

Globotruncana appeninica Renz

G. helvetica Bolli

G. lapparenti Brotzen

ENVIRONMENT

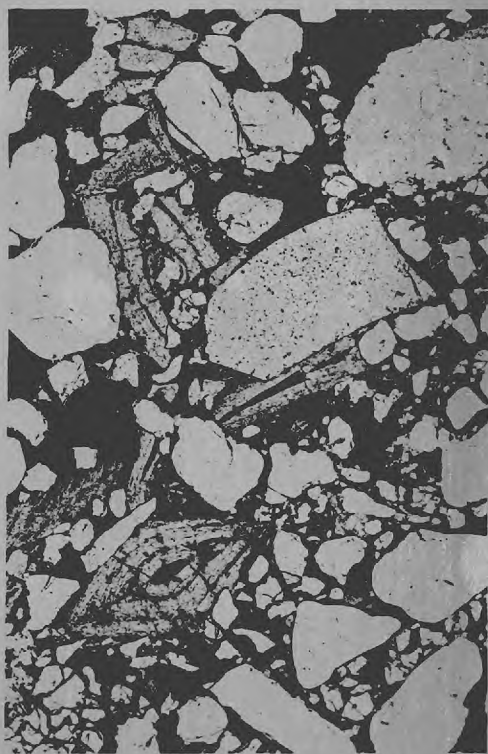
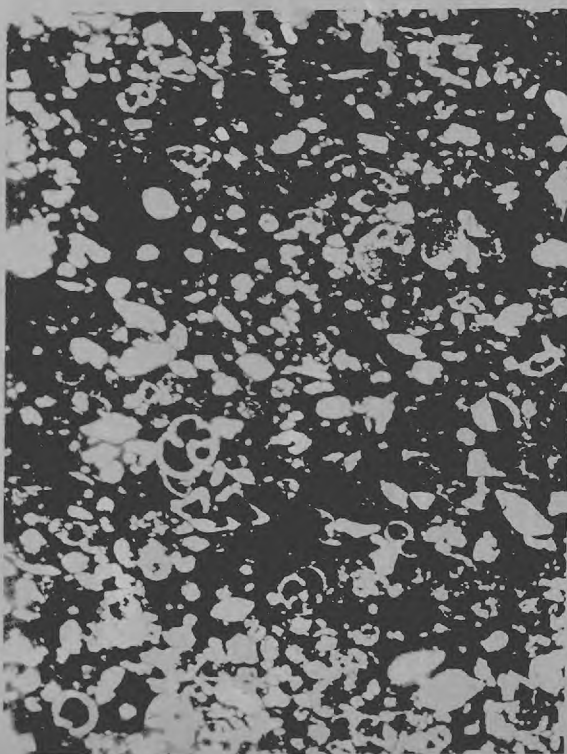
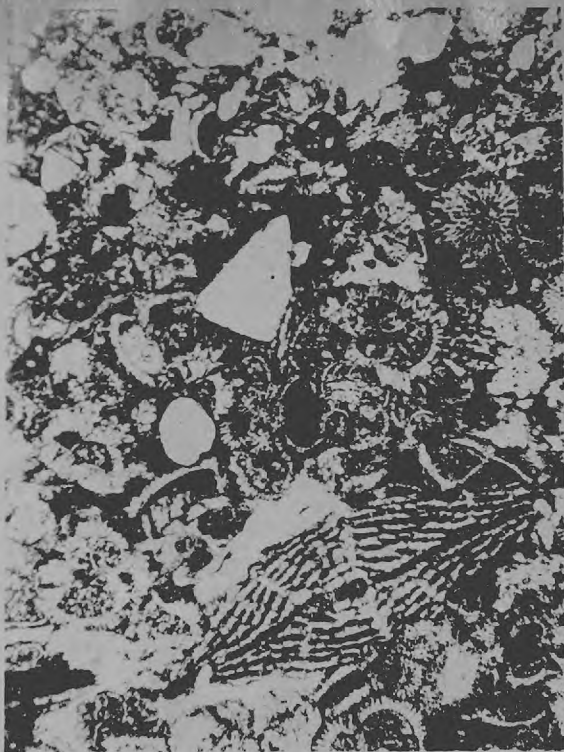
The lithology and fauna of the radiolarites, radiolarian shales, and cherts of this Formation are so similar to those of the Wai Bua Formation that it may be reasonably supposed these rocks were deposited under similar conditions. These conditions, it was suggested for the Wai Bua Formation, were a far distance from land, and a bathymetry that was probably either infraneritic or bathyal.

The graded arenites are interpreted as indicating either a shallowing of the environment, or as representing a mixture of pelagic and neritic material brought about by turbidite-like flow of the shallow water material into the deeper water zone further from land.

The ferromanganiferous foraminiferal limestones are very similar to modern calcareous manganiferous mud in the Easter Island Rise in the Pacific described by El Wakeel and Riley (1961). The similarity in the behavior of the ferromanganiferous cement that coats the inside and outside of the foraminiferal tests that make up most of the rock, and the similar chemical composition (see Appendix II) of the two deposits is so striking as to suggest possibly similar environments.

PLATE 25

- A. Seical Formation - arenite of mixed Foraminifera and quartz grains. A little calcite mud matrix present (x 60).
- B. Dartollu Limestone - typical bedding features. Note figure for scale.
- C. Seical Formation - ferromanganiferous limestone composed of tests of small Foraminifera and quartz grains in a pyrolusite cement (x 45).
- D. Seical Formation - arenite of quartz grains very poorly sorted with large Foraminifera (x 20).



DARTOLLU LIMESTONE.

SUMMARY

A shallow water, near-reef highly fossiliferous limestone formation of Eocene age is described and defined as the Dartollu Limestone. Its maximum thickness is about 100 metres. The formation is composed of mainly massive biocalcarenites of two main types; algal limestones and Alveolina - limestones. The fauna is described, and the formation correlated with similar shallow water limestones of Eocene age in western Timor.

INTRODUCTION

In their reconnaissance study of eastern Timor Gageonnet & Lemoine (1958) grouped together under the name of the Series de Samé shallow marine limestones of Eocene age and eruptive rocks, tuffs and volcanic conglomerates of uncertain age. These eruptive rocks are now known to overlie the Eocene limestones with strong unconformity. In this thesis these two units which were separated in the field are regarded as distinct formations; the Dartollu Limestone and the Barique Formation. Gageonnet & Lemoine (1958) considered the rocks of these two formations (their Series de Samé) as having been overthrust to their present position and therefore part of their Allochthonous Complex (Complexe Charrié). No doubt they were influenced in this view by their failure to distinguish the in-situ volcanic rocks of the Oligocene Barique Formation from the allochthonous crystalline metamorphic rocks of the Lolotoi Complex. Detailed mapping reveals that in the Samé area the Eocene Limestones rest unconformably on Mesozoic rocks

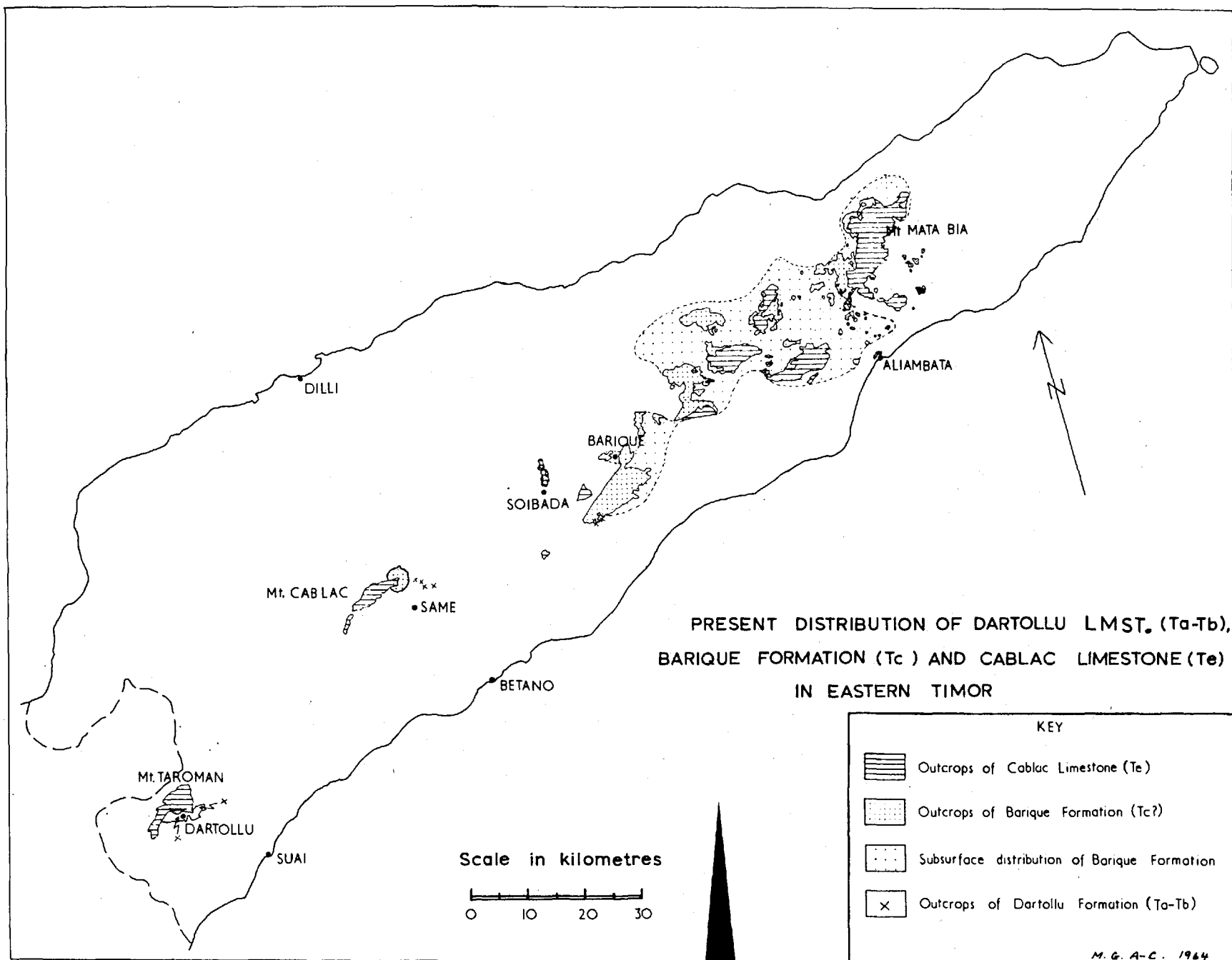


Fig. 6

of Aitutu and Wai Luli Formations, and without any intervening tectonic slices. Elsewhere in eastern Timor the Dartollu Limestone rests on the Lolotoi Complex (but unconformably not tectonically), however Gageonnet & Lemoine (1958) do not appear to have seen these other outcrops. Thus in brief, both the Dartollu Limestone and the Barique Formation (to be discussed later) are now shewn to be separate in-situ marine formations.

The type locality for the Dartollu Limestone is the low terrace-like feature about the village of Dartollu (enclosure 1B). Here dense generally massive or thickly bedded limestones (plate 25B), in which Nummulites and Alveolina are prominent even in the hand specimen, form a small broken terrace with little cliffs. Some of the limestone, that is always a honey-brown colour, is clearly an algal limestone and shews the characteristic finely banded algal structures. Larger fossils mainly echinoids and molluscs are quite common locally but are extremely difficult to extract from the dense matrix. In the type locality the formation, that seems to be a little crumpled, is estimated to be about 100 metres thick.

Outside the type locality the formation is found in situ in only two areas. One is north of the village of Samé (enclosure 1A) where it forms a number of small remnant outliers usually having steep cliffs. Further east it occurs in the valley of the River La Mara near the village Fehuc Reen (enclosure 1C). In both of these localities the character of the formation is the same as in the type locality except that interbedded with the limestones are thin beds of siliceous shales and siltstones. These grey radiolarian rocks form a very small proportion

of the whole.

LITHOLOGY AND PETROGRAPHY

All the limestones of this formation are biocalcarenites. They are composed almost entirely of allochems of calcareous skeletal fragments in a micrite matrix. There are two types of these biomicarenites; those that contain varying proportions of calcareous algae, and Foraminifera, and those that contain Foraminifera and echinoderm fragments but no algae. The limestones without algae are the Alveolina-limestones.

Algal biomicarenites.

The proportion of calcareous algae varies widely from about 20 percent to more than 90 percent of the allochems present. They all contain densely packed allochems of calcareous algae, Foraminifera, echinoderm fragments and rare fragments of molluscs (plate 26A). Very little diagenesis seems to have taken place, although in some recrystallisation of the micrite matrix to a coarser (microsparite) granular mosaic is quite advanced. All the allochems and the micrite matrix are composed of iron-free calcite. No dolomitisation and no silicification has been observed.

Alveolina-biomicarenite.

The mutual exclusiveness between the Alveolina and the calcareous algae in the limestones of this formation is noted. It is interesting that Mr. G.F. Elliott (personal communication, 1963) has noticed this same

exclusiveness in limestones from the Middle East and elsewhere.

These rocks consist of the allochems of large Foraminifera and their debris together with fragments of echinoderms and rarely bryozoan and molluscan debris in a matrix of dense micrite (plate 26B). Very little diagenesis seems to have taken place, no dolomitisation and no silicification being observed. Like the other limestones in this formation both the allochems and the matrix are composed of iron-free calcite.

STRATIGRAPHIC POSITION

The age of the Dartollu Limestone is determined as Tab (Middle and Upper Eocene) on the basis of the Foraminifera. No sample older than Ta (Lower-Middle Eocene) has been found, and very few Tb (Upper Eocene) outcrops are known, most of the formation being Middle Eocene.

In the type locality the Dartollu Limestone overlies the Lolotoi Complex unconformably, and is itself overlain unconformably by the eruptives, tuffs and conglomerates of the Barique Formation. The same stratigraphic position is found in River La Mara. In the outliers north of Samé the situation is different in that the Dartollu Limestone sits unconformably on the Mesozoic sedimentary rocks of the Aitututu and Wai Luli Formations, but is itself uncovered. Clearly from its age and stratigraphic position it may be seen that the Dartollu Limestone was deposited after the overthrusting of the Lolotoi Complex and before the deposition of the Barique Formation.

The following Foraminifera were identified by
Dr. I. Crespin (unpublished report, 1956):

Aktinocyclus cf. A. aster Woodring
Biplanispira absurda Umbgrove
Crespinella sp. nov.
Discocyclus dispana (Sow.) var. minor Rutten
Discocyclus cf. D. pratti (Michelin)
Eorupertia sp.
Globigerina sp.
Operculinoides sp.
Pellatispira orbitoidea (Frovalet)
Pellatispira rutteni Umbgrove
Rotorbinella sp.
Cymbalopora cf. C. cushmani Cole
Pellatispira madarassi Hantken

Dr. C.G. Adams (personal communication, 1965) has
commented that this fauna indicates an undoubtedly Tb
(Upper Eocene) age.

The following Foraminifera have been identified by
Dr. D.J. Belford (unpublished report, 1961):

Alveolina sp. aff. A. subpyrenaica
Alveolina sp. aff. A. oblonga
Operculina sp.

Dr. C.G. Adams (personal communication, 1965)
commented on this fauna that "on the evidence of the
Foraminifera I would place this sample as Ta (Lower-Middle
Eocene)".

The following Foraminifera have been identified by Dr. D.J. Belford (unpublished report, 1960):

Nummulites sp.

Alveolina sp.

Hantkenina alabamensis Cushman

Globigerina yeguaensis Weinzierl & Applin

Globorotalia centralis Cushman & Bermudez

G. sp. cf. G. acuta Toulmin

G. spinulosa Cushman

Truncorotaloides sp. cf. T. topilensis

Vulvulina advena Cushman

Uvigerina dumblei Cushman & Applin

Dr. C.G. Adams (personal communication, 1965) has commented on this fauna that if it contains true Alveolina then it is of Middle rather than Upper Eocene age.

Dr. C.G. Adams (personal communication, 1964) has identified the following Foraminifera which indicate a Ta age:

Alveolina sp. (cf. A. timorensis Verbeek sensu Henrici)

Nummulites sp.

Alveolina cf. A. celebensis Bakx

Alveolina cf. A. ovicula Nuttall

Opertorbitolites cf. O. douvillei Nuttall

Discocyclina sp.

Nummulites cf. N. javanus Verbeek. A & B forms.

Carpentaria cf. C. proteiformis Goes

Orbitolites cf. O. complanata Lamarck

The following red calcareous algae have been identified by Mr. G.F. Elliott (personal communication, 1963):

Archaeolithothamnium saipanense Johnson
Corallina matansa Johnson
Jania sp.
Dermatolithon nitida Johnson
Lithoporella melobesioides Foslie
Lithothamnium cf. L. cymbicrusta Johnson
Lithophyllum sp.

Mr. Elliott commented that this micro-flora is like that of the Pacific Upper Eocene described by Johnson from Saipan.

Two echinoid specimens were determined by Dr. R.P.S. Jefferies of the British Museum (personal communication, 1964) as: Echinolampas sindensis d'Archiac. This is a new record for Indonesia; it is known previously from the Khirthar Series of Sind (i.e. Middle Eocene).

ENVIRONMENT

The algal limestones contain only red algae of the reef and reef crevices, and probably accumulated in shallow water adjacent to the reef. Although the water was shallow, the presence of a micrite matrix and the absence of a sparry calcite cement may indicate the absence of strong bottom currents. The foraminiferal limestones indicate slightly deeper fore-reef conditions.

In Lower Eocene times the great thrust sheets of the

Lolotoi Complex were emplaced. During Middle & Upper Eocene times shallow marine conditions in which algae and Foraminifera flourished were probably extensive throughout much of Timor. It seems likely that the Dartollu Limestone was originally far more extensive than is suggested by the few scattered outcrops that exist today. These outcrops probably represent remnants resulting from the erosion of much of the formation that occurred before Lower Miocene times.

CORRELATION WITH WESTERN TIMOR

The Dartollu Limestone of eastern Timor can be correlated with the Eocene (Tab) limestones of western Timor described in van Bemmelen (1949). In western Timor the Eocene limestones represent a shallow marine facies in which the larger Foraminifera are common. Basal conglomerates are developed locally, and shales, sandstones and tuffs are said to be associated with the limestone.

Like the Dartollu Limestone the Eocene Limestones of western Timor rest unconformably on the allochthonous crystalline schists and on the autochthonous Mesozoic rocks.

Although some of the Eocene limestones of western Timor are considered as possibly Lower Eocene in age, no definitely Lower Eocene horizons have been proved. It seems probable, having regard to the tectonic events of Lower Eocene times, that as in eastern Timor the oldest Eocene limestones in the west are Middle Eocene and that these pass up into the Upper Eocene.

BARIQUE FORMATION

SUMMARY

The Barique Formation is widely distributed and consists largely of lavas and tuffs that were deposited in a submarine environment. The age of the Formation is determined as Oligocene (Tcd), and the maximum thickness is estimated to be about 300 metres. The Barique is possibly equivalent to the volcanic rocks of western Timor described by Brouwer (1942) as being Eocene and old-Miocene in age. Evidence from the Barique Formation supports Brouwer's (1962) theory that during the Tertiary the site of volcanism migrated northward from the north coast of Timor.

INTRODUCTION

The stratigraphic unity of the rocks of this Formation was first recognised by I.B. Freytag, who called them the Barique Volcanics, in an unpublished report dated 1959. Earlier workers such as Grunau (1953, 1956 & 1957) and Gageonnet & Lemoine (1958) did not distinguish this formation, but instead grouped all the igneous rocks with the overthrust rocks of Permian age (Maubisse Formation) and with the overthrust crystalline schists (Lolotoi Complex).

The Barique Formation consists largely of tuffs with a small proportion of lavas. Locally quartz arenites containing volcanic rock particles are developed. The tuffs and lavas represent a wide range of composition.

The type locality for the Barique Formation is the section in the River Quique due south of the village Barique (8°52'S, 126°05'E). Here in the banks of the river is exposed a poorly bedded series of tuffs with an occasional lava. The whole section is estimated to be about 300 metres thick, and to be gently dipping.

Outside the type locality this Formation is widely distributed, being found at the base of the mountain Mata Bia in the east and at the base of the mountain Taroman on the frontier with Indonesia in the west (figure 6). Wherever it occurs the Barique Formation gives rise to a rugged topography (plates 3A, 27D). Commonly it supports a good growth of eucalyptus trees. It is relatively easy to distinguish this Formation from all others (except the Lolotoi Complex) on the aerial photographs.

LITHOLOGY & PETROGRAPHY

Pyroclastic rocks predominate in this Formation. Their grain size varies from pebbly conglomerate to fine sandstone grade. The clastic particles are mostly angular and subangular. The coarser conglomerates that contain much angular material sometimes have a breccious appearance but are nevertheless conglomerates and not breccias.

Volcanic conglomerates.

The conglomerates are locally very coarse, for instance in the Cena River, near the village of Fehuc Reen (8°55'S, 125°59'E), massive unsorted and unstratified angular boulder conglomerates form the basal conglomerates

of the Formation. At the easternmost development of this Formation, in the Cai Dilla Laly River (9km N.E. of Aliambata) similar basal conglomerates occur. Here a tuffaceous matrix cements the boulders and pebbles together. Some of these boulders and pebbles are rounded and subrounded (plate 26D). The composition of the larger clastic particles in these basal conglomerates is variable. They are derived from the erosion of various local non-volcanic formations as well as from basic volcanic rocks having characteristics similar to those of the lavas of the Barique Formation. In the west (Cena River) the clastic volcanic material is largely serpentinitic and basaltic, while in the east basaltic and andesitic boulders and pebbles seem to be more common.

Tuffs.

There are two principal types of tuff in this Formation; one may be classed as acid and the other as basic. The basic tuffs are more important in the region of Barique and further west, while the acid tuffs predominate in the region east of Barique.

The basic tuffs consist largely of fragments of serpentinites and basalts. Zeolites are commonly developed between the tuff fragments. The acid (possibly mostly dacitic) tuffs are composed mainly of feldspar laths, with quartz, pumice and glass forming less important constituents. The pumice and glass is usually considerably altered. Some of the tuffs contain pelagic Foraminifera, and some contain large round grains of quartz that were probably derived from sedimentary non-volcanic rocks (plates 27A, 27D).

Most of the fragments of the tuffs are angular or subangular, but a small proportion of the tuffs studied seemed to be largely composed of reworked tuffaceous particles that are rounded and subrounded.

Nearly all the tuffs are cemented by either sparite or microsparite that forms a granular mosaic. In general the basic tuffs are less well cemented, and many of them are almost friable (plate 26C).

Sandstones.

Interbedded with the tuffs locally are sandstones consisting largely of quartz and containing less than 25 percent of igneous rock fragments. Texturally these should be classified as medium sandstones (Folk, 1954); their composition would place most of them in the subgreywacke category of van Andel (1958). These sandstones frequently contain Foraminifera.

The greatest development of sandstones is found in the region south of Mt. Cablac, where they may be about 20 metres thick.

Igneous rocks.

Serpentinities occur in the Dilor River, Quique River, north of Mt. Bibiliu and in the Mt. Cablac region. They are massive, tough, dark greenish-black and veined. In thin section the degree of serpentinisation is seen to be very variable; some contain large clear crystals of olivine. Large phenocrysts of feldspars are common.

Basalts and dolerites varying in texture and composition are found wherever the Barique Formation occurs. In the west they are the most common igneous rock member of the Formation, in the east they are less frequent. Alteration of these rocks has usually been quite severe, producing mainly chlorites and carbonate minerals. Albite is common and much of it appears to be secondary.

Greenstones are perhaps the most common igneous rock of this Formation. Most of the igneous rocks of the Mt. Cablac region are best termed greenstones. They now consist largely of amphiboles and epidote. Calcite is an important alteration product.

Andesites often with zoned feldspars are among the least altered of the igneous rocks of this Formation. In the east the andesitic rocks are more frequent than the basaltic.

Field relations among the various strata of this Formation are not always clear, so that it is seldom possible to be able to determine whether the tuffs have been invaded by sills or are interbedded with lavas. Occasionally very well developed pillow structures are seen in the lavas (plate 27C), this suggests that the majority of the igneous rocks may be lavas, perhaps all of them.

STRATIGRAPHIC POSITION

The rocks of this Formation are always unconformable at the base, and locally a coarse basal conglomerate is developed. The youngest rocks on which the Barique

Formation rests unconformably are the Middle & Upper Eocene Dartollu Limestone. Most commonly the Barique Formation is found unconformably on the metamorphic rocks of the Lolotoi Complex which were all overthrust to their present position during the Lower Eocene. The Barique Formation is overlain unconformably by the Cablac Limestone of Lower Miocene (Te) age. Thus the Barique Formation must have been deposited during the time interval between late Tb to early Te (Upper Eocene to Lower Miocene inclusive).

Further evidence comes from the basal conglomerate of the Barique Formation which contains boulders and pebbles of the Dartollu Limestone whose Foraminifera have been dated as Tab stage. The strong unconformity at the base of the Barique Formation, together with the scattered preservation of a few erosional remnants of the Dartollu Limestone, and the presence of boulders of that formation in the basal conglomerate of the Barique Formation suggest there was an important period of erosion after the deposition of the Dartollu Limestone (Tab) and before the deposition of the Barique Formation. According to van Bemmelen (1949) there was a phase of moderate folding in the nearby island of Sumba between Eocene and Oligocene. Thus it appears most likely that the base of the Barique Formation is post-Eocene.

As there is a strong unconformity between the Barique Formation and the overlying Cablac Limestone of Te age, it seems probable that the Barique Formation is pre-Te rather than early Te in age. It can only be concluded therefore on all the evidence available that the age of the Barique Formation is Oligocene (Tcd). It is regrettable that the Foraminifera present in the tuffs and sandstones of the

Barique Formation are not diagnostic of any stage of the Tertiary. The only Foraminifera that have been identified are Globigerinidae.

ENVIRONMENT

The conglomerates, tuffs and sandstones with pelagic Foraminifera indicate that the environment was marine. The well developed pillow structures of some of the lavas indicate that they too were extruded into a submarine position.

As the Dartollu Limestone that underlies the Barique Formation and the Cablac Limestone that overlies the Barique Formation **were** both deposited in very shallow water (both fore-reef environments), it seems probable that the rocks of the Barique Formation were also deposited in a shallow or very shallow sea. The presence of Foraminifera and a calcite cement in the Barique Formation suggest that had this region not received the effusive products of vulcanism during the Oligocene, it would probably have been the site of shallow water carbonate deposition by organisms such as Foraminifera, corals and calcareous algae, as it was in the Middle & Upper Eocene and in the Lower Miocene.

No volcanic necks, nor possible feeder dykes have been found in eastern Timor that could have served as vents for the extrusion of the lavas and tuffs of the Barique Formation. The most probable source area for these products seems to be either the present site of the volcanic Inner Arc (islands of Wetar and Alor especially), or else the region between the present Inner Arc and Timor (i.e. the area now occupied by the Wetar Strait).

PLATE 27

- A. Barique Formation - tuff with shell fragments and Foraminifera (x 20).
- B. Barique Formation - characteristic terrain north of Samé (n) - Barique Formation.
- C. Barique Formation - pillow lavas.
- D. Barique Formation - coarse tuff with rounded grains and a little calcite cement (x 20).

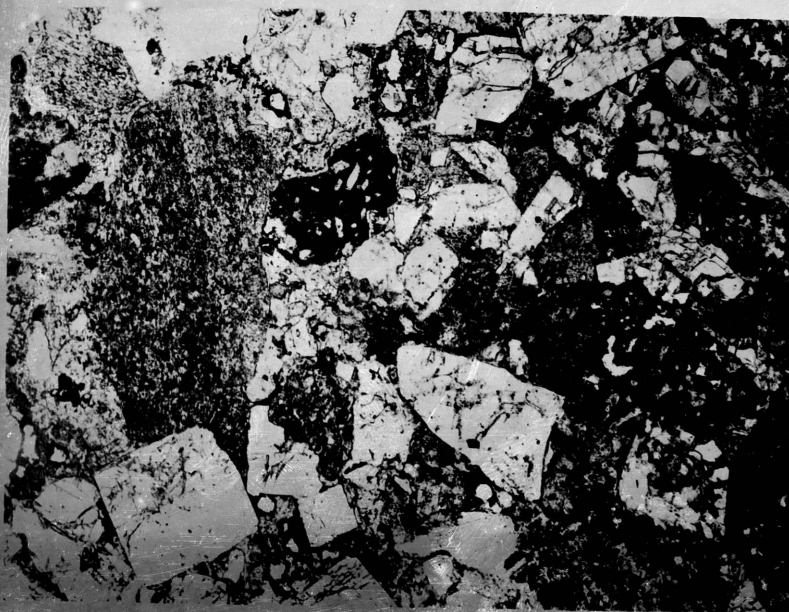
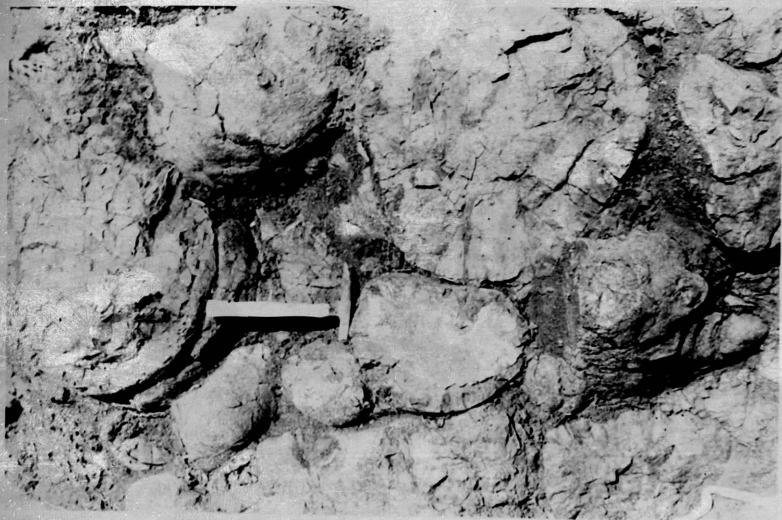


PLATE 28

A. Barique Formation - olivine-poor basaltic sheet
medium grained (x 20).

B. Cablac Limestone - Mt. Lari Tame

(n) - Cablac Limestone

(o) - Bobonaro Scaly Clay

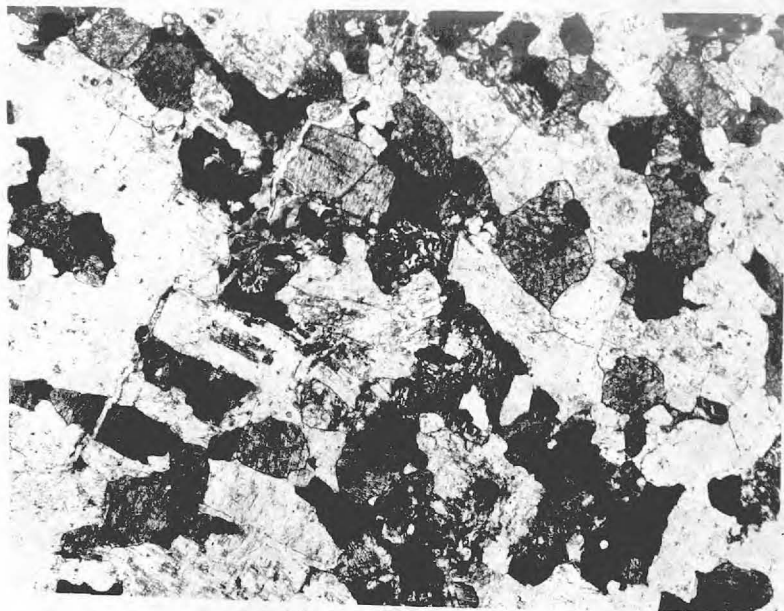
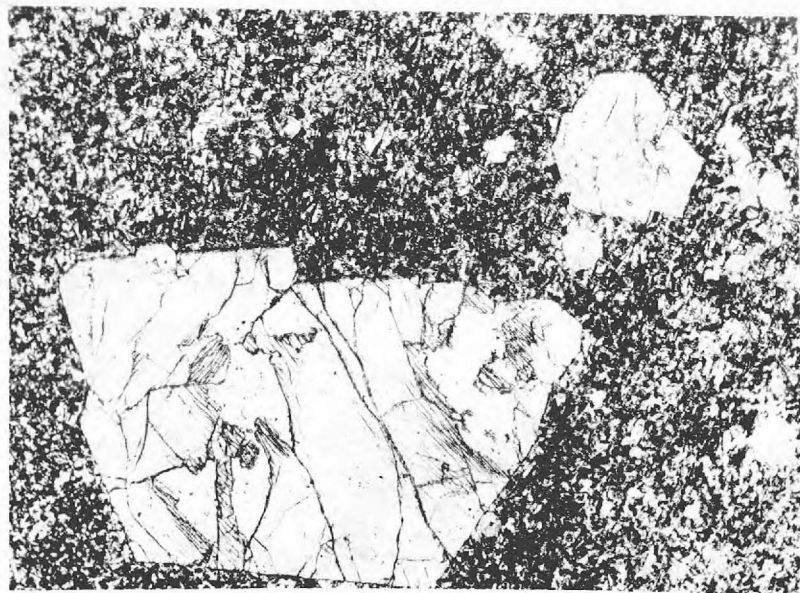
Note faulting in the Cablac Limestone and the
unconformity between the two formations.

C. Barique Formation - porphyritic basalt with large
phenocrysts of titaniferous
augite (x 20).

D. Cablac Limestone - Mt. Cablac

(o) - Cablac Limestone unconformable upon

(n) - Wai Luli Formation.



Brouwer (1962), who had earlier (1942) studied the Tertiary volcanic rocks of western (formerly Dutch) Timor, has argued that the site of the vulcanism moved from the south to north. He suggested that during the lower and mid-Tertiary times the active volcanic zone was close to the present north coast of Timor, and that during the Cenozoic it migrated northwards. The evidence from eastern Timor seems to support this theory of Brouwer (1962).

CABLAC LIMESTONE

SUMMARY

During Lower Miocene times Bahaman-type limestones were deposited over a large part of eastern Timor. This is called the Cablac Limestone, now represented by scattered erosional remnants and having a maximum thickness of about 600 metres. The petrography has been studied in detail and particular attention is given to certain unusual microfacies. Eight different diagenetic processes that have altered these rocks are described. The fauna and micro-flora are recorded.

INTRODUCTION

Earlier workers in Timor (van Bemmelen, 1949; Grunau, 1953 and Gageonnet & Lemoine, 1958) grouped the Lower Miocene limestones with those of Eocene, Cretaceous and Permian ages under the "sack" term 'Fatu Limestones'. Since the constituent members of this group have now been assigned to various appropriate formations by the present writer it is suggested that the term 'Fatu Limestones' is dropped. The lower Miocene bahamite facies is here named the Cablac Limestone. The pelagic facies found at Aliambata is regarded as a separate formation and is here named the Aliambata Limestone (discussed later).

The type locality for this formation is the dramatic mountain called Cablac ($8^{\circ} 55'S$, $125^{\circ} 35'E$) in the central ranges. This mountain rises in steep cliffs from about 1000 to 2630 metres. Hard, massive limestones make up this mountain. Bedding planes are very rarely seen. A few softer intraformational conglomerates whose weathering pattern reveals their nature occur near the base of the formation and at a few horizons higher up the succession. Most of the limestones weather to a soft grey colour and a spikey surface that is highly characteristic. The freshly broken surface is usually white or a very pale yellow or pink.

The present distribution of this formation is closely associated with the principal watershed which strikes E.N.E. - W.S.W. forming the mountainous spine of eastern Timor. Here the Cablac Limestone occurs as isolated remnant bodies forming formidable steep walled cappings to mountains whose peaks range mostly between 2400 and

1500 metres (plates 2B, 28B).

The thickness of the formation is difficult to estimate because its attitude is difficult to gauge in the absence of bedding planes. In the type locality it is probably about 400 metres thick and in the mountain Mata Bia it may achieve more than 600 metres thickness.

On aerial photographs the Cablac Limestone is readily identified by the characteristic precipitous escarpments, its lack of bedding and the heavy growth of large trees that it supports.

Although in the field this formation presents a rather monotonous appearance, petrographic studies have revealed a wide variety of composition and texture. Outcrops of this formation are scattered from east to west over a distance of about 200 km. in eastern Timor; yet some highly characteristic microfacies have been recognised in all the principal outcrops.

The sampling of the various localities (in which changes in microfacies are rapid and numerous) was not sufficiently detailed to permit a reliable series of stratigraphic sections to be drawn. Instead some of the more interesting microfacies that occur over a wide area are described, and the succession of the formation as a whole is expressed in very general terms in enclosure 10. It was not possible in the field to recognise any mapable lithological unit. The very poor development of master bedding planes aggravates the problem of determining the succession.

LITHOLOGY AND PETROGRAPHY

In the field five types of limestone were recognised; calcilutites, oolitic limestones, fragmental skeletal limestones (rich in skeletal debris, oolites and pellets), and intraformational conglomerates of two very different kinds. The weathered appearance of these rocks is very similar except the conglomerates that are readily distinguished.

Thin section study has led to the recognition of a number of microfacies distributed over all of, or a large part of, the survey area; these are described below.

1. Calcirudites.

All the rocks whose allochems average greater than 1 mm. diameter are placed in the calcirudite grade. These have been subdivided into five groups on the basis of their composition:

- a. Polymict intracalcirudites.
- b. Intrasparudites.
- c. Intradismicrudites.
- d. Intramicrudites.
- e. Biodismicrudites.

a. Polymict intracalcirudites

This category includes medium to fine conglomerates of unusual composition and texture. The majority of the clasts have diameters between 6 and 1 mm. Larger clasts are quite common up to 10 mm. and a few larger than 14 mm. The smallest clast (strictly allochems)

mostly pellets and oolites extend down to 0.06 mm. These pellets are present as discrete particles in the interstices between the larger clasts.

To illustrate the polymict nature of these rocks a list of the clasts commonly present is given below: -

pelspararenite, pelmicarenite, oospararenite, oomicarenite (not seen in all samples), oolites, pellets, intramicarenites, micrite clasts, dolomitised micrite, dolostone, skeletal fragments of Lower Miocene age (predominantly algae and Foraminifera with lesser amounts of echinoderms and bryozoans). Terrigenous clasts also occur, the most commonly seen are; volcanic detritus, calcilutites containing Globigerina (some of Cretaceous age and some of Lower Miocene age), radiolarian chert (possibly Cretaceous in age), biomicarenites (probably Upper Triassic in age), detrital quartz and magnetite.

Because the large majority of the clasts are of the rudite grade it has been possible to study them in detail. This has enabled many comparisons to be made between identical and similar clasts present in different calcirudites. Further it is possible to find clasts in these polymict conglomerates that are identical with samples of specific arenites or lutites; e.g. a clast of pelspararenite in a polymict calcirudite is identical with a rock sample composed entirely of pelsparite. To illustrate further this very interesting group of rocks, a detailed description of a typical example from Mt. Cablac is given below: -

The hand specimen is described as follows: calcirudite, fine to medium grained conglomerate. The colour is predominantly pinkish-grey, but Phenoclasts coloured red, green and dark grey produce a mottled effect. Phenoclasts are generally subangular to subrounded, a few appearing angular (pettijohn, 1957, p. 58-59). The predominant type of clast is a buff coloured calcilutite. The other principal clasts are reddish calcarenite, a dark blue basaltic rock, a yellowish-green serpentinitic rock, and three varieties of pale coloured calcilutites. The thin section of this rock is described as follows: polymict calcirudite whose allochems average grain size falls between 5.0 and 3.5 mm. The majority of these clasts are subangular to subrounded, but as pressure solution has been active along many grain boundaries the original size and shape of the grains cannot be known precisely. This thin section is composed of the following clasts:

pelspararenites - clasts representing two distinct types of pelspararenite are present.

dismicrite - a number of clasts representing five different types are present.

pelmicarenite - several clasts of the same kind present.

cospararenite - seven quite different types of cospararenite present.

terrigenous clasts - radiolarian cherts, volcanic
detritus and lutites with
Globigerina are present.

biomicarenites - two similar clasts present.

dolostone - one large clast present.

skeletal fragments - calcareous algae and
bryozoans only.

pellets and oolites - numerous with much
variation in kind and size.

The orthochemical constituents of this polymict calcirudite form a very insignificant fraction of the whole rock. This feature is typical of all the polymict calcirudites of this formation studied in thin sections. All these rocks are characterised by highly sutured grain boundaries; these are microstylolitic contacts formed by pressure solution. These stylolites are visible in the hand specimens. Thin section study reveals local developments of a little sparry calcite cement either in a granular mosaic, or as a drusy mosaic filling what must have been an interclast cavity. This sample also contains local areas of calcite mud mixed with comminuted allochemical debris (fragments of oolites, pellets, skeletal fragments, and fragments of terrigenous material). Plate 31 shows part of the thin section of this sample; where it can be seen that this 'matrix' is confined to very few regions between larger clasts. Strictly this 'matrix' is not within the definition of orthochemical constituent, because it is highly unlikely that it was precipitated in the region

where the clasts accumulated, but was instead swept in (i.e. transported), and thus must be regarded as a complex type of allochem.

The nature of the boundaries between the clasts is best seen by studying the etched surface of a previously polished face under the binocular microscope (plate 30A). The microstylolitic boundaries between the clasts can be seen to be marked by a thin line of insoluble minerals mainly limonite, pyrite and various clay minerals.

The dolomitisation that has taken place in this rock will be discussed in detail later under the heading of diagenesis. It is noted here that small dolomite rhombs tend to be developed either along the microstylolites or very close to them. This is well brought out by the etched surface (plate 30A).

Before closing the description of these polymict calcirudites there is one variety that contains a very unusual type of clast that is worth considering. The thin section contains only two clasts. One of these is a well sorted medium pelspararenite. The other clast is exceptional; it is itself a fine grade polymict calcirudite that contains clasts of the kind that characterise the microfacies at present under discussion, viz: oospararenite, pelspararenite, polymict intracalcarenite, micrite, clasts of sparry calcite having a granular mosaic, pelmicrite, pellets, oolites and terrigenous clasts. Very little orthochemical material is present between these clasts, they are largely welded together by pressure solution. The clast that is termed a 'polymict intracalcarenite' (above) is of particular

interest because it repeats the whole pattern again, on a smaller grade of course. These polymict intracalcirudite and polymict intracalcarenite clasts can be regarded almost as mirror images of themselves with the grain size diminishing centipetally of course. In the case described (above) it is seen that it contains a fourth generation particle, in that it is itself a polymict conglomerate that contains a clast that is a polymict conglomerate, that this also contains a smaller clast that is a polymict conglomerate, and that this contains among others a clast of oospararenite.

b. Intrasparudites

Two types of intrasparudites are found and are described below. One type is represented by a rock in which the size limits of the clasts are very similar to those of the previous group, viz. 6 to 1 mm. The thin section is composed of angular and subangular intraclasts of three similar but slightly different calcilutites. These may be summarised as follows:

- (i) biocalcilutite clasts in which both argillaceous and bituminous particles are disseminated and locally aggregated, and diagenetic silica has made some selective replacement.
- (ii) biocalcilutites indistinguishable from those in (i) except that dolomitisation has taken place.
- (iii) intraclasts of highly bituminous argillaceous lutite containing skeletal structures identical with those in (i) and (ii).

The skeletal fragments present in them all are long thin shell fragments of what are probably bivalve molluscs. These intraclasts are cemented together by sparry calcite (slightly ferroan) forming a granular mosaic.

The other type of intrasparudite has a very different composition but similar texture. All the intraclasts present have the same composition, viz: calcilutites containing comminuted debris of Foraminifera, algae and echinoderms. Numerous dolomite rhombs are scattered through the matrix of the clasts. The intraclasts are well packed and cemented by a slightly ferroan sparry calcite forming a granular mosaic.

c. Intradismicrudites.

Two types of intradismicrudite occur; one type is represented by the plate 30B. In this sample the size of the intraclasts range widely from 14.0 to 0.05 mm. These rocks are polymodal, having maxima in both the rudite and arenite grade, but the rudite grade predominates. The example illustrated is composed of angular intraclasts of oomicarenite together with discrete oolites and pellets. All the oolites present have the same appearance; they have a dark pellet-like nucleus and a wide clear brownish corona. Occasionally this corona is slightly corroded and there is a final very thin outer coat of micrite. The oolites within the clasts are sometimes broken and worn, some are distorted. These oolites are 'floating' in a dark, dense micrite. A few discrete oolites have a piece of dense micrite attached to them indicating that they have been derived by the reworking of an earlier comicrite. Many of the pellets have a final coat of clear

fibrous calcite and are therefore superficial oolites (Illing, 1954). A few very large algal pisolites are present.

The density of packing of the allochems is variable. All are 'floating' in a mixture of microsparite and a much smaller quantity of wispy micrite.

The other type of intradismicrudite is represented by a sample which contains angular intraclasts of oospararenites, pelspararenites, oomicarenites and pelmicarenites of various kinds. Discrete pellets and oolites are present, many of the oolites are broken. One interesting intraclast is a pelmicarenite containing numerous small rod shaped areas of drusy calcite, suggesting the later infilling of voids formed by dissolved aragonitic structures.

All these intraclasts and other allochems 'float' in a dismicrite matrix.

In closing this description it must be said that even more than the polymict intracalcirudites these intradismicrudites resemble breccias. This type of pseudobreccia is quite common in all the principal developments of the Cablac Limestone. The originally micrite matrix in which the angular clasts 'float' points up the contrasting environments in which the allochemical and orthochemical constituents were formed.

d. Intramicrudites.

These are typically composed of angular clasts with a

wide range of size; 20.0 to 0.5 mm. in one sample for instance, and 30.0 to 0.08 mm. in another.

The intraclasts of the first sample are all composed of biodismicrite, being mainly dismicrite with a few scattered structures now filled with drusy calcite. These structures are described in detail later for the biomicarenite (S.476). Scattered through the intraclasts are numerous very small dolomite rhombs that have replaced the micrite.

The matrix between the clasts is a dense micrite with widely disseminated dolomite rhombs (about 0.08 mm. diameter) replacing the micrite.

The intraclasts of another sample of the intramicrudites shew a wider range of composition; with the following types of clast being recognised: pelmicrite, micrite, biomicarenite and pelspararenite. An interesting occurrence is the presence of several different kinds of grapestones (Illing. 1954) that are associated with pellets of the pelmicrite intraclasts.

The matrix between the intraclasts is a dense micrite with very small dolomite rhombs (0.08 mm.) that have replaced some micrite (plate 30C).

e. Biodismicrudite.

This microfacies is commonly recognised in the field, the skeletal debris being visible with the aid of a hand lens. Thin section reveals that there is a wide variety of allochems present. Strictly the allochems are

polymodal within the range of 4.0 to 0.05 mm. As the largest proportion of the allochems fall into the rudite range the rocks are so classified. The principal allochems present are: algae, Foraminifera, bryozoans, echinoderms and molluscs with intraclasts of micrite and a calcilutite containing Globigerina. The orthochemical constituent is dismicrite. A modal analysis based on 300 point counts shewed that calcareous algal fragments constitute nearly half the volume of the rock.

Two points of petrographic detail are of interest; one is the presence of what were cavities in the skeletal fragments now filled with sparry calcite in a drusy mosaic that in two instances produced 'level bubble' structures. The other interesting observation is calcareous algae have acted as a sediment binding mechanism, the manner of which is revealed in thin sections (plate 30D).

2. Calcarenites.

Rocks are classified as calcarenites on the basis of most of their allochems being between 1.0 and 0.062mm. in diameter. They are further subdivided on the basis of composition into the following groups:

- a. Pelspararenite.
- b. Peldismicarenite
- c. Pelmicarenite
- d. Biomicarenite
- e. Biospararenite
- f. Biodismicarenite
- g. Intradismicarenite

a. Pelspararenite.

These may be subdivided into two groups; those that are composed of only one allochem (pellets) in a sparry calcite cement, and those that have mixed allochems (in which pellets are the predominant type) also with sparry calcite mosaic. There is a wide variety of pellets in this microfacies, and if the variety of pellets seen in the clasts of pelspararenites that are incorporated in the polymict calcirudites are taken into account, then there is an extremely wide variety of pellets in the Cablac Limestone. Within the pelspararenites there is considerable variation in texture. The parameters that show most variation are: nature of pellet material, size, sorting of pellets by size and type, variations in other allochems associated with the pellets, the textural relations between the pellets and the cement, the nature of the cement.

The pellets in the pelspararenites have long diameters that vary between 0.68 and 0.06 mm. They all have oval outlines and are composed of micrite of varying grades between the limits of 0.04 and 0.001 mm, mostly averaging between 0.008 and 0.003 mm., that is in the very finely crystalline to aphanocrystalline grades. Some of the pellets have 'ghost' concentric structure suggesting they were once oolites. Some have a nucleus but the majority do not. Two of the samples studied contain different kinds of grapestones (Illing, 1954). Broken pellets occur very infrequently.

The orthochemical constituent is sparry calcite, generally it forms a granular mosaic about the typically

well packed allochems. Occasionally a little wispy calcite mud and patches of microsparite are present in the cement. To illustrate the nature of this group of pelspararenites three samples representing different types are briefly described.

Sample S.232 is composed of pellets in a sparite cement with many patches of microsparite. Where this microsparite is in contact with the pellets they have been altered to microsparite. The pellets range in size from 1.2 to 0.3 mm. with the large majority falling between 0.6 and 0.3 mm. They are composed of dense micrite, tightly packed. Many are distorted and very few are regular in shape.

Another sample S.233 contains the following allochems: pellets, grapestones, micrite intraclasts, superficial oolites and skeletal fragments. The structure of the grapestones is very clear; they are about 1.2 mm. long, and composed of pellets that average 0.17 mm. diameter. The pellets vary in size between 0.42 mm. and 0.07 mm. and have a polymodal distribution. The oolites vary between 0.9 and 0.4 mm. The sparry calcite cement forms a granular mosaic that is locally coarse forming a poikilitic texture by engulfing several allochems. Some 'ghosts' of skeletal fragments, probably dissolved aragonitic structures are present. The textural relations permit one probable molluscan fragment to be recognised that must have been broken in situ, when it was aragonite, that is before it was dissolved and its mould filled by drusy calcite.

In the sample S.234 (plate 33C) the allochems vary

between 0.25 and 0.05 mm. This rock is particular in the Cablac Limestone in that it contains detrital grains of glauconite (4.2 percent by volume). Another singular feature of this rock is the very large proportion of the oolites, pellets and skeletal particles that are in a highly fractured state. Many of the allochems are coated with a thin layer of micrite. They are cemented together with typical sparry calcite forming a granular mosaic. A little microsparite is present in patches.

b. Peldismicarenites

This group consists typically of dark pellets of microcrystalline calcite that are not well rounded, being more in the nature of clots. They are notably well sorted, averaging between 0.08 and 0.06 mm. in diameter. The allochems are well packed in a matrix of dismicrite (an intimate mixture of sparite and micrite forming finely crystalline calcilutite).

c. Pelmicarenites

Two different types of rock fall into this category. One type is exemplified by a sample (S.1083) which is composed of densely packed, poorly rounded, dark micrite pellets (the principal allochem) with a few rare larger calcareous algae and molluscs. The pellets ('clots' is perhaps a better term) are about 0.085 mm. diameter. The matrix is a dark, dense, aphanocrystalline micrite containing very small patches of sparry calcite in a drusy mosaic. These patches of drusy calcite are probably filling original voids in the mud or dissolved aragonitic structures.

The other type of pelmicarenite (represented by the sample S.464) has a very different composition. It is a rock of densely packed allochems of two main types: pellets and Foraminifera, other allochems present in small percentages are calcareous algal fragments, echinoderm fragments and sponge spicules. The allochems fall between the size limits of 0.17 and 0.06 mm., this classifies the rock as a fine calcarenite. The orthochemical constituent is a dense dark micrite with much disseminated limonite. Silica diagenesis has been extensive, forming local areas of chert around which the limonite is frequently concentrated. The significance of this is discussed later under the section on diagenesis. An unusual feature is the ferroan microcrystalline calcite concentrated near the periphery of the chert; this is probably related to silica diagenesis.

d. Biomicarenite.

Three varieties of biomicarenite are found in the Cablac Limestone. One variety is composed of a very dark aphanocrystalline calcite matrix in which very small Globigerina sp. are 'floating'. These Foraminifera are sometimes densely packed (probably all in contact with each other) when only a little of the extremely fine interstitial calcite mud is present. These Foraminifera are mostly about 0.08 to 0.05 mm. in diameter (plate 29C).

Another type of biomicarenite (represented by S.503) is an exceptional rock. In the hand specimen it appears to be a dense very even textured calcilutite, but its weathered surface exhibits fine cross-laminations typical of current bedded arenites. The presence of cross-

cross-laminations in limestones has been discussed by Harbaugh (1959) who regards it as evidence of the detrital origin of these limestones. In thin section the rock is seen to be composed of densely packed, well sorted small Foraminifera whose average diameter is 0.08 to 0.05 mm., and very small subangular quartz grains of 0.05 to 0.008 mm. diameter. The fine cross-laminations are seen in the thin section to be associated with the variations in the density of packing of the allochems. An interesting feature is that the size of the Foraminifera in each laminae is distinctly larger than the size of associated quartz grains. They are clearly paired off as hydraulically equal. The matrix is a fine mixture of micrite and dismicrite.

Another type of biomicarenite is represented by the sample S.476. In the thin section (plate 45B) the contact between two microbeds is visible. The orthochemical constituents of both beds appear identical, viz; a dark, dense, fine micrite. The dark colour may be due to finely disseminated organic (hydrocarbon) material. The two microbeds are distinguished on the basis of the allochemical constituents. In one microbed there are two kinds of allochem; they are 'recrystallised' skeletal debris that forms about 60 percent of the allochems, and pellets that form about 40 percent. The pellets average about 0.08 to 0.06 mm. in diameter. The skeletal remains are particularly interesting; they are of two forms, globular and rod shaped. Both these forms now consist of sparry calcite in the form of a drusy mosaic. The rods vary in width from 0.08 to 0.03 mm., the majority falling between 0.06 and 0.03 mm. They are of any length up to a maximum of 1.0 mm. The globular structures vary in

diameter between 0.04 and 0.008 mm. Both the rods and the globules are interpreted as probably having been aragonitic structures originally that were dissolved after burial, the resulting voids being subsequently filled by drusy calcite. It is noted that the rods always lie parallel or subparallel to microbedding. The exact faunal or floral origins of these structures is obscure.

In the other microbed the only allochems present are the globular structures.

e. Biospararenites.

A grain size analysis of a representative sample of this group (plate 32) shows a range of 2.5 to 0.10 mm. for the allochems with an average of 0.6 to 0.2 mm., which classifies this a medium calcarenite. Although there are more skeletal allochems than any other type, there are more intraclasts present than any particular group of skeletal allochems. The principal orthochemical constituent is sparry calcite with small amounts of dismicrite. The sparry calcite exhibits three textures, granular mosaic, drusy mosaic and rim cementation (on echinoderm fragments only). In addition to this cementation much pressure solution between allochems has resulted in considerable interpenetration of their grain boundaries. There is an unusual variety of terrigenous detritus present; discrete quartz grains (unstrained), very fine metamorphic quartzites and silica cemented grains of quartz arenites. Another unusual feature is the nature of a multinucleate core of an oolite. The fibrous crystals that cement together the particles that make up the nucleus have a habit that strongly resembles

aragonite. The pellets, oolites and pseudo-oolites in this thin section shew considerable variety in structure that suggests they have been derived from several different environments. Many of these oolites and pellets are broken, this seems to confirm a change in environment. A wide variety of intraclasts are present. All the allochems are poorly sorted and well packed.

f. Biodismicarenite.

A few samples of this category have been seen, they shew no major differences from the biomicarenites.

g. Intradismicarenite.

Samples of this group contain intraclasts that have a size range from 3.2. to 0.08 mm., with a large average falling between 1.0 and 0.06 mm. Most of the intraclasts are angular and subangular, composed of pelmicrites of various kinds, particularly of the clotted (grumeleuse) type. Other allochems include fragments of calcareous algae and of the large Foraminifer Spiroclypeus. A few echinoderm fragments with overgrowths of rim cementation are present. Many of the intraclasts are lumps of micrite and poorly shaped pelletoid intraclasts. The orthochemical component is a typical dismicrite matrix that forms about half of the rock volume.

3. Calcilutites.

These are defined as rocks containing less than 10 percent allochems and more than 90 percent of their constituents being in the form of calcite mud (i.e. having

a grain size less than 0.062 mm.). These are divided into micrites and dismicrites; the dismicrites are characterised by containing some microsparite as well as micrite.

a. Micrites.

Some of the micrites contain up to 20 percent by volume of small dolomite rhombs that average 0.006 mm. in diameter. A few thinly scattered allochems are present. They are the rod and globular structures filled with clear, very small sparry calcite forming a drusy mosaic that were discussed earlier in the section on the biomicarenites (S.476). The dolomite rhombs that replace the microcrystalline calcite of the matrix tend to be clustered about the allochemical elements.

b. Dismicrites.

The principle on which this subdivision is based is that **some** of the coarser calcilutite is microsparite. The criteria for distinguishing between the sparite that is a chemical (or biochemical) precipitate and that which has recrystallised in situ (microsparite) have been discussed by Bathurst (1958 and 1959), Folk (1959) and Stauffer (1962). The following are commonly observed in the present samples of dismicrites:

- (1) Irregular grain size of the crystal mosaic with no systematic variation. This varies from irregular patches to an intimate reticulate relationship.

- (2) Curved, serrated and interlocking intergranular boundaries between crystals.
- (3) Gradational boundary between calcite mosaic and microcrystalline calcite.
- (4) Irregular patches of crystal mosaic in microcrystalline calcite.
- (5) Residual irregular 'floating' patches of microcrystalline calcite in the midst of a coarser calcite mosaic.

4. Diagenesis in the Cablac Limestone.

A discussion now follows on the principal diagenetic processes that have left their mark on the rocks of the Cablac Limestone. By the term diagenesis is meant all the changes within the sediment that have taken place after deposition. The following diagenetic processes are recognised in the Cablac Limestone:

- a. Solution of aragonite
- b. Cementation by sparry calcite
- c. Pressure solution
- d. Recrystallisation of microcrystalline calcite to sparry calcite
- e. Dolomitisation
- f. Dedolomitisation
- g. Silicification
- h. Carbonate-silica-carbonate reversible reactions

a. Solution of aragonite.

This is a widely known and observed phenomenon whereby skeletal particles composed entirely or in part of aragonite have their aragonitic structures selectively dissolved, leaving unaffected any calcite in the skeletal particle, the matrix or cement that surrounds the particle. This selective dissolution of aragonitic particles results in a number of voids in the surrounding calcite medium (microcrystalline mud or sparry calcite cement). These voids are then filled with sparry calcite by chemical precipitation, usually in the form of drusy mosaic. Only under these conditions does the process leave its mark on the rock. Presumably there are many instances where the cavities so formed are collapsed by pressure and no record is left of the event. A very large number of samples exhibit this early diagenetic process, some of which have already been described when describing individual microfacies (above). One uncommon example of this process occurs in what was probably originally an oomicarenite. This consists of a clast of micrite in which areas the size and shape of oolites are now filled with a drusy calcite mosaic, suggesting that the originally aragonitic oolites or pellets were dissolved selectively. In other samples the areas of drusy calcite are surrounded by a fringe of calcite mud.

b. Cementation by sparry calcite.

Five different types of sparry calcite cement are recognised in the Cablac Limestone, the differences being textural not mineralogical, they are:

- (1) Granular mosaic
- (2) Drusy mosaic.
- (3) Rim cementation
- (4) Poikilitic mosaic
- (5) Acicular drusy mosaic

The textures 1, 2 and 3 have been defined by Bathurst (1958). There are many examples of these three in the Cablac Limestone, some of which have already been described. A few selected varieties of these three are described below:

- (1) Granular mosaic with 'seed' crystals; these form by small prismatic elongated crystals of calcite 'seeding' onto the long prismatic fibrous crystals of the oolite corona (radial texture). The c-axes are perpendicular to the surface of the oolite. It is noticed that the broken surfaces (of broken oolites) are cemented by the granular mosaic without the presence of prismatic 'seed' crystals. This demonstrates that it is the presence of the c-axes terminations that controls the texture. Another variety of granular cementation is seen where a large clast of coarse sparite (forming a granular mosaic) is coated with a very thin layer of linonite. The sparry calcite that cements this clast to its neighbours is a granular mosaic of much smaller grain size than the mosaic of the clast itself.
- (2) Drusy mosaic; this has been discussed several times in the foregoing pages and no more descriptions will be given. It is a common

phenomenon recognised between some clasts in the calcirudites and in some of the allochems of the calcarenites.

- (3) Rim cementation; this is commonly seen cementing the echinoderm fragments. The variation in composition within the calcite of the rim cement has been described from rocks of the French Jura by Evamy (1963). In the Cablac Limestone only one sample was found to contain these compositional changes in the rim cement to echinoderm fragments. In this sample the echinoderm fragment is surrounded first by calcite lacking any ferrous iron in the lattice and then by ferroan calcite. All the other overgrowths on echinoderm fragments were without ferrous iron in the latticelike the fragments themselves.
- (4) Poikilitic mosaic; this is of rare occurrence in arenites whose allochems are carbonate, although it has often been reported from arenites with non-carbonate allochems, when it is usually called lustre mottling. In the Cablac Limestone this texture is seen in two pelspararenites described earlier (samples S.233 and S.234), In both these rocks a number of allochems are enveloped by a single crystal of calcite. A particularly unusual feature is present in sample S.234 where a thin layer of calcite mud outlines a shape strongly reminiscent of a shell fragment, this fragment is now filled with a single crystal of calcite (the fragment was probably originally aragonite) that is in crystallographic continuity

one one margin with a cement external to this 'ghost' fragment; this same cementing crystal of calcite has also enveloped poikilitically a detrital quartz grain.

- (5) Acicular drusy mosaic; this as the name suggests is a particular form of drusy mosaic. Only three occurrences of this texture were seen in the rocks of the Cablac Limestone and they all involve oolites. One of the biospararenites (S.1080) contains an oolite with a multinucleate core. This core consists of five very small micrite pellets that are partly cemented together by a typical granular mosaic, but three of the pellets are cemented by highly acicular calcite that has the habit of aragonite, but a fine rhombohedral cleavage suggests they are calcite. It is not understood why calcite should take on this form unless it is pseudomorphic after aragonite. Another example of the acicular drusy mosaic is seen in the clast of oospararenite in a polymict conglomerate (S.497). The oolites have a radial structure with a trace of concentric structure, they are cemented together by long prismatic crystals of calcite with their c-axes perpendicular to the surface of the oolite. The cement is formed by the interlocking of the clear calcite prisms originating in adjacent oolites. This texture is very reminiscent of beach-rock (Ginsberg, 1953). There is another example of this acicular texture that is also strongly reminiscent of the beach-rock described by

Ginsberg (1953). It is not possible to determine whether this type of texture (beach-rock in the Cablac Limestone was formed by the acicular calcite directly or whether the calcite pseudomorphic after aragonite. If it is pseudomorphic it seems strange that it is so rarely seen.

c. Pressure solution

This process has recently been summarised by Bathurst (1958). In the Cablac Limestone pressure solution has been extensively active. The interpenetration of allochems on all scales can be seen. Stylolitic contacts are well developed in many of the calcirudites and a particular form of stylolite is found in one calcarenite. It was found that the particular form taken by pressure solution is related to the size of the particles involved.

1. Pressure solution in the polymict intracalcirudites.

It is in this group that the phenomenon is most marked, not only because the high degree of interpenetration between the clasts is much greater than in the other groups, but because it frequently involves nearly all the clasts in the rock. Plate 31 shews the degree of interpenetration and widespread effects of the process. In this group of rocks the clasts themselves are complex rocks, and it can be seen that pressure solution does not respect the microstructure of clasts such as pelspararenites or oospararenites, but cuts indiscriminately through them.

2. Pressure solution in the intrasparudites and intramicrudites.

The effects of pressure solution in this group is far less extensive, only a few of the intraclasts are involved and the degree of interpenetration is much less. Perhaps the main difference is that the intraclasts are largely surrounded by cement or matrix, this leaves less area of contact between the clasts. It was noticed when studying the polymict intracalcirudites that those which have been cemented are less affected by pressure solution.

3. Pressure solution in the calcarenites.

None of the calcarenites were seen to have a welded texture like that of the polymict calcirudites. Pressure solution phenomena are commonly seen in this group but are usually confined to a restricted interpenetration between adjacent grains locally. All these rocks have either a cement or matrix that forms at least 25 percent of the whole rock. A rare example of profound interpenetration of adjacent allochems can be seen in the biospararenite S.1080 which is illustrated in plate 32. It can be seen that as a response to external pressure the Foraminifer has penetrated the oolite with radial texture, but has itself dissolved against the oolite with concentric structure, whilst the calcareous alga has cracked, and the two parts have moved apart leaving a space that has been filled by calcite cement having a granular mosaic. This strongly suggests that the pressure solution and the movement of the calcareous alga took place before cementation. This accords with the conclusion reached by Bathurst (1958) who said that "this process (pressure solution) therefore, acts

before sediment pores have been closed by cementation". He noted that some of the early cement would be redistributed by the same process.

An interesting variety of this process is seen in the pelspararenite (S.234) in which some interpenetration has taken place between allochems that are both carbonate fragments and between quartz and carbonate allochems. This rock is exceptional in having such a large number of stylolitic seams cutting through the rock. In thin section these stylolitic seams are seen to have formed mainly within the cement, where they have concentrated along their path the more insoluble allochems such as quartz, chert, ferric oxides, glauconite and clay minerals (plate 33A).

In the calcarenites with a micrite matrix allochems are also found that have suffered pressure solution.

4. Pressure solution in the calcilutites.

No evidence of pressure solution was seen in this group of rocks.

d. Recrystallisation of microcrystalline calcite to sparry calcite.

This process has already been described in the discussion of the various groups that have a dismicrite matrix. The actual mechanism by which this commonly observed diagenetic change takes place is not properly understood. It seems that some kind of 'solution transfer' must be involved, because some grains grow whilst

others 'dissolve'. The probability that the presence and action of pore solutions are important seems high to the writer despite the arguments of Bathurst (1958) for what he calls grain growth. In the various intradismicrudites and intradismicarenites the recrystallisation of the matrix, and pressure solution of some of the intraclasts (many being micrite intraclasts) have taken place in the same rock. This association of pressure solution and recrystallisation in space, and possibly in time, offers some suggestion that the two processes may be related.

e. **Dolomitisation.**

There are two principal ways in which the mineral dolomite occurs in the Cablac Limestone. One is as the exclusive constituent of the dolostone clasts that occur in some of the polymict calcirudites, the other mode of occurrence is as discrete crystals (rhombs) of dolomite, clearly of diagenetic origin in some of the rudites, arenites and lutites of the succession.

The detrital clasts of dolostone are characterised by one outstanding feature, namely that they are composed only of the mineral dolomite (except where the subsequent process of dedolomitisation has occurred). The texture of these clasts, that vary from clast to clast in grain size, colour, density of inclusions and zoning, is typically what Cayeux (1935, Pl. xxv, Fig. 94-95 and Pl. xxvi, Fig. 101) called "dolomie grenue". Most of the grains appear to be moulded into each other, while a few crystals retain a tendency for euhedral outline, and a rare crystal shews good rhombic form.

The dolomitisation (as distinct from the clasts of dolostone) of the present group of rocks will be discussed for each of the main microfacies below.

1. Dolomitisation in the calcirudites.

Not all of the polymict calcirudites that contain the clasts of dolostone (dolomie grenue) have been dolomitised, and some of this group that do not contain these clasts have been dolomitised. Two types of dolomitisation are recognised in the calcirudites. One is the development of fairly large rhombs (averaging about 0.5 mm. to 0.1 mm. diameter) that have replaced various allochems, cement and clasts quite indiscriminately, cutting across several clast boundaries, microstylolites and other features. Some are well developed rhombs, others are incomplete with many inclusions. Some (few) have suffered dedolomitisation. The other type of dolomitisation consists of usually smaller rhombs that are restricted to certain clasts (often the micrite or pelmicrites) and do not cut clast boundaries. Usually these rhombs do not have the strong relief and dark outline with water-clear rims that characterise the rhombs of the first type. Although it cannot be proved from the available evidence it is suggested that the second type (small poorly defined rhombs) of dolomitisation developed earlier, and were present within the clasts before they were incorporated in these conglomerates. If this suggestion is correct it may be inferred that there was very early dolomitisation of the carbonate muds and pellet muds in situ before they were eroded to form clasts in the conglomerates. A wide variety in the extent of dolomitisation of this type is found. One clast of a biomicarenite in a polymict calcirudite (S.502) has been

dolomitised to the stage where only a few slivers of the original rock are left 'floating' in what is now essentially a rock composed of the mineral dolomite.

Other types of dolomitisation are found in various kinds of calcirudites including some that contain dolomite crystals that are later than the sparite cement, and form up to 10 percent of the rock volume.

2. Dolomitisation in the calcarenites.

Some samples of pelspararenite have been dolomitised to such an extent that dolomite crystals form about 10 percent of the rock volume. The size of the rhombs varies from 0.4 to 0.3 mm. Most have clear rims with dark outlines, many are zoned by inclusions. These rhombs cut indiscriminately across allochems and cement. This type of dolomitisation is indistinguishable from that in the polymict calcirudites.

3. Dolomitisation in the calcilutites.

Dolomitisation is very rarely seen in the calcilutites of the Cablac Limestone. The rhombs are always small (about 0.04 to 0.006 mm.) and widely disseminated through the matrix, but with a tendency to form clusters. One sample was found to contain about 30 percent dolomite by volume.

Looking at the dolomitisation in the Cablac Limestone there emerges the possibility that there is a correlation between grain size of the host rock and grain size of the dolomite rhombs. How much this depends upon the mobility

of pore solutions and how far upon the mechanical and (or) chemical properties of the microcrystalline calcite is not known.

f. Dedolomitisation.

This diagenetic process has taken place only in the clasts of dolostone within the polymict calcirudites and in the discrete rhombs that cut the various clast boundaries in the same group. Dedolomite has not been found in any other rudites, arenites or lutites of the Cablac Limestone.

1. Dedolomite of the dolostone clasts.

This can be seen in various stages of progress in different clasts. The most extensive development has resulted in the whole of the clast of dolostone (originally consisting of only dolomite crystal mosaic) . being altered to a fine granular mosaic of calcite with numerous dark dusty inclusions (probably of an iron mineral) with the outlines of the anhedral and subhedral dolomite grains being preserved as 'ghosts'. This has been accomplished by many small calcite crystals growing together to pseudomorph the dolomite crystal. A very similar phenomenon has been described by Shearman et al. (1961) in rocks of the French Jura. This is described by them under the heading of "type 1". Other clasts have been less completely altered. These have suffered in one of two ways; either those crystals of dolomite in the core of the clast have been preserved while those nearer the surface have gone over to calcite, or else all of the dolomite crystals have been only partially altered. This partial alteration is always centrifugal with the rims of the

dolomite crystals being preserved (plate 29D).

2. Dedolomitisation of the discrete (diagenetic) rhombs of dolomite.

The discrete rhombs have sometimes been altered to a granular mosaic of calcite crystals that are much smaller than the original size of the rhomb. This process is seen to be always centrifugal. This is the same process as that described by Shearmen et al. (1961) mentioned above.

g. Silicification.

This term is applied to the replacement of calcite structures by chalcedony, and to the production of silica overgrowths on quartz crystals. The replacement of carbonate structures by chalcedony in the Cablac Limestone results in very small chert nodules with sharp boundaries. Islands of the original limestone 'floating' in the chert, tiny fragments of carbonate islands, and many relics or 'ghosts' of fossils in the chert provide unquestionable evidence that chert has replaced limestone textures. .. One silicified limestone that was stained for ferrous iron reveals areas of chert surrounded by a rim of ferroan calcite, while the matrix away from the chert is ferrous iron-free calcite. These 'reaction rims' are clearly associated in some way with the chert development. Perhaps ferrous iron-rich solutions were released by the solution of the limestone before it was replaced, more probably these solutions arrived with the silica.

It is frequently observed in these rocks that the replacement of carbonate structures by chert is highly

selective. Typically skeletal fragments of calcite (or aragonite) have been replaced by chalcedony in a matrix that remains unaffected.

One interesting occurrence is the biomicarenite that has been partially silicified and contains rhombs of ferroan dolomite that appear to have replaced the chalcedony. The sharp sides of the rhombs cut across the microstructures (fibrochalcedony) of the chert.

Detrital quartz grains serving as nuclei for pellets and oolites in the pelspararenite S.234 can be seen sometimes (rarely) to have a 'reaction rim' about them in which the microcrystalline calcite has been replaced by an overgrowth on the quartz grain. The original outline of the quartz grain can be seen, and a number of inclusions of microcrystalline calcite are present in the overgrowth rim of the quartz.

h. Carbonate - silica - carbonate reversals.

Two types of process that fall under this heading are recognised in rocks of the Cablac Limestone:

- (1) Detrital quartz or chert replaced by calcite.
- (2) Diagenetic chert replaced by dolomite.

The first process can be recognised in a number of samples where the periphery of quartz and chert grains appear to have been replaced by micro-sparry calcite. The criteria are lack of inclusions of calcite in the quartz or chert grains, together with the 'ghost' of the

original perimeter of the detrital grains now within the calcite mosaic.

The second process of replacement of diagenetic chert by ferroan dolomite rhombs has been described above in dealing with silicification.

STRATIGRAPHIC POSITION

With one small exception the Cablac Limestone always rests unconformably upon the Barique Formation that is probably Oligocene in age, or on the Lolotoi Complex of pre-Permian age. The exception is in the Soibada region where two small outcrops of Cablac Limestone rest unconformably on the Aitututu Formation of Upper Triassic age.

Situated as it is on mountain tops this formation is seldom overlain by another, except locally in the east where the Bobonaro Scaly Clay of Middle Miocene age rests on it unconformably. In a few instances the Viqueque Formation of Upper Miocene age sits unconformably on the Cablac Limestone.

The formation has been dated on the basis of its microfauna as Lower Miocene or Te. The following Foraminifera have been identified by Dr. D.J. Belford (unpublished report, 1960), and by Mr. D.J. Carter (personal communication, 1963):

Spiroclypeus sp.

Eulepidina sp.

Cycloclypeus sp.

Miogypsina sp.
Lepidocyclina sp.
Nephrolepidina sp.
Pararotalia sp.
Amphistegina sp.
Planorbulina sp.
Textularia sp.
Globigerina sp.

The following calcareous algae have been identified by Mr. G.F. Elliott (personal communication, 1963):

Calliarthron antiquum Johnson
Lithoporella melobesioides (Foslie) Foslie
Dermatolithon cf. nitida Johnson
Melobesia sp.
Lithophyllum glangeaudi Lemoine
Lithothamnium sp. cf. L. bourcarti Lemoine
Corallina sp.
? Halimeda fragments
Corallina cf. neuschelorum Johnson

ENVIRONMENT

1. Shallow water.

Evidence of the environment in which the Cablac Limestone was deposited comes from a number of elements discussed in the foregoing pages; principally the fossil content is important. The predominant type of fossil in these rocks is calcareous algae, represented by coralline and melobesioid fragments. The word 'fragment' is important because of the highly broken, fragmental condition

in which these fossils are found. Johnson (1961) discussing algae as indicators of environment says "in general algal limestones are indicative of shallow water, usually very shallow water. Rocks built chiefly of fragments (particularly heads of branching coralline algae) may be assumed to have developed close to low tide level, probably at depths of less than fifty feet". Mr. G.F. Elliott (personal communication, 1963) has described the micro-flora of the Cablac Limestone as "off-reef accumulations". The foraminiferal assemblage of these rocks has been described by Mr. D.J. Carter (personal communication, 1963) as "fore-reef material". As Foraminifera and algae together make up about 75 percent of the fossil material in the Cablac Limestone, the evidence for a shallow or very shallow water environment is overwhelming. Other fossils commonly found in this formation (in fragments) are also shallow water types; bryozoans, echinoids, molluscs and sponges.

The widespread occurrence of oolites and pellets, often with a sparry calcite cement, indicate shallow water with winnowing currents. The presence of very fine cross bedding demonstrates deposition from currents.

The very small quantity of terrigenous mud accords with a shallow marine environment in which currents play an important part, although the absence of this mud is not proof of such an environment. The terrigenous material that is present is mainly in the form of sand and silt sized particles of volcanic and other rocks. Quartz grains are present in very few samples and are conspicuously poorly rounded.

2. Very shallow water and violent conditions.

The large proportion of oolites and pellets that are broken indicate violent conditions such as could be expected in very shallow water where the effect of waves is severe.

The polymict calcirudites indicate shallow water and violent conditions in two ways. Since most of their clasts consist of the various rock types that make up the bulk of this formation, and since these are a variety of calcarenites and calcilutites that were compacted and cemented before they were eroded and brought together to form the polymict calcirudites, the mechanism that broke up these compacted and cemented arenites and lutites (some of which had already been dolomitised and silicified) must have possessed very considerable force and violence. The subangular nature of these intraclasts suggests that having been broken up they were rapidly winnowed away from the scene of destruction to a place where they were not subjected to much abrasion (rounding) if any. Strong currents could transport rudite size clasts rapidly into deeper and quieter water.

The presence in the Cablac Limestone of the texture described earlier as typical of beach-rock, if correctly interpreted, is evidence of very shallow water.

3. Warm tropical seas.

The nature of the fauna and micro-flora indicate temperatures in the tropical range. The abundance of oolites, pellets and grapestones suggest analogies

with such regions as the Bahamas and the Trucial Coast of the Persian Gulf.

4. Comparison with the Bahama Banks.

The indigenous fauna and micro-flora, the oolites, superficial oolites, pellets, grapestone intraclasts and the calcareous mud all suggest a close comparison with the sediments forming today on the Bahama Banks as have been described by Illing (1954), Newell (1955) and Cloud (1962). The intimate association of the various kinds of calcarenites with calcilutites is typical of the Bahama Banks. The biomicarenites, especially the calcite muds containing many small Globigerinidae are readily understood in terms of the quiet lee areas that develop behind the surf zone where in lagoons calcareous muds are found today. Into these lagoons oolites and pellets from the shallower or more dynamic portions of the Banks are washed by freak tides or even blown by the wind.

One important feature that does not bear comparison with the Bahama Banks is the polymict intracalcirudite microfacies. The presence in these conglomerates of terrigenous clasts of Triassic, Cretaceous and Eocene age as well as volcanic clasts probably derived from the underlying Oligocene tuffs and lavas demonstrates that the formation, on the shallow platform that eastern Timor must have formed during the Lower Miocene, of Bahaman-type limestones was accompanied by erosion of older formations that very probably formed island cores to the shallow banks.

5. Changes in sea level.

The polymict calcirudites in particular indicate that rocks previously consolidated and cemented were subsequently brought within the influence of waves and currents that rapidly eroded them. The other rocks that contain intraclasts point to the same mechanism.

The common occurrence of broken oolites and pellets clearly suggests that these particles were brought into an environment where they were no longer stable, from one in which they had either been forming or were stable.

The presence of these rocks and allochems at several horizons within the stratigraphic column indicates that these changes in environment occurred several times. These changes are most easily explained by postulating changes in sea level. These movements of sea level must have been rapid since several took place within the time interval of the Lower Miocene. It seems most probable that such relative movements in sea level were caused by orogenic forces.

THE POST-CONSOLIDATION EFFECTS OF TECTONISM

One notable feature of the Cablac Limestone is that it has been intensely fractured. A large proportion of the samples studied are cut by numerous small cracks filled with clear sparry calcite that is nearly always a ferroan calcite. (This distinguishes it from the sparry calcite of the cement, that is usually free from ferrous iron). The reticulate pattern often formed by these cracks is interpreted as the response of a hard, essentially massive

limestone to the intensive fold movements that resulted in the overthrusting of great sheets of Permian strata from the north onto eastern Timor during mid-Miocene times. Bedding planes being very rare in this formation it is almost impossible to detect any folds, but large faults are common and frequently form great scarps. It can be shown that the Cablac Limestone was never very deeply buried; it is reasonable to suppose that a massive limestone formation under stress in these conditions would react by fracturing rather than flexing. This brittle quality is noticed in some of the calcarenites where detrital quartz grains have been fractured in situ after cementation. Likewise some dolomite rhombs are found with these sparry calcite filled cracks bordering the perimeter of the dolomite rhomb. Where the rhombs are cut by the calcite filled cracks it is seen that the crack always runs parallel to the cleavage of the rhomb.

Some of the polymict calcirudites have responded to folding stress by fracturing along the sutured clast boundaries previously formed by pressure solution; some cracks have cut indiscriminately across clast boundaries.

PLATE 29

- A. Cablac Limestone - Mt. Mata Bia, note the rarely
seen bedding in this formation.
- B. Cablac Limestone - basal conglomerate.
- C. Cablac Limestone - biomicarenite (x.25).
- D. Cablac Limestone - dedolomitisation of dolostone
clasts of polymict calcirudite
(x 45).

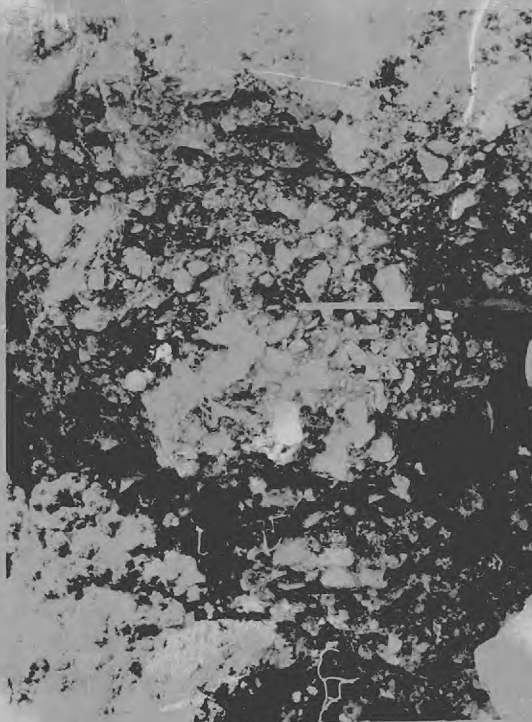
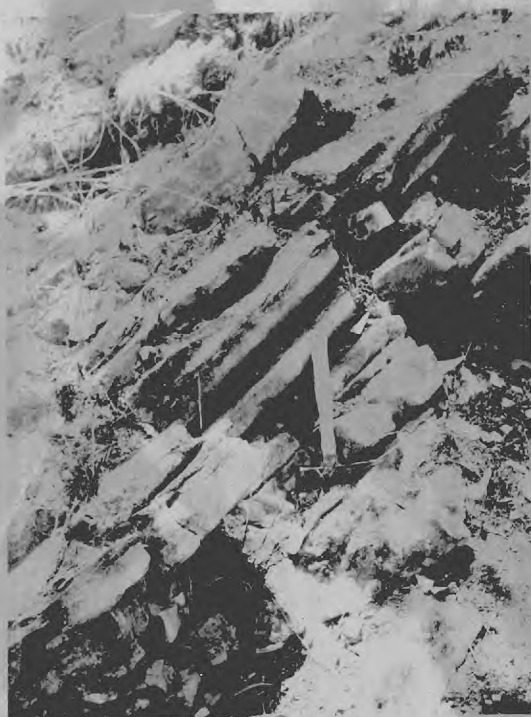


PLATE 30

- A. Cablac Limestone - polymict calcirudite etched with dilute acid and seen by oblique light. The calcite clasts have been etched so that the interclast boundaries are proud due to the concentration of dolomite and other 'insolubles' such as clay along these boundaries. Note rare chert and dolostone clasts standing proud. See also the interlocking of the clast boundaries resulting from extensive pressure solution (x 2).
- B Cablac Limestone - intradismicrudite, note different composition of the intraclasts and their angularity (x 25).
- C. Cablac Limestone - intramicrudite in which the micrite matrix between intraclasts has been dolomitised by very small rhombs (x 25).
- D. Cablac Limestone - biodismicrudite in which calcareous algae are important. Note 'level bubble' structure and large Foraminifer (x 20).

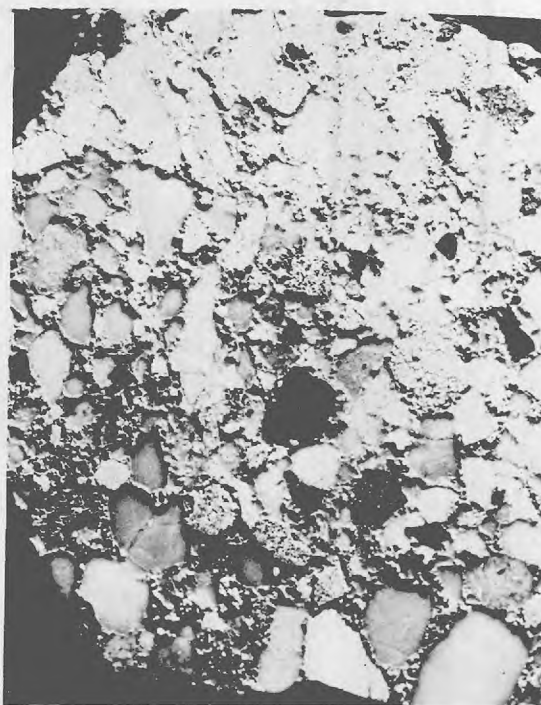
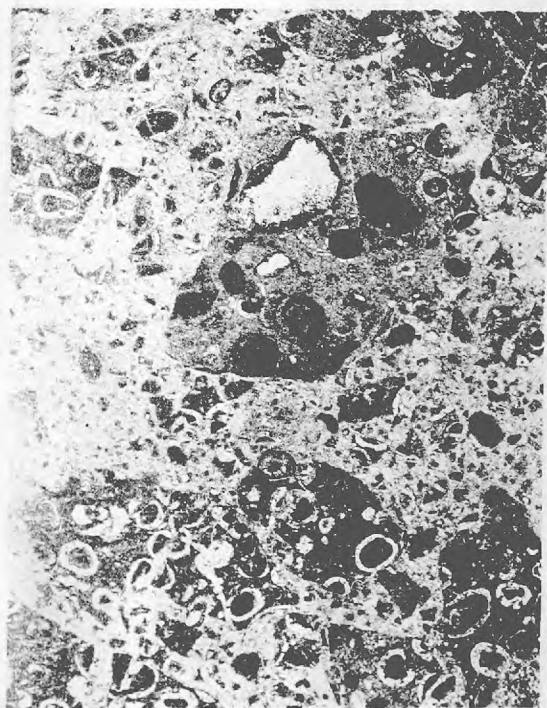
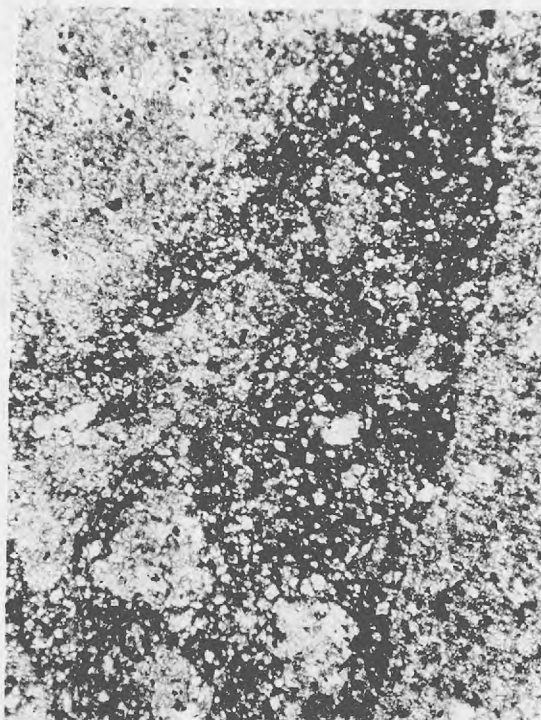


PLATE 31

Cablac Limestone - polymict calcirudite, note
wide variety of clasts and
the strong degree of pressure
solution with very little
matrix or cement between any
clasts (x 10).

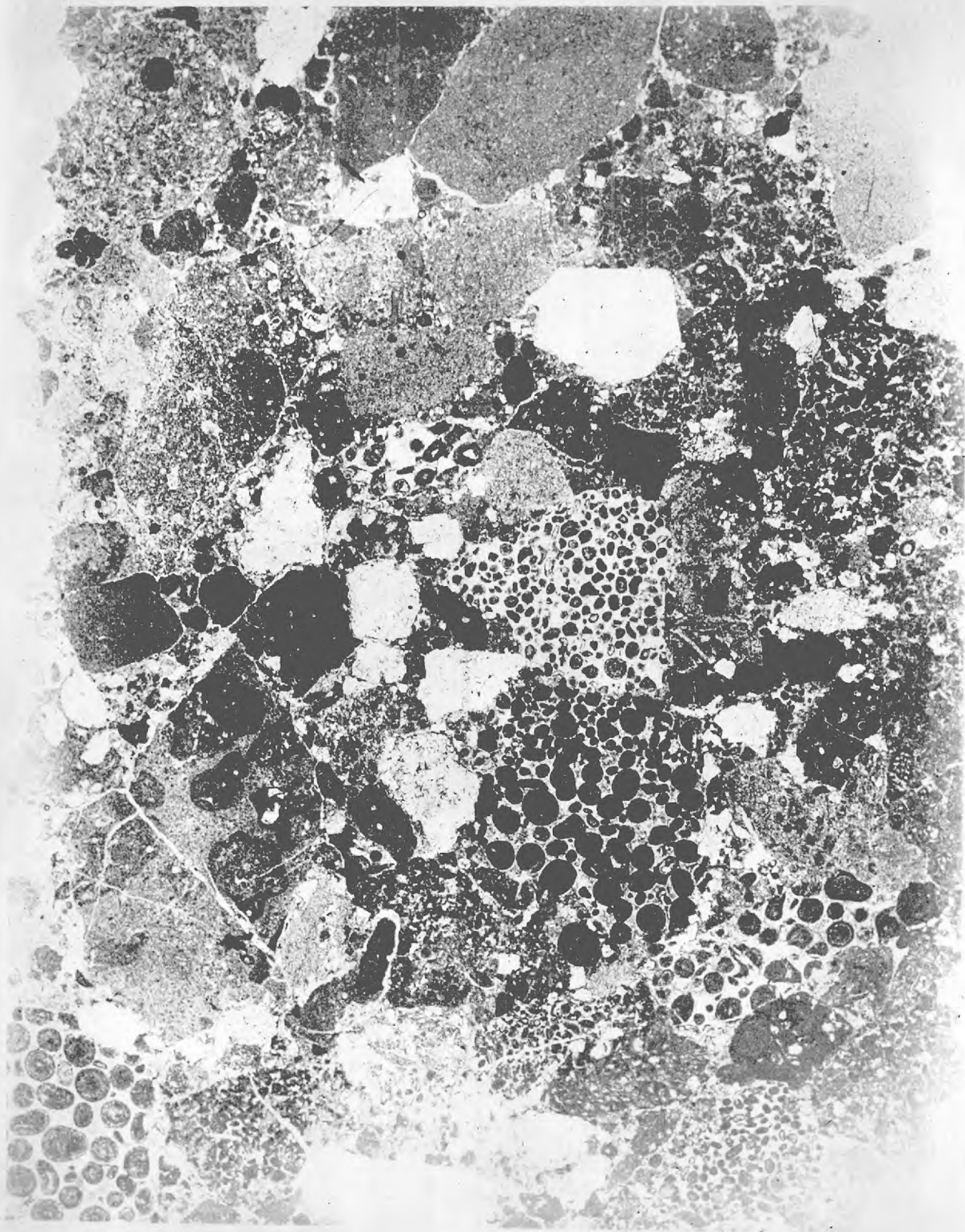
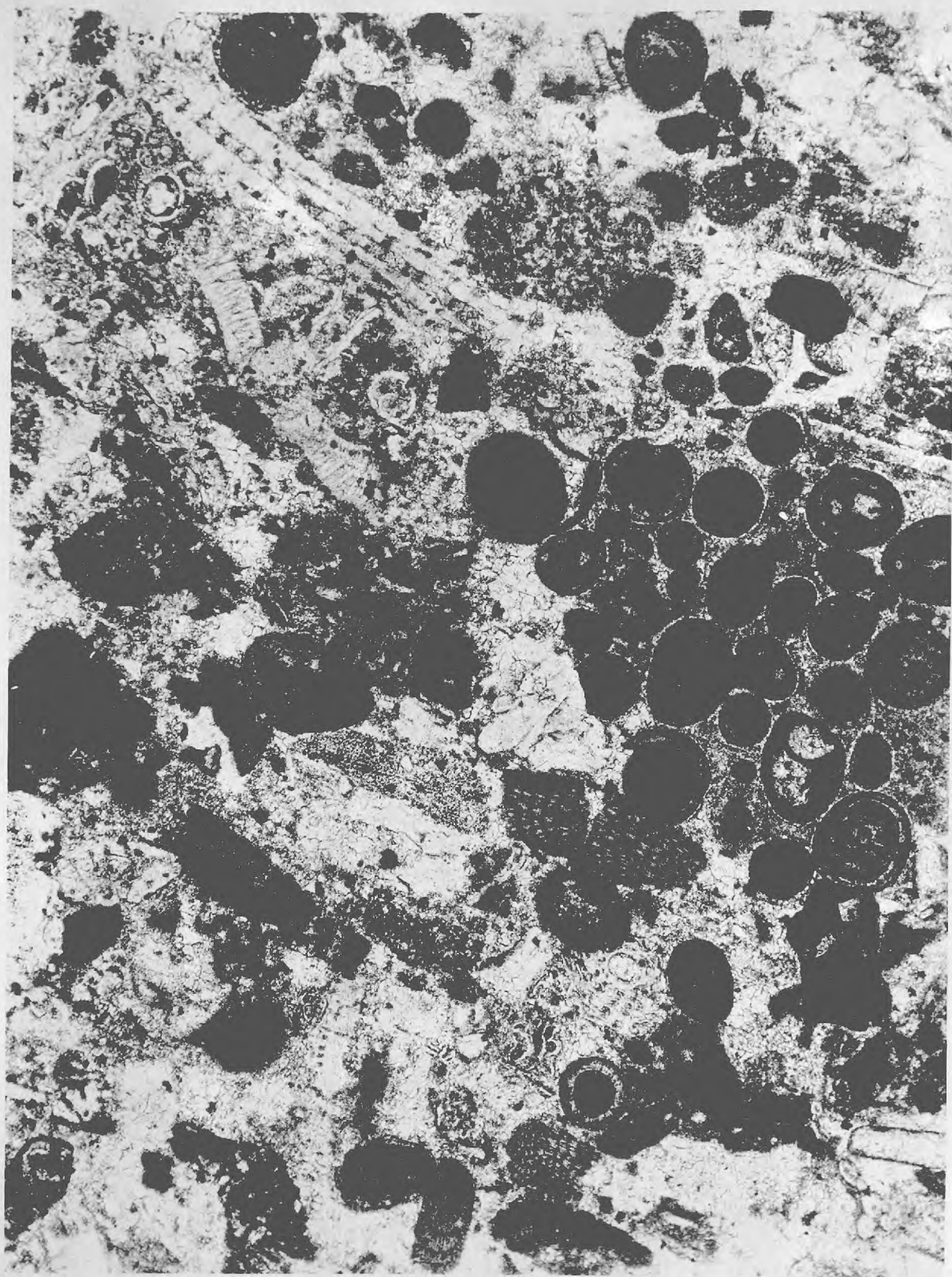


PLATE 32

Cablac Limestone - biospararenite, note the patches of micrite and dismicrite, and the broken fragment of alga in the center with adjacent oolites shewing pressure solution effects against Foraminifer (x 15).



ALIAMBATA LIMESTONE

SUMMARY

The Aliambata Limestone of probable Lower Miocene age is known only from one hill near Aliambata. It is about 50 metres thick and consists of limestones containing only calcite mud and pelagic Foraminifera. Some of the rocks are a fossil Globigerina-ooze. The Aliambata Limestone was deposited in much deeper water than the contemporaneous Cablac Limestone.

INTRODUCTION

The type locality for this formation is the uppermost 100 metres of the hill called Borolalo, just north of Aliambata ($8^{\circ} 46'S$, $126^{\circ} 36'E$). The lower part of this hill is the type locality for the Borolalo Limestone of Upper Cretaceous age. Outside the type locality the Aliambata Limestone has not been found. It is a distinctive limestone, being pale yellow coloured with numerous large Foraminifera visible in hand specimen. These Foraminifera give the rock a saccharoidal appearance. The formation is poorly bedded, and is probably about 50 metres thick.

LITHOLOGY AND PETROGRAPHY

Only two rock types are recognised, they are:

1. Biomicarenite.

The biomicarenites of this formation consist almost

entirely of the tests of pelagic Foraminifera. A variable quantity of microcrystalline calcite is present as a matrix between the tests. The plate 33A illustrates this type of limestone, that may be regarded as a fossil Globigerina-ooze.

2. Biomicrite.

These rocks are distinguished from the biomicarenites by consisting of more than 90 percent microcrystalline calcite. In this calcite mud a few pelagic Foraminifera are found.

STRATIGRAPHIC POSITION.

The Aliambata Limestone rests on the Borolalo Limestone of Upper Cretaceous age. The contact is obscured by scree but it must be unconformable. Since the Aliambata Limestone forms a hill top it is not overlain by any other formation. It has been dated as probably Lower Miocene on the basis of the Foraminifera. The following Foraminifera have been identified by Mr. D.J. Carter (personal communication, 1963):

Globorotalia sp.

Turborotalia sp.

Pararotalia sp.

Globigerina spp.

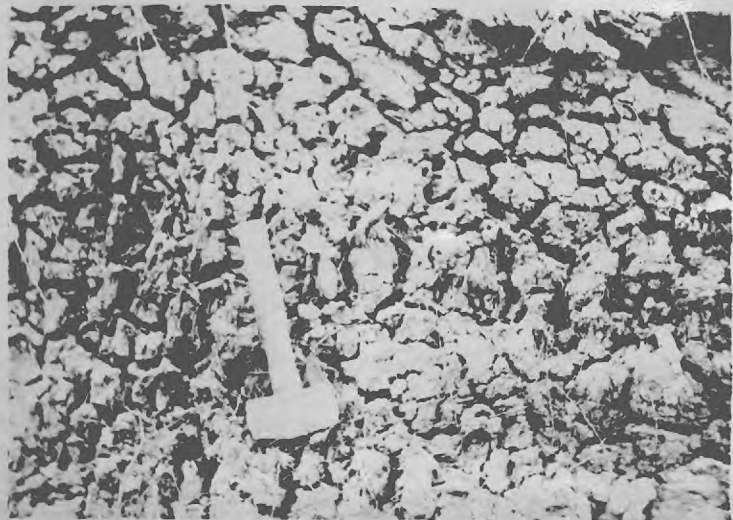
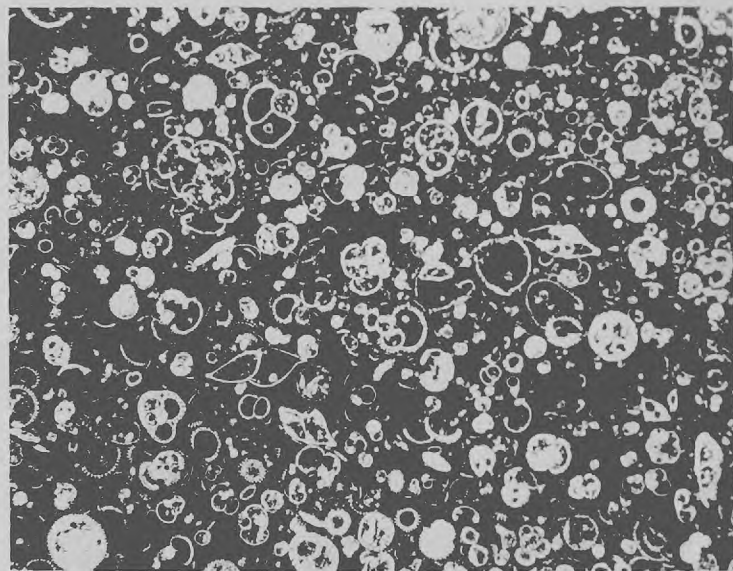
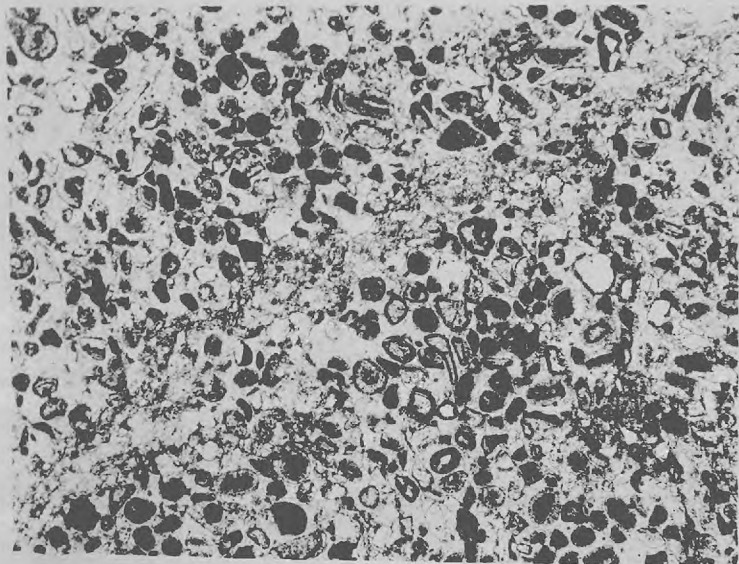
Sphaeroidinella sp.

Globigerinoides sp.

Sphaeroidina sp.

PLATE 33

- A. Aliambata Limestone- biomicarenite with tests of pelagic Foraminifera in a micrite matrix. This closely resembles foraminiferal-ooze (x 25).
- B. Bobonaro Scaly Clay- the man is standing next to an exotic block of sandstone in the Bobonaro Scaly Clay (s).
- C. Cablac Limestone - pelspararenite, note (i) numerous broken oolites and pellets, (ii) strong 'vein' of insoluble materials such as glauconite, quartz and clay which form the infilling of the stylolite (x 25).
- D. Bobonaro Scaly Clay- jigsaw-puzzle cracks in the bentonite clay matrix.



ENVIRONMENT.

The environment indicated by the microfauna is that of a fairly deep open basin. The presence of fossil ooze indicated that relatively little land derived detritus entered the basin of deposition. The carbonate mud in these rocks was probably formed over the shallow banks where the limestones of the Cablac Limestone formed contemporaneously, subsequently this mud was probably swept off these banks into the deeper water where it settled.

THE BOBONARO SCALY CLAY

SUMMARY

The Bobonaro Scaly Clay is a synorogenic formation composed of unbedded scaly bentonitic clay containing abundant scattered exotic blocks, boulders pebbles and smaller fragments. The discovery and definition of this formation has, more than any other factor, helped to bring about the radical revision of the published views of the stratigraphy and structure of Timor by earlier workers. The Bobonaro Scaly Clay is compared closely with the Argille scagliosa of the northern Apennines. Its origin is ascribed to submarine sliding of an unstable clay mass from the area north of Timor under the influence of gravity, closely associated with the emplacement of large overthrust

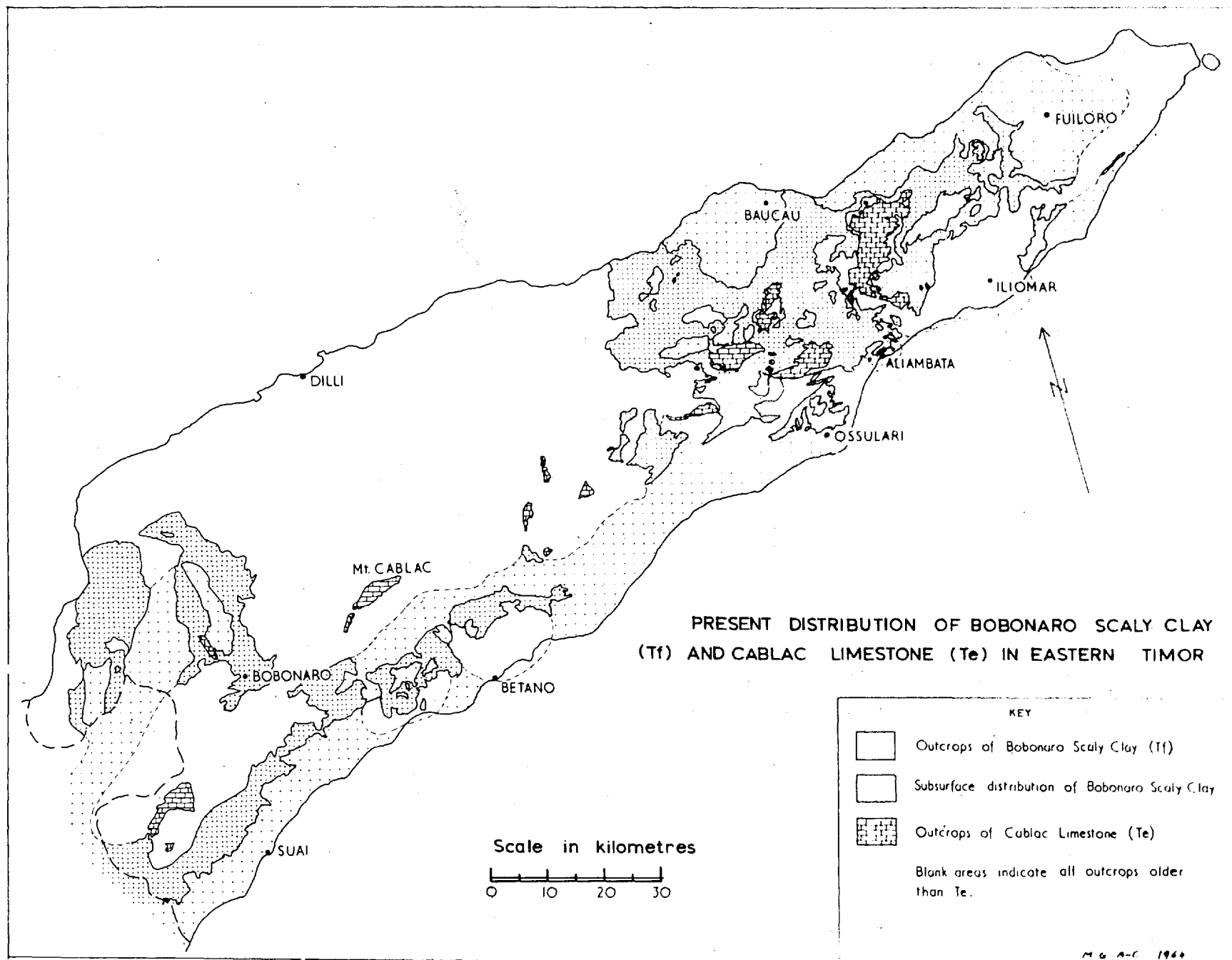


Fig. 7

slices of strata that marked the climax of the mid-Tertiary (Tf) orogeny in eastern Timor.

INTRODUCTION

The Bobonaro Scaly Clay is more widespread and outcrops over a larger area than any other formation in eastern Timor; its area of outcrop exceeding 4000 sq. km. There are only two large areas in the eastern half of Timor where it is not exposed: the eastern tip of the island where autochthonous Permian and Mesozoic rocks are covered by terraces of Pleistocene reef limestones, and the north-west where there are large overthrust slices of Permian strata (figure 7 and 8).

Grunau (1953) grouped together under the title of 'Bibiliu Series' a variety of sedimentary rocks that he considered ranged in age from the Upper Cretaceous to the Pliocene. His geological sketch map reveals that the few extremely small areas he mapped as Bibiliu Series are now known to be occupied either by the Seicel Formation or the Bobonaro Scaly Clay. Gageonnet & Lemoine (1958) followed Grunau (1953) in using the term 'Bibiliu Series' to group together Cretaceous radiolarites and marls with Eocene limestones. They considered the age of the Bibiliu Series to range from the Upper Cretaceous to the Middle Eocene. None of these workers appear to have recognised the enormous spread of the Bobonaro Scaly Clay containing a wide variety of large exotic blocks. Gageonnet & Lemoine (1958) in their geological sketch map of Portuguese Timor (1: 500,000) mapped very large areas as Mesozoic "Complexe Triassico- Jurassique" that are undoubtedly occupied by the Bobonaro Scaly Clay containing

much Mesozoic exotic material. However, included in some of the areas they mapped as Bibiliu Series are areas of exposed Bobonaro Scaly Clay. Similarly Grunau (1953) in his much smaller sketch map (1: 1,500,000) of Portuguese Timor has shewn large areas as Mesozoic (Triassic-Jurassic) which are occupied by the Bobonaro Scaly Clay.

I.B. Freytag, in an unpublished report in 1959, was the first to recognise the unity of this formation that he called the Tuca River Block Clay. The term 'block clay' is being dropped in favour of 'scaly clay' because while exotic blocks are not always present, the clay is always scaly.

The type locality for this formation is beside the River Lomea, east of the village of Bobonaro ($125^{\circ} 20'E$, $9^{\circ} 02'S$). Here steep cliffs provide an almost continuous outcrop for about 8 km.

LITHOLOGY AND PETROGRAPHY.

Lithologically the Bobonaro Scaly Clay has two principal constituents:

(i) a scaly clay matrix, and (ii) a wide variety of unsorted, angular and subangular exotic blocks derived from other formations.

(i) The scaly clay matrix:

This is remarkably uniform in character, being always soft, scaly and variegated. The clay is generally dark reddish brown, but a green (particularly a dark olive

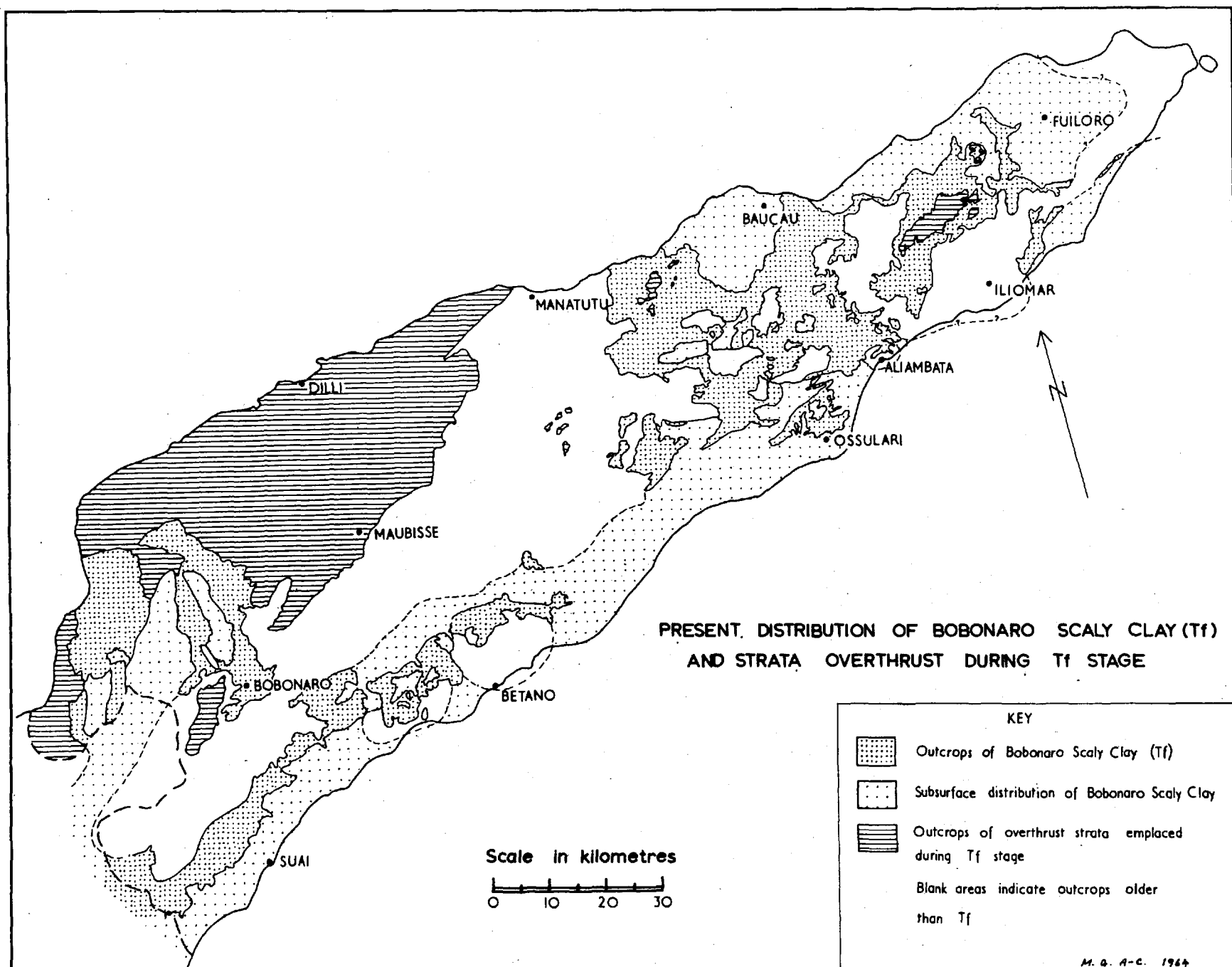


Fig. 8

green) variety is quite common. Black, grey, yellow and bright red clays also occur. Contorted divisions of these contrasting clays indicate plasticity and flowing movement. Lines of flowage and slickensiding are particularly common around the exotic blocks; since these features surround the blocks they can probably be attributed to compaction subsequent to emplacement. It is most unlikely that they were caused by blocks falling into soft mud.

The composition of this clay matrix is fairly complex. Montmorillonite is the predominant clay mineral, forming up to 35 percent of the whole, with lesser amounts of sepiolite and another mineral that is probably palygorskite. The quartz content is noteworthy, being about 10 percent, while calcite is a variable constituent.

(ii) The exotic material:

The exotic blocks and smaller fragments vary in age from pre-Permian to Lower Miocene, the most common material being Permian. More than 90 percent of the exotic material seems to have been derived from the same rock formations as outcrop in eastern Timor. Among those rocks that cannot be matched is a cephalopod limestone of Lower Triassic age. Similar rocks have been reported in situ however from western Timor (Umbgrove, 1938). The size of the exotic material varies from blocks more than 0.5 km. long down to silt grade particles (plates 33B, 34A, 35B, 35C). Most of the exotic material is angular or subangular, but a few huge blocks shew a remarkable degree of rounding (plate 35C). The distribution of exotic material within the clay matrix is chaotic and has random

orientation. The only pattern that can be discerned in the distribution is that locally exotic material of a particular formation is much more abundant than elsewhere. For example, in the type locality there are two adjacent cliffs, in one cliff the exotic material is predominantly Upper Triassic limestones and shales, while the other cliff is characterised by red, crinoidal Permian limestones.

Where the exotic material is relatively easily eroded, for example blocks of soft shales, the scaly clay matrix frequently takes on the colour of these shales due to the presence in the clay matrix of fine grade fragments of them. Where hard limestones or lavas are present they usually have no apparent affect on the colour of the matrix.

The quantity of exotic material mixed with the scaly clay matrix is very variable. Many areas are known where the Bobonaro Scaly Clay is exposed as cliffs without exotic material of any grade being found (plate 35D). Elsewhere the amount of exotic material forms a considerable proportion of the whole (plate 35A).

The erosion of this formation under tropical conditions, during the rapid elevation of the island since the beginning of the Pliocene, has been very severe. It gives rise to a characteristic topography of deep gullies, landslips and rugged nobbly hillsides where the much more resistant blocks of hard rocks protude above the soft clay matrix (plates 34B. 35B).

The high percentage of montmorillonite (bentonite) in the scaly clay gives it a waxy appearance when fresh. After it has weathered it develops what Grim (1953) described as

the "characteristic 'jigsaw puzzle' set of fractures" due to shrinking on drying (plates 33D, 35A).

There is a total absence of recognisable bedding in this formation. In those exposures where there is little or no exotic material, the scaly fissility of the clay suggests a flat lying disposition (plate 35D). This is however probably a secondary feature due to the compaction of the soft clay.

The problem of deciding whether a large block of hard rock that protrudes through the mantle of scaly clay is an exotic block or a buried topographic peak (inlier) is frequently encountered. The evidence is always equivocal wherever the base of the hard rock is not discernible. Two examples of this problem are illustrated by plates 34A, & 35B.

Since this formation is unstratified, and no marker horizons have been recognised, an accurate determination of its thickness is not possible. The base of the formation is a highly irregular unconformity. Locally the formation can be seen to thin out rapidly, while the greatest thickness that can be deduced is the section in the well Ossulari No. 1, which encountered 1906 metres of this formation. It seems possible that the thickness of the formation beneath the south coastal plains may locally exceed 3000 metres, and that in general the formation increases in thickness from north to south across the island.

STRATIGRAPHIC POSITION

The base of the formation is an irregular unconformity that locally is probably very rugged. The Bobonaro Scaly Clay forms a blanket that rests somewhere on every older formation. It is overlain by the Viqueque Formation which is Upper Miocene & Pliocene in age (the base of which probably belongs to the Tg stage), and elsewhere by various Pleistocene beds.

Microfossils varying in age from Permian to Upper Miocene are found in scaly clay part of this formation. The individual exotic blocks have been found to contain both macrofossils and microfossils whose ages vary from Permian to Lower Miocene. Since the evidence is clear that the exotic material arrived in its present position at the same time as the clay matrix two dates are pertinent: the age of the clay at the time of its formation, and the age of its emplacement in its present position, since it is clearly an allochthonous formation.

The exceptional uniformity of the clay matrix, and its particular nature (discussed below) indicate that it probably formed very rapidly. The fact that it contains Foraminifera ranging in age from Permian to Upper Miocene means that its age can only be stated in terms of its youngest fossils, namely Upper Miocene. Since the youngest rocks on which this formation rests (unconformably) are Lower Miocene of Te stage, and the oldest rocks that overlie (unconformably) the Bobonaro Scaly Clay belong to the Viqueque Formation of the Upper Miocene (Tg stage), then the Bobonaro Scaly Clay must clearly have been emplaced in its present position between late Te and early Tg stages.

There is no evidence to suggest that this formation was anywhere emplaced outside this time interval. However it is not certain whether the whole formation achieved its present position as a single event, or by a succession of small emplacements. Part of the clay matrix (perhaps a large part) must be Upper Miocene in age since the indigenous microfauna is Upper Miocene.

The following Foraminifera, that indicate an Upper Miocene age, have been determined from the clay matrix of this formation by Dr. D.J. Belford, (unpublished reports dated 1960 and 1961):

Globigerinoides quadrilobatus quadrilobatus
(d'Orbigny)

G. quadrilobatus immaturus Le Roy
G. quadrilobatus trilobus (Reuss)
G. quadrilobatus irregularus Le Roy
G. ruber (d'Orbigny)
Globigerina bulloides (d'Orbigny)
G. suboretacea Lomnicki
Globorotalia cultrata (d'Orbigny)
G. scitula (Brady)
G. truncatulinoides (d'Orbigny)
Pulleniatina obliquilocata (Parker & Jones)
Sphaeroidinella dehiscens (Parker & Jones)
Bolivinita quadrilatera (Schwager)
Pullenia bulloides (d'Orbigny)
Nonion pompilioides (Fichtel & Mull)
Cassidulina laevigata (d'Orbigny)
Caratobulinina pacifica Cushman & Harris
Uvigerina sp.
Stilostomella lepidula (Schwager)

Bulimina aculeata d'Orbigny

Astrononion sp.

Hyalinea balthica (Schroeter)

Sphaeroidina bulloides (d'Orbigny)

Bulimina inflata Seguenza

Bolivina robusta (Brady)

Laticarinina pauperata (Parker & Jones)

Hoglundina elegans (d'Orbigny)

ORIGIN

The violent unconformity at the base of the Bobonaro Scaly Clay together with the absence of any bedding planes, and the prevalence of contorted flow structures suggest that this formation was emplaced in its present position by sliding or slumping, and is therefore an allochthonous sedimentary formation. Other evidence that supports this view include the variety of scattered, unsorted, exotic material that could not possibly have arrived in its present position by any known sedimentary mechanism other than sliding or slumping. The scaly nature of the clay matrix suggests stress and flow. The whole formation is very similar to the Argille scagliosa of the northern Apennines of Italy as described by Merla (1951). The nature and distribution of the exotic material suggests comparison with the Wildflysch of the Swiss Alps. There is, however, a major difference between the Wildflysch and the Bobonaro Scaly Clay, in that associated with the Wildflysch are beds of greywacke and shale commonly having graded bedding, convolute bedding, loadcasts and current bedding (Crowell, 1957); such rocks are never found bedded with the Bobonaro Scaly Clay, nor apparently with the Argille scagliosa.

Kuenen (1956) pointed out that deposits resulting from slide movements are characterised by usually a fair proportion of lutite, and that they may contain huge blocks. He stated that the original structure varies from slightly deformed to entirely mixed, and that there is a piling up at the lower end of the slide. There is no grading and no segregation of larger particles in slide deposits. By contrast, he found that deposits that result from turbidity currents are characterised by "more or less graded granular bed(s), poorly sorted at each level. Coarsest grains do not exceed 10 cm. Upper part (of the deposit) may be laminated and current ripple laminated. One current produces one single bed". Clearly the Bobonaro Scaly Clay is a typical slide deposit and shews none of the features of a turbidity current deposit.

There is general agreement that the Swiss Wildflysch, the northern Apennine Argille scagliosa, and similar deposits described by Crowell (1957) as "pebbly mudstones" have been generated by unstable masses of sediment moving down a submarine slope under gravity. From various parts of the world deposits originating in this manner have been described by Lugeon (1916), Bailey et al. (1928), Merla (1951), Dorreen (1951), Kugler (1953), Renz et al. (1955), Kuenen (1956) and Crowell (1957).

Because of the high proportion of montmorillonite (bentonite) in the Bobonaro Scaly Clay it would have had the ability to flow very easily, as bentonitic clays are, according to Grim (1953), generally highly colloidal and plastic. Kuenen (1956) has shewn that a submarine slope of 1 or 2 degrees is sufficient "under certain favourable conditions" for a slide to be set off and kept going.

Many workers have considered that tectonic activity and earthquake shocks could provide a trigger mechanism to initiate the sliding of the unstable sediment down the slope.

In eastern Timor during the time interval between late Te and early Tg stages (when the Bobonaro Scaly Clay was emplaced) the great overthrust sheets of principally Permian strata achieved their present position (figure 8) by being overthrust from the north; the same direction from which (as will be shown below) the Bobonaro Scaly Clay was derived. In the field the Bobonaro Scaly Clay is always found overlying the thrust sheets and never below them. Obviously the movement of the thrust sheets and the emplacement of the Bobonaro Scaly Clay are closely related. The overthrust movements formed the climax of the mid-Tertiary orogeny in Timor. The emplacement of the scaly clay probably occurred after the emplacement of the thrust sheets because they have not been found superimposed on the clay. There seem to be two possible mechanisms by which the Bobonaro Scaly Clay could have been emplaced. One is as a gravity slide down a submarine slope brought about by the orogenesis that elevated the volcanic Inner Arc and downwarped the Outer Arc where folding of the pre-Upper Miocene culminated in the overthrusting described above. The other mechanism involves the thrust front (that moved from north to south) acting as a bulldozer and pushing the bentonitic clay before it. It is possible that the submarine sliding of the clay mass was initiated by bulldozing the clay mass to a position where a slope was created down which the clay could slide freely under gravity.

ENVIRONMENT

There are four environmental problems associated with this formation in Timor:

- 1) The location of the basin in which the clay matrix of the Bobonaro Scaly Clay was originally deposited.
- 2) The determination of the source area of the exotic material.
- 3) The nature of the submarine slope down which the gravity slides moved to their present position.
- 4) The determination of the bathymetry and submarine topography of the area now occupied by the land mass of eastern Timor at the time of the emplacement of the Bobonaro Scaly Clay.

These problems are discussed below:

- 1) The presence of montmorillonite as the most important constituent indicates that a large part of the clay was probably derived from the submarine weathering of volcanic ash. The volcanic Inner Arc of islands is today about 50 kms. N. of north coast of Timor (enclosure 14). This volcanic arc opposite Timor (islands of Alor and Wetar) produced effusive igneous rocks during the Lower Miocene. This volcanic activity ceased temporarily in mid-Miocene times when this part of the volcanic arc was uplifted (van Bemmelen, 1949).

About 130 km. south of Timor is the northern edge

of the Australian continental shelf (Sahul Shelf). Between the Sahul Shelf and Timor is a trough about 3000 metres deep. Although the age of this trough is still uncertain, there is no evidence at all to suggest that the clay slide was derived from this direction, so that we can be sure that the clay was originally deposited in the region between the Inner and Outer Arcs, that is in the region of the Wetar Strait (enclosure 14). This accords with the conclusion reached by van Bemmelen (1949) who considered that the exotic blocks (without any scaly clay matrix), described from the island of Leti (enclosure 14) by Molengraaff (1915), were derived by submarine gravity sliding of a pebbly mudstone from the area north of Leti. It is also highly significant that the youngest dated exotic block on Leti is (as in Timor) Lower Miocene. Both Molengraaff (1915) and van Bemmelen (1949) were unaware of the existence of the Bobonaro Scaly Clay in eastern Timor.

2) The exotic material of the Bobonaro Scaly Clay (and the exotic blocks from Leti) consist mainly of four types of rock: Permian limestones, Upper Triassic limestones and shales, Cretaceous siliceous sedimentary rocks, and a wide variety of lavas and tuffs. Much of the exotic material can be matched with formations that outcrop in eastern Timor. Together the Permian limestones and the volcanic rocks probably form about 70 percent of all the exposed exotic material.

The mass of unstable clay sediment, once it began to move down the submarine slope, could be expected to remove any obstruction in its path. Since the sliding of the clay either accompanied the overthrusting of the Permian strata or followed immediately after, it is to be expected

that the sea floor was littered with debris from the thrust front itself (Permian rocks), and from the rocks over which the thrust sheets moved. This debris would be rapidly incorporated in a sliding clay mass. Kuenen (1950) arguing the case for submarine canyons having been cut by turbidity currents, admits the possibility of sliding clay also effecting such erosion. Ericson et al. (1952) appear to hold very similar views. Thus apart from picking up the loose debris resulting from thrusting, it seems very likely that some of the exotic material was incorporated into the sliding mass by its erosive action on the sea floor in that region that now separates the two arcs, and to a lesser extent from the Timor area.

3 & 4) The submarine slope down which the gravity slide moved must have been between the Inner and Outer Arcs (and closely associated with the thrust front), increasing in depth towards the Outer Arc. The indigenous microfauna of the scaly clay suggests that the clay was deposited in a basin environment in which the depth of water was not extreme.

During Lower Miocene (Te) times, before the emplacement of the Bobonaro Scaly Clay, the region now occupied by much of the central land area of eastern Timor formed a platform on which Bahaman-type limestones were deposited. On the site of the present south coast, where pelagic limestones were deposited during the Lower Miocene, conditions were those of a deeper basin. There was therefore in existence at that time (Te) a steep submarine slope from the present central longitudinal axis of eastern Timor down to the present south coast.

Between the Bahaman-type platform that occupied much of eastern Timor and the volcanic Inner Arc (i.e. in the region now occupied by the Wetar Strait), the sea must have been deeper than it was over the Timor 'platform', probably considerably deeper. In order for gravitational forces to move the unstable clay mass southward from the Wetar Strait a submarine slope, increasing in depth southward, must have been created during the Tf time interval. Thus the region of Timor must have subsided relative to the area to the north (now occupied by the Wetar Strait), from which the clay and much of the exotic material were derived. This movement involved folding of the pre-Tf rocks and the overthrusting of large sheets of Permian strata in Timor, while the evidence from the islands of Alor and Wetar (van Bemmelen, 1949) indicates that the Inner Arc was elevated in mid-Miocene times. That the Timor region was downwarped by the Upper Miocene (Tg) is confirmed by the deeper water facies of the lower part of the Viqueque Formation (Tg), which contrasts with the very shallow Bahaman-type limestones of the Cablac Limestone (Te).

PLATE 34

- A. Bobonaro Scaly Clay- River Manuleden, large hill (m)
of volcanic rocks surrounded by
matrix of Bobonaro Scaly Clay (o).
This is either an inlier of
volcanic rocks of the Maubisse
Formation or else a large exotic
block in the Bobonaro Scaly Clay.
- B. Bobonaro Scaly Clay-type locality in the River Lomea.
Note the erosion characters of the
soft clay matrix.

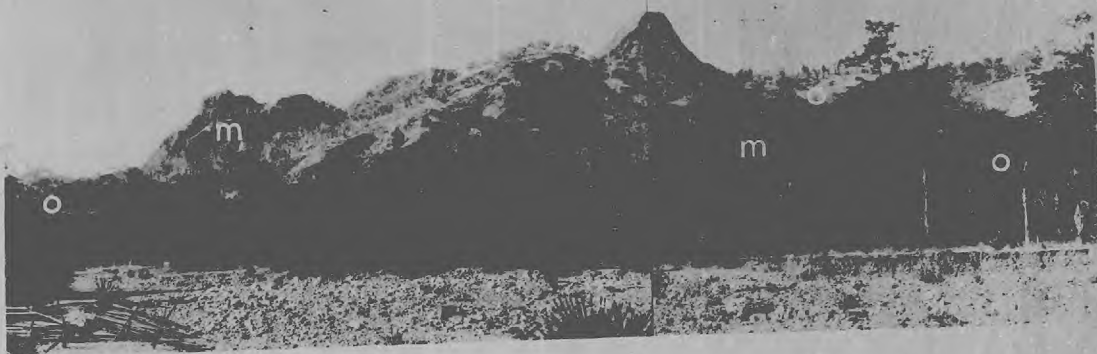
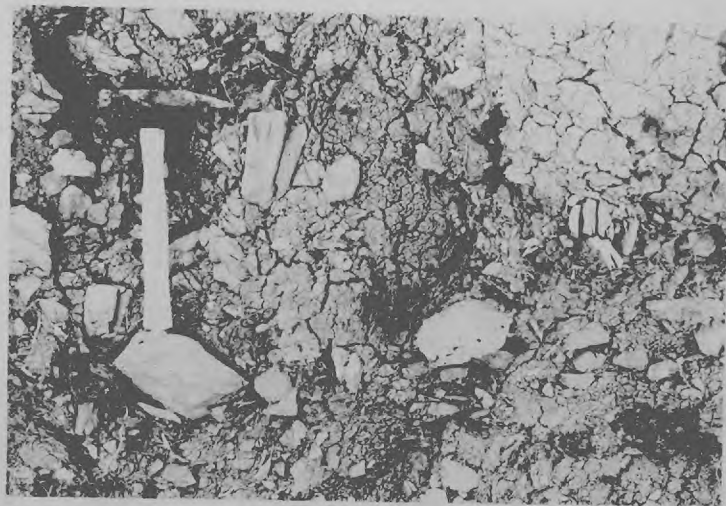
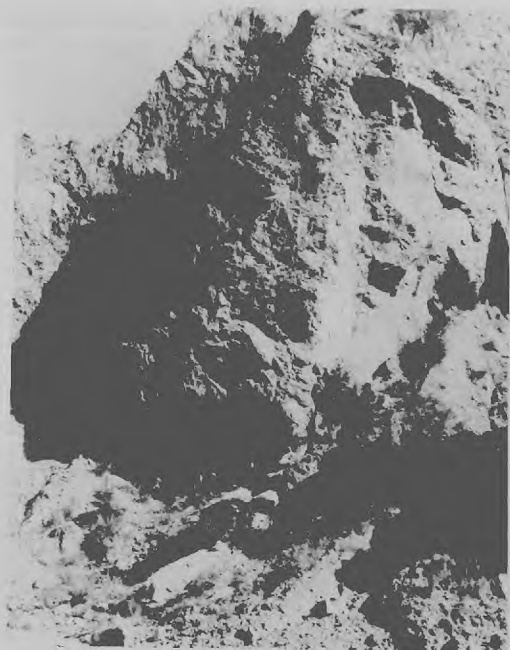


PLATE 35

- A. Bobonaro Scaly Clay- jigsaw-puzzle cracks in the bentonite clay matrix and the variety of the unsorted exotic material.
- B. Bobonaro Scaly Clay- hill (o) is Mt. Ossu, the village of Ossu is just visible at the base of the hill. (o) - Cablac Limestone, (n) - Cablac Limestone of the Builo Range, (p) - Bobonaro Scaly Clay. The hill (o) is either a large exotic block or an inlier of Cablac Limestone.
- C. Bobonaro Scaly Clay- type locality, note that the large exotic block of limestone is rounded (for the scale see the standing men at the base of the block). The matrix of the formation surrounds the block.
- D. Bobonaro Scaly Clay- clay matrix without any visible exotic material. Note the horizontal layering effect.



THE VIQUEQUE FORMATION

SUMMARY

The orogenic climax of mid-Miocene time (Tf) was followed by the gradual emergence of Timor during the Upper Miocene and Pliocene (Tgh). The sediments that formed during this time exhibit a repeated regressive pattern marking the phases of uplift of the island. The resulting sedimentary rocks are classified as the Viqueque Formation in which three members are distinguished. The whole of the Viqueque Formation is a marine facies and exemplifies many of the features regarded as characteristic of molasse. The principal lithologies of conglomerates, sandstones, siltstones, claystones, marls and limestones are described, and some uncommon petrographic details are discussed. The fauna and micro-flora are recorded.

INTRODUCTION

The Viqueque Formation is a marine molasse deposit formed after the emplacement of the large overthrust sheets of Permian strata, and while Timor was emerging from the sea. While the lower part of the Formation consists mainly of clays and marls, the upper part is a regressive facies in which sandstones and siltstones become increasingly important.

The recognition of these rocks as a stratigraphic unit was first made by Grunau (1953) who referred to them as the Plio-Pleistocene Series, later (1956) he called them the Viqueque Series. Gageonnet & Lemoine (1958) followed Grunau (1956) and called these rocks the Viqueque Series.

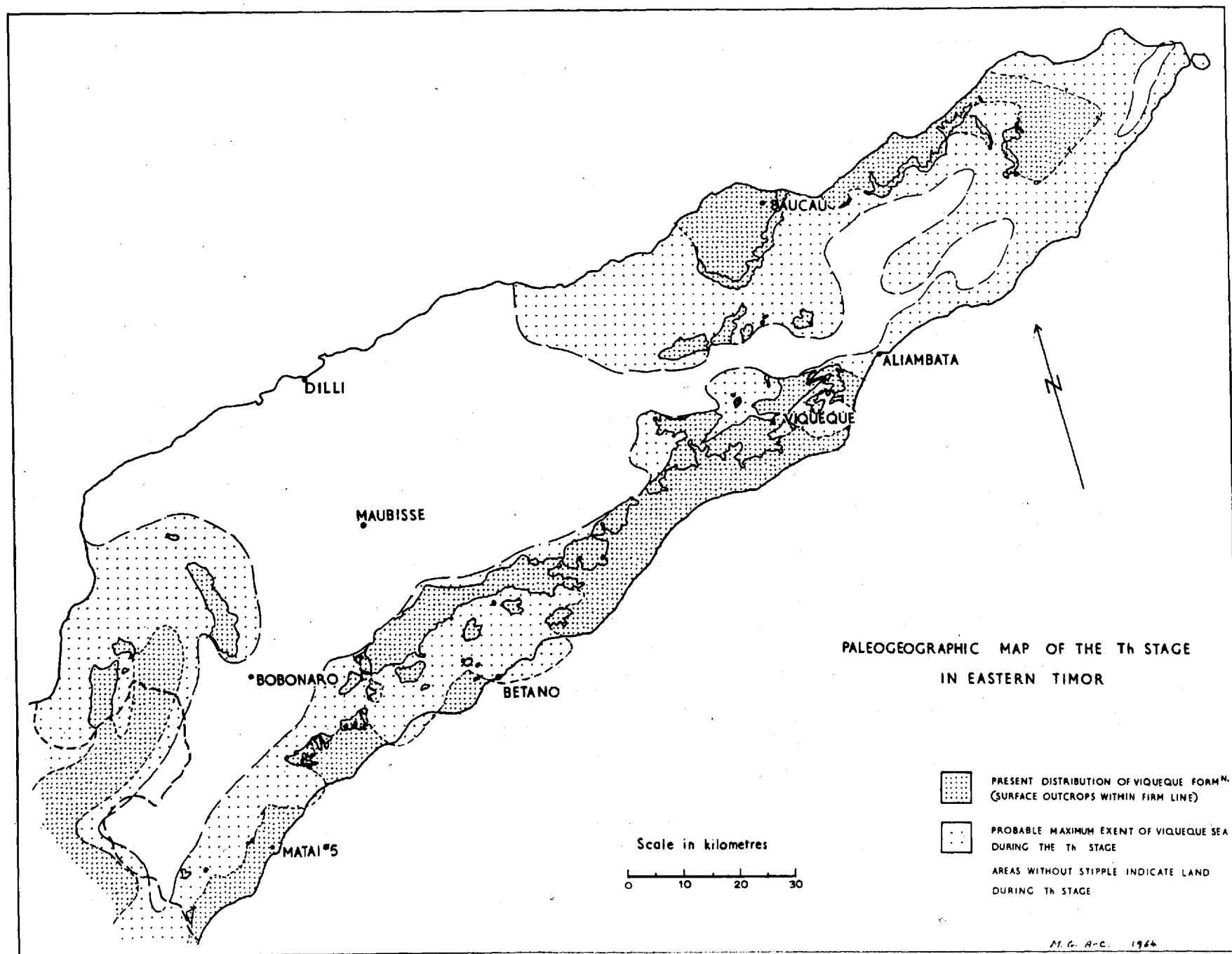


Fig. 9

None of these workers defined a type locality nor described any detailed section, but instead dealt with these rocks in a very brief and general manner. Grunau (1953 & 1956) considered the age of this Formation to be Plio-Pleistocene, while Gageonnet & Lemoine (1958) thought it ranged from Upper Miocene (Tf₂) into the Lower Pleistocene. Results of the present study indicate that the Viqueque Formation is most probably Tg and Th in age (i.e. Upper Miocene to upper Pliocene). One of the reasons for the belief of earlier workers that the Formation extended into the Pleistocene is that they did not distinguish between reef limestones of Upper Miocene age and those of Pleistocene age. Lithologically these raised reefs are extremely similar and their microfauna indicates that they range from Tg to the Recent. Since there is a strong unconformity at the top of the Pliocene it is essential to separate them stratigraphically.

In the present study three different facies are distinguished as Members of the Viqueque Formation, they are the Lari Gutí Member, the Dilor Conglomerate Member and the Seketo Block Clay Member. These are described and defined after the section on the Viqueque Formation.

The type locality for the Viqueque Formation is the hilly country immediately about the village of Viqueque (8° 52'S, 126° 18'E). The Formation is well exposed in the banks of the River Cua where it cuts through the Viqueque Anticline north of Viqueque village. The rocks of this Formation are highly characteristic and readily identifiable, so much so that they are distinguished by the native people, who call them 'Fatu Luca' (meaning rocks of Luca) after the village of that name, where they

are well exposed. The most distinctive features of the Formation are the soft rocks that mostly weather to a white colour, particularly the white chalky limestones and marls. The sandstones and siltstones although soft usually form topographic ridges that contrast with more easily eroded marls. The Formation is generally well bedded.

In the type locality the basal 130 metres of the Formation consists of white marls, grey claystones, a few white chalky limestones and two beds of vitric tuff. These rocks pass up into a succession that becomes gradually more silty and sandy. Silty marls and silty claystones, siltstones and sandstones predominate in the upper part of the Viqueque Formation, that in the type locality is about 370 metres thick.

The highly characteristic appearance of this Formation makes it readily identifiable not only in the field but also on the aerial photographs where it is light toned and has well defined ridges. Most of the rocks of this Formation weather white, and, with the exception of the yellowish sandstones, form a white puggy soil. In the type locality the Formation has a rugged relief due to deeply dissected valleys.

Outside the type locality the general succession is the same. Summarily this consists of a lower part mainly composed of claystones and marls and an upper part in which siltstones and sandstones become increasingly important upwards. One feature that characterises the upper part of this Formation, wherever it is found, is the extreme lenticularity. It is seldom possible to trace a particular bed for more than 300 metres in any direction.

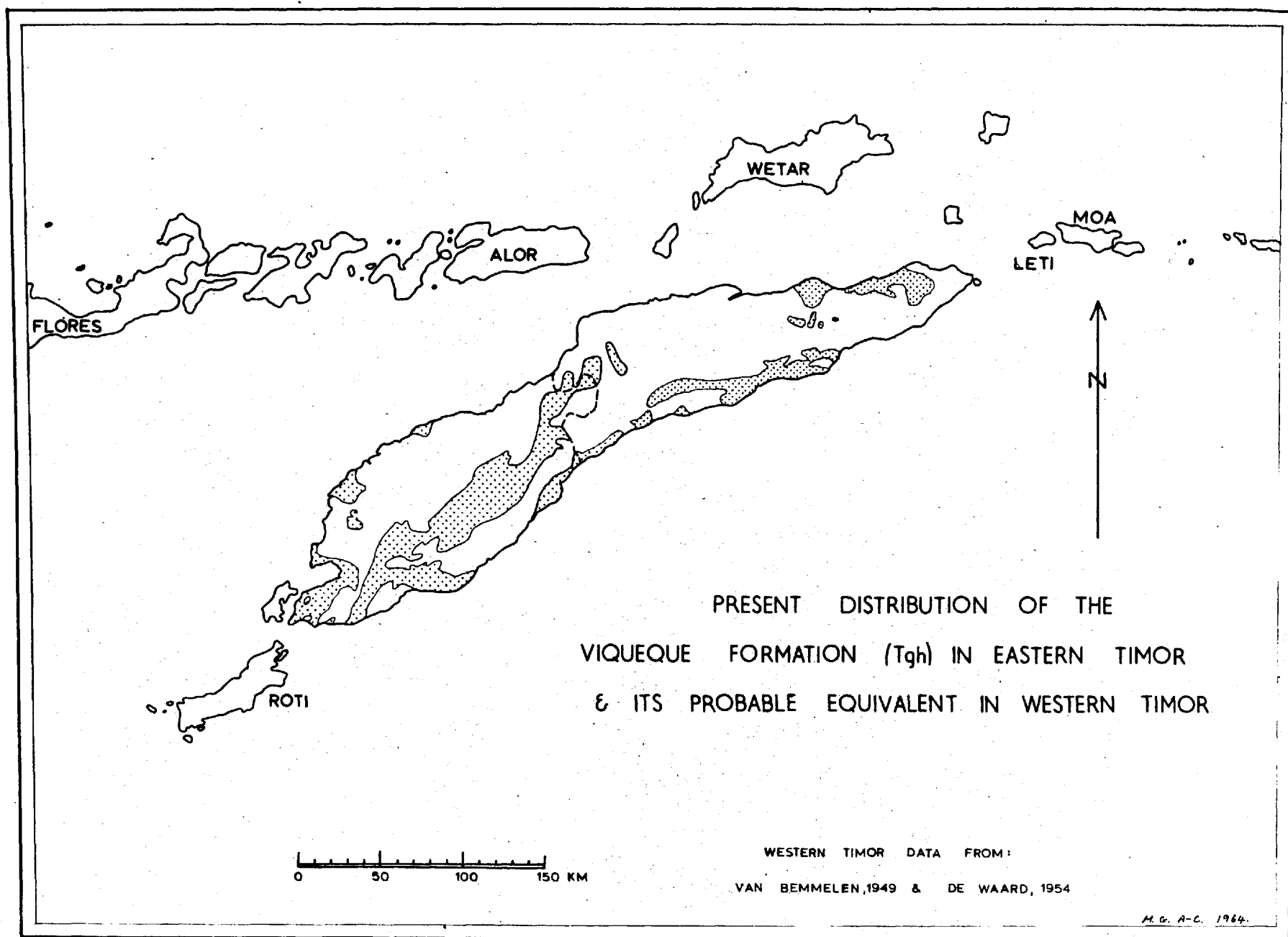


Fig. 10

Consequently no useful marker horizons have been found in the Viqueque Formation. The rapid change in facies occurs not only in a lateral direction but also vertically. Because of this remarkable interdigitation of facies the stratigraphic columns shewn in enclosure 11 are necessarily generalised.

The present surface distribution of the Viqueque Formation and its members is shewn in the outcrop maps enclosures 1A, 1B, 1C, 1D. The surface and subsurface distribution of the Viqueque Formation (members not being separated) may be seen in figure 9 & 10. As the palaeogeographic map figure 9 suggests, the Viqueque Formation may be considered to be distributed in three separate 'basins'. These may be termed the central basin, the southern basin and the north eastern basin. The southern basin contains the greatest thickness, probably at least 800 metres and the most interesting development. The north-eastern basin contains a much reduced thickness of about 100 metres, due to the upper part of the Formation being missing, most likely eroded during the late-Pliocene orogeny. The central basin is really the eastern end of what van Bemmelen (1949) called the Central Basin of Timor, and what de Waard (1956) has called the Central Depression of Timor. The eastern end of this basin, that is a very important feature of western Timor where it is 120 kms. long and 20 km. wide, does not expose much of the Viqueque Formation due to a thick Pleistocene and Recent cover. In western Timor this Central Basin probably contains at least 800 metres (van Bemmelen, 1949) of rocks that are the equivalent of the Viqueque Formation.

LITHOLOGY AND PETROGRAPHY

Lower part of the Viqueque Formation.

The lower part of the Viqueque Formation consists mainly of three rock types: marls, claystones and limestones. Other rocks that are locally important are basal conglomerates and mottled marls.

The lower part of the Viqueque Formation has a maximum known thickness of about 200 metres in the southern basin. Elsewhere in eastern Timor it is thinner. The north-eastern basin is characterised by a higher proportion of marls and limestones than is found in the southern basin. The central basin in eastern Timor is not sufficiently well known to make these comparisons, but evidence from De Bruyne (1941) quoted in van Bemmelen (1949) suggests that in western Timor this Central Basin contains about 300 metres of rocks equivalent to the lower part of the Viqueque Formation, and like those of all the basins of eastern Timor consist of marls, claystones, limestones and tuffs.

Marls.

Most of the rocks that in the field were classified as marls should on the basis of Pettijohn's (1957) classification be termed clayey marls; relatively few of them fall into Pettijohn's marl category. In accord with the general principles of Folk (1954) these rocks are termed silty mudstone-marl, and silty mudstone-clayey marl.

Most of these clayey marls and marls are pale grey when fresh, but white on weathered surfaces. They are

soft, generally fairly massive with poorly developed master bedding planes and have a blocky jointing. Locally fragile molluscan debris is concentrated, usually in an indeterminable condition. Large pelagic Foraminifera are present in small numbers, and are usually visible on fresh surfaces of the hand specimen. Well preserved Radiolaria are found in varying proportions. Silt grade material is present very occasionally in excess of 15 percent (by volume). This silt usually consists of volcanic glass fragments, chlorite, mica, quartz and calcilutite particles. The calcilutite particles have the appearance of detrital particles and not in situ chemical precipitates of primary or diagenetic origin. The clay mineralogy has not been studied, but it seems probable that some bentonite may be present. The evidence leading to this conclusion is the presence of volcanic glass, which reacted with water and Canada balsam so that the slides had to be ground in paraffin and mounted in Permount.

Claystones.

Strictly these rocks are marly clays (Pettijohn, 1957), and on the basis of Folk's (1954) textural classification they are silty claystones. Therefore they should be termed silty claystones-marly clays.

These claystones are dark grey and greenish grey in colour on fresh surfaces, their weathered surfaces are usually pale grey or white. They are soft and usually poorly bedded although locally bedding is well developed with beds about 10 cm. thick. Large pelagic Foraminifera and well preserved Radiolaria are common in the claystones. Occasionally molluscan debris in a highly divided fragile

condition is seen. Most of these rocks contain about 50 percent (by volume) of silt grade particles consisting of volcanic glass, chlorite, mica, quartz, and fragments of Foraminifera. The clay minerals have not been studied, but as with the marls (above) it seems probable that some bentonite is present.

Limestones.

The limestones are calcilutites with varying proportions of calcite mud, clay minerals, Foraminifera and Foraminiferal debris. They should be termed biocalcilutites (or biomicrites). The amount of clay minerals is never greater than 7 percent, and mostly less than 5 percent (by weight). These rocks are white, soft, and chalky. Large Foraminifera are usually common and seen in the hand specimen. These Foraminifera are mixed benthonic and pelagic types. Radiolaria are common and well preserved. These limestones are not well bedded and are variable in thickness.

Basal conglomerates.

These only occur locally, for instance at the foot of the mountain Suru Lau, between the villages of Ainaro and Samé where they are 100 metres thick. Here the River Wai Luli exposes massive, unsorted, uncemented, friable, cross bedded conglomerates. On the basis of Folk's (1954) classification these rocks are classified as cobble conglomerates-submature greywacke. They contain cobbles as large as 50 cm. diameter with much smaller particles of gravel, sand and silt grade. Most of the clastic material is derived very locally, and consists of fragments of

volcanic and metamorphic rocks. Some fragments of calcilutites are present. Mineral grains identified include quartz (which is largely predominant), amphiboles, chlorite and epidote.

The basal conglomerates from the foot of Suru Lau are illustrated in plates 36A, 36C and 36D. The cross section No 10 in enclosure 3 AB demonstrates the stratigraphic position of these conglomerates (see also enclosure 1B).

Mottled marls.

Close to the base of the Viqueque Formation in many places, and at the actual base in others is a particular marl. It is mottled white and reddish brown, and consists of two main constituents; a typical white clayey marl of the lower part of the Viqueque Formation, and a reddish brown clay that is highly reminiscent of the Bobonaro Scaly Clay (that is nearly everywhere found underlying the Viqueque Formation). The proportions of these two constituents vary widely, yet the rock retains its unique appearance.

The nature of the rock suggests that the brown clay constituent has been derived directly from the Bobonaro Scaly Clay while the white marls appear to be reworked Viqueque marls rather than primary precipitates.

Tuffs.

The lower part of the Viqueque Formation in the southern basin contains in many places two and possibly more vitric tuff beds. These beds that are about 3 metres

thick contain about 90 percent (by volume) of volcanic glass and devitrified glass. A little calcite and clay minerals are present. These rocks are very light, and porous. They are white, very soft, pumice tuffs.

Upper part of the Viqueque Formation.

The upper part of the Viqueque Formation is transitional to the lower part, there being no break. The upper part is characterised by two features; the appearance of siltstones and sandstones that become increasingly important up the section, and the presence of graded bedding that dominates the sedimentary structures together with numerous sedimentary slump structures. The most common rock types are marls, siltstones, sandstones, biocalcarenites and calcilutites.

Marls.

Strictly these should be termed clayey marls like those of the lower part of the Formation. The silt content of these clayey marls is noticeably higher than those of the lower part, and the marls become more silty as one moves up the section, and grade finally into marly siltstones. Texturally (Folk, 1954) these marls rank from silty mudstone to muddy siltstone.

Those marls with a relatively low silt content are, like those of the lower part of the Formation, pale grey when fresh and weather white, while with increasing silt content they become darker and distinctly green. This is due to the green minerals (chlorite and amphiboles) that form an important fraction of the silt grade. All the

marls are soft, and the silty varieties tend to be friable. Bedding is finer in the silty marls than in less friable marls. The most interesting feature is the graded bedding; commonly silty marls grade upwards into marls. The silt fraction of these rocks is composed principally of the following grains: calcilutite, quartz, mica, chlorite, amphibole and volcanic glass fragments. Most of these silt particles are subangular to subrounded. There is a marked lack of sorting emphasising the immaturity of the rocks (immature stage of Folk, 1954). Locally fragile comminuted molluscan debris makes a notable contribution to the rocks.

Another feature of these marls is their association with sudden boulder beds, sandstones and siltstones that usually grade upwards. In a well exposed section in the River Wai Luli, south of the point where the Hatu Udo - Ainaro road crosses the river a bed 1.5 metres thick of large boulders, cobbles and pebbles in an unsorted sand-silt-mud matrix makes a sudden appearance in a bedded sequence of marl and silty marl. This bed is illustrated in plates 36B. 37A. The boulders and cobbles are mostly well rounded limestones of the Aitututu Formation. Higher up this same section, above the boulder bed, is an alternation of marl and silty marl layers about 3 cm. thick with poorly sorted fine to medium sandstone layers (immature greywacke) about 1 to 5 cm. thick occurring every 30 cm.

Armoured mud balls consisting of typical Viqueque marls or clays forming a core that is studded with sand derived largely from igneous and metamorphic rocks, makes occasional appearances in the marls.

Siltstones and sandstones.

Beds of sandstone and siltstone occur with increasing frequency in the upper part of the succession. Individual beds vary in thickness from a few millimetres up to 12 metres. That are generally soft and friable, the sandstones having good porosity. Some of the beds of sandstone have a patchy cement of sparry calcite forming a granular mosaic. Almost invariably these arenites exhibit graded bedding. A variety of grades is found from pebble conglomerates grading up to the fine siltstones and mudstones (plate 37B). Generally the arenites are poorly sorted, immature greywackes (Folk, 1954) whose clasts are mainly volcanic and metamorphic rock fragments, calcilutites, quartz, chlorite, mica, amphibole, epidote, zoisite and volcanic glass shards (plates 40A, 40D, 41A, 41C, 41D). The clay content of these arenites is very variable and usually more than 5 percent. The quartz grains are frequently extremely angular. A few sandstones of the submature and mature grade are found interbedded with the immature arenites.

The sandstones and siltstones frequently contain comminuted debris of mollusca, Foraminifera, corals and wood (plates 40B, 40D, 41A). Some of the unsorted pebble conglomerates and poorly sorted medium sandstones (immature greywackes) contain large fragments up to 30 cm. of corals together with large subangular to subrounded clasts of typical white Viqueque marls and claystones.

Plate 37B illustrates a fairly common feature in the upper part of the Formation; a massive blocky marl is overlain suddenly by an immature greywacke type of pebble

conglomerate that grades rapidly upwards.

Another characteristic of the upper part of the Viqueque Formation is rhythmic patterns of sedimentation. The rhythms involve repeated sequences of units that vary from a few millimetres to whole cycles that consist of 100 metres thickness. Some of these rhythms are represented in enclosure 12.

Biocalcarenites.

One of the less common rocks of this Formation, the biocalcarenites consist almost exclusively of pelagic Foraminifera (plate 39B). A little sparry calcite cement in the form of a granular mosaic is present. In the well Matai No. 5 a 700 metres thickness of the Viqueque Formation was encountered, and contained one horizon 50 metres thick of uncemented friable Foraminifera. In outcrop these biocalcarenites are a creamy white colour, and are seldom found to be more than 3 metres thick. They occur interbedded with the marls and clayey marls.

Calcilutites.

The calcilutites, coloured white and cream, are fairly massive and found interbedded with the marls and clayey marls. They consist of varying proportions of calcite mud (micrite), foraminiferal debris, Foraminifera and Radiolaria (plate 39C).

While these two types of limestone form a relatively small proportion of **all** the Viqueque Formation in the southern basin of eastern Timor, in the north-eastern basin

the limestones together with the marls form a bulk of the Formation. It is however probable that most of the Viqueque Formation of the north-eastern basin belongs to the lower part of the Formation.

STRATIGRAPHIC POSITION

The base of the Viqueque Formation is always unconformable. Usually the Viqueque Formation overlies the Bobonaro Scaly Clay, which is an unstratified gravity slide deposit of Upper Miocene (Tf) age, but locally it is known to sit angular unconformity on the Lower Miocene Cablac Limestone, on the Cretaceous Wai Bua Formation, the Jurassic Wai Luli Formation, and on the Lolotoi Complex (pre-Permian metamorphic rocks, always tectonically allochthonous in eastern Timor). The Viqueque Formation is overlain with apparent conformity by two of the Members of this Formation namely the Seketo Block Clay Member and the Dilor Conglomerate Member. These two Members and the Viqueque Formation itself are locally overlain with angular unconformity by both the Baucau Limestone and the Suai Formation, both of these overlying formations are Pleistocene to Recent in age.

The Viqueque Formation has been dated as Upper Miocene to Pliocene (Tgh) on the basis of its extremely rich microfauna. This is in accord with its stratigraphic position between the Bobonaro Scaly Clay (Tf) at the base, and the Pleistocene to Recent deposits above. The following following Foraminifera have been identified by Dr. I. Crespín (unpublished report, 1956), Dr. D.J. Belford (unpublished reports, 1960 & 1961), and by Mr. A.R. Lloyd (unpublished report, 1962), all of the Bureau of Mineral Resources,

Canberra, Australia; and Mr. D.J. Carter (personal communication, 1963). Although some samples were dated as Upper Miocene (Tg), or Pliocene (Th), the fauna is listed together for convenience.

Globigerina rubra (d'Orbigny)
G. bulloides d'Orbigny
G. subcretacea Lomnicki
G. mayeri (Cushman & Ellisor)
Globigerinoides sacculiferous (Brady)
G. trilobus (d'Orbigny)
G. quadrilobatus trilobus (Reuss)
G. quadrilobatus immaturus Le Roy
G. quadrilobatus irregularus Le Roy
G. quadrilobatus sacculifer (Brady)
G. ruber (d'Orbigny)
G. conglobatus (Brady)
G. obliquus Bolli
G. bollii (d'Orbigny)
G. triloba triloba (Reuss)
G. triloba sacculifera (Brady)
Globorotalia menardii (Parker & Jones)
G. tumida (Brady)
Globorotalia truncatulinoides (d'Orbigny)
G. scitula (Brady)
G. menardii menardii (d'Orbigny)
Orbulina universa (d'Orbigny)
Sphaeroidinella dehiscens (Parker & Jones)
Globoquadrina altispira (Cushman & Jarvis)
G. venezuelana (Hedberg)
Hastigerina aequilateralis (Brady)
Sphaeroidinellopsis seminulina (Schwager)
Pulleniatina obliquilocata (Parker & Jones)

Pleurostomella brevis (Schwager)
P. alternans Schwager
Robulus sp.
Siphonodosaria lepidula (Schwager)
Uvigerina hispida (Schwager)
U. schwageri Brady
U. peregrina Cushman
U. proboscidea Schwager
U. gemmaeformis Schwager
Anomalina balthica (Gmelin)
Bulimina inflata Perner
B. aculcata d'Orbigny
B. rostrata (Brady)
Planulina wuellerstorfi (Schwager)
Sphaeroidina bulloides d'Orbigny
Eponides umbonatus (Reuss)
E. praecinctus (Karrer)
Nonion pompiloides (Fichtel & Moll)
Cassidulina subglobosa Brady
C. sp. nov.
Bolivinita quadrilatera (Schwager)
Ceratobulimina pacifica Cushman & Harris
Ehrenbergina serrata Reuss
Siphogenerina indica Le Roy
S. striata (Schwager)
S. dimorpha (Parker & Jones)
Stilostomella lepidula (Schwager)
S. insecta (Schwager)
Loxostomum karrerianum (Brady)
Cibicides pseudoungerianus (Cushman)
Hogulundina elegans (d'Orbigny)
Pullenia bulloides (d'Orbigny)
Gyroidinoides soldanii (d'Orbigny)

Nodosaria longiscata d'Orbigny
N. sp. cf. N. perversa Schwager
Spiroloculina circularis Cushman
Schenckiella sp.
Eggerella bradyi (Cushman)
Laticarinina pauperata (Parker & Jones)

Radiolaria are common in the finer grained rocks of the Viqueque Formation; the following have been identified by Dr. I. Crespin (unpublished report, 1956):

Acanthosphaera sp.
Porodiscus sp.
Rhapolodictyum sp.

An extremely rich but poorly preserved molluscan fauna is present in local pockets. In particular a coarse friable gravelly sandstone interbedded with clayey marls in the tiny creek called Hebor (N.W. of Hatu Udo, in the southern basin) is remarkable for its molluscan fauna. The following molluscs from the Hebor Creek have been identified by Mr. C.P. Nuttall of the British Museum (personal communication, 1964):

Gastropoda:

? Patella or Acmaea sp.
Fissurella sp.
Trochus sp.
Turbo cf. petholatus (Linné)
Strombus spp.
Naticids
Bursid

Thais cf. carinifera (Lamarck)

Buccinid

Nassarius sp.

Oliva sp.

Neritids of 3 or 4 species

Cypraea belonging to several species

Conus belonging to several species

Scaphapoda:

? Dentalium sp.

Bivalvia:

Barbatia sp.

Glycymeris sp.

Chlamys cf. senatoria (Gmelin)

Ostrea sp.

Anomia sp.

Cardita aff. variegata Bruguière

Miocardia cf. vulgaris (Reeve)

Chama sp.

Lucina sp.

Cardium spp.

Hemicardium sp.

Lamelliconcha cf. philippinarum (Hanley) ?

var. molengraaffi (Tesch)

Lamelliconcha cf. martini Tesch

Veneriids

Corbula cf. erythrodon Lamarck

ENVIRONMENT

The composition and textural immaturity of the silty and sandy rocks, that probably make up more than half of the Viqueque Formation, indicate rapid deposition and crustal instability. The prevalence of graded bedding and graded cycles, the scarcity of current bedded features, together with the frequency of such sedimentary slump structures as armoured mud balls, boulder beds making a sudden appearance in marls, all indicate a molasse type of sedimentation, that in the case of the Viqueque Formation is entirely marine.

Immediately preceeding the Viqueque sedimentation (i.e. during Tf) was an orogenic climax. Compressive forces at that time resulted in the overthrusting of great sheets of Permian strata from the north to their present position in eastern Timor (figures 8 & 13). A huge gravity slide deposit (Bobonaro Scaly Clay) was also emplaced at this time. Also at this time the volcanic activity of the Inner Arc ceased temporarily in Wetar and Alor (van Bemmelen, 1949), probably as a result of this climax of compression. The Viqueque Formation therefore is an immediately post-orogenic deposit.

Since the Bobonaro Scaly Clay was emplaced over probably all the area now occupied by eastern Timor (and far beyond), and since this emplacement was totally submarine, the Viqueque sedimentation began (during Tg) with all of the present island mass submerged. During Tg the present area of Timor began to emerge from the sea and this movement has continued into the present. Thus the clue to all Viqueque sedimentation is that it took

place under regressive conditions.

The lower part of the Viqueque Formation, in which silt and sand are rare, was probably deposited either before the emergence of any land, or while the predominant rock being eroded was the soft clay of the Bobonaro Scaly Clay. With the erosion of hard rocks the composition of the sediments began to change. As the local erosional area increased (due to the island continuing to rise) with the consequent withdrawl of the sea, the shore lines moved outwards, so that in any one vertical section the sediments tend to increase in general coarseness upwards.

The graded bedding and slump structures can be readily understood in terms of periodic phases of uplift of the island resulting in instability of recently deposited sediments with turbidite production.

The elevation of the island during the time of the deposition of the Viqueque Formation was exceptionally rapid (about 2500 metres between Upper Miocene Tg and the end of the Pliocene, i.e. in about 12×10^6 years). Wherever shorelines of the Viqueque sea have been preserved, there is every indication that the shores were steep and rocky. It is extremely unlikely that any coastal plains were developed over which rivers could sort their load. Great torrents of boulders, pebbles, gravels, sands, silts and clays must have poured into the sea during the rainy seasons.

The development of the limestones, marls and finer grained rocks suggest that they must have been deposited some distance from the shorelines and probably during

periods when there was little detritus coming off the island. Such periods could have resulted from a temporary pause in the uplift, or when heavy rains were absent from the region. Today along the coasts of Timor after heavy rains brown muddy waters disgorged by the ephemeral rivers spread out over the surface of the sea for distances up to five miles from the shore, while during the dry seasons the present coastal waters are clear.

The presence of vitric tuffs in the lower part of the Viqueque Formation and the occurrence of volcanic ash in various rocks of the Formation indicate that the volcanic quiescence of the Inner Arc, that accompanied the orogenic climax of mid-Miocene times, was over. Presumably with the waning of compressive forces the volcanoes were regenerated.

The sedimentation of the Viqueque Formation was brought to an end by another orogenic phase at the end of the Pliocene. This was a much milder phase than that which preceded the Viqueque Formation. After the Viqueque Formation was folded it was eroded before marine sedimentation, of a very similar facies, continued through the Pleistocene and Recent to the present time.

PLATE 36

- A. Viqueque Formation - basal conglomerate, cross bedded,
in the Wai Luli River.
- B. Viqueque Formation - slumped horizon of pebbly
mudstone with boulders in marl-
siltstone succession, Colitie
Syncline, River Wai Luli section.
- C. Viqueque Formation - the basal conglomerates (v)
overlie unconformably the Lolotoi
Complex (1), the contact is
exposed in the River Wai Luli.
- D. Viqueque Formation - basal conglomerates in the River
Wai Luli, note the rounding of
pebbles and the sand-silt matrix.

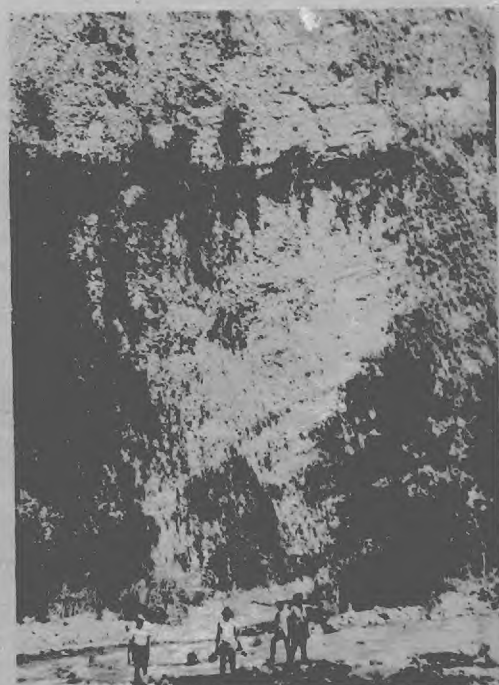


PLATE 37

- A. Viqueque Formation - pebbly mudstone slump interbedded with marls and silty clays. This is a closer view of part of plate 36 B.
- B. Viqueque Formation - graded arenite above marls.
- C. Viqueque Formation - intraformational conglomerate with clasts of white marls and chalk in a clay matrix.
- D. Viqueque Formation - siltstone with cross bedding.

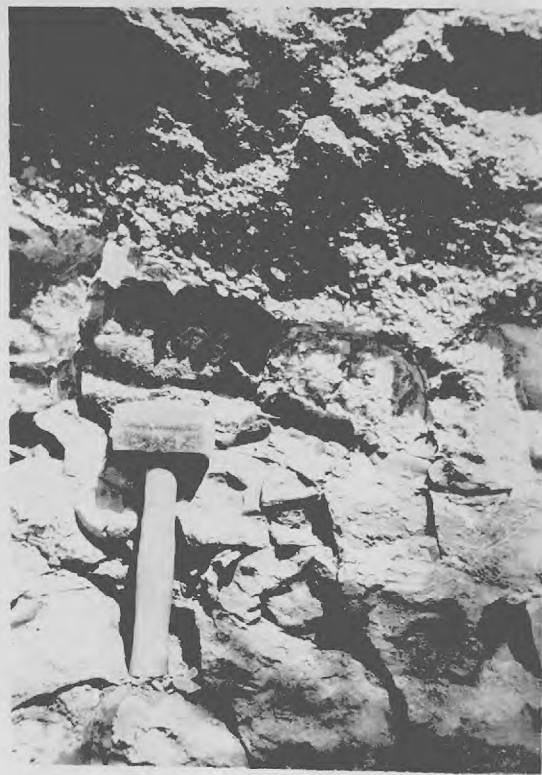


PLATE 38

- A. Viqueque Formation - note northward dipping beds of the Colitie Syncline.
- B. Viqueque Formation - pebbly mudstone (silty) slumped horizon in marls, Colitie Syncline.
- C. Viqueque Formation - bedded marls and sandstones of the Viqueque Anticline in the River Cua section.
- D. Viqueque Formation - Dilor Conglomerate Member from the Dilor Syncline.



PLATE 39

- A. Viqueque Formation - Lari Gutí Limestone Member, biospararenite with some terrigenous clasts present (x 20).
- B. Viqueque Formation - biospararenite consisting exclusively of Foraminifera with a very little sparry calcite cement: a foraminiferal-ooze (x 20).
- C. Viqueque Formation - calcilutite (biomicarenite) with numerous Foraminifera and a few Radiolaria: a foraminiferal-ooze (x 20).
- D. Viqueque Formation - biospararenite with recrystallised echinoderm fragment (e). This fragment of an echinoderm (e) is now composed of a granular mosaic of microsparite. Note other allochems present, algae and Foraminifer (f) (x 55).

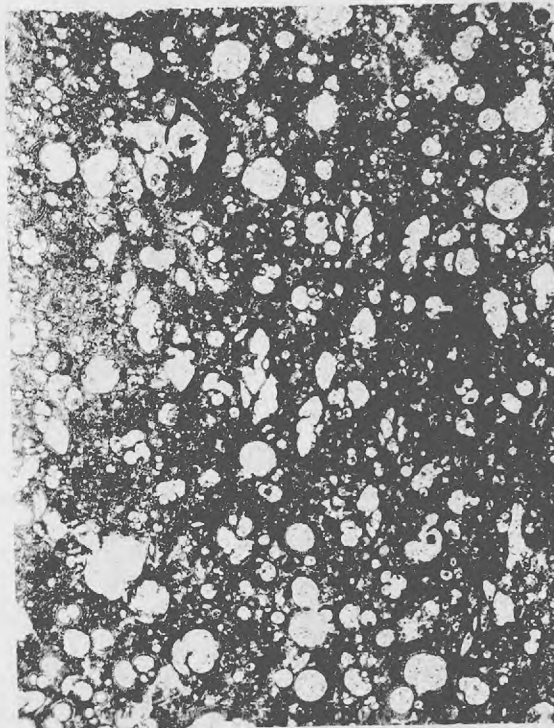
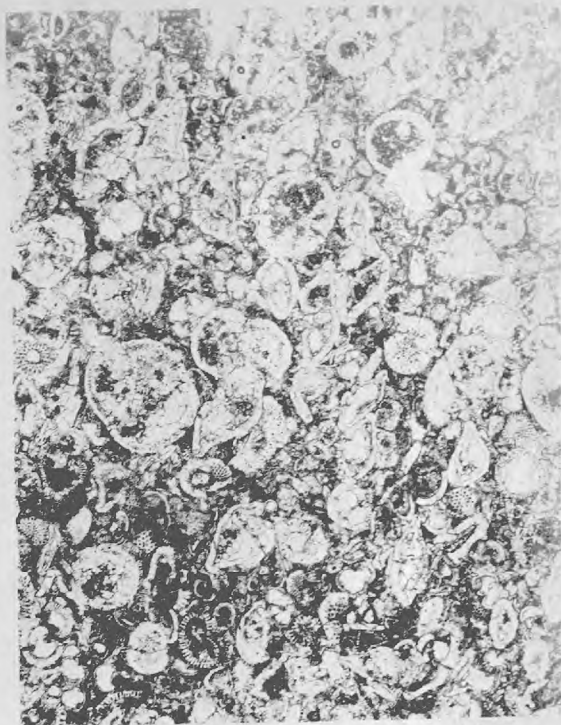
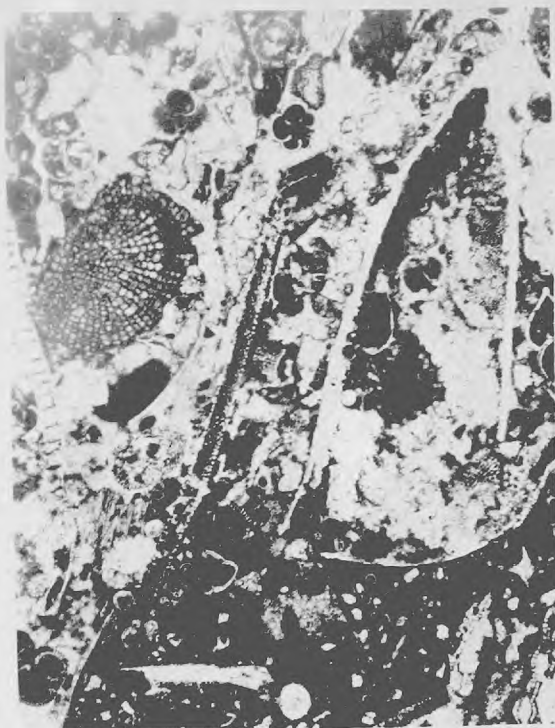


PLATE 40

- A. Viqueque Formation - arenite with well rounded clasts most of which are lithic grains of volcanic rocks (x 20).
- B. Viqueque Formation - arenite with large Foraminifera and some lithic grains (x 20).
- C. Viqueque Formation - Lari Gutí Limestone Member, stromatoporoid reef limestone with cavity filled with reef debris with a micrite matrix (x 4).
- D. Viqueque Formation - arenite, siltstone with large Foraminifer and many volcanic rock clasts (x 50).

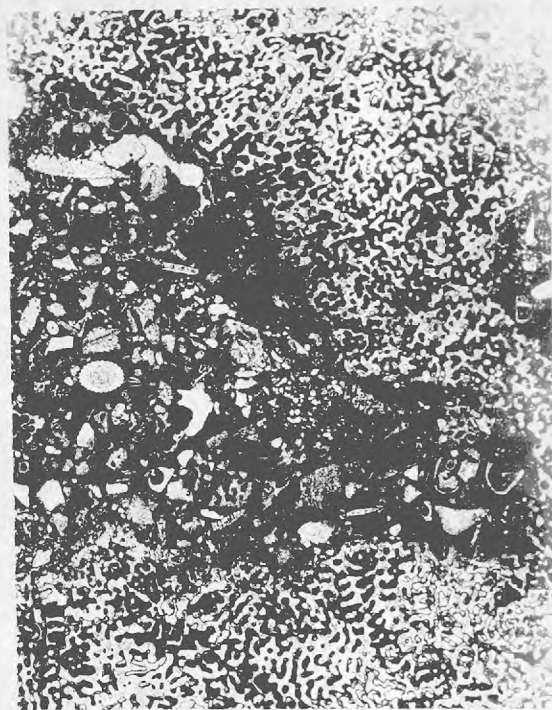
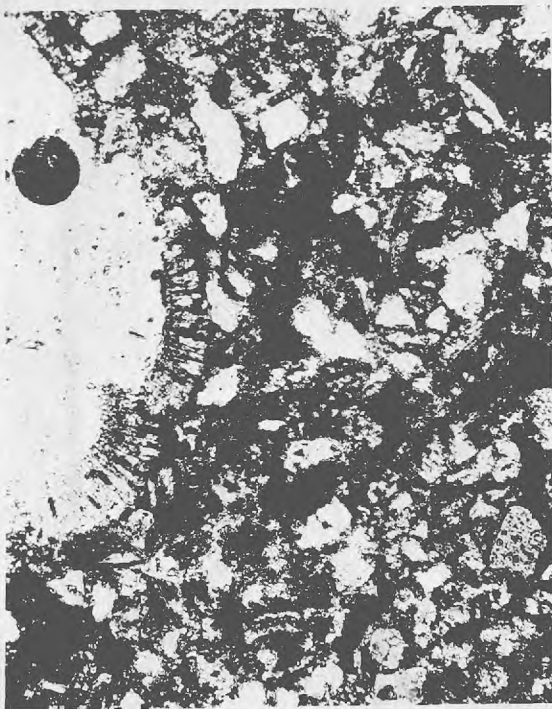
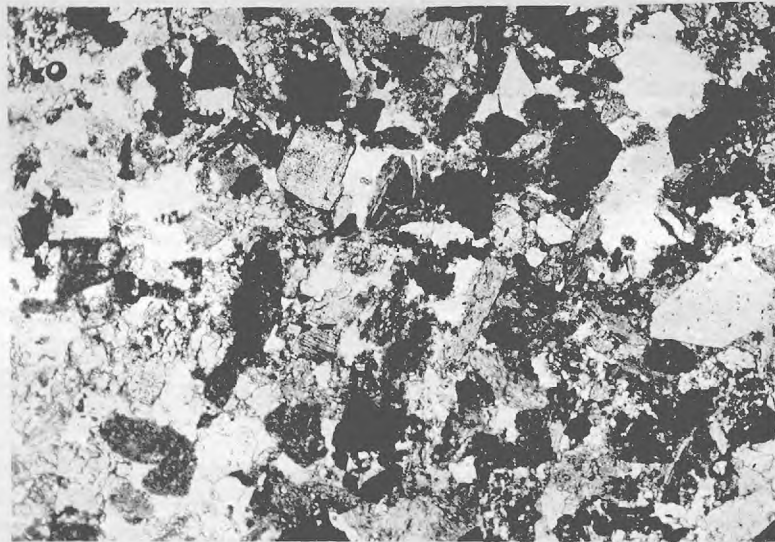
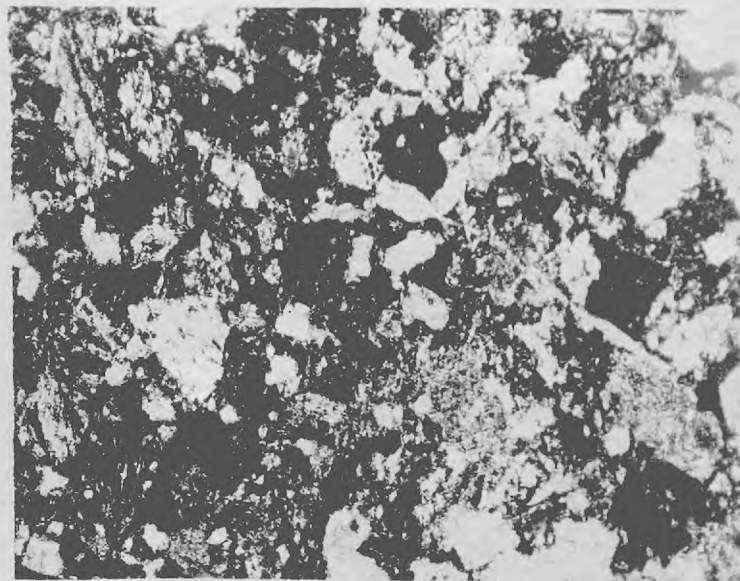
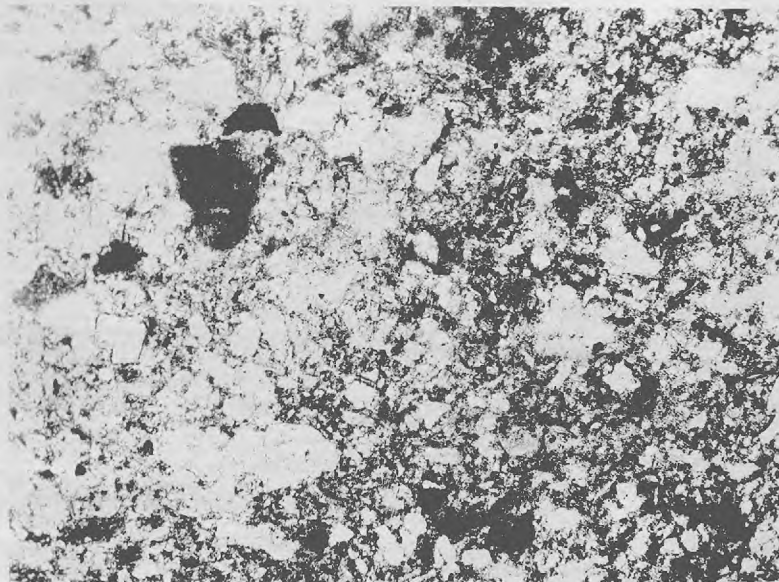


PLATE 41

- A. Viqueque Formation - arenite with a silt-clay matrix, note lithic grains of quartzite, volcanic rock and limestones with some foraminiferal debris (x 25).
- B. Viqueque Formation - Dilor Conglomerate Member, hills of Dilor Conglomerate near Beco, looking north.
- C. Viqueque Formation - arenite with many calcite clasts of uncertain origin, some are limestone detritus. Other clasts of quartz and volcanic rocks, clay-silt matrix (x 20).
- D. Viqueque Formation - arenite with mixed clasts of limestone, volcanic rocks and quartz with a little calcite cement. Porous (x 20).



LARI GUTI LIMESTONE MEMBER OF
THE VIQUEQUE FORMATION.

The type locality for this Member is the series of cliffs on the west side of the Lari Guti Pass between the mountains Lari Guti and Mundo Perdido (also known as Wai Neti). This Member has no known representative outside the type locality. It was probably never deposited over a very wide area but erosion must have reduced it quite considerably.

LITHOLOGY AND PETROGRAPHY

Basically this Member consists of an alternating series of calcarenites and in situ thin coral bioherms. The total thickness is about 75 metres. Two types of limestone are distinguished: calcarenites and biolithites.

Biolithites.

These consist of in situ growths of colonial corals, algae and stromatoporoids forming beds about 5 metres thick. Intimately associated with these reefs are small banks of molluscan shells loosely and patchily cemented together. Plate 40C illustrates a small cavity in the stromatoporoid reef filled with reef debris of various kinds. This demonstrates that micrite as well as sparry calcite is closely associated with these reef limestones.

Calcarenites.

The calcarenites are coloured a honey yellow, and well bedded, with individual beds varying between 1 and 3

metres thick. In the field these beds of calcarenite have a very similar appearance. Thin section reveals that their texture and cementation is very similar but that there is a wide variety of allochems and terrigenous clasts. Some of these calcarenites consist of little else than foraminiferal sands with a sparry calcite cement. This type of rock is illustrated in plate 39B. Other calcarenites contain a much wider spectrum of allochems such as: coral fragments, bryozoans, Foraminifera, calcareous algae, echinoderms, molluscan debris, quartz grains and various rock fragments. The terrigenous clasts are always of minor importance. Plate 39A illustrates another type of calcarenite.

Diagenetic changes in these calcarenites seem to be limited to the following processes: (i) exsolution of aragonitic structures, (ii) the conversion of aragonitic structures such as corals to calcite, (iii) sparry calcite cementation, (iv) an unusual process whereby echinoderm fragments have recrystallised to a fine granular calcite mosaic. As far as is known this last phenomenon (iv above) has not been reported before. Plate 39D shews one of these recrystallised fragments. It is difficult to suggest a cause for this process; perhaps it is related to the relative solubilities of Mg-poor calcite, Mg-rich calcite and aragonite. Echinoderms are composed of Mg-rich calcite which is the most soluble of them all.

STRATIGRAPHIC POSITION

The Lari Gutti Limestone Member rests with angular unconformity on the Barique Formation (Oligocene Tcd), the Cablac Limestone (Lower Miocene Te), and the Bobonaro

Scaly Clay (Upper Miocene Tf). The Lari Gutí Limestone is uncovered. It has been dated as Upper Miocene (Tgh) on the basis of its microfauna. It is now about 1300 metres above sea level, and probably represents some of the oldest rocks (Tg) of the Viqueque Formation, having been deposited when the peaks of the Cablac Limestone began to emerge from the sea in the centre of the rising island.

The following Foraminifera have been identified by Mr. A.R. Lloyd (unpublished report, 1962) of the Bureau of Mineral Resources, Canberra, Australia:

Orbulina universa d'Orbigny
Globigerina mayeri (Cushman & Ellisor)
Globorotalia menardii menardii (d'Orbigny)
Sphaeroidinella dehiscens (Parker & Jones)
Pulleniatina obliquiloculata (Parker & Jones)

Dr. C.G. Adams (personal communication 1964) has identified the following Foraminifera from Lari Gutí:

Slumbergerella floresiana (Slumberger)
Slumbergerella neotetraedra (Tobler)

The following calcareous algae have been identified by Mr. G.F. Elliott (personal communication, 1963):

Halimeda sp.
Amphiroa cf. fragillissima (Linn.) Lamx.
Lithothamnium cf. engelhardtii Foslie
Lithothamnium sp.

Other fossil material found in these rocks includes

bryozoans, echinoderms, corals and molluscs. The following molluscs have been identified by Mr. C.F. Nuttall of the British Museum (personal communication, 1964):

Gastropoda:

- Trochus sp.
- Turbo cf. petholatus (Linné)
- Turbo (Marmarostoma) cf. ticaonicus (Reeve)
- Vermetus sp.
- Strombus sp.
- Trivia sp.
- "Amphiperas" sp.
- Cypraea (Erosaria) cf. erosa Linné
- Cypraea (Cribraria) aff. teres Gmelin
- Cypraea indet. belonging to several species
- Mammila sp.
- Naticid
- Lampusia cf. pileare (Linné)
- Cymatiids or Bursids indet.
- ? Peristernia sp.
- Conus lividus Bruguière
- Conus spp.

Bivalvia:

- Barbatia sp. A.
- Barbatia sp. B.
- Glycymeris pectunculus (Linné)
- Lithophaga sp.
- Spondylus sp. A.
- Spondylus sp. B.
- Lima cf. lima (Linné)

Plicatula cf. *australis* Lamarck

Gloripallium pallium (Linné)

Pectinid indet.

Ostrea sp. A.

Ostrea sp. B.

Cardita aff. variegata Bruguière

Miocardia cf. vulgaris (Reeve)

Trapezium aff. oblongum (Linné)

Chama sp.

Nemocardium (? Lyrocardium) bechei (Reeve)

Vasticardium sp.

? Pitar sp.

Dosinia sp.

Echinoids from this Member have been identified as largish Clypeasteroids by Dr. R.F.S. Jefferies (personal communication, 1964)

ENVIRONMENT

The rocks of this Member represent a shore facies of beach sands of varying composition, fringing coral, algal, and stromatoporoid reefs and shell banks. Conditions were very much like those of today around the rocky beaches of Timor, with shallow, clear warm water. From the position of these rocks in relation to the Lower Miocene Cablac Limestone and Oligocene volcanic rocks of the Barique Formation, it is apparent that the Lari Gutí Member formed a fringing beach and reef to a number of small islands composed of older limestones and volcanic rocks. The composition and angularity of the non-carbonate grains in these rocks suggests a very local derivation.

The interesting alternation of calcarenites with reef growths in a vertical section probably reflects the phases of uplift of the emerging island. The coral growth representing the more stable periods, and the sands resulting from the elevation of the reefs with their concomitant subjection to erosion.

It is probable that while this Member was being deposited the lower part of the Viqueque Formation was accumulating in the deeper seas to the north and south of the central topographic axis where this Member is found today.

DILOR CONGLOMERATE MEMBER OF THE VIQUEQUE FORMATION

The type locality for this Member is the axis of the Dilor Syncline immediately south-east of Dilor village. (enclosure 1C). Here and north-west of the village the poorly consolidated conglomerates with coarse unsorted sands form small hills. A wide range of grain sizes is found from large boulders to silt. Locally silts and silty muds form lenticles in the conglomerates. The composition of the detritus varies widely, but most of the material appears to have been derived from the metamorphic rocks (particularly the quartzites) of the Lolotoi Complex, that since the beginning of Pliocene times have formed

steep mountains north of Dilor.

Graded bedding is seldom seen, and in contrast to the upper and lower parts of the Viqueque Formation cross bedding is widespread. Numerous local unconformities are recognisable. There is a distinct increase in sorting in a southerly direction, that is away from the old shore line into deeper water.

The Dilor Conglomerate Member has a wide distribution along the southern part of eastern Timor (i.e. in the southern basin), between the Luca River and the South Laclo River, a distance of about 30 km. Here it forms a narrow belt of poorly consolidated boulder and pebble conglomerates that grade south into coarse sands (plate 38D). It occurs elsewhere in the southern basin as small remnant outcrops of what must have been part of this same belt, (plate 41B). This Member has not been distinguished in the other 'basins' of eastern Timor, but a very similar facies has been seen locally in both the other 'basins'.

The thickness of this Member is very variable; in the type locality it is about 300 metres thick, elsewhere similar thicknesses are observed only locally, generally it is less than this.

Commonly this Member has a dark red lateritic cover of about 1 or 2 metres thickness. This is particularly well developed in the type locality.

STRATIGRAPHIC POSITION

In the type locality the Dilor Conglomerate Member

overlies marls of the Viqueque Formation with a slight disconformity. Elsewhere when not overlying the Viqueque Formation this Member is found to be unconformable upon the Bobonaro Scaly Clay (Tf), the Cablac Limestone (Te) or the Barique Formation (Tcd). The Dilor Conglomerate Member is commonly overlain unconformably by the Pleistocene Baucau Limestone, or by the Pleistocene Suaí Formation. On the basis of the microfauna contained in sand and mud lenses within the Dilor Conglomerate it has been dated as Pliocene. This accords well with its stratigraphic field relations to other formations.

The following Foraminifera have been identified by Dr. I. Crespin (unpublished report, 1959):

Globigerina subcretacea Lominicki
Globigerinoides rubra (d'Orbigny)
G. trilobus (Reuss)
Globorotalia menardii (d'Orbigny)
G. sp.
Orbulina universa d'Orbigny
Amphistegina lessonii d'Orbigny
Bulimina marginata d'Orbigny
B. ovata d'Orbigny
B. striata d'Orbigny
Cassidulina pacifica Cushman
Ceratobulimina pacifica Cushman & Harris
Eponides praecinctus (Karrer)
Elphidium macellum (Fichtel & Moll)
Planorbulinella larvata (Parker & Jones)
Rotalia schroeteriana Parker & Jones
Uvigerina hispida Schwager
Ammodiscus sp.

Cyclammina sp.

Glomospira aff. G. charoides (Jones & Parker)

Pullenia sp.

Rectoglandulina comata (Brady)

Operculina sp.

Radiolaria: Cenosphaera sp. and Carposphaera sp.
and indeterminate Ostracods were also recorded by Dr. I.
Crespin.

ENVIRONMENT.

The textural immaturity of the boulder beds and sands, the strong cross bedding, the absence of graded bedding, and the lenticular bodies of sand and mud all suggest that this Member represents a marine deltaic deposit. These deltas formed when crustal movements began to fold the Viqueque Formation and rapidly regenerated the topography towards the end of the Pliocene.

The compressive forces that folded the soft rocks of the Viqueque Formation probably resulted in a tightening of the folds in the older formations with much concomitant faulting. It was some of these larger faults (probably rejuvenated older structure) that produced great fault scarps such as the Bibiliu Fault north of the type locality. This huge fault scarp (a reversed fault) elevated the metamorphic rocks of the Lolotoi Complex from which much of the material of the Dilor Conglomerate is derived.

SEKETO BLOCK CLAY MEMBER OF
THE VIQUEQUE FORMATION

The type locality for this Member is on the banks of the Seketo River (enclosure 1C), south of the Builo Range, and in the axis of the Bibiliu Syncline. Here the block clay has a white to pale grey colour, and consists of a clayey marl matrix in which a variety of unsorted, angular and subangular blocks (clasts) of older formations (and of the Viqueque Formation itself) are scattered. It may be classified as a pebbly mudstone type of deposit as defined by Crowell (1957). In this respect it may be compared with the Bobonaro Scaly Clay, but it does not have the scaly, fissile clay matrix that is so characteristic of that formation. There is no difficulty in distinguishing these two deposits. The Seketo Block Clay Member consists of a number of these pebbly mudstones interbedded with typical Viqueque marls rich in large Foraminifera.

Outside the type locality this Member is found in a number of isolated pockets in the southern basin. The maximum thickness of this Member is about 20 metres.

STRATIGRAPHIC POSITION

This Member always overlies the upper part of the Viqueque Formation. It is sometimes itself overlain by the Dilor Conglomerate Member. The Seketo Member belongs therefore to the upper part of the Viqueque Formation. The marls with which this Member is interbedded have been dated as Pliocene on the basis of their microfauna.

ENVIRONMENT

This kind of pebbly mudstone is usually formed as a submarine gravity slide of an unstable clay mass (Crowell, 1957). This block clay may be considered as a particular kind of slumped sediment. Sedimentary slump structure of various kinds are common in the upper part of the Viqueque Formation. Such structures reflect the instability of the environment.

CORRELATION OF THE VIQUEQUE FORMATION BETWEEN EASTERN AND WESTERN TIMOR

As has been shewn above the Viqueque Formation and its members represent a marine molasse deposit having highly characteristic features. They were deposited during the time interval of the Upper Miocene and Pliocene (Tgh). During this time the island of Timor emerged from the sea, so that these sedimentary rocks are essentially a regressive facies.

In western Timor there is a large Central Basin filled with sedimentary rocks that range from the Upper Miocene to Pleistocene or Recent (van Bemmelen, 1949). Although there is some obscurity about the actual age of various horizons, due to variations resulting from the employment of either a molluscan or foraminiferal fauna, it is possible to make the following tentative correlations based on the data in van Bemmelen (1949): -

- 1) Dilor Conglomerate Member, Seketo Block Clay Member, and the upper part of the Viqueque Formation are correlated with the Zone III and Zone IV of De Bruyne, (1941); the age of these rocks being Th.
- 2) Lari Gutu Limestone Member, and the lower part of Viqueque Formation are correlated with Zone I and Zone II of De Bruyne (1941); the age of these rocks being Tg.

There is an unconformity at the base of Tg and at the end of the Pliocene in eastern and western Timor.

In western Timor outside the Central Basin little seems to be known of the rocks of this age and facies. In the correlation map figure 10 it is tentatively suggested that below the wider coastal plains of western Timor the Viqueque Formation (i.e. its equivalent in the west) is present, as it is below the wide coastal plains of eastern Timor.

THE POST-PLIOCENE ROCKS OF EASTERN TIMOR.

SUMMARY

Four separate formations representing three very different environments((marine, lacustrine and alluvial) are described. They were all deposited after the folding of the Viqueque Formation that took place in late Pliocene times. They all reflect the continued emergence of the island of Timor from the sea.

INTRODUCTION

Four post-Pliocene formations are recognised in eastern Timor, They are named and defined here for the first time as the Baucau Limestone, Poros Limestone, Suai Formation and the Ainaro Gravels. With the exception of the Ainaro Gravels, that probably ranges in age from lower Pliocene to Recent, they were all deposited after the folding of the Viqueque Formation in late Pliocene times (Th).

Earlier workers van Bemmelen (1949), Grunau (1953 & 1956), Gageonnet & Lemoine (1958) and Leme (1963) while recognising some or all of the various facies did not define formations nor describe type localities, but dealt with them in a cursory general way.

BAUCAU LIMESTONE

The type locality for the Baucau Limestone is the series of terraced coral reef limestones that outcrop about the town of Baucau (8° 30'S, 126° 30'E) from the

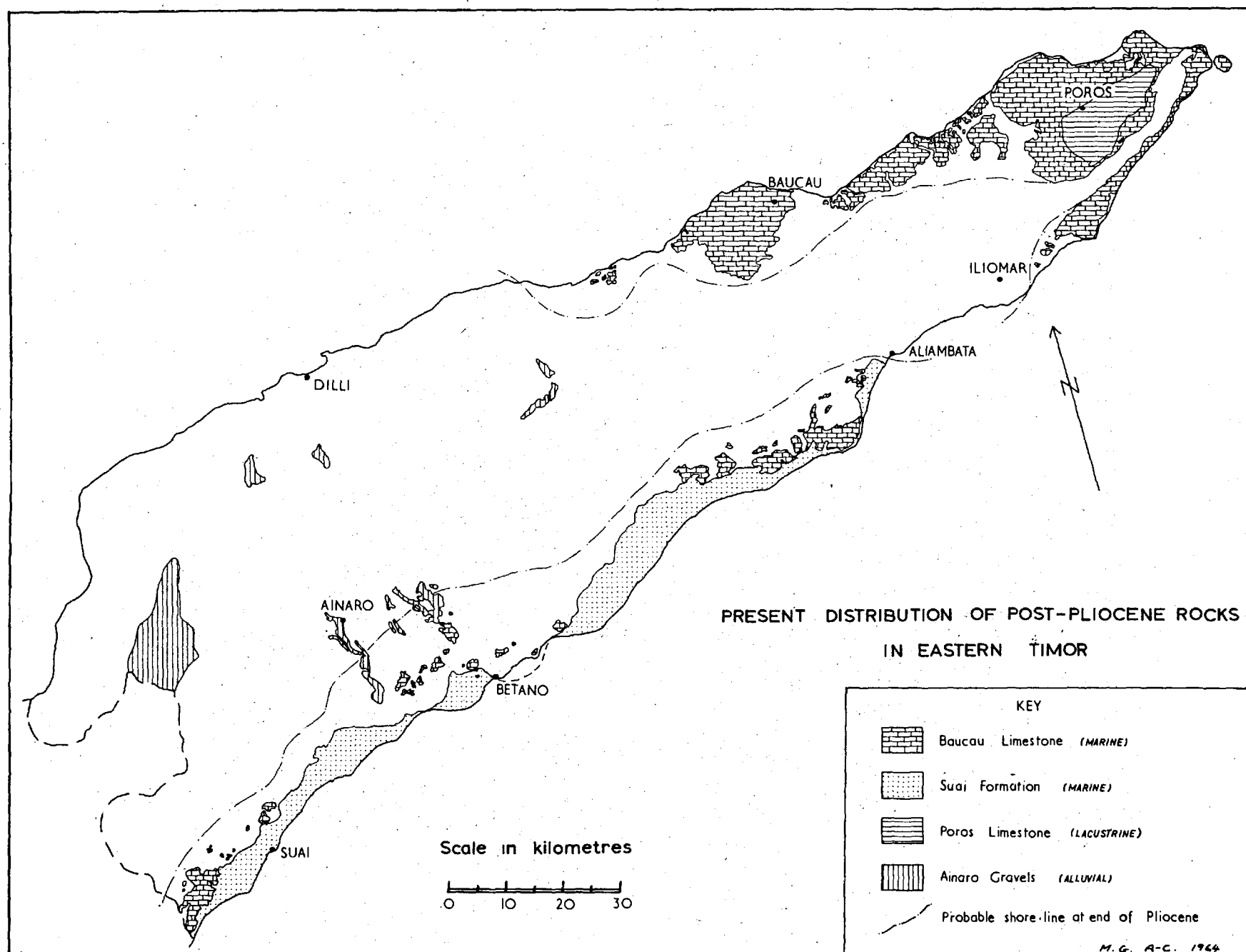


Fig. 11

airstrip on top of the plateau down to the present beach. In the type locality the formation is composed of a hard, vuggy, cavernous, massive, white coral reef limestone. The limestone weathers to a pale grey colour. It is particularly susceptible to a weathering by dissolution, so that karst topography with a dark reddish soil characterises the top of the Baucau Plateau (plate 2A). The thickness of the formation is difficult to estimate because it is composed of a series of terraces that are either horizontal or have a dip of less than 2 degrees. These terraces, that may be seen in plates 2C, 42A, 42C, 42D & 45D, rise from present sea level to about 500 metres on top of the plateau. The maximum thickness, based on the greatest vertical separation between two terraces, is probably about 100 metres.

This formation consisting predominantly of massive reef limestones is very widespread (figure 11), and particularly well developed in the eastern part of eastern Timor. It forms two prominent topographic features, the Baucau Plateau and Lospalos Plateau (plates 42C & 2C) respectively. Between these two features there is almost continuous outcrop of the formation along the north coast. In the foothills close to the southern coast of Timor the Baucau Limestone forms scattered remnant outcrops, some of which, such as those of the Ossulari region (south of Viqueque village), are extensive. It is significant that the elevated coral reefs and their debris of the Baucau Limestone are not found above 500 metres, and furthermore that the highest preserved terrace of the Baucau and Lautem Plateaus is at about the same height as the highest terrace in the south-west part of eastern Timor (i.e. close to the border with Indonesian

Timor). Earlier workers reported much greater elevations for these reefs, for example Umbgrove (1938) quoted 600 metres, Gageonnet & Lemoine (1958) about 1000 metres, Leme (1963) mentioned reefs at 1300 metres. These coral reefs found at elevations above 500 metres are Upper Miocene and Pliocene (Tgh) in age and belong stratigraphically to the Lari Gutu Member of the Viqueque Formation.

At the western and eastern extremities of the Baucau Plateau and close to the present coast a different facies of this formation is exposed. This facies is composed essentially of arenites: a series of pebble and gravel conglomerates, sands and silts as well as calcarenites rich in reef detritus. Various beds of pebble conglomerates, sands and silts are illustrated in the plates 45A, 43D, 45C. These arenites are well exposed in the cliffs that run parallel to the north coast between the two Plateaux. This facies is also developed in the region west of the Baucau Plateau towards Manatutu. Strictly this facies should be separated from the Baucau Limestone as a Member of that formation. However as insufficient attention was paid to detail in the mapping of this region the distinction is not practicable at the present time. The village of Laga ($8^{\circ} 40'S$, $126^{\circ} 37'E$) on the north coast east of Baucau would provide a very suitable type locality, for the Laga Sand Member.

LITHOLOGY

Coral reef limestones.

These limestones are massive and dense growths of coral with subordinate amounts of other reef organisms

such as stromatoporoids, calcareous algae, molluscs and echinoderms. They are in situ growths of colonial corals with closely associated reef debris that fills cavities of various dimensions in the coral reef. Much of the actual coral material is aragonite, although locally some is now calcite. The calcareous mud that fills cavities is usually calcite. Sparry calcite in the form of granular and drusy mosaics is commonly developed.

Calcirudites.

Massive, poorly bedded conglomerates, composed of reef debris of various kinds lightly cemented by micrite and locally sparry calcite form lenticles with the in situ coral growths. These semi-friable rubble conglomerates are illustrated in the plates 43A, 43B, 43C.

Calcarenites.

Locally the reef limestones are interbedded with calcarenites and calcirudites of the kind described above. Sands consisting largely of terrigenous grains are also developed locally. The calcarenites consist almost entirely of sand size grains of corals, bryozoans, stromatoporoids, Foraminifera, calcareous algae, molluscs and echinoderms. A small fraction (usually less than 10 percent) of the grains are terrigenous in origin, mainly quartz and volcanic rock fragments. Many of the calcarenites contain pebbles of various sizes as well as gravel sized grains of terrigenous origin (mainly quartz, volcanic rock and limestone fragments). Plate 43A illustrates these calcarenites.

One interesting feature is the rhythmic pattern of sedimentation; in situ coral reef growths alternate with arenites consisting largely of reef debris. This same pattern was found in the Lari Gutu Member of the Viqueque Formation (enclosure 12) that represents the same facies developed before the late-Pliocene folding.

Submature greywacke - pebbly sandstone.

Under this heading are grouped the sediments that predominate the Laga Sand Member. They are gravels, sands and silts, all poorly sorted, all submature greywackes (Folk, 1954). They are composed mainly of quartz, with lesser amounts of volcanic rock particles and limestone clasts. The pebbles are mostly rounded and subrounded while the finer grade particles are angular or subangular. These sands are illustrated in the plates 43D, 45A, 45C.

It is significant that this member is found along the north coast between the two plateaux and to the west of Baucau Plateau towards Manatutu. It is developed in those areas where today rivers flow into the sea. This will be discussed later in dealing with the problem of the environment.

STRATIGRAPHIC POSITION

The Baucau Limestone is always unconformable at the base. Generally it overlies the Viqueque Formation, but locally it is found on older formations. It is clearly younger than the late-Pliocene folding that affected the Viqueque Formation, and it is therefore reasonable to regard it as Pleistocene at the base of the higher terraces.

The terraces can be traced outwards and at decreasing elevations towards the present shore line. Thus the formation ranges from the Pleistocene (probably lower Pleistocene) to the Holocene. The formation can be seen in the process of development and growth today in the sea below the terraces (plate 42A).

Most of the fauna of this formation has received very little attention, but the following molluscs have been determined by C.P. Nuttall of the British Museum (personal communication, 1964):

Trochus sp.

Turbo cf. petholatus (Linné)

Cypraea (at least two species)

Manupecten aff. tigris (Lamarck)

ENVIRONMENT

The composition of the cliffs along the coast east of Manatutu are so often a mirror image of the sediments forming today in the sea at the foot of these cliffs that it is immediately apparent that the Baucau Limestone is a series of raised beaches. The terraces mark the stages of uplift of the island during the Pleistocene and Recent. These terraces must of course incorporate the effects of world wide sea level changes due to the Pleistocene glaciation, but as the terraces rise to 500 metres above present sea level the effects due to glaciation are much less than those resulting from uplift (plates 42C, 42D, 45D and 46B).

The Laga Sand Member which is found developed about

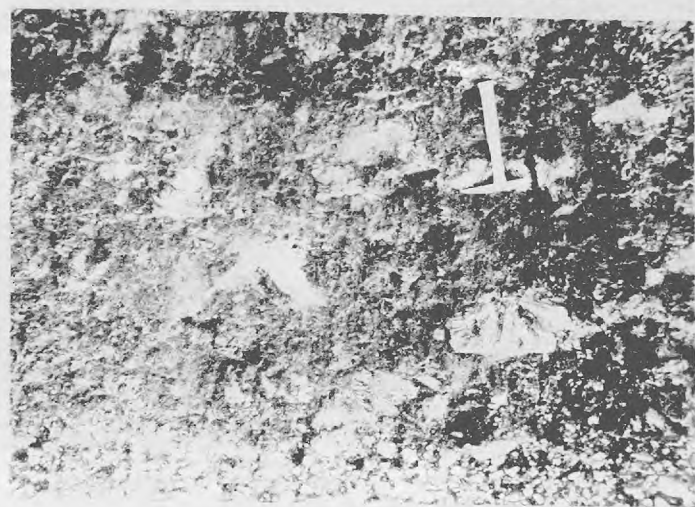
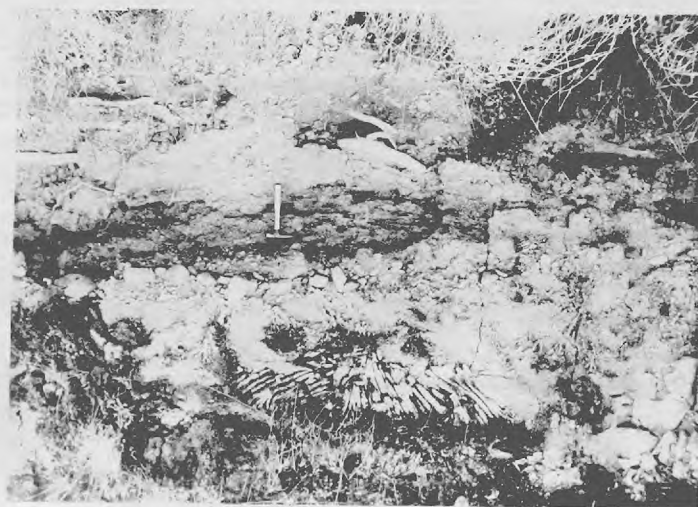
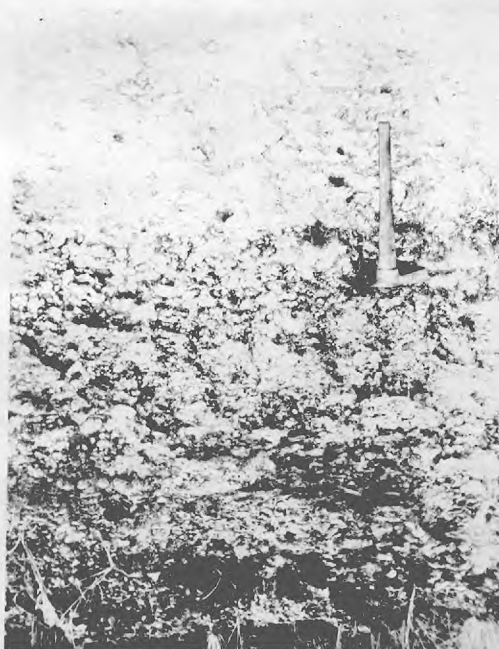
PLATE 42

- A. Baucau Limestone (r) and modern living coral reef (e).
- B. Baucau Limestone - sea stacks of coral limestone
now being eroded in the place
where they grew after being
uplifted.
- C. View looking west from Mt. Mata Bia, (s) - Mt. Lari
Tame composed of Cablac Limestone, (n) - Baucau
Plateau composed of Baucau Limestone, note the extremely
flat horizontal disposition of the Plateau which is
seen in profile against the setting sun.
- D. Looking north up the River Veru. The rugged hills (r)
of Aitututu Formation, and the raised terraces (s) of
the Baucau Limestone.



PLATE 43

- A. Baucau Limestone - in situ coral growths,
calcarenites and calcirudites.
- B. Baucau Limestone - calcirudites
- C. Baucau Limestone - in situ coral growths, calcarenites
and calcirudites.
- D. Baucau Limestone - arenites and calcarenites.



the present day rivers demonstrates that the same rivers were active during the Pleistocene and Recent. It was probably these rivers with their load of detritus that inhibited coral growth and resulted in the development of the largely terrigenous sands.

The alternation of the coral limestones with beds of reef debris and calcarenites of various kinds reflects the periodic shifts in sea level during the Pleistocene and Recent due to the uplift of the island and to a lesser degree to the phases of glaciation at higher latitudes.

POROS LIMESTONE

The type locality for this formation is about the village of Poros ($8^{\circ}27'S$, $127^{\circ}05'E$) near the centre of the Lautem Plateau. This limestone was first distinguished by Leme (1963) who referred to it as the Lacustrine Limestone. This formation is restricted to the central part of the Lautem Plateau (figure 11 and enclosure 1D). It is poorly exposed, very pale brown or cream in colour when fresh, it weathers to a grey colour that renders it superficially similar to the Baucau Limestone. A hard, thinly bedded limestone, it is very rich in gastropods and algal growths. Locally it is vuggy partly because the gastropods tend to dissolve away more readily than the matrix. When freshly broken the limestone frequently has a strong foetid odour.

Since this formation supports a particular vegetation it can be distinguished from the Baucau Limestone on the aerial photographs.

LITHOLOGY

Principally this is an algal limestone. It is difficult to estimate its thickness since it is poorly exposed and flat lying, but it is possibly of the order of 20 metres.

In thin section the algal structures are apparent but poorly defined. The polished surface of the hand specimen reveals the characteristic algal banding. All the rocks of this formation are very similar. They are composed mainly of a dense micrite in which algal structures and gastropods are enveloped. Occasionally vugs are filled with sparry calcite having a drusy mosaic. A few very small and sharply angular quartz grains are usually present.

STRATIGRAPHIC POSITION

The base of the Poros Limestone is never seen, but there must be a diastem between the Poros Limestone and the underlying Baucau Limestone. The Poros Limestone is now about 400 metres above sea level, it rests only on the Baucau Limestone, and is covered only by a modern soil and in places by a lake. As the Poros Limestone is a lacustrine limestone, the eastern end of Timor (where it is found) must have been elevated above sea level before the deposition of the Poros Limestone could begin: this elevation took place after the older part of the Baucau

Limestone, on which the Poros Limestone rests, had been deposited. It is therefore unlikely that the base of the Poros Limestone is older than middle Pleistocene, probably it is considerably younger. The upper part of the Poros Limestone is Holocene, and it seems probable that it is still forming today in the Surubeco Lake on the southern side of the Plateau.

The following non-marine molluscs have been determined by Dr. M.Kerney (personal communication, 1965):

Melaniidae

Planorbidae

ENVIRONMENT

The molluscan fauna indicates that this is a lacustrine limestone. The stratigraphic position of this formation, and the presence of the Lake Surubeco in which a modern molluscan fauna is apparently thriving and in which a calcite mud is being deposited enables the environment in which the Poros Limestone formed to be defined without equivocation. The withdrawal of the lake to the southern part of the plateau may be due either to very gentle tilting in that direction; in any event the size of the lake has decreased, perhaps this is due to lower rainfall, or to drainage schemes imposed on the area by man.

SUAI FORMATION

The type locality for this Formation is the coastal plain around Suai village. There is a wide coastal plain where the Formation is developed from Aliambata in the east to the frontier with Indonesia in the west (figure 11). This plain is only seriously interrupted in the Betano area. The Formation is very poorly exposed because the terrain is without relief, and because often dense vegetation of the 'jungle' type, provides a thick cover, and because of the Holocene deposits of the numerous braided rivers that cross these plains (plate 4B).

Most of the information about this Formation has come from the slim hole drilling programme carried out in the area north of Suai, and from the well Matai No. 5 put down at the village of Camanassa (3 km. north of Suai). This well encountered about 600 metres of marine post-Viqueque Formation sediments, most of which were arenites. On the north coast this Formation is developed in small isolated pockets where it is probably always less than 20 metres thick.

LITHOLOGY

No detailed study has been made of this Formation that is really only made accessible to study by drilling. Information available from what little drilling has been done (all in the Suai area) indicates that most of the sediments are arenites ranging from pebbly gravels to fine silts, often rich in Foraminifera, and largely unconsolidated. One horizon consisting of 50 metres of loose uncemented Foraminifera was penetrated in well

Matai No 5. The Suai Formation may be regarded as being very similar to the upper part of the Viqueque Formation, except that there is an absence of cement or consolidated sediments.

The thickness of the Suai Formation in the well Matai No. 5 is about 600 metres (the base is difficult to define accurately on the available information). The Formation very probably thickens rapidly to the south and continues to do so for some distance beyond the present shore line. The maximum thickness attained by this Formation within the present limits of Timor is probably under the plain between Betano and Aliambata (enclosure 1C) where a total of about 1000 metres or more may be achieved.

STRATIGRAPHIC POSITION

The Suai Formation overlies the Viqueque Formation and the Dilor Conglomerate Member of the Viqueque Formation. It is very probable, as the Viqueque Formation was folded in late-pliocene times, that there is a diastem of varying local importance at the base of the Suai Formation. Further south and particularly off the present shore line this break will become of decreasing importance.

Although the fauna of the Suai Formation has not been studied it is most likely that at the base it is lower Pliocene and ranges up through the Quaternary.

ENVIRONMENT

The presence of Foraminifera throughout most of the section of Matai No. 5 indicates that the Formation

accumulated under marine conditions. The very close similarity between the Suai Formation and the upper part of the Viqueque Formation that underlies the Suai Formation suggests that they were deposited under similar conditions. The Suai Formation may be considered as a molasse deposit of a totally marine facies. Like the Viqueque Formation it is essentially a regressive facies deposited during the continual emergence of Timor from the sea.

AINARO GRAVELS

The type locality for this formation is the terrace now about 800 metres above sea level on which the village of Ainaro stands (enclosure 1A). This terrace is the highest of a series of river terraces decreasing in elevation downstream (southward). These terraces are composed of typical alluvium; boulder and pebble gravels, sands, silts, strongly cross bedded and lenticular in geometry. At Ainaro these terraces have been left behind by the river that has cut a deep gorge now about 60 metres below the top of the highest terrace (plate 44A).

Outside the type locality similar alluvial terraces left stranded above the present river beds are found at Laclubar, Cribas, Samé, Aileu, Railaco, and a huge terrace is found immediately east of the River Lois, (plate 3A, 44B). This latter terrace forms the eastern end of the

great Central Basin of Timor discussed earlier when dealing with the Viqueque Formation. The distribution of these various terraces is shown in figure 11. After the terraces at Ainaro the most dramatic are those in the Laclubar - Cribas district in the valley of the Sumasse (enclosure 1C). Here the upper terrace is now about 1000 metres above the bed of the River Sumasse.

These alluvial terraces were given only brief attention in the field. For the most part the sands and gravels of this formation are friable, but locally a calcite cement or a dark red coloured lateritic cement has produced a very tough conglomerate. Frequently these terraces are capped by a hard lateritic deposit.

One feature of these terraces that renders them easily identifiable on aerial photographs, apart from their obvious relation to the rivers, is the dense growth of large eucalyptus trees that they support.

STRATIGRAPHIC POSITION

These alluvial terraces rest with strong unconformity on various formations whose ages range from the Permian to the Pliocene (Tgh). Since they are all alluvial they must have formed since the island emerged from the sea in post-Upper Miocene times. It is very probable that these alluvia vary in age along their length, so that the terraces close to Ainaro are older than the lowest terraces of the same series much further seaward. From their position in the central part of eastern Timor and from their considerable elevation above the Viqueque Formation it seems likely that the oldest parts of the terraces are Pliocene

PLATE 44

A. Ainaro alluvial terrace, looking south-west.

(n) - limestones of the southern limb of the Aitutu
Anticline.

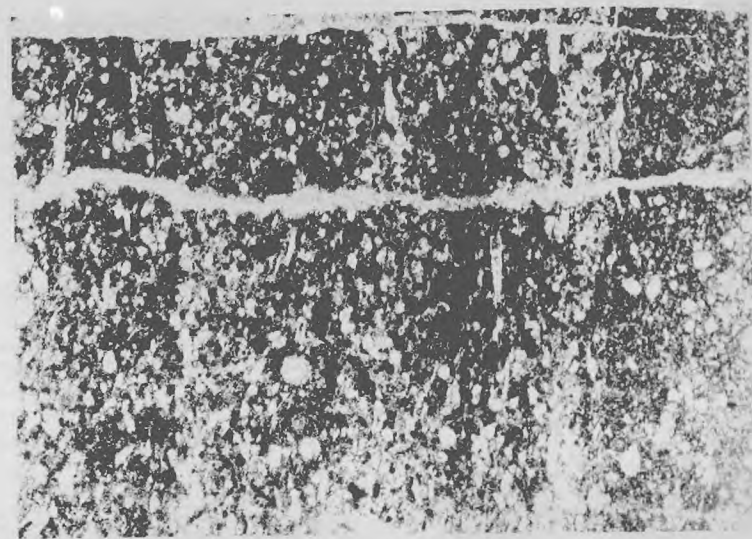
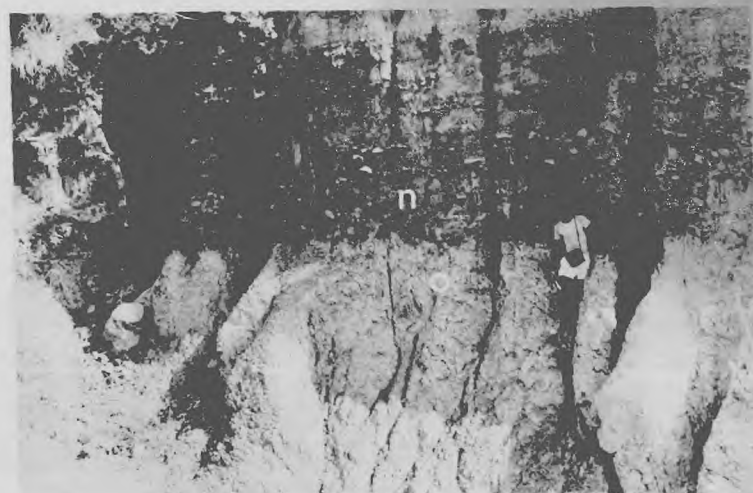
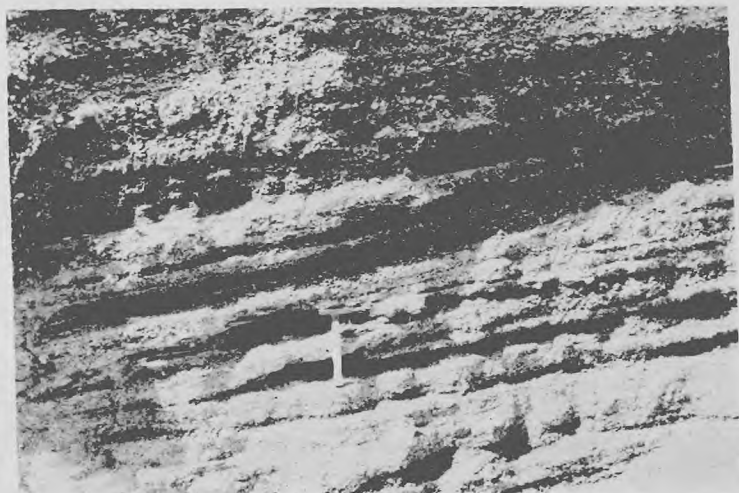
(o) - Ainaro Gravels of the highest and oldest
terrace of a series extending southward to
the south coast plain.

B. Railaco alluvial terrace - note horizontal
stratification.



PLATE 45

- A. Baucau Limestone - 'Laga Sand' (n) overlying the Wai Luli Formation (o) unconformably.
- B. Cablac Limestone - note contact between two beds of biomicarenite. The rods and globules of uncertain origin may be algal (x 25).
- C. Baucau Limestone - 'Laga Sand' at the western end of the Baucau Plateau, consisting of pebble conglomerates and sand, cross bedding common.
- D. Looking west from the River Veru towards the raised reef terraces of the Baucau Limestone (r). Modern coral sand conglomerate beach in the foreground.



contemporaneous with the deposition of the Viqueque Formation. The youngest (i.e. lowest) of these raised alluvial terraces that overlies the Viqueque Formation in the Same area are certainly post-Pliocene, probably post-Pleistocene.

ENVIRONMENT

The Ainaro Gravels are ancient river terraces; that is subaerial alluvial deposits. Locally they may be seen filling huge valleys as in the plates 3A, 44B. There seems little doubt that much of these great valley filling gravels were deposited very rapidly as the island began to emerge.

AN OUTLINE OF MODERN SEDIMENTATION IN EASTERN TIMOR

No attempt was made to study the modern sediments forming in and around Timor, but the various sedimentary processes active today were noted. In the case of marine sediments only the littoral was recorded.

A. MARINE SEDIMENTS.

1) Coral and algal reef limestones:

In numerous places around the shores of Timor coral and algal fringing reefs are growing (plate 42A). There appear to be differences between the morphology of the reefs growing on the north coast, where conditions are very quiet, and those growing on the south coast, where for much of the year a strong surf develops. The reefs on the south coast have a strongly developed barrier zone on the outer perimeter of the reef which seems to be absent from the north coast reefs.

2) Carbonate skeletal sands:

Two principal types of carbonate sand are found on the beaches: one is composed of the debris of reef organisms mainly corals and calcareous algae, and the other is composed mainly or almost exclusively of tests of Foraminifera. There are many examples of mixed sands (plate 45D).

3) Beach Rock:

Beach rock (Ginsburg, 1953) is forming in a few places on both north and south coasts of Timor (e.g. Betano and Suai on the south coast). At Suai it is composed of non-carbonate grains (viz. lithic sands derived from the metamorphic rocks of the Lolotai Complex, and igneous rocks of various formations) cemented by aragonite. At Betano it is composed of carbonate skeletal grains cemented by aragonite. Beach rock always dips seaward usually between

5 and 15 degrees, but locally it dips at 20 degrees. It has a characteristic pattern of strong joints both vertical and horizontal. The maximum observed thickness was 2 metres (at Suai).

4) Oyster beds:

Very small local developments of oyster beds are found associated with some coral-algal reef limestones.

5) Non-carbonate sands:

Many beaches on the north and south coasts are covered by non-carbonate sands and gravels having a wide range of grain size. The non-carbonate sands and gravels are found where reefs are not actively growing, where rivers enter the sea, and in many places have a close spatial association with carbonate sands and growing reefs. The elevated littoral sediments of the Lari Gutu Member of the Viqueque Formation (Tgh. age), and the Baucau Limestone (Pleistocene - Recent) which are equivalent facies, demonstrate that the carbonate sands and non-carbonate sands interdigitate both laterally and vertically.

B BRACKISH WATER SEDIMENTS

1) Lagoonal deposits:

A wide variety of lagoonal deposits (sands and muds) is forming today around the coasts of Timor. Some of the lagoons on the north coast are probably entirely marine, but the south coast lagoons are certainly brackish.

2) Evaporite deposits:

Along the north coast there are a number of flat areas that are slightly depressed topographically within the narrow coastal plain. In these salt marsh areas evaporite deposits are forming due to two processes. One is the occasional entry of the sea by flooding at exceptionally high tides, and the other, probably a far more important process, is the contamination of the water table by marine waters as has been described by Curtis et al. (1963), Evans & Shearman (1964), and Evans et al. (1964), from the Sabka of the Trucial Coast of the Persian Gulf. On a very much smaller scale these salt marshes fringing the north coast of Timor appear to be similar to the Sabkas of the Gulf.

The salt marsh deposits have a crust of 'salt cake' which covers a brine saturated mud, and sometimes appears to be floating on a concentrated brine (plates 46A, 46B).

C. NON-MARINE SEDIMENTS

1) Alluvial deposits:

Alluvial deposits are being developed by the rivers in the foothills and particularly on the south coast plain where braided streams (plate 4B) are building out the deltaic sediments of the south coast as the island continues to emerge (plate 41D).

2) Lacustrine lime mud:

Calcite mud is being deposited in Lake Surubeco on

PLATE 46

- A. Looking south from near River Seical. The salt lake in the foreground and Mt. Mata Bia composed of Cablac Limestone in the background.

- B. Looking south from near Manatutu. A salt lake in the foreground with wave cut benches in the hills of Wai Iuli Formation in the background.



the Lospalos Plateau. This deposit is associated with calcareous algae and gastropods.

STRATIGRAPHY OF THE ALLOCHTHONOUS FORMATIONS

INTRODUCTION

There are three formations in eastern Timor that are entirely allochthonous, having been overthrust to their present position. One of these formations the Lolotoi Complex was overthrust during the Lower Eocene, while the other two, the Aileu Formation and the Maubisse Formation, were emplaced together during mid-Miocene (Tf) times. The Aileu and Maubisse formations are known to have been derived from the region somewhere north of Timor, although the 'roots' of these formations are not known. Nothing is known of the direction of thrusting of the Lolotoi Complex, but it is assumed that it too was derived from the north. Like the other two formations it has no known 'roots'.

The allochthonous formations have been studied very briefly and little is known of their detailed stratigraphy and structure.

The Lolotoi Complex of eastern Timor can be correlated with the crystalline schists of the Schist-

Palelo Complex of western Timor. The Maubisse Formation of eastern Timor can be correlated with the Permian part of the Sonnebait Series of western Timor. It is not yet possible to make any direct correlation with the Aileu Formation of eastern Timor due to the lack of detailed information about western Timor.

LOLOTOI COMPLEX

SUMMARY

A series of sedimentary and eruptive rocks that have suffered a low grade of regional metamorphism are briefly described. The age of the original sediments is uncertain but they are most probably pre-Permian. Wherever the rocks of the Complex are found in eastern Timor they are allochthonous. They were overthrust to their present position during the Lower Eocene, probably from somewhere north of Timor.

INTRODUCTION

The Lolotoi Complex is a highly distinctive group of rocks in eastern Timor by virtue of their having been metamorphosed. Wherever the rocks of the Complex are found they are allochthonous.

Van Bemmelen (1949) grouped the rocks of this complex under the headings 'North Coast Schists' and 'Manufai Diabase'. Grunau (1953 and 1956) referred to these rocks as the Crystalline Schists and Ophiolites. Gageonnet &

Lemoine (1958) called them the Crystalline Schists, but under this they included tentatively both the metamorphic rocks of the Lolotoi Complex and the much younger and autochthonous group of eruptives defined in this thesis (earlier) as the Barique Formation. None of these earlier workers distinguished the rocks of the Barique Formation from those of the Lolotoi Complex.

The Lolotoi Complex is defined as the series of metamorphic rocks of both sedimentary and eruptive origin that occur as allochthonous sheets now consisting of four very large Klippen (figure 12). The type locality is the section exposed in the River Foho Ra south of the village Lolotoi (enclosure 1B). The section exposed in this river and in the other rivers that cut through the Lolotoi klippe, that extends west nearly to the frontier with Indonesia, consists of a series of phyllites, schists and metamorphosed eruptive rocks that have been isoclinally folded. The most characteristic rocks are quartz-mica phyllites, quartz-mica schists, a black sericite chlorite schist with white quartz stringers and an apple green epidote-feldspar-quartz gneiss, together with a whole suite of metamorphosed basic and ultrabasic eruptive rocks in which gabbroic and doleritic types predominate.

The other three large overthrust sheets (figure 12) consist mainly of the same rock types. However locally a higher grade of metamorphism is recorded by the presence of garnets. Garnet-mica schists and quartz-mica-feldspar-garnet gneisses are developed for instance in the area north east of the village Fatu Berliu (enclosure 1C) and in the area north-west of Mt. Bibiliu.

LITHOLOGY AND PETROGRAPHY

The treatment of the rocks of this Complex both in the field and the laboratory has been very brief, consequently they can only be discussed in general terms (plates 47A, 47B, 47C, 47D). The thickness of the Complex is difficult to determine because the rocks have been so intensely folded and faulted. It is estimated that the maximum thickness of the overthrust sheet of Lolotoi Complex is to be found in the largest klippe (termed the Laclubar-Samé klippe) where it is probably about 1300 metres.

The commonest rocks found in the Lolotoi Complex of all the klippen are:

Sericite-quartz-chlorite schist - this is a soft lustrous black rock with augen of white quartz. It is a distinctive rock generally very broken in outcrop and it rapidly disintegrates on weathering.

Quartz-mica phyllite - these form quite tough phyllites that are commonly stained a rusty brown colour on their weathered surface.

Quartz-mica schist - Hard tough rocks similar to the phyllites.

Epidote-quartz-feldspar gneiss - Pale green distinctive rock in which pygmatic veins and folds are developed. Large quartz-feldspar augen are frequent.

Quartz-amphibole schist - The amphibole(s) is dark green or black and tends to acicular habit. The size of the

amphibole and quartz crystals is variable.

Meta-gabbro, meta-dolerite and meta-diorite - These are the most common metamorphosed eruptive rocks. Generally they are fresh and have their texture well preserved though some are very altered. They are intimately associated with the meta-sediments of the Complex. Other less common metamorphosed eruptive rocks include ultrabasic types of which pyroxenites are the most notable.

STRATIGRAPHIC POSITION

There are three cardinal problems of chronology associated with the Lolotoi Complex. One of these problems concerns the time of emplacement of the overthrust sheets of the complex in their present position: - The youngest rocks of the autochthon found below the overthrust sheets of the Complex are Jurassic in age. But as the thrust plane cuts across major folds that involve the Upper Cretaceous (Senonian) it seems most likely, but it cannot be proven, that the thrusting was post-Senonian. The fact that the Cretaceous sedimentary rocks represent a bathyal facies deposited far from land, and that the Cretaceous rocks are followed by an unconformity before the Middle & Upper Eocene neritic limestone facies (Dartollu Limestone) supports the idea of post-Senonian thrusting. The oldest strata found overlying the Lolotoi Complex with a sedimentary (NOT a tectonic) contact are Middle and Upper Eocene (Tab) limestones called the Dartollu Limestone. It is therefore most probable that the overthrusting of the sheets of Lolotoi Complex took place during Lower Eocene times.

The age of the original sediments and eruptives of the Lolotoi Complex and the time of their metamorphism are difficult problems to resolve. No fossils have been found in these rocks and it is not known where these thrust sheets came from. It may be assumed they came from the north because the large sheets of Permian strata that were overthrust onto Timor during the mid-Miocene orogenic phase came from the region north of Timor. Gageonnet & Lemoine (1958) suggested that the crystalline schists may be Permian in age. They based this suggestion on the work of Molengraaff (1915) in the island of Leti where fossiliferous Permian beds of great thickness overlie crystalline schists, the contact being regarded as a transition. The present writer considers a pre-Permian age as more likely in view of the isoclinal folding and degree of metamorphism suffered by these rocks. If they are Permian in age then they must have been metamorphosed between late-Permian and early Jurassic times, which on the regional evidence available seems improbable. At the moment all these questions remain open.

CORRELATION WITH WESTERN TIMOR

The Lolotoi Complex can be correlated with the crystalline schists of the Schist-Palelo Complex of western Timor. Brouwer (1942) described the crystalline schists of western Timor as being "derivates of sedimentary and basic igneous rocks". He mentions that they shew widely differing degrees of metamorphism, being largely neso- to epi-zone rocks with kata-zone types developed locally; in this they are comparable to the Lolotoi Complex. Brouwer (1942) described low-metamorphic phyllites, epidote-chlorite schists and garnet-nica schists that

suggest close comparison with the Lolotoi Complex. The staurolite- and kyanite-bearing granulites of western Timor have not yet been found in the Lolotoi Complex. The "amphibolites and fine crystalline actinolite-bearing schists" of the Schist-Palelo Complex can probably be matched in the Lolotoi Complex.

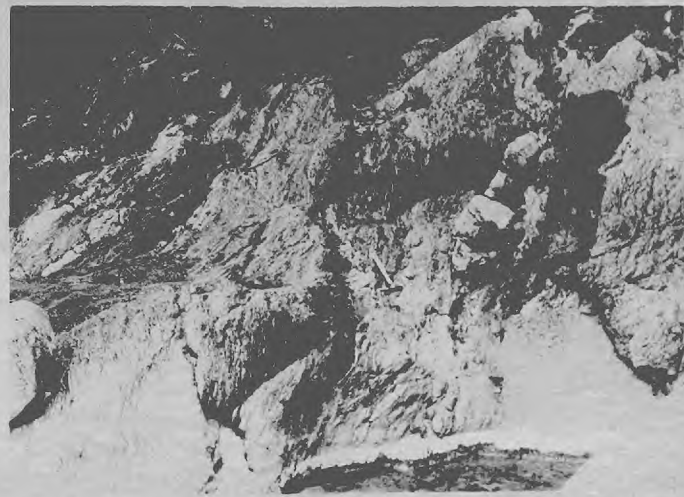
It seems possible that some of the rocks grouped by Brouwer (1942) with the crystalline schists of the Schist-Palelo Complex can be correlated with the metamorphic rocks belonging to the Aileu Formation (of eastern Timor) that outcrop along the north coast between Manatuto and the River Lois.

The age of the original sediments of the crystalline schists of western Timor was considered by Brouwer (1942) to be partly pre-Permian and partly Permian. These two divisions may roughly correspond to the Lolotoi Complex and the Aileu Formation respectively.

De Waard (1956) reported the presence of Eocene limestones overlying the crystalline schists of western Timor. This is exactly comparable with the Dartollu Limestone of Middle & Upper Eocene (Tab) age found overlying the Lolotoi Complex in eastern Timor. This indicates that in both eastern and western Timor the Lolotoi Complex and the crystalline schists of the Schist-Palelo Complex were overthrust before Middle Eocene times.

PLATE 47

- A. Lolotoi Complex - greenschist from the Baguia klippe.
- B. Lolotoi Complex - mica schist and feldspar-quartz-epidote gneiss from the Lolotoi klippe.
- C. Looking south towards Mt. Aitana up the River Laleia. Mt. Aitana is composed of Lolotoi Complex (Lacluta klippe) but the base of the mountain is covered by the Bobonaro Scaly Clay.
- D. Lolotoi Complex - crumpled schist from the Laclubar klippe.



THE AILEU FORMATION

SUMMARY

Always allochthonous in eastern Timor, the Aileu Formation consists of at least 1000 metres of regionally metamorphosed sedimentary and eruptive rocks. The grade of metamorphism increases steeply northwards at the north coast. The age of the original sediments is uncertain, they are probably Permian or older. The Formation was overthrust to its present position during the mid-Miocene (Tf) orogeny.

INTRODUCTION

This Formation that outcrops only in the north-west part of eastern Timor (figure 13) has received very little attention. Van Bemmelen (1949) did not separate it from the crystalline metamorphic rocks of the Lolotoi Complex, but grouped them together as North Coast Schists. Grunau (1953 and 1956) followed Van Bemmelen (1949) in grouping them with the crystalline schists. Gageonnet & Lemoine (1958) were the first to distinguish the rocks of this Formation. They referred to them as the lower part of their Maubisse Series, but did not differentiate them in their sketch map.

The Aileu Formation is here defined as the series of shales, phyllites, slates and occasional meta-eruptive rocks exposed about Aileu, and occupying most of the N.W. part of Portuguese Timor, that have been carried to their present position as an overthrust sheet. This allochthonous formation is well exposed. It outcrops

along the north coast from Manatuto to the Indonesian border (plates 1B, 48A). Inland the Formation outcrop extends to a line passing roughly through Aileu and Ermera. Apart from the area close to the present north coast the Formation has a monotonous appearance of usually deeply weathered slightly metamorphosed rocks that are very largely shales, phyllites and slates. Along the north coast metamorphism has been far more severe producing quartz-mica schists, and feldspathic amphibolites (plates 48B, 48C).

The type locality is the hilly country about Aileu (enclosure 1A). Here in roadside cliffs and in creeks are exposed a very monotonous sequence of light greenish grey shales that weather to a deep red colour. The red soil produced is characteristic of this Formation, so too is the vegetation in which large eucalyptus trees predominate. Locally blocky blue-grey and light purple coloured slates are developed. Some of the slates are fairly well cleaved. Quartz phyllites become important locally. These phyllites usually exhibit lustrous surfaces due to chlorite and mica. Metamorphic eruptive rocks are not common, but become important in a few places, for instance about Ermera.

The thickness of the Aileu Formation is difficult to estimate because it has not been studied in any detail and virtually nothing is known of the folds and faults within the thrust sheet itself. From its general field relationships it can be seen to be at least 1000 metres

STRATIGRAPHIC POSITION

There are two cardinal stratigraphic problems associated with the Aileu Formation; one is the age and time of metamorphism of the original sediments and eruptives, the other is the time of the emplacement of the Formation as a thrust sheet in its present position in eastern Timor. On the basis of finding some poorly preserved pelecypods in this Formation near Maubisse, that are similar to those of the autochthonous Permian rocks of the Cribas Formation, Gageonnet & Lemoine (1958) suggested that the rocks of the Aileu Formation are probably Permian in age. Further they drew an analogy between the Aileu Formation and the epimetamorphosed Permian strata in the island of Leti. Leti lies about 45 km. E.N.E. of the eastern tip of Timor. From this island Molengraaff (1915) described a series of rocks dipping steeply to the north. In the south of the island very fossiliferous Permian rocks occur, in the centre of the island epimetamorphosed sedimentary rocks are interbedded with fossiliferous Permian limestones and eruptive rocks, while in the north more highly metamorphosed rocks are found whose origin is not determinable. The whole series is regarded as being an isoclinal imbricated structure possibly more than 5000 metres thick. The tentative correlation by Gageonnet & Lemoine (1958) is an attractive idea but needs further field study for confirmation.

The problem of the time of the emplacement is eastern Timor of the overthrust sheets consisting of the Aileu Formation and the Maubisse Formation has been discussed earlier in dealing with the Bobonaro Scaly Clay.

Strictly all that can be evinced for the Aileu Formation is that it was emplaced in post-Lower Eocene (since it is superimposed on the Lolotoi Complex that was emplaced in the Lower Eocene) and pre-Bobonaro Scaly Clay emplacement. It can however be shown by field relationships that the Maubisse Formation with which the Aileu Formation is intimately associated was emplaced in post-Lower Miocene times. It is extremely probable that these two formations were emplaced together, and the Maubisse Formation was definitely emplaced in mid-Miocene (Tf) times.

ENVIRONMENT

The original sediments of the Aileu Formation must have formed a thick monotonous sequence of shales with sandstones. Such a mass of sediment was probably deposited in deep basinal or geosynclinal environment, but there is at present no real evidence of this (figure 17).

CORRELATION WITH WESTERN TIMOR

It is difficult, in the absence of any detailed account of the geology of western Timor, to be sure whether there is any equivalent of the Aileu Formation present in western Timor. It seems possible that some at least of that part of the crystalline schists of the Schist-Palelo Complex described by Brouwer (1942) as possibly Permian, may be equivalent to the more highly metamorphosed rocks of the Aileu Formation that outcrop along the north coast. It is also possible that part of the Permian section of the Sonnebait Series of western Timor may be equivalent to the Aileu Formation.

PLATE 48

- A. Aileu Formation - dipping north into the Wetar Strait west of Manatutu.
- B. Aileu Formation - metamorphosed to amphibolite along the north coast.
- C. Aileu Formation - closer view of part of Plate 48B.



^M
THE MAUBISSE FORMATION

SUMMARY

An allochthonous Permian formation consisting of highly fossiliferous limestones and eruptive rocks is defined. The fauna is listed and the petrography of the sedimentary rocks briefly described. The rocks of this Formation were deposited in a shallow warm shelf sea in which volcanoes were active.

INTRODUCTION

The rocks of this Formation, predominantly fossiliferous limestones and eruptives, form three large klippen and numerous smaller ones (figure 13). The three large overthrust sheets form steep mountainous country, the smaller klippen generally form rugged cliffs and hills. Van Bemmelen (1949) mentioned the rocks of this Formation briefly and included them in the Fatu Limestone group. Grunau (1953 and 1955) followed van Bemmelen. Neither of these workers offered any detailed description of the Formation. Gageonnet & Lemoine (1958) described these rocks as forming the upper part of their Maubisse Series, which they distinguished from the limestone Fatus. Lemoine (1963) described briefly rocks of this formation that occur at the eastern end of the island in the Legumau klippe as the Legumau Formation. Following Gageonnet & Lemoine (1958) but with some modification to bring the nomenclature into line with accepted usage (Australian Code of Stratigraphic Nomenclature, 1964), this Formation is named the Maubisse Formation. The type locality is defined as the large cliffs south-west of Maubisse. Here

well exposed are a series of beds of dense limestones, well bedded but tending to be massive and coloured mostly red and pink but with white and grey varieties. The large majority of the limestones are biocalcarenites with a sparry calcite cement. These limestones are exceptionally rich in reef organisms: corals, bryozoans calcareous algae, brachiopods and cephalopods. Some coarse conglomerates with many clasts of eruptive rocks are interbedded together with tuffs and eruptives. Higher up the section on the slopes of the great mountain Ramelau is an impressive sequence of at least 500 metres of basic eruptives. Between Maubisse and the peak of Ramelau (the highest mountain in Timor more than 3000 metres above sea level) the thickest section of the Maubisse Formation is preserved. The upper part consists of about 500 metres of basic eruptives and the lower part of about 400 metres of limestones (mainly biocalcarenites).

Elsewhere, in other klippen these same two major divisions are developed. Shales everywhere form a very minor proportion of this Formation; usually the shales are confined to thin developments between the limestones. The Formation has a very characteristic appearance. The limestones are typically red and rich in crinoidal and bryozoan debris, while the eruptives are usually brightly coloured and porphyritic or vesicular. These rocks are readily distinguished from those of other formations (plates 49A, 49B, 49C, 49D).

Apart from the klippen the rocks of this Formation make an important contribution to the Bobonaro Scaly Clay as exotic blocks. Many of these exotic blocks are very large, some as large as 0.5 km. having been mapped.

LITHOLOGY AND PETROGRAPHY

Calcarenites and calcirudites.

All the calcarenites and calcirudites studied were composed of the debris of calcareous organisms particularly bryozoans and crinoids (plates 50B, 50D). All grades between fine calcirudites and fine calcarenites are seen, but the great majority of the rocks would be classified as coarse calcarenites. Most of the calcarenites and all of the calcirudites studied had a sparry calcite cement, relatively few of the calcarenites had a micrite matrix. The allochems were mainly fragments of bryozoans, crinoids, calcareous algae, brachiopods and cephalopods. No oolites and very few pellets were found. The non-carbonate fraction of the clasts is very small, always less than 5 percent. Two principal terrigenous clasts are quartz grains and eruptive rock fragments. These terrigenous clasts are often coated with a thin polished layer of limonite.

The sparry calcite cement forms a granular mosaic of varying grain size. Frequently the grain size of the calcite cement is so large as to strongly suggest that considerable recrystallisation has taken place. Single crystals of the cement may engulf more than one allochemical grain poikilitically. Crinoidal allochems invariably shew strongly developed calcite overgrowths. Commonly the original canals in the crinoid particle have been completely filled with calcite. It is frequently observed that the sparry calcite cement is composed of a slightly or moderately ferroan calcite. In contrast to this most of the skeletal material is composed of iron-free

calcite, similarly the overgrowths on the crinoid fragments are always iron-free, and never shew the compositional zoning that has been described by Evamy (1963) in crinoidal calcarenites with a sparry calcite cement from the French Jura.

Another diagenetic process that has affected these rocks is one involving the replacements of skeletal fragments probably originally aragonite by a granular mosaic of calcite. This process has been recorded in these rocks by the thin outline of the skeletal fragment in micrite that must have originally coated the fragment (plate 50A).

Dolomitisation takes two forms in these rocks. The most commonly observed dolomitisation is that of the calcareous algae fragments by small rhombs. The other variety is that of large rhombs that appear to have replaced the original calcite of allochems and matrix indiscriminately (plate 50D). This is more commonly observed in the calcarenites with a micrite matrix than those with a sparry calcite cement.

Arenites.

Non-carbonate arenites form an insignificant proportion of the sedimentary rocks of this Formation. The commonest are well sorted mature quartz medium sandstones. Most of the lethic and quartz arenites have a sparry calcite cement in the form of a granular mosaic. Usually the grains are coated with a thin polished layer of limonite (plate 50C).

Tuffs.

A wide variety of tuffs are interbedded with the limestones. They are all very altered and little can be determined about their original composition. They now consist largely of chlorite and carbonate minerals.

Eruptives.

Basic eruptives form a very important proportion of this Formation. They are all very altered, making proper identification difficult, and have been given very little attention. The main feature of these rocks noticed in the field is that most of them are vesicular. After brief study it seems probable that many of these eruptives were amygdaloidal basalts. Spilites were probably well represented. Albite is a common feldspar. Most of the zeolites have been altered beyond recognition.

STRATIGRAPHIC POSITION

The Maubisse Formation is allochthonous everywhere in eastern Timor. It can be seen from the relationships between Legumau Range and the Mata Bia Range, and from that between the Ramelau Range and Mt. Cablac that the emplacement of the thrust sheets must have taken place after the consolidation of the Cablac Limestone. That is the thrusting took place in post-Lower Miocene (i.e. post-Te) times. Overlying the Maubisse Formation locally is the Bobonaro Scaly Clay of Tf age. As was shewn earlier in the section dealing with the Bobonaro Scaly Clay, the emplacement of the Bobonaro Scaly Clay was intimately associated with the overthrusting of the Maubisse Formation.

The Maubisse Formation was overthrust to its present position in post-Te times and immediately before the emplacement of the Bobonaro Scaly Clay, i.e. it was overthrust in Tf.

The age of the limestones and eruptives that make up this Formation is readily determined from the rich fauna of the limestones as ranging from Lower to Upper Permian. The following ammonoid was determined by Dr. M.K. Howarth of the British Museum (personal communication, 1963): Metalegoceras sundaicum (Haniel). Another ammonoid from this Formation was reported by Grunau (1953) namely Propinacoceras simile Haniel. These ammonoids indicate a Middle Permian age.

The following brachiopods have been determined by Dr. H.M. Muir-Wood of the British Museum (personal communication, 1963):

Schizophoria ? indicaeformis (Hamlet)
Waagenoconcha waageni (Rothpletz)
Krotovia ? opuntia (Waagen)
Marginifera transversa Waagen
Marginifera sp?
Reticulatia sp.
Stenoscisma cf. purdoni (Davidson)
Stenoscisma globosa (Tschernyshev)
Stenoscisma gigantea (Diener)
"Rhynchonella" cf. wynnei Waagen
'Spirifer' oldhamianus Waagen
Spirifer tibetanus (Diener)
Spiriferinellina sp. cf. insculpta (Schlotheim)
Martinia nucula Rothpletz

Neophricodothyris indica (Waagen)
Eumetria cf. grandicosta (Davidson)
Cleiothyridina subexpansa (Waagen)
"Athyris" globulina Waagen
Dielasma biplex Waagen
Dielasma nummulus Waagen

Dr. Muir-Wood commented on this fauna that the specimens appeared to be nearer to those of the Middle and Upper Productus Limestones of the Salt Range described by Waagen rather than to the brachiopods described from the Permian of Dutch Timor.

The following echinoderms have been identified by Dr. R.P.S. Jefferies of the British Museum (personal communication, 1962):

Neoschisma verrucosum Wanner
Delocrinus depressus Wanner
Spiraculata

Dr. R. Birenheide of the Natur-Museum und Forschungs-Institut Senckenberg (personal communication, 1965) has identified the following corals that he considers probably represent an Upper Permian fauna:

Amplexocarinia bitauniensis Schouppe & Stacul
A. sp. nov.
Duplophyllum sp.
Lophophyllidium spinosum (Martin)
L. sp.
Pentaphyllum (Tachylasma) gracile Schindewolf
P. (Tachylasma) variabile Schindewolf

Polycoelia cf. compressa (Ludwig)
Verbeekiella cf. gerhti Schouppé & Stacul
Wannerophyllum cristatum (Gerth)

Nogami (1963) has described four Fusulinids collected from kleppen and the Maubisse Formation:

Codonofusiella weberi (Schubert)
Triticites sp.
Schwagerina nakazawae sp. nov.
Parafusulina sp.

These Fusulinids are said to indicate a probable Lower Permian age.

ENVIRONMENT

The limestones and their fauna evince beyond doubt that they were deposited in a shallow, shelf sea with warm clear water in which reef organisms flourished. At intervals volcanoes were active. The sea in which these rocks were deposited must have been swept by currents. The many intraformational conglomerates in this Formation suggest at least a mild degree of instability in the depositional area.

An interesting problem in that Northern and Western Australia are reported to contain glacial deposits of Permian age (David, 1950; Gerth, 1952; Veevers and Wells, 1961, and Schwarzbach, 1963). The overthrust rocks of the Maubisse Formation are today about 1000 km. from the Permian glacial deposits of Western

Formation has been overthrust a considerable distance from the north as is suggested in figure 17.

CORRELATION WITH WESTERN TIMOR

It was pointed out by Gageonnet & Lemoine (1958) that the Maubisse Formation is equivalent to the Permian strata of the Sonnebait Series of western Timor. The Permian contribution to the Sonnebait Series is largely composed of highly fossiliferous (largely crinoidal) limestones and eruptive rocks. It is from these rocks that the famous Permian faunas of western Timor have been described. It is clear that these shallow water limestones and eruptives are very similar in both parts of Timor. De Waard (1954) has shown that the Sonnebait Series of western Timor was overthrust between late Te and early Tg time, most probably during the Tf stage. It can be shown that the Maubisse Formation in eastern Timor was overthrust during the Tf stage; thus the correlation between the Permian strata of the Sonnebait Series of western Timor and the Maubisse Formation extends to their time of emplacement.

PLATE 49

- A. Maubisse Formation - reef limestones of Mt. Lacouse klippe.
- B. Maubisse Formation - limestones of the Legumau Range klippe.
- C. Maubisse Formation - (n) - overthrust onto the Wai Iuli Formation (1): looking west across the River Laclo.
- D. Maubisse Formation - eruptive rocks of the Mt. Lacouse klippe.

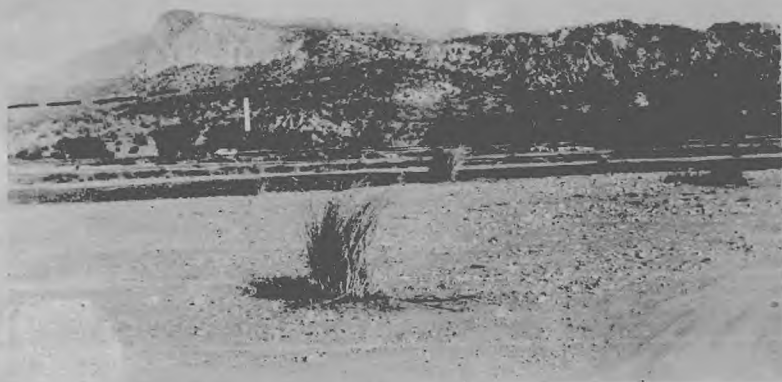
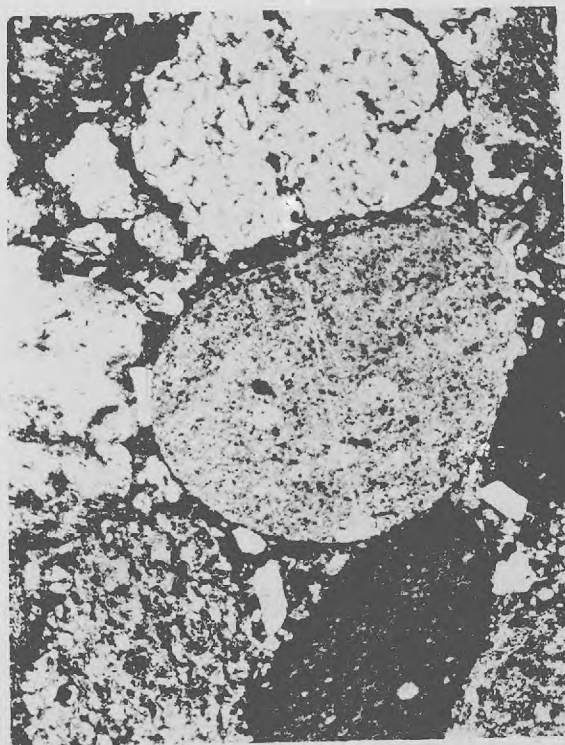
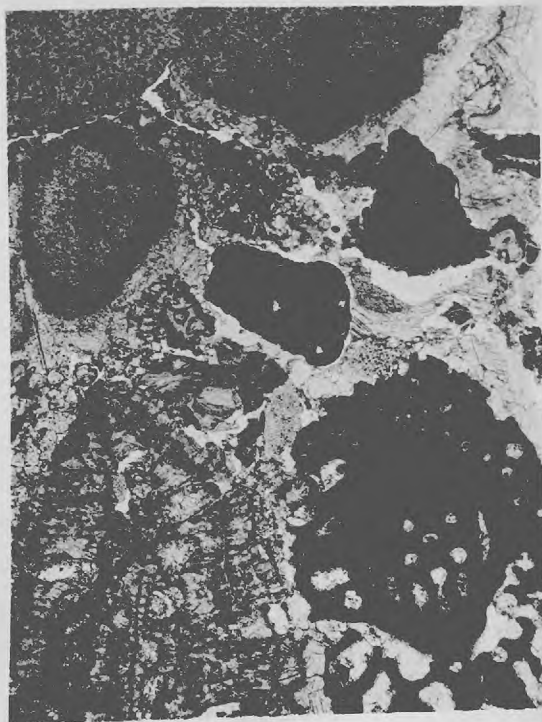
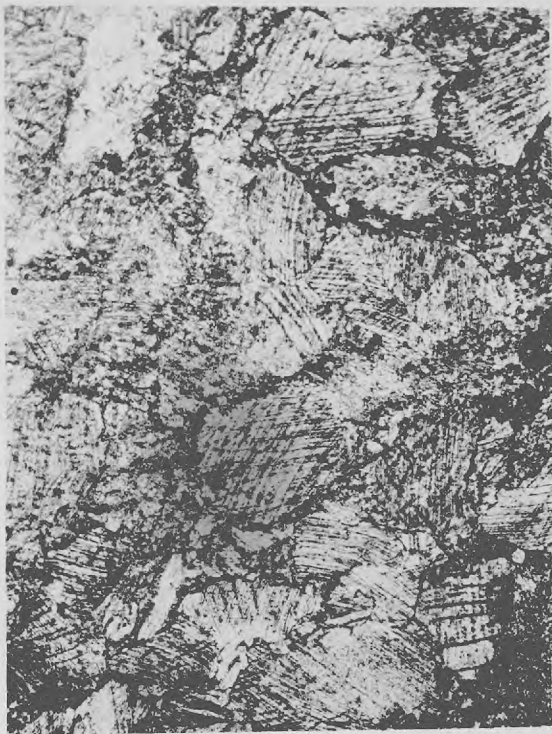


PLATE 50

- A. Maubisse Formation - calcarenite with strongly developed lamellae due to strain (x 20).
- B. Maubisse Formation - biospararenite with echinoderms, bryozoans and clasts of volcanic rocks (x 20).
- C. Maubisse Formation - arenite with well rounded lithic clasts mostly of volcanic rocks (x 4).
- D. Maubisse Formation - calcarenite with strongly dolomitised cement.



BOROLALO LIMESTONE

A number of small klippen of Borolalo Limestone occur in several places in eastern Timor. The composition of these klippen is indistinguishable from the autochthonous Borolalo Limestone. The klippen which generally overlie the Lower Miocene Cablac Limestone (e.g. Mt. Mata Bia and Mt. Wai Nete) were overthrust from the north together with the Maubisse Formation during the mid-Miocene orogeny.

These klippen provide a valuable indication of the widespread extent and uniformity of the Borolalo Limestone which accords with the nature of that formation.

CHAPTER III

TECTONICS

A. STRUCTURES OF THE AUTOCHTHONOUS FORMATIONS

a) INTRODUCTION

The autochthonous rocks of Portuguese Timor may be divided into four groups on the basis of their structural characters: -

i) The Permian, Triassic, Jurassic and Cretaceous rocks; these have all suffered intense deformation. They form large broad folds, having an axial plane separation of more than 5 km., the limbs of these folds are complicated by minor folding and faulting (plates 21A, 51B, 51D, 52A).

ii) The Eocene, Oligocene and Lower Miocene rocks; these are represented by scattered remnants from which it is difficult to discern fold patterns. Another impediment is the poorly stratified nature of these formations. Faulting has severely affected these rocks producing many excellent fault scarps (plate 2B). An attempt to interpret the fold pattern in the Lower Miocene rocks is shown in figure 15.

iii) The Middle Miocene, Upper Miocene and Pliocene rocks; these are characterised by relatively simple parallel folds modified by varying degrees of diapiricism. In the region of Viqueque village a complex pattern of interference folds have developed. The effects of faulting on these rocks have been severe. A number of structures are illustrated in the plates 53A, 38A,B,D.

iv) The post-Pliocene rocks; these have been only slightly folded, dips seldom exceed 2 or 3 degrees. The post-Pliocene rocks are noticeably less faulted than the Miocene and Pliocene rocks.

b) STRUCTURES IN THE PRE-EOCENE FORMATIONS.

The folds of the pre-Eocene autochthonous formations are of two distinct types. One which may be termed major folds has an axial plane separation between adjacent anticlines of more than 5 kms, the other type, (minor folds) has an axial plane separation between adjacent anticlines of less than 50 metres. The minor folds are found as crenulations complicating the limbs of the major folds. An index to the major folds is provided in figure 14.

1) Aitututu - Bazol Anticline.

The eastern part of this structure (the Aitututu Anticline) is the only major fold to have clear expression in the field. It is the only one that can be seen as a structural unit from one vantage point in the field, as plate 51C shews. The Aitututu Anticline plunges at about 5 degrees eastward below the large klippe of Lolotoi Complex (enclosure 3A,B, section 10).

The Aitututu Anticline is divided from the Bazol Anticline by an important cross fault that brings up the Cribas Formation to the west of the fault, and displaces the axial plane trace. The precise nature of the fault is not known.

The Bazol Anticline has been more deeply eroded than

the Aitututu Anticline, revealing the Cribas Formation in the core. Like the Aitututu Anticline the Bazol Anticline is overlain on its eroded surface by a large klippe of Lolotoi Complex (enclosure 3A,B, Sects: 11, 12, & 13). The disposition of the outcrops of Mesozoic formations at the western end of the anticline, although poorly exposed and covered in part by the klippe, suggest the Bazol Anticline plunges west. The minor folding in the Bazol Anticline is very complex, in having a high intensity and varying axial planes, particularly in the Cribas Formation. The anticline is revealed not by the record of dips and strikes (which minor structures have caused to be chaotic) but by the spatial distribution of the three formations: Cribas, Aitututu & Wai Luli (enclosures 1B & 3AB). The behaviour of the rivers Bazol and Lomea as they cut their way through the Bazol Anticline accords with a structural control of drainage.

2) Cribas Anticline.

This structure was first identified by geologists of Allied Mining Corp. (Wittouck, 1937), and later reported on by Grunau (1953) and by Gageonnet & Lemoine (1958). These workers mapped the structure on the basis of dip and strike observations despite the disturbances of complex minor folds and faults. The present writer confirms the structure on the basis of the spatial distribution of the formations involved.

The strike of the Cribas Anticline is nearly E.W. It appears to plunge west below the klippe of Lolotoi Complex, and east below another klippe of Lolotoi. It is partly overlain with great unconformity by the Bobonaro

PLATE 51

- A. Strong regional dip of the Aitutu Formation in the southern limb of the Cribas Anticline.
- B. Minor contorted folding of the Aitutu Formation in the eastern limb of the Aliambata Anticline.
- C. Aitutu Anticline, looking west.
- D. Minor folding in the Wai Luli Formation of the Bazol Anticline.



Scaly Clay of mid-Miocene age (enclosure 3C, sections 7 & 8).

3) Mac Fahic - Ossu Anticline.

The evidence for the existence of the Mac Fahic structure is poor. Most of the outcrops exhibit considerable minor folding. The delimitation of the two Mesozoic formations Aitututu and Wai Luli in the valley of River Sahem is difficult and the solution shewn on the map (enclosure 1C) is only tentative, and almost certainly requires revision.

The Ossu Anticline is no more than conjectural based as it is on two widely separated areas of outcrop (figure 5).

In support of this structure it may be said that the tentative interpretation of the distribution of the pre-Eocene formations in figure 5 is a reasonable solution of the available evidence. Most of this structure is covered by various Tertiary formations. The distribution of some of the Tertiary formations seems to support the hypothesis, thus figure 15 shews the distribution of the Cablac Limestone and its field relations to the proposed pre-Eocene folds. This relationship it is suggested resulted from the refolding of the Timorean structures in the Ramelauean orogeny (enclosure 5).

4) Aliambata Anticline.

This structure is complicated by minor folds and by faults whose throw is probably considerable. Only the

S.E. limb is exposed, the N.W. limb being covered by Tertiary formations and klippen of Lolotoi Complex and Maubisse Formation. The exposed core of the anticline is Cribas Formation, and the manner in which the River Ira Bere and its tributary the Afolita cut through the core is very reminiscent of action of the rivers Bazol and Lomea in the Bazol Anticline.

The steep circle of hills north of Aliambata composed of Aitututu Formation, Wai Luli Formation and Borolalo Limestone are interpreted as forming part of the N.W. limb of the Aliambata Anticline (enclosure 3C section 5). The outcropping of these formations at Aliambata is ascribed to a number of faults whose precise action is not clear. The overlying spread of the unconformable Bobonaro Scaly Clay hides the crucial area (enclosure 1D).

5) Veru Anticline.

This is a conjectural structure interpreted on the basis of the exposed N.W. 'limb' (figure 5). The minor folding and faulting are intense so that dip and strike observations are not helpful in readily determining the major fold. The structure was conjectured from the spatial distribution of the formations involved as interpreted in figure 5.

6) Loiquero Anticline.

This is also a conjectured structure derived in the same way as the Veru Anticline. The assumption is that most of the Iospalos plateau is underlain by the Aitututu Formation and possibly by the Wai Luli Formation. The

absence of any subsurface data in this region which is blanketed by late Tertiary and Quaternary deposits is particularly unfortunate.

7) Pualaca Syncline.

This structure separates the Cribas and Mac Fahic anticlines which lie to the north and south respectively. The syncline is largely filled with Wai Luli Formation. To the east and west it is overlain by klippen of Lolotoi Complex.

8) Betano Syncline.

This broad structure is conjectured on the basis of the occurrence of the Wai Bua Formation in the Betano region, and the probability of a 'negative' structure between the Ossu and Aliambata anticlines, and a 'negative' structure south of the Mac Fahic, Aitutu and Bazol anticlines.

The region south of the Bazol, Aitutu, Mac Fahic and Ossu anticlines was a major basin of deposition from Upper Miocene to Recent times, i.e. in the period following the Ramelauean Orogeny. This could be explained as resulting from the downwarping of the synclinal zone, that originated during the Timorean Orogeny (enclosure 5), by refolding during the Ramelauean.

The gravity data while not unequivocally supporting the synclinal structure of this zone does accord with it (enclosure 2B, 2C, 3AB & 3C). The sections: 9 of enclosure 3C and 10 of enclosure 3AB illustrate the

interpretation of the Cretaceous rocks about Betano as representing the depression of the large syncline. This area formed a topographic 'high' in the late-Tertiary basin, which accords with the residual nature of synclines after erosion. The local gravity positive anomaly over this syncline can be interpreted as due at least in part to the density contrast between the Mesozoic rocks of Betano and the relatively less dense Tertiary rocks surrounding the Betano inlier.

There is very little direct evidence for the eastern extension of the Betano Syncline between the Mac Fahic and Aliambata anticlines, and beyond the necessity to have a 'negative' structural zone between the two anticlines little can be said to justify it.

9) Lospalos Syncline.

This is a conjectured structure based largely on the probable distribution of the Permian and Mesozoic autochthonous formations beneath the postulated Tertiary basin below the Lospalos Plateau (enclosure 3D, sections 1 & 2 and figure 16). In the absence of any subsurface data it is difficult to be positive about the structure of Mesozoic and Permian strata beneath the younger cover.

c) MINOR FOLDING IN THE PRE-EOCENE FORMATIONS

The style of minor folding is of parallel-type with strong disharmonic elements. No similar-type folding has been seen in these rocks. Conjugate folds are quite common and vary greatly from place to place in scale and frequency (plates 21A, 51B, 51D & 52A).

PLATE 52

- A. Minor folding in the Aitututu Formation of the Aliambata Anticline (east limb).
- B. Thrust plane between Maubisse Formation (m) and the Aitututu Formation (a), in the Ramelau Range klippe.

DISTRIBUTION OF THE LOLOTOI COMPLEX & THE RELATIONSHIP
BETWEEN THE KLIPPEN & TIMOREAN FOLDS

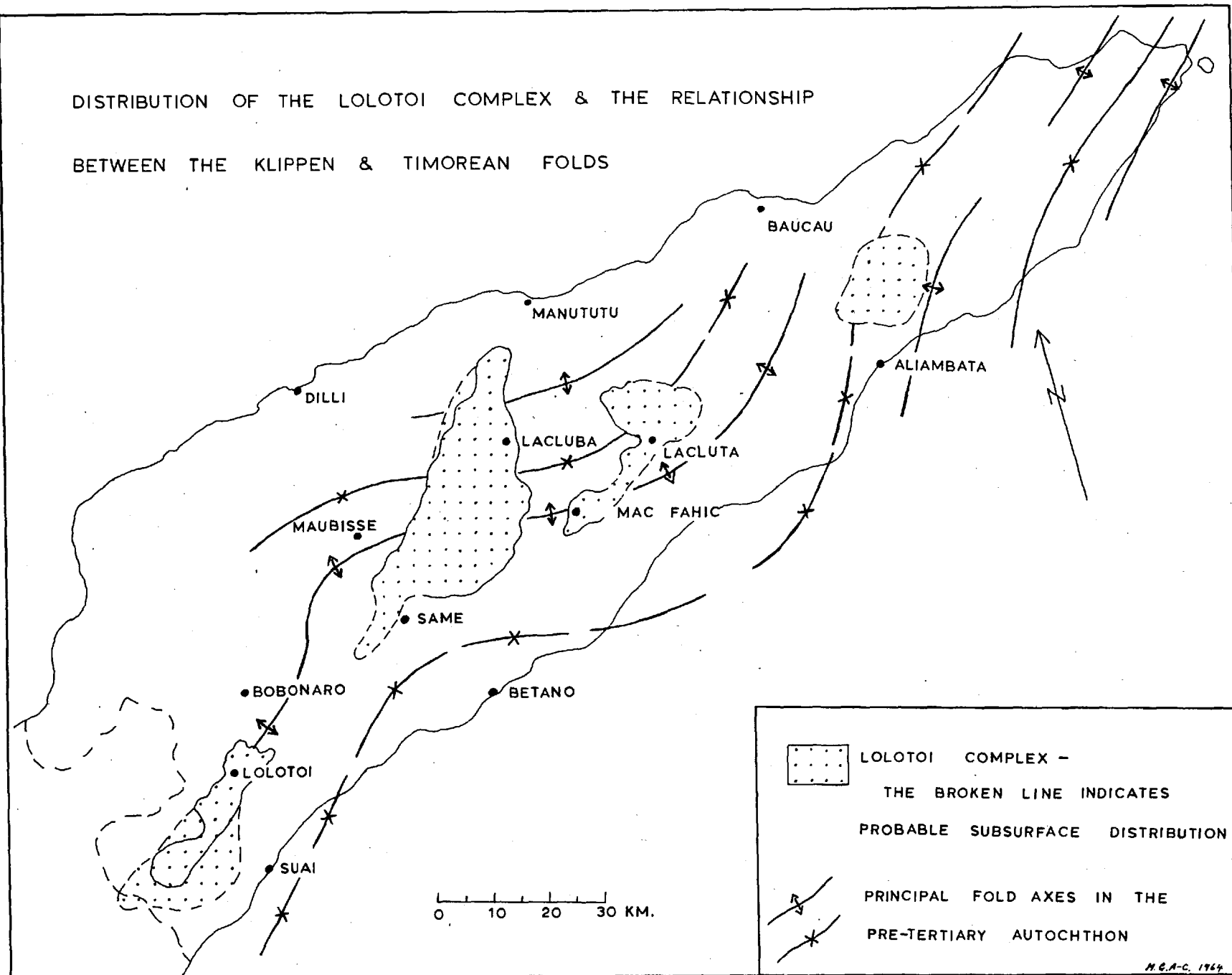


Fig. 12

d) STRUCTURES IN THE FORMATIONS OF MIDDLE EOCENE TO
 LOWER MIOCENE AGE.

These rocks have such a scattered and remnant distribution in eastern Timor that their fold patterns have not been determined. The Eocene rocks (Dartollu Limestone) are so restricted in outcrop that nothing is known of their folds. The Oligocene rocks (Barique Formation) and the Lower Miocene (Cablac Limestone) have a similar distribution (figure 6) and although separated by an erosion surface have been folded together in the Ramelauean Orogeny. The lack of stratification in the Barique Formation and the Cablac Limestone makes accurate determination of folds difficult. Dips between 5 and 50 degrees have been recorded. The figure 15 indicates a possible solution of the major folds in the Cablac Limestone.

These formations have been greatly broken up by faulting. Many huge fault scarps (plate 2B) formed by the Cablac Limestone dominate the scenery. Both the direction and throw of the faults appears to vary widely. Most of the minor faulting (largely interpreted from aerial photographs) has been omitted from the enclosures 1A, 1B, 1C, 1D.

e) STRUCTURES IN THE FORMATIONS OF MID-MIOCENE TO
 PLIOCENE AGE.

Parallel folds which are generally broad are the dominant structures. Locally, as in the Viqueque-Aliambata region, there is an overturning and tightening of folds with steeper dips. There are two formations involved in these folds; the Bobonaro Scaly Clay and the

Viqueque Formation. The Bobonaro Scaly Clay, which is an unstratified highly bentonitic deposit, has acted as an incompetent layer to varying degrees, whilst the overlying Viqueque Formation is a competent well stratified sequence. This has resulted in a diapiric element affecting most of the folds to a slight degree and occasionally, where folding has been tighter (e.g. Viqueque Anticline), it is quite marked.

As the Bobonaro Scaly Clay is entirely unbedded and contains no recognisable marker horizons it is only possible to map folds where the well bedded Viqueque Formation is present. It is however sometimes possible to recognise 'dips' in the Bobonaro Scaly Clay from the aerial photographs, but checking of these 'photo-dips' on the ground has always failed to reveal them.

The figure 16 outlines most of the recognised and interpreted folds in the Bobonaro Scaly Clay and the Viqueque Formation. These folds are described briefly below in three groups depending whether they occur in the Southern Basin, Central Basin or N.E. Basin (as defined in the section on stratigraphy).

i) Folds in the Southern Basin.

1) Matai Anticline.

This fold has been established by detailed field mapping, slim hole core drilling and gravity surveying. The fold is known over a strike length of 12 kms. The anticline strikes N.E. - S.W. and plunges N.E. from Matai to a cross fault after which it is unknown. It is

possible that the fold continues east of this cross fault with a very different strike direction (E.-W.) as shewn in figure 16 as the Fe Sour Anticline. The western limit of the anticline is unknown, but it is suspected (from the gravity data) that it plunges S.W. from Matai (the culmination) below the Suai Formation.

The Matai Anticline is developed parallel to and on the downthrown side of the Matai Fault (enclosure 3AB). The anticline is slightly asymmetrical having a steeper northern limb. Along the crest of the fold the Viqueque Formation has been deeply eroded and in places completely removed.

2) Beco Syncline.

This structure has been proved by field mapping. It is considerably broken by cross faulting. The axial plane trace although displaced by faulting strikes slightly south of east, and the fold plunges in this direction under the Suai Formation of the coastal plain. The gravity data suggest that the Viqueque Formation and the Suai Formation in this syncline thicken rapidly towards the coast.

3) Colitie - Malore Syncline.

This large structure has been mapped in the field, and is also discernible from the aerial photographs because it is expressed in the well stratified Viqueque Formation. The gravity data accords well with the syncline although the gravity minimum axis is displaced south of the axial plane trace. This is due partly to the regional gradient, but mostly to the gravity anomaly values reflecting the

shape of the Tertiary basin rather than the folding of the beds within the basin.

The Colitie Syncline is the western half of the largest structure in eastern Timor produced by the Matai Folding Phase which is defined later in the section on Tectonic History. It is 30 km. long and has preserved in its thickest part about 700 metres of Viqueque Formation. It is strongly asymmetrical having a steep northern limb and a flat southern limb that steepens rapidly near the hinge of the Hatu Udo Anticline. This asymmetry is ascribed to the diapiric effects of the incompetent Bobonaro Scaly Clay below the Viqueque Formation.

Minor faulting within the syncline includes some rare reversed movement (plate 53A). Most faults affecting this syncline appear to be normal.

Figure 16 shews that bordering the northern limb of the fold are harder older formations that acted as a relatively rigid block against which the very much softer Bobonaro Scaly Clay and Viqueque Formation were folded.

Around the Alas Posto the syncline is very shallow, and the Viqueque Formation is thin and **flat lying**, so that the structure almost fades out. Gravity anomaly values confirm that the Tertiary rocks here are very thin.

The Malore Syncline is the eastern part of this structure; it is about 35 km. long of which the easternmost 15 km. is conjectural since the post-Pliocene cover of Suai Formation masks any expression of the fold. The gravity survey in this area is on a regional scale and does

nothing to elucidate Tertiary folds. The Bouger Anomaly map reveals that south of the relatively rigid block (figure 16) between the River Cua and the River Iaclo do Sul a deep Upper Tertiary - Quaternary basin is developed. This basin contains the conjectured extensions of the Malore Syncline and Bibiliu Syncline (enclosures 1C & 3C). It is probable that the thickest developments of the Viqueque Formation and Suai Formation occur in this basin, and that the Viqueque Formation may achieve a thickness of 1000 metres in the deepest part of the Malore Syncline. The Viqueque Formation is expected to thicken towards the south. This rapid thickening of the formation could be expected to affect the folding.

4) Hatu Udo Anticline.

This structure is conjectural; it assumes that the broad outcrop of Bobonaro Scaly Clay in the Hatu Udo region represents the core of the anticline, the Viqueque Formation having been removed by erosion. The exposure of Cretaceous rocks (Wai Bua Formation) in the area north of Betano suggests that erosion here has been more profound, and that possibly the Bobonaro Scaly Clay and the Viqueque Formation, that originally covered this area, were thinner than in adjacent areas. The Hatu Udo Anticline may be considered the complementary structure to the Colitie Syncline.

The gravity anomaly values shew a very strong positive trend almost coincident with the Hatu Udo Anticline, and with the outcropping of Mesozoic rocks that form an inlier in the late-Tertiary formations. This positive anomaly is probably largely due to the strong

density contrast between the Mesozoic rocks and the Tertiary rocks which is emphasised by the buried topography effect.

5) Bobo Syncline, Teetor Anticline, and Cela Syncline.

These three folds are entirely conjectural. They are surmised as possible structures on the basis of the pattern of other folds in the region, the distribution of Bobonaro Scaly Clay and the Viqueque Formation (figure 16), and on the nature of interference folds in the Viqueque village region.

6) Tucu Beci - Luca Anticline.

The Tucu Beci structure is conjectural, being the complementary fold to the Malore Syncline. It is based on the distribution of the Bobonaro Scaly Clay and the Viqueque Formation. It is largely covered by Suai Formation and plunges below the coastal plain which obscures the evidence.

The Luca Anticline is the conjectured extension of the Cassulari Anticline that is considered to plunge below the coastal plains where the Suai Formation obscures any evidence.

7) Dilor Syncline.

This fold which is 8 km. long was first mapped in the field by Freytag (unpublished report, 1959). It lies in front (south) of the Bibiliu Fault which bounds the Lacluta klippe and Mt. Bibiliu which together formed a bastion against which the relatively soft late-Tertiary

rocks were folded.

8) Bibiliu Syncline.

This fold has been mapped over a distance of 35 km. It can be mapped more easily from the aerial photographs than in the field, partly due to the infrequency of exposures. This is quite a broad feature that has been folded against the bastion of Mt. Bibiliu and Mt. Builo. The western part (about 10 km.) of the Bibiliu Syncline is interpreted as extending under the coastal plains where it forms a complementary fold to the Luca Anticline. Like the Malore Syncline, to which it may be an extension, there is no surface expression of the fold because of the cover of the Suai Formation.

9) Viqueque Anticline.

This fold was recognised (but not mapped in detail) by Grunau (1953) and Gageonnet & Lemoine (1958). Like the other folds in this area its detail is more clearly discerned from the aerial photographs than on the ground. The steep dips of the Viqueque Formation on the limbs of the anticline flatten out quickly away from the hinge. This accords with diapiric behaviour of the core of Bobonaro Scaly Clay. The anticline is asymmetrical having a more steeply dipping northern limb. It is 20 km. long.

The Viqueque Anticline is considerably broken up by cross faults which are associated with its change in strike.

A Bouguer Anomaly positive axis coincides closely with the axial plane trace of the Viqueque Anticline.

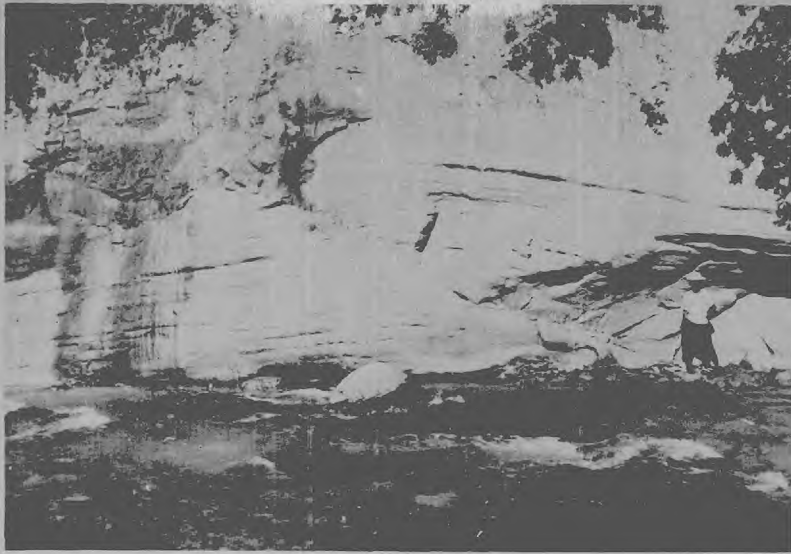
10) Ossulari Anticline.

This structure is almost a continuation of the axial plane trace of the Viqueque Anticline. It has been determined by field mapping and photogeology, the latter providing a more detailed picture.

Like the Viqueque Anticline a Bouguer Anomaly positive axis is almost coincident with the axial plane trace of the fold over much of its length. However the anomalous gravity field due to these two anticlines alone cannot account for the 26 mgl. anomaly (Viqueque) and 10 mgl. anomaly (Ossulari) that were found by the writer (unpublished report, 1959). Using a smoothed profile technique reveals anomalies of the order of 1.5 to 2.5 mgl. which accords with the size of the folds and the probable density contrasts involved. Using other interpretive techniques, such as that which assumes that the cause of the anomaly approximates to a long horizontal cylinder shaped body (Nettleton, 1940), and methods given by Bott & Smith (1958), it can be shewn that the density contrast involved is high (much higher than is found among sediments) and that the gravitating body has its upper surface between 3000 and 7000 metres. Geological reasoning suggests that there are probably three different factors operating here: the superficial effects of the Upper Tertiary folds, the effects of a probably rugged buried topography of folded Mesozoic strata (having a S.G. 2.6) draped by the Bobonaro Scaly Clay (S.G. 2.1), and a deep seated effect due to changes or structure in the basement.

PLATE 53

- A. Viqueque Formation, reversed faulting in the Colitie
Syncline.
- B. Looking north from the north coast of Timor to Atauro
I. Which is part of the volcanic Inner Arc.



11) Musam Anticline.

The axial plane trace of this fold strikes perpendicularly to that of the Viqueque - Ossulari anticlines. Strongly asymmetrical, with a steeper northern limb it too accords with diapiric behaviour of the Bobonaro Scaly Clay core.

12) Saqueto Syncline.

This structure which has been mapped in the field is more sharply defined on the aerial photographs. It is interpreted as extending eastward and plunging under the narrow coastal plain between the Saqueto Creek and River Bui.

13) Suete Anticline.

This fold which is expressed largely in the Bobonaro Scaly Clay has been determined from photogeology only. None of the photo-dips could be recognised in the field because the Bobonaro Scaly Clay is unbedded. This also applies to the other folds revealed by photogeology east of the River Bui that are expressed in the Bobonaro Scaly Clay (enclosure 1D).

(ii) Structure of the Central Basin.

This is interpreted as a graben structure on the basis of its linearity and the evidence from western Timor (Brouwer, 1942; de Waard, 1956). The Maliana Graben as it is called here is the easternmost extension of the Central Basin of Timor. The flat lying cover of post-

Pliocene sedimentary rocks inhibits the determination of any folds in this basin.

(iii) Folds in the North-East Basin.

1) Pere Syncline.

This is a tightly folded syncline that was formed by being folded against the rigid bastions of the Lacluta klippe and Mt. Mundo Perdido.

2) Baucau Syncline.

This has been interpreted from the spatial distribution of the Bobonaro Scaly Clay and the Viqueque Formation because there is very little evidence available from dip measurements. The Baucau Limestone that overlies the Viqueque Formation is flat lying so that the Viqueque Formation is only found outcropping around the perimeter of the Baucau Plateau. The Baucau Syncline, it is conjectured, plunges gently north under the Plateau.

3) Gamimau Anticline.

This fold is entirely conjectural; it is based on the spatial distribution of the Bobonaro Scaly Clay and the Viqueque Formation.

4) Laivai Syncline.

This is another conjectured structure for which there is no direct evidence.

5) Laleno Anticline.

This is a conjectural fold based on the distribution of the Bobonaro Scaly Clay and the Viqueque Formation.

6) Vailoro Syncline.

This structure is conjectured on the basis of the distribution of the Bobonaro Scaly Clay and the Viqueque Formation. It is assumed that these formations that are found outcropping around the Lospalos Plateau extend under the Plateau beneath the cover of the Baucau Limestone. The presence of the Poros Limestone on the Plateau and the Lake Surobeco may reflect the structural depression being infilled or indicate very slight post-Pliocene flexing.

f) STRUCTURES OF THE POST-PLIOCENE FORMATIONS.

The only two widespread post-Pliocene formations are the Baucau Limestone and the Suai Formation. Both these formations are seen to rest on the Viqueque Formation with strong unconformity in places. Folds in the Viqueque Formation are frequently truncated by flat lying or almost flat lying Baucau Limestone which commonly overlies a deeply eroded surface.

While most of the Baucau Limestone appears to be lying horizontally, dips of 1 or 2 degrees are by no means uncommon. Nearly always these dips accord with the attitude of the folds in the underlying Viqueque Formation and Bobonaro Scaly Clay (see particularly enclosure 1C). Whether these inclined beds in the Baucau Limestone are drape structures or due to gentle fold movements of the

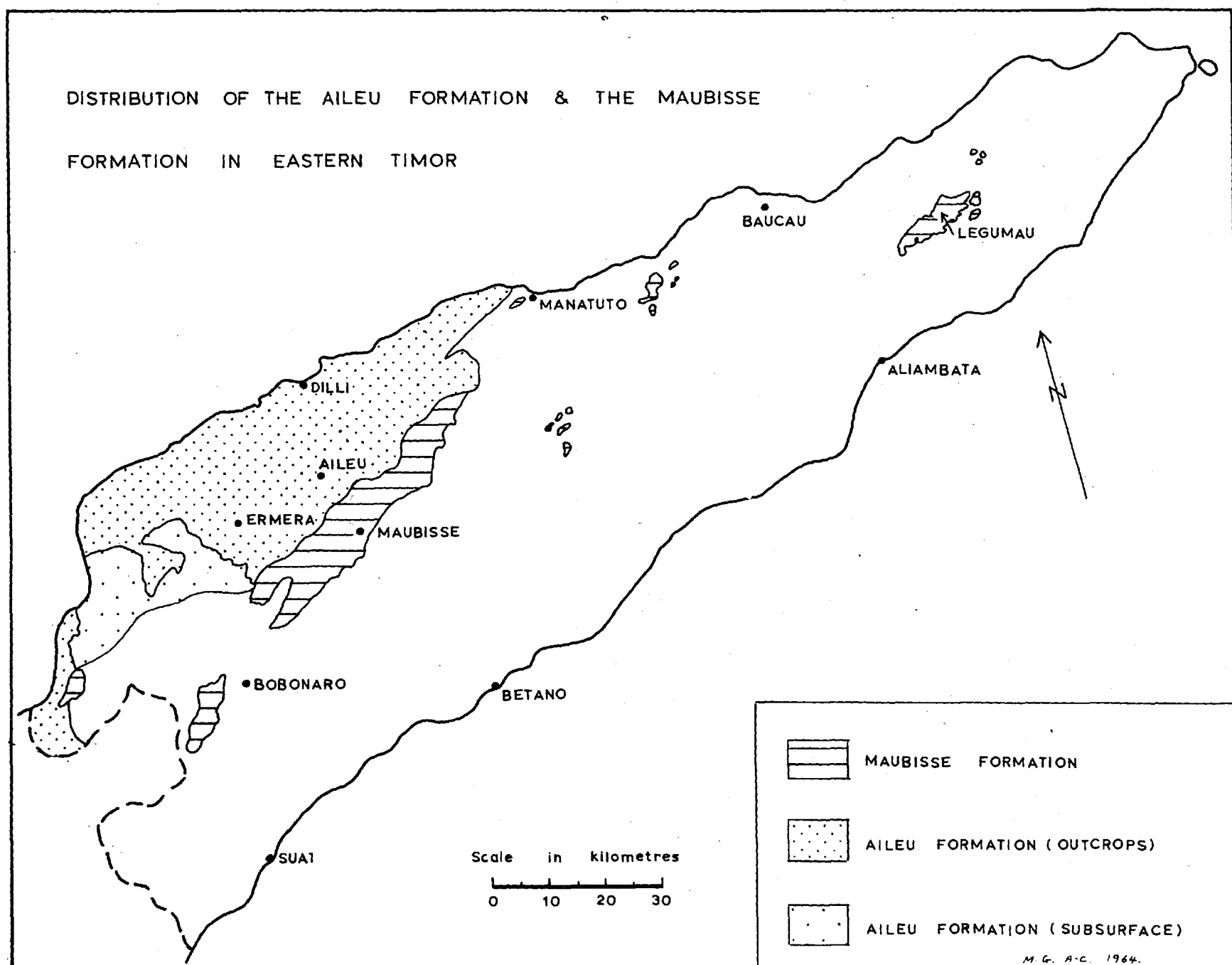


Fig. 13

same orientation as those that folded the Viqueque Formation in late-Pliocene times is uncertain.

Normal faulting has considerably disturbed the Baucau Limestone. Much of the faulting affecting the Viqueque Formation appears to be post-folding, and therefore possibly post-Pliocene. This post-Pliocene faulting is probably associated with the continued uplift of the island which began in the Upper Miocene.

B. STRUCTURES OF THE ALLOCHTHONOUS FORMATIONS

a) INTRODUCTION

In eastern Timor three groups of rocks occur which are entirely allochthonous, that is wherever they occur in eastern Timor they rest on a thrust plane, and their 'roots' have not been recognised anywhere. These groups are: the Lolotoi Complex, the Aileu Formation and the Maubisse Formation.

The Borolal Limestone is generally autochthonous but is known to form a few isolated klippen.

The Bobonaro Scaly Clay has been discussed in detail in the section on stratigraphy and in Audley-Charles (in press). It is entirely allochthonous in that it was originally deposited outside the present position, but it was emplaced in its present position by sedimentological processes and rests now on an erosion surface and not a thrust plane. Thus from a tectonic point of view it is autochthonous, and has been discussed earlier.

b) THE LOLOTOI COMPLEX

The Lolotoi Complex is considered to rest everywhere in eastern Timor on a thrust plane. The following evidence is adduced for this statement:

- (i) The manner in which the contact between the Lolotoi Complex and the pre-Eocene autochthonous rocks is entirely unrelated to the folds in the pre-Eocene autochthon indicates that the Lolotoi Complex cannot be in situ. Note particularly the relationship between the Cribas Anticline and the Lolotoi Complex (enclosure 1C).
- (ii) If the Lolotoi Complex were in situ it would have to be pre-Permian in age because it is regionally metamorphosed while the adjacent Permian and Mesozoic formations are not. Yet the Atahoc and Cribas formations are never found overlying the Lolotoi Complex despite the fact that they are found together both in the Cribas Anticline and the Bazol Anticline. Regrettably the actual contact has never been found in the field where it is obscured by scree, vegetation or thick weathering products.
- (iii) The distribution of the Lolotoi Complex can only be explained satisfactorily as four separate klippen sitting like cakes on the eroded surfaces of major folds in the pre-Eocene autochthonous formations.
- (iv) The relationships between these klippen and the major folds in the autochthon are illustrated in figure 12, while the cross sections in enclosures 3AB, 3C, & 3D demonstrate the cogency of this interpretation.

The time of overthrusting of the Lolotoi Complex.

The youngest rocks seen to be directly overlain by the klippen of the Lolotoi Complex are Jurassic Wai Luli Formation. The klippen sit on the strongly eroded surface of the folded autochthonous Permian and Mesozoic rocks, the youngest constituent of these folds are Upper Cretaceous (Senonian). This demonstrates that the klippen of Lolotoi were emplaced after the folding and erosion of the pre-Maestrichtian rocks.

The oldest rocks resting on the klippen of Lolotoi Complex (with sedimentary unconformity) are Middle & Upper Eocene Dartollu Limestone. This situation occurs in the S.W. part of the klippe overlying the Bazol Anticline. Elsewhere in eastern Timor the Oligocene Barique Formation and Lower Miocene Cablac Limestone rocks are found resting unconformably on the Lolotoi Complex.

Thus the Lolotoi Complex was overthrust to its present position in eastern Timor between the end of the Senonian and the opening of the Middle Eocene. But before the overthrusting took place the pre-Maestrichtian autochthonous strata were folded and deeply eroded during the same time interval (end of Senonian - Middle Eocene). It seems most probable that the overthrusting took place at the very end of this time interval, as this allows most time for the folding and erosion. Therefore it is concluded that the Lolotoi Complex was overthrust onto eastern Timor during the Lower Eocene, or possibly early in the Middle Eocene.

The place of origin of the Lolotoi Complex.

All the thrust planes on which Lolotoi Complex rests appear to have a southerly dip which might suggest a southerly derivation for the Lolotoi. However it must not be overlooked that there was another major orogenic phase during the mid-Miocene which must have greatly altered the attitude of the thrust planes.

Outside eastern Timor rocks similar to those of the Lolotoi Complex have been reported from western Timor (Brouwer, 1942; van Bemmelen, 1949; and de Waard, 1954), and from the islands of Kisar, Leti, Moa and Sermata (Molengraaff, 1915, and van Bemmelen, 1949). In no case has it been found that these rocks are autochthonous. It is therefore not known where the Lolotoi Complex was derived from, but detailed studies of the field relationships between the Lolotoi Complex and the underlying strata should reveal the direction of thrusting.

c) AILEU FORMATION.

This Formation is confined to the N.W. part of eastern Timor. It can be seen to have been overthrust onto the Jurassic Wai Luli Formation in the western side of the valley of the River Laclo. In the region of the western slopes of the Rendau Range the Aileu Formation appears to have been thrust over the Lolotoi Complex. The Aileu Formation is clearly closely associated in space with the Maubisse Formation. The Maubisse Formation, as will be shewn below, is known to have been overthrust during the mid-Miocene (Tf), and it seems certain therefore that the Aileu Formation was emplaced in eastern Timor at

the same time.

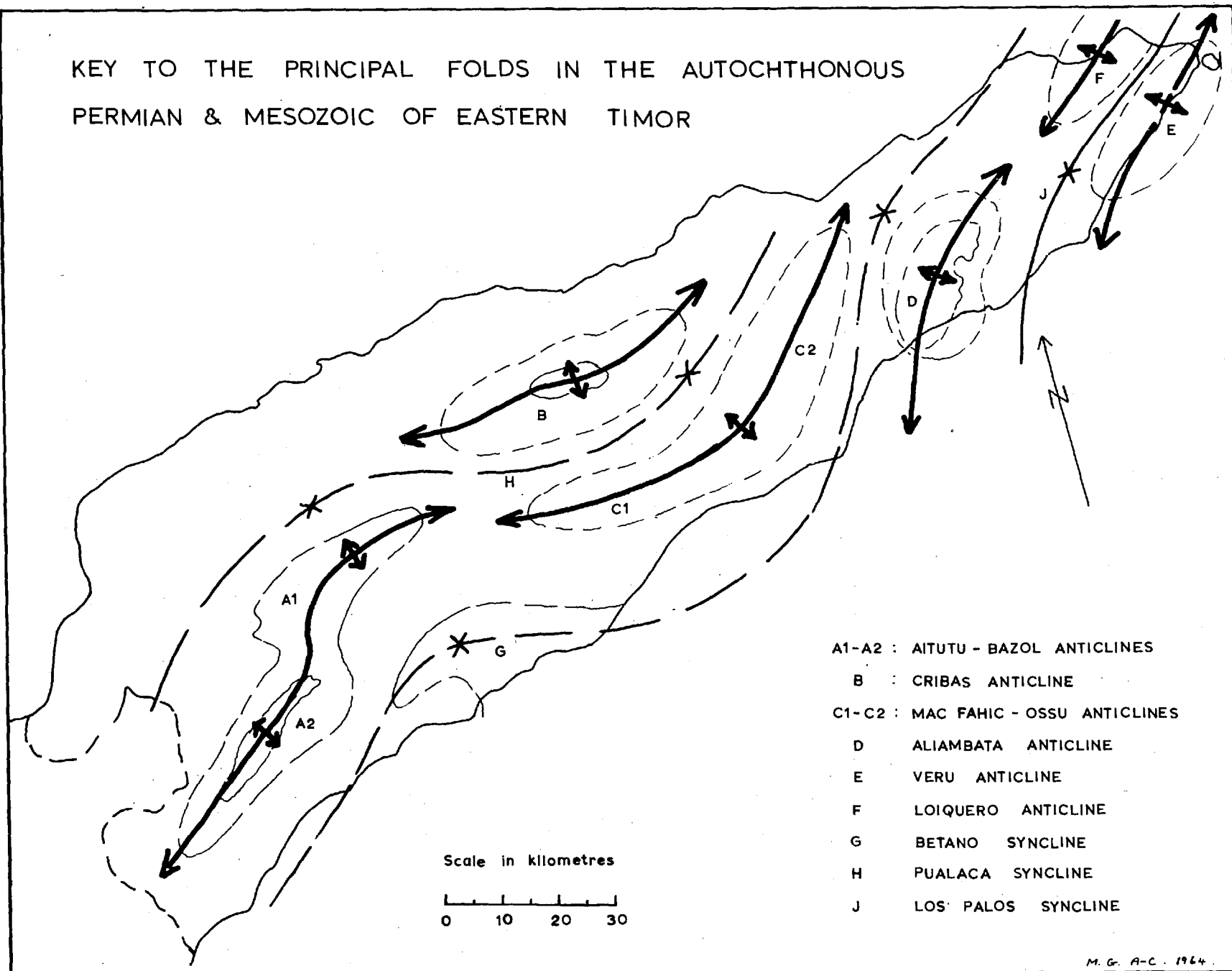
The place of origin of the Aileu Formation.

The thrust planes that carry the Aileu Formation appear to dip northwards (enclosure 3AB), as do the thrust planes that carry the Maubisse Formation. This suggests that the Aileu Formation was derived from the north. One point of particular interest is that there is a much higher degree of metamorphism of the Aileu Formation in the zone close to the north coast. This affect dies out rapidly to the south. It seems highly probable that this metamorphism is associated with the igneous activity of the volcanic Inner Arc that is found to the north of Timor. As this activity is dormant in the region opposite Timor and is considered to have been so since the Pliocene (van Bemmelen, 1949 and Brouwer, 1962) the likelihood that the present north coast metamorphic zone was metamorphosed before it was thrust onto Timor in mid-Miocene times seems proved because the other rock formations along the north coast adjacent to the Aileu Formation are not metamorphosed. This would indicate that the Aileu Formation was derived from the region north of Timor.

d) MAUBISSE FORMATION.

The Permian Maubisse Formation is seen to be resting on younger rocks of the autochthonous Mesozoic formation with a thrust plane at the contact, This situation is well exposed on the north limb of the Aitututu Anticline where the Maubisse Formation gives rise to the Rammelau Range, and further west the allochthonous position can be observed at Mt. Lacouse and Mt. Oileau on the north limb

KEY TO THE PRINCIPAL FOLDS IN THE AUTOCHTHONOUS
PERMIAN & MESOZOIC OF EASTERN TIMOR



M. G. A-C. 1964.

Fig. 14

of the Bazol Anticline. The cross sections in enclosures 3AB, 3C and 3D illustrate these and other examples.

Many scattered klippen of the Maubisse Formation occur (figure 13). Some of them are draped by Bobonaro Scaly Clay, as for instance in the River Vemassee, where it is not certain whether the exposed Maubisse Formation represents a large exotic block in the Bobonaro Scaly Clay, or whether part of one or more klippen.

The exact relations between the Aileu Formation and the Maubisse Formation have not been determined. But their spatial distribution indicates they were overthrust together. The interpretation adopted here (enclosure 3AB) that these allochthonous formations that occupy the N.W. part of eastern Timor form a very large nappe is tentative. The sections (enclosure 3AB) that suggest the Maubisse Formation is folded about the core of Aileu Formation to form a large recumbent fold is not based on any direct evidence. The field relationships between the various allochthonous formations would probably reward careful investigation.

Time of overthrusting of the Maubisse Formation.

The juxtaposition of the thrust front of the Maubisse Formation (to the north) and the Cablac Limestone (to the south) across the valley of the Wai Luli (enclosure 3AB, section 10) demonstrates that the Maubisse Formation must have arrived in its present position after much of the Cablac Limestone had been removed by erosion. A similar relationship demonstrating the same point is found across the valley of the Tahafara where the Cablac Limestone forms

the Mt. Oohooshkine and the Maubisse Formation gives rise to Mt. Lacouse. Similarly this is seen for Mt. Mata Ria and Mt. Legumau in the east. These field relationships prove that the Maubisse Formation was emplaced in its present position after the erosion of the Cablac Limestone, i.e. post-Te. It is important to recall that in western Timor red crinoidal Permian limestones (equivalent to the Maubisse Formation) are found resting directly on limestones of Te age (de Waard, 1954).

The Bobonaro Scaly Clay of Tf age is seen to rest unconformably on the Maubisse Formation in a number of places (enclosures 1A, 1B & 1D), and the most common exotic material in the Bobonaro Scaly Clay is derived from the Maubisse Formation. Thus the field relationships amply demonstrate that the Maubisse Formation was overthrust to its present position in eastern Timor during the time interval between the end of Te and before the end of Tf. As a large part of the Cablac Limestone had been removed by erosion before the arrival of the Maubisse Formation, it seems certain that the overthrusting took place in Tf time. This would accord with the catastrophic nature of the Bobonaro Scaly Clay, which, as was shewn earlier (in section on stratigraphy), arrived very quickly and was undoubtedly closely connected with the climax of this orogenic phase, which was marked by major overthrusting.

Place of origin of the Maubisse Formation.

The northward dip of the thrust planes that carry the Maubisse Formation (and the Aileu Formation) suggest a derivation from the north. The arguments for the northern derivation of the Bobonaro Scaly Clay, which was clearly

very closely associated with these overthrust formations have already been given in the section dealing with the stratigraphy of the Bobonaro Scaly Clay. Furthermore the whole configuration of these thrust sheets indicates a northern derivation.

iv) SUMMARY OF TECTONIC HISTORY

A tabular summary of the tectonic history is given in the Table I and in enclosure 5. The procedure adopted in this thesis has been to define orogenic phases in local terms rather than employ broad regional orogenic terms, this follows the recommendations of de Sitter (1964).

A) BAZOLIAN FOLDING

The base of the Aitutu Formation is strongly diachronous, ranging from Ladinian in the Cribas Anticline to Norian on the north limb of the Bazol Anticline. In the Loi Quero Anticline at Tutuala the base is probably a conglomerate of Carnian age. Below the Aitutu Formation the Permian Cribas Formation is always found. There is therefore a considerable break with at least all of the Lower Triassic missing, and probably part of the Upper Permian as well, as there is some palaeontological indication that the Cribas Formation may be of lower Upper Permian age.

In the field the unconformity has not been identified because the exposure at the contact of the two formations is poor, and because minor folding in these rocks is so complex that any difference in attitude between the two formations is not apparent. Detailed mapping backed by palaeontology in the crucial areas would probably be rewarding.

The diachronous base of the Aitutu Formation is interpreted as probably being an unconformity representing a folding phase that is here defined as the Bazolian Folding. The name is taken from the Bazol Anticline, where in the north limb there appears to be a gap between the Cribas Formation and the Aitutu Formation, representing a time interval from the end of the Permian to the base of the Norian.

Contemporaneous folding elsewhere.

- i) Western Timor: The reported presence of the whole of the Lower Triassic in a condensed sequence 2 metres thick (Umbgrove, 1938) suggests the folding may not have affected western Timor, but this occurrence should be checked in the light of the discovery of the Bobonaro Scaly Clay, as it might be an exotic block.
- ii) Borneo: In west Sarawak an unconformity is reported (Liechti, 1960) between the Lower Permian and the Upper Triassic, and also from Central Borneo (van Bemmelen, 1949).
- iii) In other parts of the Indonesian Archipelago: van Bemmelen (1949) states there is no important folding known to have occurred during this time.

iv) New Guinea: Visser & Hermes (1962) reported no evidence of any folding during this time, except in Misool where there was a strong folding phase of Carnian age.

v) Northern Australia: David (1950) says that the sea withdrew from the northern part of the continent at the end of the Permian when there were folding and epeirogenic movements that would appear to be contemporaneous with the postulated Bazolian Folding in eastern Timor.

B) BETANEAN FOLDING.

Throughout eastern Timor the Upper Jurassic and Lower Cretaceous seems to be missing. The Lower & Middle Jurassic is widely represented by the Wai Luli Formation, and the Upper Cretaceous is represented by two formations; the Wai Bua Formation and the Borolalo Limestone. Unfortunately the base of these two Upper Cretaceous formations is never well exposed, but the contact of the Borolalo Limestone with the underlying Aitututu Formation (Norian at the top) in the Iliomar area can be determined as unconformable from the differences in attitude of the two formations, and particularly from the minor folding. In this instance the whole of the Jurassic and the Lower Cretaceous is missing. The situation with the Wai Bua Formation is more obscure because the base is never seen, but the youngest known part of the underlying Wai Luli Formation is Lower Jurassic.

This unconformity at the base of the Upper Cretaceous formations in eastern Timor is here defined as the Betanean Folding. The name is derived from Betano, the most important geographic point in the only area where the Wai

Bua Formation is developed. The maximum range of the unconformity is in the Iliomar region where it extends from the end of the Norian to the base of the Senonian.

Contemporaneous folding elsewhere.

- i) Western Timor: No data is available except that the Upper Cretaceous and Upper Jurassic (Oxfordian) have been reported by van Bemmelen (1949). However this should be checked in the light of the knowledge of the Bobonaro Scaly Clay to determine that they were not large exotic blocks.
- ii) Borneo: An unconformity with intense folding and overthrusting is reported from Central Borneo (van Bemmelen, 1949).
- iii) Celebes: Jurassic and Upper Cretaceous rocks have been reported but the Lower Cretaceous has not been recorded.
- iv) Ceram & Buru: There appears to be a gap in sedimentation between the Jurassic and the Upper Cretaceous, the Lower Cretaceous being missing. Van Bemmelen (1949) stated there must have been an orogenic phase between Upper Jurassic and Upper Cretaceous in East Ceram.
- v) New Guinea: In the Vogelkop Visser & Hermes (1962) reported an epeirogenic gap widening to the west involving the absence of successively younger parts of the Jurassic and older parts of the Cretaceous.
- vi) Northern Australia: Marine transgressions are reported (David, 1950) in the Upper Jurassic and the Aptian

with a withdrawal in the Lower Cretaceous (pre-Aptian).

There appears to be widespread evidence for folds movements throughout the Archipelago during the Upper Jurassic - Lower Cretaceous time interval. In the Banda Arcs this was possibly a very important phase. The epeirogenic movements in northern Australia appear to be contemporaneous.

C) TIMOREAN OROGENY

The style of folding of all the pre-Eocene autochthonous formations of eastern Timor is distinctly different from that of all younger formations. The overthrusting of the Lolotoi Complex onto eastern Timor took place during the Lower Eocene, as has been shewn in an earlier section. This overthrusting followed a period of intense folding and subsequent erosion that affected all the pre-Eocene autochthonous rocks. It is clear from the size of the major folds, and the intensity of the associated minor folding, together with the huge overthrust slices of metamorphic rocks (Lolotoi Complex), that this was a major period of earth movements. This is named here as the Timorean Orogeny, and defined as the folding movements in eastern Timor that took place between the Maestrichtian and the Middle Eocene inclusive, and which culminated in the overthrusting of the Lolotoi Complex. The term Timorean is applied because the results of the orogeny can be seen throughout eastern Timor, and because this was the most important orogenic phase in Timor's history.

Contemporaneous folding elsewhere.

- i) Western Timor: Strong compressional movements are reported in post-Senonian and pre-Eocene time by de Waard (1954).
- ii) Borneo: There were major earth movements in Borneo between the late-Cretaceous and the late-Eocene (van Bemmelen, 1949 & Liechti, 1960).
- iii) Ceram: Overthrusting movements from south to north are reported to have occurred in the Eo-Oligocene (van Bemmelen, 1949) together with intense folding.
- iv) Celebes: An orogenic phase has been reported (van Bemmelen, 1949) to have occurred at the end of the Cretaceous.
- v) New Guinea: Geosynclinal downwarping during the Eocene has been reported by van Bemmelen (1949).
- vi) Tenimbar & Misool: A transition from pelagic limestones of Upper Cretaceous age to shelf deposits of Tertiary age (Visser & Hermes, 1962) suggests large scale crustal movements.
- vii) Northern Australia: There appears to have been an uplift of the continent at the end of the Cretaceous and the Danian is said to have been a period of erosion (David, 1950).

The Timorean Orogeny would appear to be contemporaneous with the world-wide movements of the

Laramide Orogeny, but in the Indonesian Archipelago outside Timor the available evidence seems to indicate that principal movements took place in the Upper Eocene rather than the Lower Eocene. In northern Australia epeirogenic movements seem to be contemporaneous with the Timorean Orogeny.

D) DARTOLLU UPLIFT

The Upper Cretaceous Formations of eastern Timor were deposited either in an infraneritic bathyal environment. After this Timorean Orogeny, which culminated in the Lower Eocene overthrusting of the Lolotoi Complex, the first rocks deposited (Middle & Upper Eocene Dartollu Limestone) were a shallow off-reef facies. This demonstrates that after the climax of the orogeny (marked by overthrusting) there was an immediate uplift of the region. The subsequent formations; the Oligocene Barique Formation and Lower Miocene Cablac Limestone are also shallow water facies.

E) BARIQUEAN UNCONFORMITY

The base of the Barique Formation is everywhere marked by a strong unconformity, usually with a basal conglomerate. This conglomerate contains rounded boulders and pebbles of Middle & Upper Eocene Dartollu Limestone. Since the Barique Formation is overlain unconformably by the Lower Miocene Cablac Limestone it is probably Oligocene in age. Generally the Barique Formation is found resting unconformably on the Lolotoi Complex klippen, which proves that it is post-thrusting.

The Barique Formation is the only example of igneous

activity in or very near eastern Timor except for very minor occurrences of extrusives in the Cribas Formation and rare tuffs in the Viqueque Formation. Thus the commonly observation that in unstable areas orogenic compression (Timorean) is followed by uplift (Dartollu) which is followed by vulcanism (Barique Formation) is exemplified by the history of eastern Timor.

The Barique Unconformity which represents earth movements at the end of the Eocene and the beginning of the Oligocene is probably equivalent to the important movements reported from Borneo, Ceram, Celebes and many other parts of the Indonesian Archipelago.

F) MATABIAN UNCONFORMITY.

The base of the Cablac Limestone, which is dated as Lower Miocene (Te), is a strong unconformity throughout eastern Timor. Although it cannot be proved palaeontologically there is some suggestion from the microfossils that the Cablac Limestone belongs to the upper part of the Lower Miocene, probably Te₅. The marine transgression that resulted in the deposition of the Cablac Limestone is a very widespread event in the Indonesian Archipelago (called the Bebulah transgression by Brouwer, 1942). An important marine transgression of Te₁₋₄ age took place in Sumatra, Java, Borneo, most of the Lesser Sunda Islands, Banda Arcs, and the Philippines.

G) RAMELAUEAN OROGENY.

The most dramatic and widespread unconformity in eastern Timor occurs at the base of the Bobonaro Scaly

RELATIONSHIP BETWEEN THE DISTRIBUTION OF THE
CABLAC LIMESTONE (Te) & MAJOR TIMOREAN FOLDS
OF THE PRE-EOCENE AUTOCHTHON

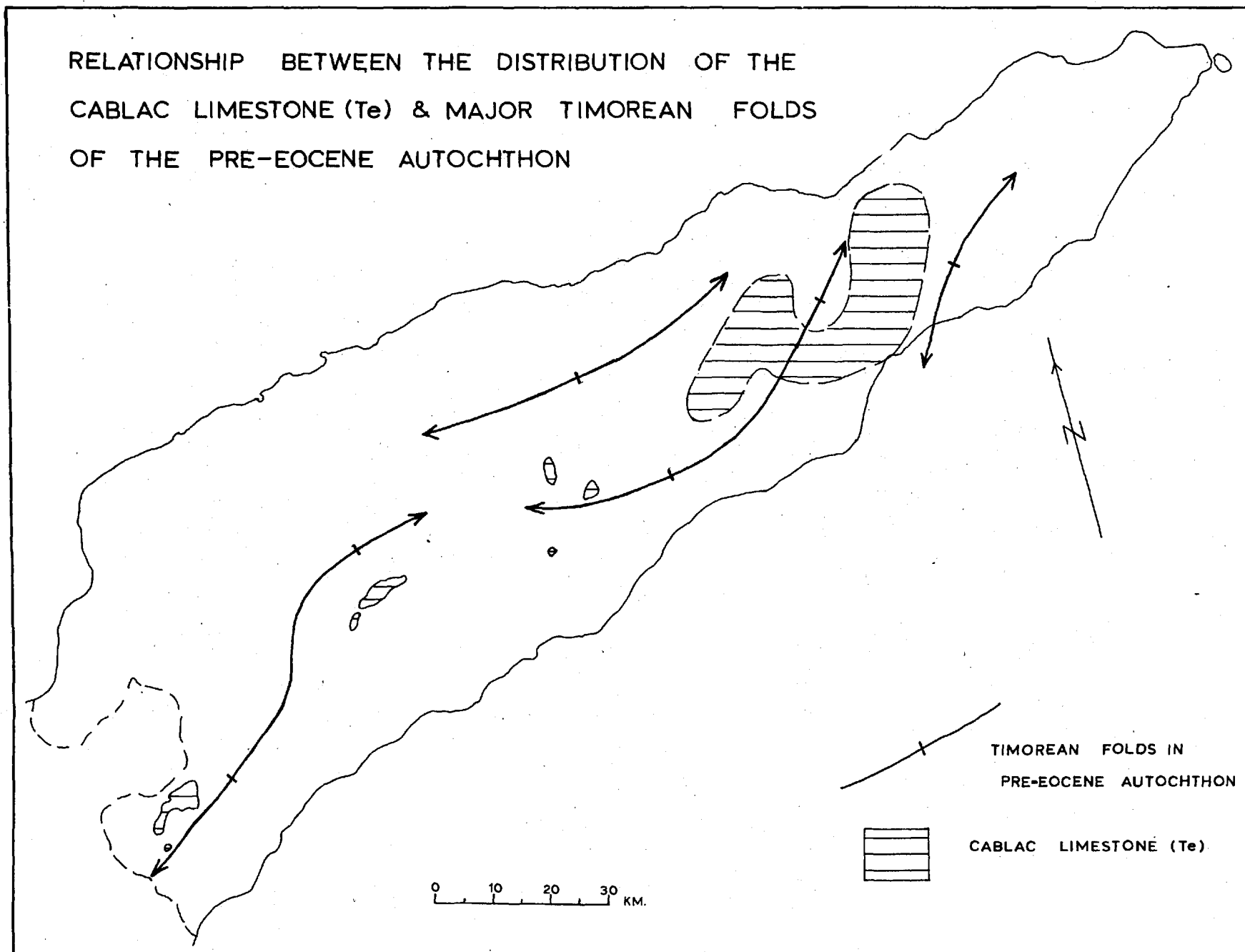


Fig. 15

Clay, which is mid-Miocene (Tf) in age. During the mid-Miocene the huge masses of Aileu Formation and the Maubisse Formation were overthrust onto Timor. This occurred at the same time or just before the emplacement of the Bobonaro Scaly Clay. These movements called here the Ramelauean Orogeny, from the great thrust front mountain range of Ramelau, occurred within the Tf time interval. The overthrusting of the Aileu and Maubisse formations must have resulted from compression. These forces doubtless refolded the structures formed by the Timorean Orogeny. Perhaps the change in strike of the major Timorean folds (figure 5) occurred as a result of the Ramelauean Orogeny. The Ramelauean Orogeny must also have folded the post-Cretaceous and pre-Tf formations, viz; Dartollu, Barique and Cablac. Because of the scattered remnant distribution of these formations it has not been possible to define these folds.

At the beginning of the mid-Miocene (Tf), before the overthrusting, and before the emplacement of the Bobonaro Scaly Clay, there was an immense erosion of all earlier formations. This must have involved the stripping away of most of Tertiary formations older than Tf. It is probable that the actual overthrusting of the Aileu and Maubisse, and the emplacement of the Bobonaro Scaly Clay were themselves important agents of erosion.

Contemporaneous folding elsewhere.

i) Western Timor: The main orogenic phase is said by de Waard (1954) to be Tf or Tg in age, and he surmises that Tf₂ is the most probable by analogy with fold movements in Southern Djawa.

- ii) Borneo: Late-Te folding with regional unconformity at the base of the Te₅-Tf formations are reported by Liechti (1960).
- iii) Celebes & Ceram: The mid-Miocene was a period of deep subsidence and orogeny here and throughout the Moluccas except in the Misool-Onin-Koemawa region (Visser & Hermes, 1962).
- iv) New Guinea: The Middle & Upper Miocene was a period of widespread transgression and basinal subsidence throughout most of New Guinea.
- v) Sumatra & Java: An orogenic revolution is reported to have occurred in the Middle Miocene.
- vi) Northern Australia: There appears to be very little evidence from northern Australia, but in Western Australia uplift and folding probably occurred towards the end of the Miocene.

Throughout the Indonesian Archipelago there was an orogenic revolution contemporaneous with the Ramelauean Orogeny in Timor. Movements on a smaller scale also occurred in Australia.

H) SORO UPLIFT.

After the emplacement of the Bobonaro Scaly Clay (Tf) at the end of the Ramelauean Orogeny the region of Timor commenced a period of rapid uplift which has continued to the present time. This uplift is indicated by the Viqueque Formation which is a marine molasse facies which

has regressed from the beginning of the Upper Miocene as the island emerged from the sea.

The term Soro Uplift is given to this epeirogenic phase because at the foot of Mt. Soro the basal conglomerates of the Viqueque Formation overlie a klippe of Lolotoi Complex. These basal conglomerates are clearly a shore line deposit of Tg age. The Soro Uplift is considered to have begun in Tg (Upper Miocene) and to have continued to the present day.

J) MATAIAN FOLDING

The folded Viqueque Formation, of which the youngest part is Pliocene (Th), is overlain unconformably by unfolded Pleistocene reef limestones of the Baucau Limestone. The unconformity marks a period of considerable erosion that followed the folding of the Viqueque Formation. This folding, which is relatively gentle, is exemplified by the Matai Anticline and must have taken place in the late-Pliocene.

The effects of the Mataian Folding are exhibited throughout eastern Timor by the characteristic style of folding of the Bobonaro Scaly Clay and the Viqueque Formation.

Contemporaneous folding elsewhere.

i) Western Timor: A late-Pliocene folding phase is recognised in western Timor by de Waard (1954). The equivalent of the Viqueque Formation is folded and overlain unconformably by the Pleistocene reef limestones.

INDEX TO THE MATAIAN FOLDS & THEIR
RELATIONSHIP TO THE PRE-T₁ RIGID MASS

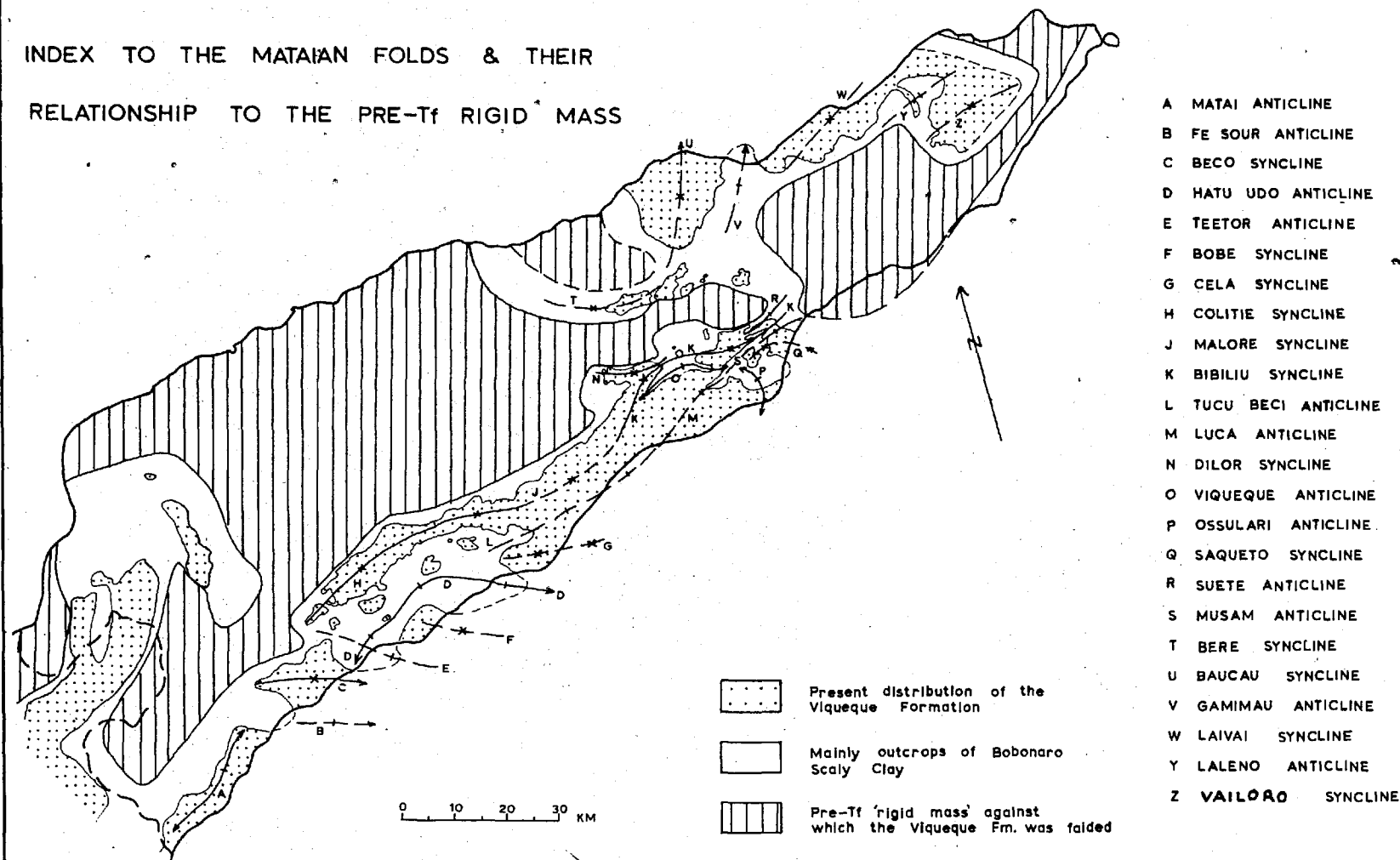


Fig. 16

ii) Borneo: Pliocene and Pleistocene folding phases of imprecise dating are known from Borneo.

iii) Sumatra & Java: Late-Pliocene movements produced gentle folding and faulting.

iv) Lesser Sunda Islands & Banda Arcs: Nearly everywhere there is evidence for gentle folding in the late-Pliocene or or early-Pleistocene.

v) Northern Australia: Very little evidence is available from northern Australia but in Western Australia there was a period of folding and uplift in late-Pliocene that appears to have been general throughout much of the continent.

Throughout the Indonesian Archipelago and in Australia there seem to have been uplift and gentle folding in the late-Pliocene or early-Pleistocene, with which the Mataian Folding is correlated.

CHAPTER IV

SUMMARY OF THE GEOLOGICAL HISTORY

An outline of the geological history of eastern Timor is given in the Introduction, and is expressed in table I, and enclosure 5. In this section a more detailed account is given; this has resulted in some unavoidable duplication of parts of the sections on stratigraphy and tectonics.

Permian.

The geological record of eastern Timor begins with the Lower Permian Atahoc Formation. This and the succeeding Upper Permian Cribas Formation represent shallow marine deposits having some flysch-like characters. Mainly shales and siltstones with some calcarenites and calcilutites, they also contain important quartz arenites with plant debris.

These neritic rocks were most probably derived from the erosion of northern Australia and represent a shelf facies, perhaps partly deltaic, belonging to a delta built out from the north-west extension of the Kimberly Block of northern Australia (figure 17).

North of Timor there was a deeper water zone, represented by the Aileu Formation that was thrust from the north onto Timor during the mid-Miocene orogeny. The Maubisse Formation, a carbonate reef-eruptive facies, was probably derived from the ancient Sunda Shelf north of the deeper water zone in which the Aileu Formation was deposited (figure 17).

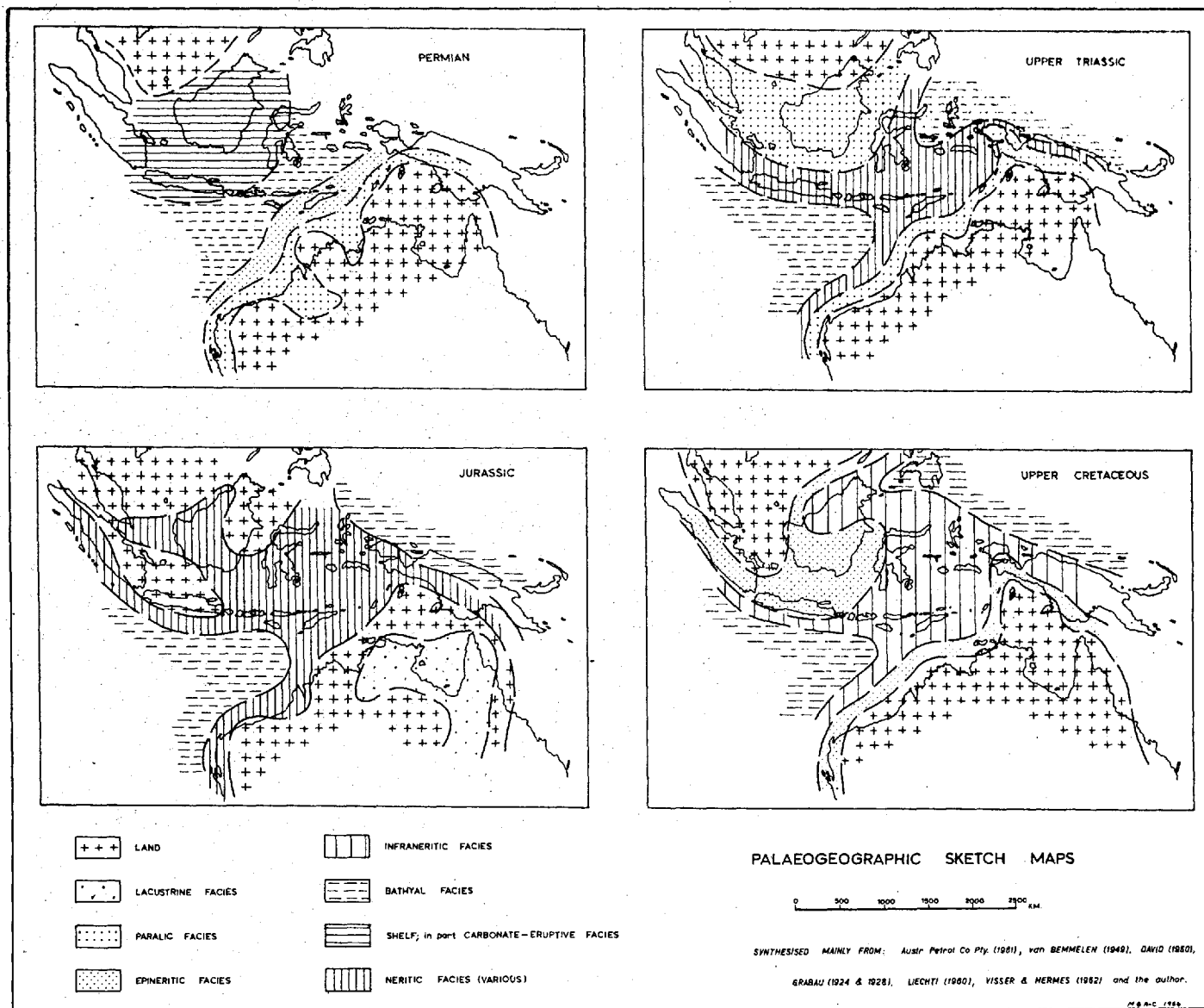


Fig. 17

To the south, northern Australia was the site of fluvial-glacial deposits, and a paralic facies probably swept the edge of the continent from West Australia north-eastwards to New Guinea (David, 1950; Veevers & Wells, 1961; Visser & Hermes, 1962).

The important unconformity in eastern Timor between the Permian Cribas Formation and the Middle & Upper Triassic Aitutu Formation is due to the Bazolian folding phase. There appears to be an equivalent unconformity in Borneo between the Lower Permian and the Upper Triassic (van Bemmelen, 1949 and Liechti, 1960), and in northern Australia folding and epeirogenic movements occurred at the end of the Permian (David, 1950). These widespread crustal movements probably resulted in a considerable shallowing at the end of the Permian of the region now occupied by the Indonesian Archipelago (figure 17).

Triassic.

The Aitutu Formation which consists mainly of calcilutites with some calcarenites and a few shales represents a shallow marine deposit. It probably accumulated in a basin in which little terrigenous detritus entered, and in which the bottom conditions were from time to time anaerobic and possibly highly saline. Outside this basin and at its periphery reef organisms probably flourished.

In the eastern part of the Banda Arcs a greywacke-shale facies is reported from the Tanimbar Islands, Misool, Ceram and the S.E. Celebes (van Bemmelen, 1949 and Visser & Hermes, 1962).

In New Guinea a paralic facies was predominant, and probably extended south-westwards around the northern margin of the Australian continent from which the sea had withdrawn at the end of the Permian (figure 17).

Jurassic.

The opening of the Jurassic is marked in eastern Timor by a considerable increase in terrigenous detritus (the Wai Luli Formation). Shales and marls became increasingly important and during the Lower and Middle Jurassic quartz arenites and siltstones became more frequent. In Misool there is a change from Norian reef limestones to Lower Jurassic neritic clastic sediments with an unconformable contact between them. These changes suggest broad crustal movements, which probably occurred in northern Australia, the probable source of much of the detritus (figure 17).

A change in distribution of land and sea is also indicated for the Sunda region at the end of the Triassic (figure 17).

The Wai Luli Formation of eastern Timor is entirely marine, and was probably deposited in shallow water.

There was a very important folding phase in eastern Timor between the end of the Middle Jurassic and the opening of the Upper Cretaceous. This Betanean Folding is represented by a strong unconformity with a deeply eroded surface below the Upper Cretaceous. The major Timorese folds (Lower Eocene) were almost certainly initiated by the Betanean movements. It seems likely that the Betanean folds were largely broad warps.

Outside Timor there were important contemporaneous folding movements in Borneo, Ceram and Buru (van Bammelen, 1949). In New Guinea an 'epeirogenic gap' (Visser & Hermes, 1962) represents these movements, and marine transgressions are reported from northern Australia (David, 1950).

Cretaceous.

In Timor the Upper Cretaceous opened with a deep marine facies (infraneritic) which contrasts with the epineritic deposits of the upper part of the Wai Luli Formation. Upper Cretaceous radiolarites (Wai Bua Formation) and pelagic limestones (Borolalo Limestone) accumulated in a basin in which very little terrigenous detritus was deposited. Very similar pelagic limestones occur in Tanimbar and Misool. This suggests that immediately in front of the Australian continent a deep downwarped zone extending at least from Timor to Misool was formed during the late-Jurassic and Lower Cretaceous, and that into this trough very little detritus was supplied from Australia during the Upper Cretaceous. In Timor this crustal downwarping would be associated with the Betanear Folding.

In north-west Borneo a geosyncline had been initiated immediately in front of the continent of S.E. Asia. These downwarping movements appear to be analogous to those in front of Australia.

The Upper Cretaceous ended with an even stronger orogenic phase in Timor, the Timorean Orogeny which resulted in the formation of major folds, their erosion and

the subsequent overthrusting of great masses of metamorphic rocks (the Lolotoi Complex). These movements all took place within the period dated as post-Senonian to pre-Middle Eocene.

Outside Timor contemporaneous movements of major importance took place in Borneo (van Bemmelen, 1949 and Liechti, 1960), in Ceram and Celebes (van Bemmelen, 1949). Evidence of dramatic facies changes in Tanimbar and Misool indicate major crustal movements. In New Guinea geosynclinal downwarping during the Eocene has been reported (van Bemmelen, 1949). In northern Australia epeirogenic movements seem to be contemporaneous with the Timorean Orogeny which is part of the world wide revolution called Laramide.

Eocene.

In Timor following the Timorean Orogeny there was a rapid phase of uplift so that after the infraneritic deposits of Senonian age the Middle & Upper Eocene Dartollu Limestone is an off-reef limestone rich in the remains of neritic organisms. This Dartollu Uplift was to continue until the next orogenic phase in the mid-Miocene.

Much of the Indonesian Archipelago in Eocene times was either land or covered by a shallow sea (van Bemmelen, 1949 and Umbgrove, 1938). It seems likely however that the deep-sea trough south of Timor had been at least initiated by the Timorean Orogeny. In particular the geology of Timor seems to have become far less related with Australia after the Lower Eocene. Similarly if the Timor Trough was in existence by Middle Eocene it seems

likely that other parts of the submarine topography of the Archipelago as we know it today were formed at this time.

Oligocene.

In Timor there is a strong unconformity between the Eocene and the Oligocene called the Barique Unconformity. This unconformity represents earth movements at the end of the Eocene (Tb) and the beginning of the Oligocene (Tc). Important movements of this date are reported from Borneo, Ceram, and Celebes (van Bemmelen, 1949).

The Oligocene Barique Formation is almost entirely igneous in origin, being composed mainly of basic tuffs and flows, many of which are pillow lavas. This period of vulcanism probably resulted from a period of tension after the Dartollu Uplift that followed immediately after the Timorean Orogeny. The site of extrusion of this material has not been located, except that it was outside Timor. Almost certainly it was north of Timor, probably either from the islands of the inner volcanic arc opposite Timor (Alor, Wetar and Atauro) or from a position intermediate between the present arc and the north coast of Timor.

Lower Miocene.

The base of the Lower Miocene Cablac Limestone is a strong unconformity called the Matabian Unconformity. The Cablac Limestone resulted from a marine transgression in Te₁-Te₅, that is almost ubiquitous throughout the Archipelago. The Cablac Limestone is a shallow water deposit comparable with the Recent deposits of the Bahamas.

Middle Miocene.

In Timor there is a dramatic change at the end of the Lower Miocene. The Middle Miocene (Tf) is represented by a catastrophic orogenic phase called the Ramelauean Orogeny, which resulted in intense folding, overthrusting of large masses of mainly Permian strata, and a huge gravity slide deposit called the Bobonaro Scaly Clay.

In order for the overthrusts and Bobonaro Scaly Clay to be emplaced in Timor the region must have been very rapidly downwarped during the mid-Miocene to a much deeper position than it occupied during the Lower Miocene (represented by the very shallow conditions of the Cablac Limestone).

Outside Timor late Te folding with a regional unconformity has been reported from Borneo (Liechti, 1960), a mid-Miocene orogeny is reported from Celebes and Ceram, and throughout the Moluccas except in the Misool-Onin-Koemawa region (Visser & Hermes, 1962). A mid-Miocene orogenic revolution in Sumatra and Java has been reported by van Bemmelen (1949). Widespread transgressions and basinal subsidence occurred in New Guinea (Visser & Hermes, 1962). Uplift and folding occurred in Western Australia towards the end of the Miocene (David, 1950).

Upper Miocene - Pliocene.

Following the Ramelauean Orogeny Timor began to emerge from the sea. This Soro Uplift has continued into the Holocene.

The sediments resulting from the uplift (the Viqueque Formation) are a marine molasse which formed a regressive facies as the island continued to emerge.

The oldest part of the Viqueque Formation is Upper Miocene (Tg) and the youngest is late-Pliocene.

There was another phase of folding in the late-Pliocene, called the Mataian Folding, This gave rise to the gentle folds in the Bobonaro Scaly Clay and the Viqueque Formation, while the older (pre-Tf) rocks seemed to have reacted to these forces by faulting not folding.

Outside Timor a late-Pliocene folding is recognised in Borneo, Sumatra, Java, the Lesser Sunda Islands, Banda Arcs and in Western Australia.

Post-Pliocene.

Since the Mataian Folding Timor has continued to emerge thus giving rise to the terraced fringing corals reefs of the Baucau Limestone, and the marine molasse facies (Suai Formation) which is comparable with the Viqueque Formation.

CHAPTER V

PETROLEUM AND NATURAL GAS

In eastern Timor there are more than thirty natural seepages of oil and gas (table III), of which twelve were first reported by the writer (unpublished report, 1962). These seeps are plotted on the geological maps (enclosures 1A, 1B, 1C & 1D). Most of them occur south of the main watershed of the island. This may be reflection of the more detailed investigation of the southern area rather than having a geological cause. From local inquiries it seems that there are at least ten seepages in the northern part of the island that have not been seen by the writer. The following account is a brief description of the seepages arranged according to the age of the formation in which the seep occurs.

OIL AND GAS SEEPAGES IN THE QUATERNARY FORMATIONS.

Three oil seeps are known to occur in Quaternary sediments:

i) Teeter Oil Seep.

This is difficult to locate because it is a small occurrence in thick jungle. It occurs in an outcrop of the Suai Formation where it forms a small bank about 3 metres high, 50 metres from the beach. In the bank brown oil staining is seen and the sweet smell of petroleum is quite noticeable. On digging into the sand and puggy clay, a clay smelling strongly of petroleum is first encountered, and as lower sections are uncovered a free sticky brown oil is visible holding the sand grains together.

Natives report that during the wet season this seep flows free oil at the surface, and that there are a number of other small oil seeps in this vicinity of similar nature.

The origin of this oil is difficult to determine. It may be that it is Plio-Pleistocene oil moving up dip from a source further south (below sea), or it may originate in the Viqueque Formation which is probably present below the Suai Formation south of and down dip of seep. The oil could be seeping from the Wai Luli Formation below the Quaternary and Tertiary rocks that are very thin here. The origin of the oil will remain uncertain until the area has been studied in more detail and by subsurface methods.

ii) Loi Quero Oil Seep.

Oil is found oozing out of modern beach sand 4 km. west of Loi Quero, and on the beach just above the high water level and below the cliff of Pleistocene - Recent Baucau Limestone. It seems most likely that the brown sticky oil is coming from the Cribas Formation which is present a few metres below the Pleistocene - Recent cover.

iii) Lospalos Oil Seep.

This was reported to writer by Dr. J.C. Azeredo Leme (verbal communication, 1962) who described it as a small oil seep on the edge of a swamp. The writer was unable to confirm this report. The seep would appear to be underlain by the Poros Limestone from which it might be derived. A more probable source would seem to be the Cribas Formation which occurs below the Poros Limestone.

Photogeology indicates minor faulting in the vicinity of the seep.

OIL AND GAS SEEPAGES IN THE TERTIARY FORMATIONS.

Seven oil, and three gas seeps are known from the Tertiary rocks; all except one occur in either the Bobonaro Scaly Clay or the Viqueque Formation.

i) Matai Oil Seeps.

These are located on the south side of Matai village and slightly to the north of the axial plane trace of the Matai Anticline. Initially these were natural seeps in a creek bed but they were opened up by the Japanese during the Second World War, who dug and timbered shafts to 7 metres in depth, and who are reported to have obtained a considerable yield of crude oil. At present the yield is low being no more than 10 gallons a day.

The shafts have been dug into the outcropping Viqueque Formation at a place where the thickness of the Viqueque Formation over the Bobonaro Scaly Clay is about 40 metres. The oil seeps from a porous medium grade quartz arenite of the lower part of the Viqueque Formation.

Slim core holes drilled in the immediate area of the Matai seeps encountered oil saturated Viqueque Formation. Particularly noticeable were the greenish foraminiferal claystones and marls that were saturated with a light greenish oil. These rocks are regarded as the probable source beds of the oil in the Matai seeps.

The question of the origin of the oil at Matai is complicated by a similar oil occurring in the Bobonaro Scaly Clay immediately below the contact with the Viqueque Formation in some of the slim hole cores, and by an apparently erratically productive horizon in the Bobonaro Scaly Clay about 230 metres below the contact with the Viqueque Formation in the core of the Matai Anticline. While the exceptionally impermeable and impervious nature of the Bobonaro Scaly Clay argues strongly against vertical migration of oil through 230 metres into the Viqueque Formation such a process cannot be ruled out, particularly in respect of faulting in the hinge region of the anticline.

ii) Nabuc Oil Seep.

In a tributary to the River Nabuc and immediately to the south of the Matai Fault is a small intermittent oil seep which appears in the creek bed. This seep produces small amounts of oil and saline water in the wet season; in the dry season dark oil stained rocks are the only indication.

This oil must be seeping from the Viqueque Formation. Whether it was generated in the Viqueque or in an older formation is uncertain. The most likely explanation is that it was generated in the Viqueque and has migrated up dip in the southern limb of the Matai Anticline.

iii) Sap Maras Oil Seep.

This is a small oil seep that has stained and saturated the white marls of the Viqueque Formation in the west bank of the River Serai where it is oozing slowly.

The oil stained area is about 3 sqr metres. Locally natives report that in the wet season a small flow of oil occurs here.

The oil seep is in the northern limb of the Colitie Syncline where the Viqueque Formation is very thin, probably less than 20 metres. It seems unlikely that this oil has been generated within the Viqueque Formation. A more probably source would be either the unconformity at the base of the Bobonaro Scaly Clay (which outcrops close to the seep), or the Mesozoic - Permian strata of the Bazol Anticline whose hinge is close to the seep.

iv) Ranuc Oil Seep.

There are several small oil seeps at Ranuc; from some the oil is emitted with mud, salt water and gas, these resemble very small mud volcanoes, while others are oozings of oil into creeks. In all cases the oil is seeping from the Bobonaro Scaly Clay, and is **sweet** smelling, light and greenish coloured.

v) Suete Oil Seep.

This is a very small oil seep in a tiny creek on the side of the hill on which Suete village stands. The seep appears to be active only in the wet season. The immediate source is the Bobonaro Scaly Clay. It may be significant that the axial plane trace of the Suete Anticline (a photogeological structure) passes very close to the seep.

vi) Kidu Oil Seep.

This is a small oil seep in the east bank of the River Bui, south-east of Sute village, which could not be found by the writer who suspects it is active only in the wet season. The seep is from the Bobonaro Scaly Clay and may be related to faulting in the valley of the Bui.

vii) Iriamo Oil Seep.

This is a seepage of small quantities of a black oil from a depression in a terraced rice field. A pit was dug here by the Japanese during the Second World War. The oil is seeping from the Bobonaro Scaly Clay.

viii) Atalele Gas Seep.

This is close to the north-west bank of the upper reaches of the Debura River. Here inflammable gas with faint oil smell escapes from fissures in an exotic block in the Bobonaro Scaly Clay. Natives report that in the nearby Basarlei Creek free oil seeped in 1942. Both these seepages are from the Bobonaro Scaly Clay.

ix) Gari Wai Oil Seep.

Below the great limestone cliff at the south-eastern end of the Mata Bia Range, near the unconformity between the Cablac Limestone and the Bobonaro Scaly Clay, a faint oil smell is detectable in the Bobonaro Scaly Clay. Natives report that at one time this was a burning gas seep.

x) Fatu Lulik - Wai Manas Oil Seep.

Hot water springs emanate from near the base of the steep mountainous peak of Fatu Lulik. Springs which are in fractured, slickensided and recrystallised Cablac Limestone carry slicks of crude oil which leaves a solid dry encrustation of tarry substance on the rocks. The probable source of the oil is in the Wai Luli Formation of the Mac Fahic Anticline which is unconformable below the Cablac Limestone.

OIL AND GAS SEEPAGES IN THE MESOZOIC FORMATIONS.

Four oil seeps and four gas seeps are known from the Mesozoic rocks. They are widely distributed throughout eastern Timor.

i) Aliambata Oil and Gas Seeps.

At Aliambata is a timbered pit dug into the foreshore by the Japanese during the Second World War. The pit, 5 metres deep, permits an accumulation of a dark brown oil without any sign of gas at a rate of about 1 gallon a day.

About 200 metres east of this pit a light brown oil escapes in small quantities onto the shore below the high water mark.

North of the road and about 200 metres north of the pit is an abandoned well that produces salt water and small quantities of a dark brown oil with inflammable gas. The well was probably drilled about 1927 by the Timor Petroleum Co.

Inflamable gas escapes from the hill slope scree about 100 metres west of the hole drilled in 1927.

Other burning gas seeps are reported from this region about Aliambata and south of the cirque of hills. A burning gas seep with H_2S is reported to occur periodically on the shore line about 2 km. east of Aliambata.

In 1957 Timor Oil Ltd. drilled a well Aliambata No. 1 to a total depth of 1356 metres just above the main seep. A number of oil and wet gas shows were reported from various horizons in the first 700 metres. An important horizon was found at about 270 metres but not tested.

All the oil and gas occurrences described at Aliambata appear to emanate from the Upper Cretaceous Borolalo Limestone where it forms the north-west limb of the Aliambata Anticline. The seepages are probably associated with faulting that is complex in this region.

ii) Be Metan Oil Seeps.

A number of small oil seepages occur in the Cretaceous Wai Bua Formation of the Betano region. They seem to be associated with faulting. The seepages are all into creeks through alluvium over Wai Bua Formation. The oil is heavy, black and accompanied by a little gas. Some of the seeps make a little water. H_2S gas is associated with one seep in the Be Metan Creek. All seeps are said to be more productive in the wet season.

iii) Wougel Gas Seep.

This is a burning gas seep smelling strongly of petroleum that occurs in the hillside north of the Bere Creek, a tributary to the Bazol. It is emanating from the Aitututu Formation in the northern limb of the Bazol Anticline.

iv) Loiba Gas Seep.

This is a petroliferous gas seep in the hillside west of the confluence of the Lacuzol and the Bazol. It occurs in a small depression in a cultivated area. It is an area of 10 sqr metres of burnt soil over which a yellow flame lightly dances. The soil of the area smells strongly of petroleum when crushed. In the wet season the blaze is much stronger, and it is said never to have been extinguished in living memory.

In the absence of nearby outcrops it is difficult to be certain of the source, but the gas appears to be seeping from the Aitututu Formation. It is probably associated with faulting in the north limb of the Bazol Anticline.

v) Horrba Gas Seep.

A hole 45 cm . deep in the steep bank of the Horrba Creek is filled with mud through which bubbles an inflambale gas smelling strongly of petroleum. Several other similar occurrences are reported in this region. The gas is seeping from the Tallibelis Member of the Aitututu Formation in the north limb of the Bazol Anticline.

vi) Bele Teu Oil Seep.

This occurs in a cliff face of the Aitututu Formation. The seep is a slow oozing of light brown oil from well bedded fine grained calcarenites. These calcarenites are interbedded with calcilutites; all are black or dark bluish grey, and have all their joints and minor cracks filled with free brown oil which on the weathered surface forms a residual black tar. Wherever these limestones are broken a thin oil film is visible which can be wiped off on the fingers. The oil evaporates rapidly. The section from which the oil is bleeding is about 6.5 metres thick. This particular region has been greatly disturbed by minor folding and faulting.

These petroliferous calcarenites may be a reservoir, but the primary porosity is so low, due to calcite cementation, that it seems likely that they are very close to source beds.

The seep is situated in the north limb of the Bazol Anticline.

vii) Sahem River Oil Seep.

It is reported from the Soibada Missão that crude oil has been taken from holes dug into the bed of the Sahem River. This oil must be seeping from the Aitututu Formation in the north limb of the Mac Fahic Anticline.

viii) Pualaca Oil and Gas Seeps.

At Pualaca in the banks of the River Mutin, from an

outcrop of contorted shales and thin limestones of the Wai Luli Formation, a light crude oil is oozing into the river, from a number of places.

In the bed of the River Mutin four oil producing pits have been dug, only one of which was being worked in 1962, the others having collapsed. These pits produced water and a black oil.

The rate of seepage at Pualaca is reported to be fairly constant, except for seasonal fluctuations due perhaps to movements of the water table. The constant flow over many years indicates an entrapment of some size below the present pits. Presumably the oil seeping into the river on the east bank is seeping from the same trap.

In 1958 the Pualaca Oil Refinery bailed 21,060 litres of crude oil from the pits. This crude is distilled into three usable fractions: a gasoline and two grades of kerosene.

Several seepages of petroliferous gas are reported in this area, on the hillsides above and to the north of Pualaca. They are all emanating from the Wai Luli Formation.

OIL AND GAS SEEPAGES IN THE CRIBAS FORMATION.

Eight petroliferous gas seeps are known in the Cribas Formation.

i) Lornil Gas Seep.

This is a gas seep smelling strongly of petroleum. It occurs on the hillside north of the River Bazol. It appears to emanate from the Cribas Formation but the evidence is obscured by landslips. The seep is on the north limb of the Bazol Anticline.

ii) Hol Mesil Oil and Gas Seep.

Just below a steep limestone crag that forms part of the bluff called Hol Mesil are two small oil seeps accompanied by burning petroliferous gas. In the wet season a small trickle of black oil occurs, but in the dry season only the oil staining is seen. The area of burning gas is about 10 sqr metres. The oil and gas are emanating from the Cribas Formation just below the contact with the Aitututu Formation. The seeps are situated on the north limb of the Bazol Anticline.

iii) Berri Gas Seep.

This occurs in the east bank of the River Lomea where there is an area of 10 sqr metres of burnt soil at the bottom of a steep slope about 7 metres above the Lomea. A very strong smell of petroleum accompanies the burning gas. The seep is said to burn more strongly in the wet season. The gas is emanating from the Cribas Formation in the north limb of the Bazol Anticline.

iv) Mol Houlu Gas Seep.

This occurs in the bed of the small Mol Houlu Creek.

A faint smell of petroleum is detectable during the dry season, but in the wet season a stream of inflammable gas bubbles is developed. The gas is seeping from the Cribas Formation in the north limb of the Bazol Anticline.

v) Querrema Gas Seep.

A small inflammable gas seep with a strong smell of petroleum bubbles through mud in a small hole in the hillside overlooking the River Bazulor. In this vicinity several other burning gas seeps are reported active during the wet season. This gas is seeping from the Cribas Formation in the north limb of the Bazol Anticline.

vi) Lubu Tura Gas Seep.

East of the village of Tualo, on the perimeter of a small native farm an inflammable gas smelling of petroleum escapes from the soil over an area of 2 sqr metres. No exposure is present in the vicinity, but the gas must be escaping from the Cribas Formation near to the hinge of the Aliambata Anticline.

vii) Beto Gas Seep.

East of Lubu Tura, near to the tiny village of Beto another similar petroliferous gas seep is reported from the Cribas Formation. This seep is very close to the hinge of the Aliambata Anticline.

viii) Tualo Gas Seep.

Natives report an irregular seep of petroliferous

gas from a hole in the bank of the small creek north of Tualo village. This seep is in the Cribas Formation and probably related to faulting in the Aliambata Anticline.

CHAPTER VI

THERMAL SPRINGS AND MUD VOLCANOES.

DESCRIPTION OF THE THERMAL SPRINGS OF EASTERN TIMOR.

At least 10 thermal springs are known in eastern Timor. They all occur in mountainous or hilly country. The principal springs are described below.

i) Wai Cana Thermal Spring

This is a warm salt water sulphurous spring northeast of Venilale. The presence of H_2S is very noticeable by smell and the presence of colloidal sulphur around the edges of the creek. The exact temperature was not recorded, but it is estimated at about 30 degrees Centigrade. The rate of flow of the spring was not recorded. It appears to emerge from near the contact between the Cablac Limestone and the Barique Formation.

ii) Viqueque Thermal Spring.

This emanates from the Bobonaro Scaly Clay just north of an exotic limestone block that is present in the core of the Viqueque Anticline. The surroundings of the spring are covered by a thick crust of sinter. The temperature of the spring is estimated to be about 35 degrees Centigrade, and the flow about 600 gallons per minute. The water is accompanied by H_2S gas.

iii) Lacluta Thermal Spring.

This was not visited by the writer but a description

given by Raimondo Soares, a native of Lacluta, suggests that the water is at least 40 degrees Centigrade, salty and accompanied by H_2S . The spring is believed to emerge from the Barique Formation near to the contact with the Cablac Limestone.

iv) Fatu Lulik Thermal Spring.

At the base of the steep hill called Fatu Lulik (south-east of Fatu Berliu village) is a hot water spring emanating from fractured slickensided Cablac Limestone. The temperature of the water is estimated at about 40 degrees Centigrade. It is faintly salty and smells strongly of H_2S . A colloidal sulphur scum deposit is seen about the springs. Slicks of light crude oil are present with the water. The flow is estimated at about 6 gallons per minute.

v) Morobo Thermal Spring.

These hot sulphurous springs occur north of Bobonaro village in the Bobonaro Scaly Clay. They were not visited by the writer.

vi) Bobonaro Thermal Springs.

Numerous hot springs occur in the smaller creeks draining into the Lomea south-east of Bobonaro. They all occur in the Tallibelis Member of the Aitutu Formation. These springs will not be described individually because they are all very similar. Their temperature is estimated to range from 30 degrees to 60 degrees Centigrade. They are all sulphurous, carry varying quantities of H_2S ,

and leaving deposits of colloidal sulphur. Some, for example the Il Belis springs, are very sulphurous and if investigated for more than about 10 minutes produce a severe headache. They are all salty.

DISCUSSION

With the exception of the Viqueque spring all the thermal waters are in the mountains. All the springs seem to be at a temperature of between 30 and 60 degrees Centigrade, all are accompanied by H_2S , and most if not all are salty.

The origin of these hot springs is uncertain, but is possibly associated with a dying phase of vulcanism. It seems likely that they all originate at depth, and appear at the surface by way of deep seated faults.

As oil is only associated with one of these springs, namely Fatu Lulik, a common origin for the oil and the thermal water should not be sought. It is quite feasible that the water at Fatu Lulik making its way to the surface from depth picks up some oil along the way, trapped perhaps in the Aitutu or Wai Luli Formation.

MUD VOLCANOES OF EASTERN TIMOR

Only five mud volcanoes are known to the writer, the large Bibiluto volcano south of the village of Viqueque, the two smaller volcanoes at Culit, north-west of Suai, and the two very small volcanoes at Ranuc near Matai.

i) Bibiluto Mud Volcano.

This was described by Schneeberger (unpublished report, 1959) as "presenting itself as a flat, shield-like cone. The inner part of it was a plain stretching out several hundred yards with the remaining wall of the old caldera on one side. The dried mud contained angular fragments, several inches across of pre-Viqueque Formations. The activity was confined to one mudcone, 2 to 3 feet high which gave off at several seconds intervals a bubble of gas, some salt water mixed with mud, and a few thin threads of brown oil. The gas is inflammable, but the quantity of gas and oil produced was too small for a sample".

ii) Culit Mud Volcanoes.

The Two mud volcanoes at Culit are very much smaller features. Both have a low, flat, shield-like cone, that in the case of the northern one has subsided. The northern mud volcano was at one time obviously a much larger structure than it is today. At present they are both small cones about 30 and 70 metres in diameter that are raised overall no more than 1 metre. In the centre from several holes filled with salty muddy water a slowly rising stream of gas bubbles is given off. This gas does not seem to be inflammable. Both of these mud volcanoes occur on the flat top of a hillside above the valley of the River Tafara.

iii) Ranuc Mud Volcanoes.

These are two tiny mud volcanoes each consisting of a shield about 10 metres diameter with several small holes through which mud, salt water and gas are gently rising.

The gas is inflammable.

ORIGIN OF THE MUD VOLCANOES.

All five mud volcanoes are produced in the Bobonaro Scaly Clay, although the Bibiluto Mud Volcano breaks through a cover of Pleistocene - Recent Suai Formation. The Bobonaro Scaly Clay is rich in bentonite which swells in water. A mechanism for the mud volcanoes suggested here is the reaction between a water spring (perhaps a hot water spring) at the base of the Bobonaro Scaly Clay, and the bentonite in that formation. This would cause a local swelling which if the spring was accompanied by gas would tend to form a rising stream of expanding clay, water, and gas. This is supported by the observation that the thermal springs of Timor are salty and accompanied by gas, as are the mud volcanoes. The principal difference appears to be the apparent absence of H_2S from the volcanoes. The greater size of the Bibiluto Mud Volcano could be explained by the greater thickness of the Bobonaro Scaly Clay and (or) the greater size of the spring at the base of that formation.

It is worth recording that the Culit and Ranuc mud volcanoes occur close to the axial plane trace of the Culit and Matai anticlines respectively. The Bibiluto volcano occurs near to the axial plane trace of the Tum Syncline. These three folds are Mataian structures of late-Pliocene age.

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APPENDIX I.

SOME ASPECTS OF THE CHEMISTRY OF CRETACEOUS SILICEOUS SEDIMENTARY ROCKS FROM EASTERN TIMOR.

ABSTRACT

Eleven representative chert and eighteen radiolarite samples from eastern Timor have been analysed. The field and petrological aspects of these rocks indicate that they were deposited in a bathypelagic environment. Their chemistry confirms the paucity of land derived detritus, and suggests a direct analogy with modern deep-sea radiolarian ooze. The principal lines of chemical evidence are an almost total absence of CaCO_3 , the Fe/Mn and $\text{Fe}_2\text{O}_3/\text{Al}_2\text{O}_3$ ratios, and the $\text{SiO}_2/\text{Al}_2\text{O}_3$ relationship. The trace element content although not entirely unequivocal lends support to this thesis.

There is strong chemical evidence to confirm the petrological conclusion that pyroclastic material has not contributed significantly to these sedimentary rocks. This is especially noted with respect to the view that radiolarites are genetically connected with vulcanism.

Chemical evidence supports the view that these rocks are largely biogenous and points to the importance of certain diagenetic processes.

INTRODUCTION

The red clays and manganese nodules of Cretaceous age that are found in western (formerly Dutch) Timor have been studied by Molengraaff (1916 and 1922), Brouwer (1925), and El Wakeel and Riley (1961a). Molengraaff, who had earlier (1909) interpreted the radiolarites and radiolarian cherts of the Danau Formation of central Borneo as being deep-sea deposits, considered these Cretaceous rocks of western Timor analogous to modern deep-sea red clays and manganese nodules. He pointed out the similarity in the chemistry of major elements between the Cretaceous samples and modern oceanic sediments. El Wakeel and Riley (1961a) who made a more detailed analysis of major and trace constituents, in addition to carrying out some clay mineral studies, agreed with Molengraaff's (1922) interpretation of the environment.

Field relations of the Cretaceous sediments of eastern Timor.

In eastern Timor (Portuguese) there occur two major facies of Cretaceous rocks that have a distinctly pelagic character. They are developed in two widely separated areas, the most westerly on the south coast at Betano where the siliceous facies (Wai Bua Formation) predominates, and at Aliambata and further east where pelagic limestones (Borolalo Limestone) are predominant. This paper deals only with the Wai Bua Formation.

The Laramide orogeny crumpled these brittle siliceous sediments so intensely that it has not been possible as yet to work out their detailed stratigraphy. The thickness of this facies is difficult to estimate, but is probably of the order of 500 metres. This siliceous facies is made up of radiolarites, radiolarian cherts, siliceous

shales, siliceous marls and some thin pelagic limestones. The marls and radiolarites sometime contain manganese in the form of primary layers of pyrolusite and nodules, and secondary dendritic growths on weathered surfaces. The more highly concentrated manganese beds are usually associated with dark red clays rich in ferric oxide.

Classification.

The distinction between cherts and radiolarites is very pronounced in the field, and no difficulty is ever encountered in deciding in which category to place a rock. This may seem surprising when comparison of the silica contents is made. The explanation is to be found in the different micro-structure of the rocks. The cherts are composed of chalcedonic silica and are entirely non-porous. The traces of radiolarian skeletons that are seen in thin section are relics discernible only by outline within a continuous mass of silica. The radiolarites are composed essentially of a compact mass of discrete radiolarian skeletons. These skeletons and their debris, although they may in many cases consists of chalcedonic silica (not opaline), have their detailed structure preserved; they have not been dissolved nor cemented together to form a continuous mass of silica. The radiolarites are frequently very porous.

This difference in micro-structure is reflected in the hand specimen. The cherts are hard, dense, vitreous, translucent and break with a conchoidal fracture. The radiolarites have an earthy aspect; they are easily scratched because the tiny constituent siliceous skeletons are only loosely held together. The radiolarites are light, never

vitreous nor translucent, and have a platy, shaly fracture. They are best described as siliceous earths. The distinction made here between opaline and chalcedonic silica is no more than a distinction based on optical properties.

Distribution of the analysed samples.

The seven samples of bedded radiolarian chert and the three samples of bedded chert without siliceous skeletons are each taken from a different bed of chert in the Cretaceous Wai Bua succession in the Betano area of eastern Timor. It is not possible to relate these cherts precisely to each other in time because the micropaleontological data is not adequate, and because of the difficulty of relating structurally dislocated outcrops. It is probable that all the samples of bedded chert range in age from the Albian to Upper Senonian and fairly probable that age decreases with increase in sample number. The chert sample 7853 is from a nodule in a limestone of Turonian age.

The radiolarite samples all represent separate beds of radiolarite in the Cretaceous succession of the same area as the cherts. The radiolarites range in age from Albian to Maestrichtian.

A. PETROLOGY AND MINERALOGY

1). CHERTS.

All the cherts consist very largely of chalcedonic silica. Other minerals present that can be recognised with a petrological microscope are calcite, clay minerals and hematite.

Two forms of chalcedony are predominant in all the cherts. The forms were defined by Smith (1960) as granular chalcedony and fibro-chalcedony. In the fibro-chalcedony a wide variety of fibre arrangement is seen. Polygonal spherulites and cored spherulites are well developed in some samples, and relics of Radiolaria are present in varying proportion in the different samples. Occasional traces of pelagic Foraminifera may be seen as calcite fragments in some cherts.

2) THE RADIOLARITES

The radiolarites consist very largely of the skeletons of radiolaria and their debris. In most of the samples analysed the radiolarian material is present as chalcedonic silica, but in a few (Nos: 7802, 7803, 7804, 7818, 7819) it is present as opaline silica. Clay minerals and disseminated opaline or chalcedonic silica form a matrix to many of the specimens some of which contain a few tiny detrital quartz grains (Nos: 7875, 7877, 7878, 7879, 7884, 7886). A few radiolarites (Nos: 7804, 7824, 7879, 7883) contain rare foraminiferal calcite fragments.

B. DISCUSSION OF CHEMICAL COMPOSITION.

Table I shews the results of analysis of samples of chert from eastern Timor (Nos: 7812, 7813, 7851-7859 inc.), and from elsewhere (Nos: a, b, c, d). The data shews that the major constituents of the Timor cherts fall within a range of composition that is similar to the various types of chert from elsewhere.

Table II shews the results of analysis of eighteen samples of radiolarites that are interbedded with the chert samples just described. Included in Table II for comparison are a number of published analyses of radiolarian ooze, deep-sea red clay, Cretaceous red clay from western Timor, and red clay from the Oceanic Deposits (Eocene-Oligocene) of the Barbados.

(i) Silica and alumina.

A distinctive feature of the Timor cherts is that the SiO_2 contents are high and indeed exceed 95 percent in all but the nodular chert (N, 7853). Consequently the values for Al_2O_3 and also Fe_2O_3 , TiO_2 and MnO are low and none exceed 1.5 percent in any of the cherts.

All the radiolarites have a SiO_2 content greater than the average of 65 percent SiO_2 for modern deep-sea radiolarian ooze. The major composition of the radiolarites is expressed in the diagram Figure 5. By comparison with data published by Cressman (1962) these radiolarites have a major composition very similar to diatomite and radiolarian chert.

The relationship between SiO_2 and Al_2O_3 is shewn in figure 1. The close relation between radiolarian cherts, radiolarites and modern siliceous ooze is clearly seen. This same relationship was found by Cressman (1962) who commented that the trend is similar to that which would shew "the theoretical change in composition that would result from the addition of SiO_2 to a siliceous ooze". With reference to the Timor cherts and radiolarites it seems to suggest that the environment in which the cherts and radiolarites formed was very poor in CaCO_3 , and therefore almost free from pelagic Foraminifera. This is a condition

that exists where siliceous ooze is collecting today. The controlling factor seems to be principally the solubility of CaCO_3 in cold waters rich in dissolved CO_2 . The influence of pressure (a function of depth) is important. In the deep-sea these factors probably all operate together as discussed by Bezrukov (1963), Bramlette (1961), Schott (1955) and Correns (1937).

(ii) Iron.

Although most bedded cherts usually contain more than 1 percent Fe_2O_3 (Cressman, 1962) those in eastern Timor are scarcely half as rich in Fe_2O_3 except for the three bedded cherts that lack siliceous skeletons (Nos: 7851, 7854, 7855). Those that are low in Fe_2O_3 however shew a relationship with Al_2O_3 (Figure 2) similar to that found by Cressman (1962) for 46 radiolarian cherts; the $\text{Fe}_2\text{O}_3/\text{Al}_2\text{O}_3$ ratios are fairly similar to the value of 0.4 found for modern pelagic clay and siliceous ooze (Revelle, 1944).

The three Fe_2O_3 -rich cherts belong to the same petrographic group. Hematite is recognised in all three, and it might be supposed that these iron-rich cherts be derived from volcanic material. However relatively low values for especially TiO_2 , Co, Ni, Cu, Cr, and V (Table I) shew that such a derivation is unlikely, and there seems no good genetic explanation for the high $\text{Fe}_2\text{O}_3/\text{Al}_2\text{O}_3$ ratio of the samples. To invoke a biogenic cause seems particularly unjustified in view of their petrological features.

The $\text{Fe}_2\text{O}_3/\text{Al}_2\text{O}_3$ ratio expressed in Figure 2 shews a distribution that approximates to the results obtained by Cressman (1962) who plotted data for 46 radiolarian cherts.

This ratio is about the same as is found in modern pelagic clay and siliceous ooze. This was explained by Cressman (1962) as addition of SiO_2 in the form of either radiolarian tests or inorganic silica to typical marine lutite.

(iii) Manganese and the Fe/Mn ratio

Manganese is particularly interesting because of the intimate association of these cherts and radiolarites with manganese-rich rocks, and because manganese-rich sediments (e.g. nodules) are often found in modern deep-sea siliceous ooze.

There is some sympathetic change of MnO content with Fe_2O_3 for most of the cherts; and figure 3 shews all but three samples have Fe/Mn ratios between 1:1 and 9:1 . The three 'anomalous' cherts are again the bedded ones without siliceous skeletons; one has a Fe/Mn ratio of 30:1 (N.7853), the other two have ratios of about 600:1 . In these two cherts (Nos; 7851, 7854) MnO is present as 30 p.p.m. Although the MnO values approximate to those shewn for an 'average' radiolarian chert (Cressman, 1962) the Fe/Mn ratios are distinctly low in comparison with those found in other cherts.

The concentration range of about 0.01% - 1.0% MnO in the radiolarites follows closely the range revealed by Cressman's (1962) review of cherts and related rocks. The relation of iron to manganese is plotted in figure 3, where it can be seen that with one exception the radiolarites have an Fe/Mn ratio that ranges from 1 to 100. Of the eighteen samples only four have an Fe/Mn ratio greater than 40, the remainder vary either side of 10. Data from Revelle

(1944) for modern siliceous ooze, quoted by Cressman (1962), reveal an average value for the Fe/Mn ratio of 10. Although the radiolarites shew a wide range of Fe/Mn ratios, there remains a strong similarity to the ratio found in modern siliceous ooze.

The concentration of manganese in deep-sea sediments has been frequently discussed. In particular Correns (1937) reported higher Fe/Mn values in shallow water sediments than in deep-sea sediments of the equatorial Atlantic. Cressman (1962) has recalculated the data of Correns (1937), by comparison with which the Fe/Mn ratios obtained for the Timor cherts suggest a bathymetry greater than 5,000 metres and the ratio of the radiolarites a bathymetry of about 5,000 metres. It is not intended here to deduce such precise values for the depth of formation of these cherts and radiolarites; that would infer more than a just adherence to the principal of uniformitarianism, and not take proper account of the limits of the analytical data.

(iv) Titanium.

The general TiO_2 content of the cherts is quite low and consistant with their non-detrital origin. The relationship of TiO_2 to Al_2O_3 tends to support this view, and figure 4 shews graphically the results for these cherts, the radiolarites and modern pelagic sediments. The sample of nodular chert from a pelagic limestone (N.7853) has a notably high Ti/Al ratio which could be due to the presence of a detrital or authigenic Ti-rich mineral although none was seen in thin section.

As figure 4 shews the $\text{TiO}_2/\text{Al}_2\text{O}_3$ ratio of all except three samples of the radiolarites fall between 0.02 and 0.1. If this data is compared with values given by Cressman (1962), it is seen that these radiolarites have a higher $\text{TiO}_2/\text{Al}_2\text{O}_3$ ratio than any group studied by Cressman except the silcretes.

Goldberg (1954) discussed the possibility that biogenous titanium might form a considerable proportion of the total titanium in pelagic sediments, since Collier (1953) had recorded the concentration of titanium by planktonic dinoflagellates. Goldberg and Arrhenius (1958) noted however that the $\text{TiO}_2/\text{Al}_2\text{O}_3$ ratio did not increase in modern deep-sea sediments with a large biogenous component, and concluded that biogenous titanium was not an important component in the modern equatorial pelagic zone. In the absence of both recognisable pyroclastic material and diagenetic anatase in these radiolarites, that, let it be recalled, consist predominantly of planktonic siliceous skeletons, Goldberg's (1954) suggestion that titanium is biogenous is a possible explanation of the high $\text{TiO}_2/\text{Al}_2\text{O}_3$ ratios in these radiolarites.

In figure 6 the Fe/Ti ratios of the radiolarites are plotted together with the average value of Pacific pelagic sediments, calculated from data published by Goldberg and Arrhenius (1958). There emerges from this plot a strong indication that these two elements are closely related. The average value of 6.0 may be compared with that of 8.9 for the average value from the Pacific. This indicates a relative enrichment of titanium in the radiolarites that we have already observed in the relation of TiO_2 with Al_2O_3 . The suggestion of Robertson and Tweedily (1953) that much

iron in the diatomaceous deposits of Skye may be in the form of an alumina - ferric oxide - silica gel may be significant in this context. If however, as it appears, the iron in these radiolarites is largely non-lithogenous, the evidence does not discriminate between the titanium being biogenous or hydrogenous. This uncertainty is shared with modern pelagic sediments.

(v) Trace elements.

The only trace element in which the cherts are enriched compared with the average igneous rock or shale is cobalt. The below average values for nickel, and the low values (less than 20 p.p.m.) of chromium and vanadium, together with the average value for the $\text{TiO}_2/\text{Al}_2\text{O}_3$ ratio indicate that there is no genetic relation between these cherts and vulcanism. In the light of this it is interesting to contrast the trace element enrichment in cherts that are associated with volcanic material, such as have been analysed by Grunau and Hugi (1957). One group was enriched in copper, lead and strontium, and another in titanium and chromium. In these Timor cherts the relatively low values for copper is probably due to the low content of organic matter. The occasional presence of strontium and barium can possibly be ascribed to the concentration from pelagic Foraminifera, whose skeletons were not stable in the environment of deposition. It is possible that the strontium values are related to celestite derived from radiolarian skeletons, but no independent evidence of this has been found.

For the purpose of comparison some trace element data of modern sediments has been culled from the literature and listed in Table II. Various element ratios of the

radiolarites are shewn in Table III.

With regard to the variable concentration of trace elements let it be recalled that Carr and Turekian (1961) found evidence for very variable values of cobalt being characteristic of modern pelagic sediments. Further, that Hutchinson et al. (1955) found that the nickel, copper and cobalt content of pelagic sediments varies along the lengths of the core, and that the copper is distributed most irregularly.

Goldberg (1961) considered that the unique feature of deep-sea accumulations is the enrichment of such metals as manganese, copper, cobalt and lead. The manganese is certainly not generally enriched in these radiolarites, but it is greatly enriched in sediments intimately associated with them (manganese nodules, crusts, slabs and manganese-rich shales). Answering Goldberg's (1961) other requirements, it is clear that copper is much enriched and cobalt moderately so (lead was not sought).

Wedepohl (1960) found that the average abundance of titanium, vanadium, chromium, gallium, rubidium and zirconium are the same in near-shore clays and pelagic clays, within the limits of error. While El Wakeel and Riley (1961b) state that in general their analyses of deep-sea sediments agree well with those of Goldberg and Arrhenius (1958), and that nickel, cobalt, lead, copper and molybdenum are all strongly concentrated in the deep-sea sediments compared with igneous rocks. With this Wedepohl (1960) would seem to agree, adding manganese and zinc.

Potter et al. (1963) consider there are no large

differences in trace element concentration between ancient and modern argillaceous sediments of the same environment. This they say "implies that trace element concentration in ancient shales is not seriously modified by post-depositional diagenetic processes". However it must be remembered that they did not study ancient deep-sea sedimentary rocks.

(a) Barium.

The barium values of the radiolarites exhibit considerable variation. Young (1954) noted that although the barium content of red clay is high it is variable. Goldberg and Arrhenius (1958) thought their studies shewed that a "slow post-depositional migration of barium takes place in the sediments". Revelle et al. (1955) found a covariance between non-hydrogenous copper and barium, but this covariance cannot be discerned in these radiolarites. Goldberg (1961) is inclined to the view that the barium content of deep-sea sediments is related to the living parts of the plankton, and thus he explains the relationship between non-hydrogenous (i.e. biogenous) copper and barium.

Barium in these radiolarites appears to be enriched relative to the average marine shale in only a few samples, the majority fall below the average value of 580 p.p.m. quoted by Turekian and Wedepohl (1961).

(b) Zirconium.

The zirconium content of the radiolarites is much lower than either the average value for modern deep-sea clays or shallow marine shales (cf. Turekian and Wedepohl, 1961). If the zirconium content reflects the quantity of

land derived detritus, these low values would accord with independent evidence supporting the view that these rocks are characterised by a paucity of land derived detritus. It is as well to recall that Goldberg (1954) and Goldberg and Arrhenius (1958) consider that a large part of the zirconium found in pelagic sediments seems to be localised in authigenic ferromanganese minerals.

(c) Vanadium.

The vanadium content is very variable and ranges from 20 to 360 p.p.m. There are not many samples enriched in vanadium relative to the average content of 200 p.p.m. for igneous rocks (Young, 1954), but about half of the samples are enriched relative to the content of 130 p.p.m. of the average shale (Turekian and Wedepohl, 1961). The concentration of vanadium in the radiolarites does not appear to be connected with those of iron, copper or barium.

(d) Chromium.

The chromium content is fairly constant and distinctly poorer than the values of 100 p.p.m. for the average igneous rock (Young, 1954), and of 82 p.p.m. for the average pelagic deposit (Young, 1954), or the average Pacific pelagic sediment of 93 p.p.m. (Goldberg and Arrhenius, 1958). This also supports the view that ferromanganese minerals or pyroclastic debris in any form play an insignificant role in these radiolarites.

(e) Cobalt and Nickel.

Compared with the value of 20 p.p.m. cobalt and

40 p.p.m. nickel for the average igneous rock (Fleischer, 1953) the radiolarites shew slight enrichment in cobalt and nickel. Compared with the average shale, for which Turekian and Wedepohl (1961) give values of 19 p.p.m. cobalt and 68 p.p.m. for nickel, some samples of radiolarite shew enrichment whilst others are impoverished. The values of 260 p.p.m. nickel and 90 p.p.m. cobalt given for the average modern pelagic deposit by Young (1954) are all much higher than the values obtained for the Timor radiolarites.

It is noted that the Ni/Co ratio is very consistent in these radiolarites being 2:1. The same ratio emerges from the analyses of Goldberg and Arrhenius (1958), and the average pelagic deposit (Young, 1954). Hutchinson et al. (1955) quote a Ni/Co ratio of 1.9 for Pacific deep-sea red clays, and values of 2.6 and 4.8 for Atlantic sediments.

Goldberg (1954) and Goldberg and Arrhenius (1958) consider that cobalt and nickel display a similar behaviour in the marine part of the minor cycle as manganese. In these radiolarites from Timor the Fe/Ni ratios (see Table III) appear to be more consistent than the Mn/Ni ratios. Further to this, the range of the Fe/Ni ratios of Pettersson and Rotschi (1952) for modern radiolarian ooze, viz: 650 - 190 completely covers the range of these radiolarites.

The Ni/Cr ratios of the radiolarites do not vary greatly, and a relationship with the Fe/Mn ratios seems indicated.

(f) Copper.

The covariance between copper and manganese found by

Goldberg (1954) does not emerge from the analyses of these radiolarites. Perhaps it is because it is not possible to separate the hydrogenous from the biogenous fraction of copper, that this and other relations found by workers with modern deep-sea sediments are not discernible in these radiolarites.

The copper values of the radiolarites shew distinct enrichment compared with the value of 45 p.p.m. for the average marine shale (Turekian and Wedepohl, 1961), and some are even enriched compared with the value of 250 p.p.m. for the average deep-sea clay (Turekian and Wedepohl, 1961). The radiolarites are greatly enriched in copper compared with the value of 100 p.p.m. for the average igneous rock (Clarke, 1924).

(g) Strontium.

The strontium content of the radiolarites is like most of the trace elements variable. A few samples shew enrichment compared with the value of 300 p.p.m. for the average marine shale whilst others are relatively impoverished (Turekian and Wedepohl, 1961). The same comment applies to the value of 250 p.p.m. for the average igneous rock (Young, 1954), whilst some are poorer than the value of 180 p.p.m. for the average pelagic clay (Turekian and Wedepohl, 1961).

The strontium may, like barium, have been derived from the tests of pelagic Foraminifera, whose calcium carbonate was dissolved in the undersaturated waters of the deep-sea, or from the living parts of plankton that decompose on the sea floor after death of the organisms. Another source of strontium, and perhaps a more likely one in view of the

Ba/Sr ratios, is the radiolarian skeletons where crystals of celestite are found.

C. ORIGIN OF THE BEDDED CHERTS OF THE WAI BUA FORMATION.

The fauna of the cherts, radiolarites and associated rocks of the Wai Bua Formation is essentially pelagic. The scarcity of quartz grains, which when present are always extremely small, together with the relatively low proportion of clay in the radiolarites associated with the cherts indicate pelagic conditions. In the absence of a benthonic fauna the depth of formation of these rocks is difficult to estimate. The Fe/Mn ratios of the cherts and radiolarites suggest, by analogy with modern pelagic sediments, that the environment was abyssal. The analogy with modern abyssal sediments is indicated by the data shown and plotted in figures 1, 2 and 4.

Some workers have thought that bedded cherts and bedded radiolarian cherts derive their silica from volcanic material. There seems to be two main mechanisms by which volcanic silica enters sea water. One is by the weathering of volcanic ash; Rubey (1929) and Bramlette (1946) both produce good evidence and arguments for this. The other mechanism is by direct volcanic emanations, this has been discussed by Davis (1918) and Tromp (1948). Taliaferro (1933) in a review of world-wide evidence concluded that a greater part of the evidence pointed to a volcanic origin of silica both as emanations and as weathering products of volcanic ash.

The manner in which this silica becomes chert is disputed. Taliaferro (1933) thought that both direct

precipitation from sea water, and indirectly by the incorporation of silica into diatom and radiolarian skeletons which collected on the sea floor were possible. Ruedemann and Wilson (1936) conclude that most bedded cherts are deep-sea sediments related to radiolarian ooze, and not to volcanic emanations. Sverdrup, Johnson and Fleming (1942) state that there is no possibility in the present seas of inorganic precipitation of silica. There is no reason to think that Cretaceous seas differed fundamentally from modern seas in this respect. Krauskopf (1956) states that the origin of sedimentary chert "may be plausibly ascribed to the dissolution of remains of siliceous organisms, and the reprecipitation of this silica (initially as amorphous silica), but not in general to direct inorganic precipitation". Siever (1957) argues that most bedded chert must have originated as Bramlette (1946) suggests for the Monterey Formation, by diagenetic dissolution of silica from diatoms being reprecipitated as chert. In this he seems in agreement with Krauskopf (1956), but in a later paper Siever (1962) concedes that "the devitrification of marine volcanic ash is also probably a significant source of diagenetic silica".

The chemistry of the Cretaceous cherts from Timor indicates that the silica was not derived from direct volcanic emanations nor volcanic ash; the evidence supports the views of Bramlette (1946), Krauskopf (1956) and Siever (1957) that the origin of the silica in bedded cherts is largely biogenic.

It must be pointed out that since diagenesis has taken place in these rocks the trace element content may have been altered during the process.

D. CONCLUSIONS

From the study of the chemistry of the cherts and radiolarites of the Wai Bua Formation the following conclusions may be drawn.

(1) The cherts shew some indications that they have been derived from radiolarian ooze by the process described by Bramlette (1946), Krauskopf (1956) and Siever (1957) as a diagenetic process involving the dissolution of the siliceous skeletons and reprecipitation initially as amorphous silica. Such a process could effectively separate most of the clay originally mixed with the siliceous skeletons.

(2) The radiolarites have a major element composition very similar to that of modern deep-sea radiolarian ooze which has been enriched in silica. Such an enrichment may possibly have taken place by a mechanism that selectively removed the clay minerals. There does not appear to be any evidence of such a process operating in the modern deep-sea oozes. A more likely process is that described for the cherts in (1) above. It is therefore considered that the radiolarites have been derived from radiolarian ooze by the early curtailment of a diagenetic process of which the end product is radiolarian chert.

(3) The Fe/Mn ratios of the radiolarites and cherts by analogy with the ratios of modern pelagic sediments indicate a paleobathymetry of the order of 5,000 metres.

(4) There are several indications that the environment in which these cherts and radiolarites were deposited was almost free from calcium carbonate. This accords with the

conditions prevailing in the deep-sea today, where as Revelle et al. (1955) observe "siliceous oozes occur in extensive areas of the Pacific where the dissolution of CaCO_3 outweighs production".

(5) There is a relative enrichment of titanium in the radiolarites, and this may support Goldberg's (1954) suggestion of biogenous titanium contributing to the pelagic sediments.

There is also a Ti-Fe covariance that in these radiolarites may indicate a biogenous component similar to that found by Robertson and Tweedily (1953) in the Skye diatomite.

(6) On balance it appears that the trace element composition of these radiolarites supports the view that they are deep-sea deposits, originally radiolarian ooze that was diagenetically silicified by biogenous silica.

(7) There is one feature that emerges clearly from the trace element study of the cherts and radiolarites and that is the confirmation that neither pyroclastic material nor other products of vulcanism have contributed significantly to these siliceous deposits.

(8) In the light of the conclusions reached above the silica diagenesis does not seem to have had much effect on other elements except possibly some dilution.

E. METHODS OF ANALYSIS

SiO_2 was determined by a combined gravimetric and colorimetric method; R_2O_3 was determined gravimetrically. Fe, Ti & Mn were determined colorimetrically enabling Al_2O_3 to be determined as the difference between R_2O_3 and the sum of Fe_2O_3 , TiO_2 & MnO_2 . Ca & Mg were determined by complexometric titration when above 1%; they were determined by an optical spectrographic method when below 1% with an estimated standard deviation of $\pm 10\%$. V, Cr, Co, Ni, Cu, & Ba (when below 500 p.p.m.) were determined by a similar optical spectrographic method (after Bray, 1942) and with similar **percentage standard deviation** down to concentrations 4 times the sensitivities (given in table I); standard deviations increased to $\pm 25\%$ as the sensitivity limit was approached. Zn, Rb, Sr, Yt, Zr & Ba (when above 500 p.p.m.) were determined by an X-ray fluorescence method (after Andermann & Kemp, 1958), estimated standard deviations were $\pm 20\%$.

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Table I. Chemical composition of chert

Sample No.	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	CaO	MgO	TiO ₂	MnO	Cu	Ni	Co	B	Sr	Rb	Ba	V	Cr	Zn	CO ₂	Total
																		H ₂ O	
7812	95.3	0.53	0.72	0.07	0.12	0.01	0.44	30	25	90	70	80	50	900	*	*	*	2.0	99.30
7813	95.8	0.12	0.37	0.81	0.06	0.01	0.18	5	25	50	35	*	*	160	*	*	*	2.0	99.88
7852	96.3	0.08	0.18	0.31	0.02	0.01	0.07	5	10	40	35	*	*	*	*	*	*	2.0	99.06
7856	96.1	0.03	0.33	1.34	0.03	0.01	0.03	5	*	110	50	*	*	*	*	*	*	3.9	99.7
7857	95.0	0.13	0.61	1.50	0.01	0.02	0.03	10	*	110	60	*	*	90	*	*	*	2.4	99.89
7858	95.5	0.29	0.82	0.14	0.08	0.04	0.12	10	15	80	75	*	*	80	*	*	*	2.3	99.21
7859	98.0	0.09	0.39	0.67	0.16	0.01	0.03	5	10	130	60	*	*	*	*	*	*	1.1	100.85
7851	95.9	1.93	0.12	0.04	0.01	0.00	0.003	5	10	50	35	*	*	*	*	*	*	1.8	99.94
7854	96.2	2.54	0.01	*	0.01	0.01	0.003	20	*	90	40	*	*	*	*	*	*	0.6	99.54
7855	95.4	1.80	0.41	0.10	0.05	0.02	0.06	10	10	90	40	*	*	*	*	*	*	1.7	99.53
7853	85.4	0.16	0.43	7.69	0.07	0.18	0.02	10	*	70	35	230	50	1900	*	*	*	5.5	99.60
S								2	5	5	20	40	40	50	20	20	50		
(a)	87.20	1.39	1.86	0.05	1.14	-	-												
(b)	89.9	2.3	3.7	0.3	0.5	0.2	0.1												
(c)	99.43	0.19	0.01	0.08	0.01	-	-												
(d)	91.4	0.5	0.9	2.7	0.8	0.02	-												

NOTE: SiO₂, Fe₂O₃, Al₂O₃, CaO, MgO, TiO₂, MnO, CO₂ and H₂O expressed in weight percent, all other elements in p.p.m.

S - Sensitivity

* - Not detected.

NOTES: (1) Samples 7812, 7813, 7852, 7856, 7857, 7858, 7859 are bedded radiolarian cherts.
 (2) Samples 7851, 7854, 7855 are bedded cherts without siliceous skeletons.
 (3) Samples 7853 is a nodular chert in a pelagic limestone.

(a) Diatomaceous chert: composite sample of 10 chert shales, Monterey formation, California. (Bramlette, 1946).
 (b) Average of 10 various bedded radiolarian cherts. (Cressman, 1962).
 (c) Chert band, Soudan Iron - Formation, Precambrian, Minnesota. (Maxwell, 1953, quoted by Cressman, 1962).
 (d) Average of 13 various chert nodules, lenses and layers in carbonate rock (Cressman, 1962).

Table II. Chemical composition of radiolarites

Sample No.	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	CaO	MgO	TiO ₂	Cu	Ni	Co	Cr	V	Sr	Rb	Ba	Y	Zr	Zn	CO ₂ + H ₂ O	Total *
7802	85.8	5.18	1.02	0.02	0.81	1.12	0.39	80	35	*	45	220	370	50	520	*	50	*	5.5	99.84
7803	92.8	2.58	0.31	0.01	0.67	0.49	0.03	40	10	5	25	90	200	*	300	*	40	*	3.6	100.49
7804	66.7	11.66	6.26	0.19	2.52	1.65	0.91	40	10	5	30	360	830	*	1100	100	120	*	9.7	94.59
7811	90.7	2.68	2.09	0.05	0.44	0.73	0.14	35	30	20	*	40	120	*	-	80	60	*	3.8	100.63
7818	69.5	10.43	6.02	0.04	1.17	1.87	0.69	380	40	*	60	330	900	100	400	*	60	100	10.7	100.42
7819	77.9	8.02	2.38	0.04	1.13	1.38	0.43	250	30	*	50	260	600	40	300	50	50	50	9.1	100.38
7824	87.2	3.88	1.74	0.40	1.10	1.45	0.03	110	40	10	35	50	270	40	1150	80	45	*	4.7	100.50
7875	92.0	3.10	0.44	0.01	0.54	0.56	0.10	90	*	*	30	110	200	40	-	*	45	*	3.8	100.55
7876	87.7	2.97	1.69	0.21	0.57	1.26	0.26	120	60	30	30	110	110	*	210	*	40	*	5.6	100.26
7877	90.5	2.55	0.97	0.81	0.41	0.50	0.06	50	35	*	15	20	85	*	530	*	70	*	4.3	100.10
7878	91.3	2.77	0.85	0.03	0.70	0.75	0.09	60	*	*	25	20	85	*	80	*	40	*	4.1	100.59
7879	75.7	7.87	4.08	0.87	0.81	1.09	0.36	280	100	50	50	285	430	100	400	*	50	100	9.3	100.08
7880	89.2	1.41	5.01	0.11	0.54	0.37	0.04	150	45	40	30	200	50	*	75	*	*	*	4.2	100.88
7882	89.3	3.17	1.40	0.11	0.90	0.81	0.31	60	20	*	30	105	180	*	560	*	50	50	4.4	100.40
7883	89.0	2.41	1.41	0.62	1.10	0.81	0.20	110	50	40	20	70	80	*	420	*	*	*	4.5	100.05
7884	83.8	4.23	2.38	0.93	0.54	2.27	0.19	280	115	70	30	220	90	70	230	*	90	50	6.2	100.54
7885	86.9	3.85	2.04	0.18	0.53	1.31	0.10	120	65	30	30	100	50	40	70		50	200	5.7	100.61
7886	91.1	3.47	0.56	0.02	0.29	0.70	0.15	80	10	5	25	170	120	40	240	*	*	200	4.2	100.49
S								5	5	2	10	10	40	40	50	50	30	50		
(a)	66.7	14.82	6.51	0.28	2.26	2.58	0.63													
(b)	64.34	15.37	6.85	0.29	1.86	3.58	0.73													
(c)	64.47	13.76	9.63	1.24	3.19	3.37	0.60													
(d)	54.48	15.94	9.50	1.06	1.96	3.31	0.98					230			2000					
(e)	56.12	16.30	10.94	1.40	1.65	1.43	2.01													
(f)	61.3	20.4	7.6		1.3	1.5	0.7													
(g)	58.98	14.34	8.63	1.38	0.39	2.44	0.84													
(h)	60.99	21.03	9.95	1.04	-	2.62	3.63													
(i)	57.05	17.22	7.37	0.12	2.04	2.17	1.27					200			600					
(j)	55.43	13.84	5.74		5.96	2.67	0.46								600					
(k)	49.0	17.4	9.3	1.61	4.06	3.36	1.22	740	320	160	93	710			3900	150	180			
(l)								37.3	40.7		66									
(m)	55.34	17.48	7.04	0.48	1.32	3.83	0.84	400	300	100	55	450			2000		126			
(n)	63.91	13.30	5.66	0.50	1.30	2.47	0.65	370	330	200	97	230			1050		170			
(o)								250	225	74	90	180			2300	90	150	165		
(p)								200	100		93									

NOTE: SiO₂, Al₂O₃, Fe₂O₃, MnO, CaO, MgO, TiO₂ and CO₂+H₂O expressed in weight per cent, all other elements in p.p.m.

* = Not detected
- = Not looked for
S = Sensitivity

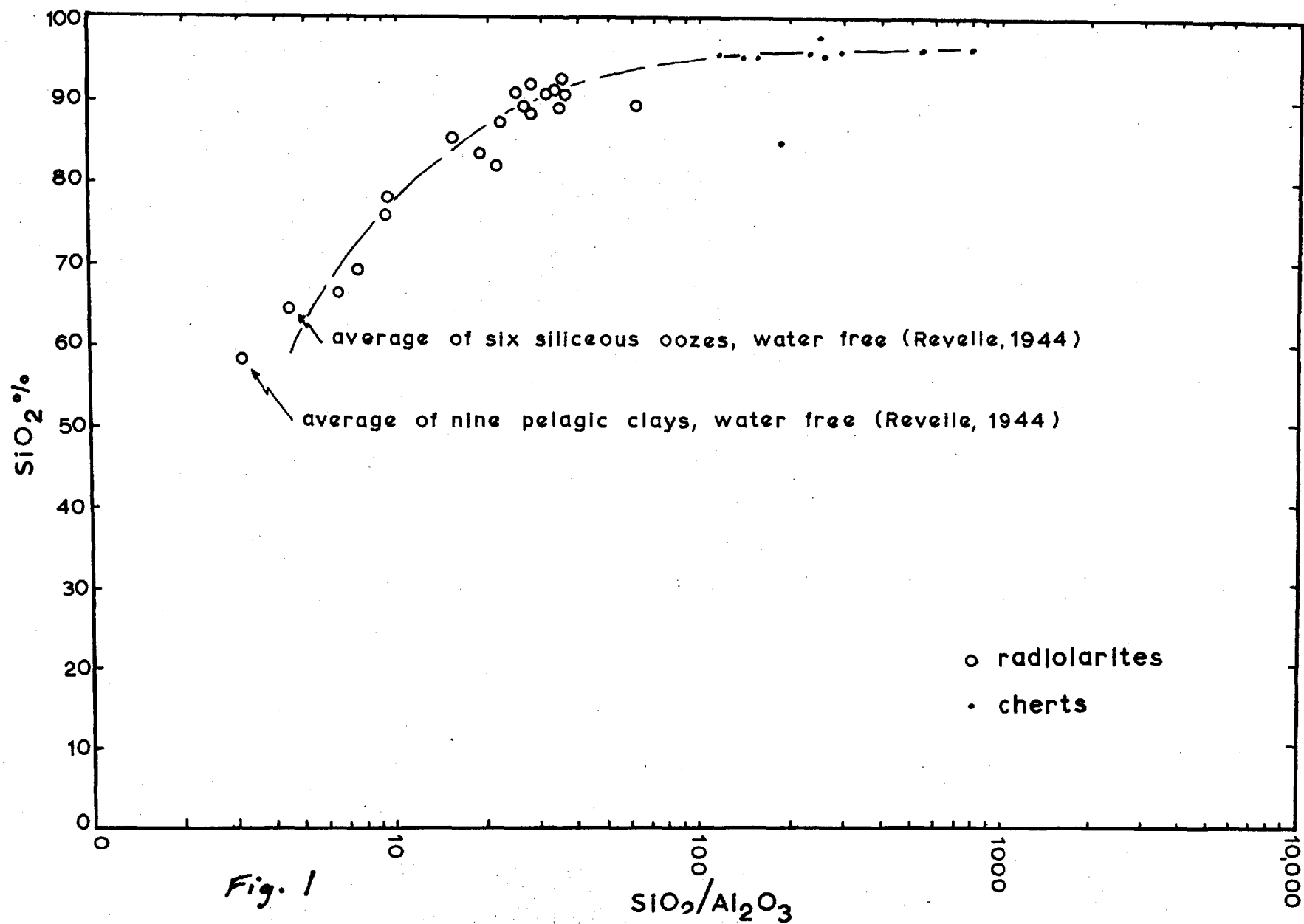
continued:

Table II.

- NOTES: (a) Radiolarian ooze (Revelle, 1944; quoted by Cressman, 1962).
 (b) " " " " " " " "
 (e) " " (Sujkowski, 1952).
 (f) Cretaceous red clay from Dutch Timor (Molengraaff, 1921).
 (g) " " " (B.R.C.) from Dutch Timor (El Wakeel and Riley, 1961a).
 (h) Red clay from Barbados (Harrison and Jukes-Brown, 1895).
 (i) Composite of 52 samples of marine terrigenous clays (Clarke, 1924).
 (j) " analyses of 27 marine shales (Clarke, 1924).
 (k) Average of 35 Pacific pelagic sediments (Goldberg and Arrhenius, 1958).
 (l) 8 " " 14 modern marine shales (Potter, Shimp and Witters, 1963).
 (m) " composition of deep-sea argillaceous sediment (El Wakeel and Riley, 1961b).
 (n) " " " " " siliceous " " " "
 (o) " " " " " clay (Turekian and Wedepohl, 1961).
 (p) " abundance of Cr, Co, Ni in deep-sea clay (Turekian and Carr, 1960).

Table III. Some element ratios of the radiolarites

Sample No.	Mn/Ni	Fe/Ni	Ni/Co	Ni/Cr	BaO/TiO ₂	Ba/Sr	Ca/Ba	Ca/Mg	Ca/Sr	Ti/Zr
7802	5	200	-	0.8	0.15	1.4	11	1.8	16	46
7803	8	220	2	0.4	1.1	1.5	16	3.4	24	5
7804	140	4400	2	0.3	0.13	1.4	16	3.8	22	45
7811	13	490	1.5	-	-	-	-	1.5	25	13
7818	8	1050	-	0.6	0.06	0.44	21	1.6	9	68
7819	10	550	-	0.6	0.08	0.51	27	2.0	13	52
7824	75	300	4	1.1	4.3	4.3	7	1.9	29	4
7875	-	-	-	-	-	-	-	2.4	20	13
7876	27	200	2	2	0.09	1.9	2	1.1	37	40
7877	180	190	-	2.3	1.0	6.2	5	2.1	34	5
7878	-	-	-	-	0.1	0.94	60	2.2	59	12
7879	67	290	2	2	0.12	0.93	14	1.9	13	44
7880	19	780	1	1.5	21.	1.5	50	3.5	78	-
7882	42	490	-	0.7	0.2	3.2	11	2.8	36	38
7883	95	200	1	2.5	0.23	5.3	19	3.4	100	-
7884	63	140	1.5	3.8	0.13	2.5	17	0.6	43	12
7885	21	220	2	2.1	0.008	1.4	55	1.0	76	12
7886	15	400	2	0.4	0.18	2.0	9	1.0	17	-



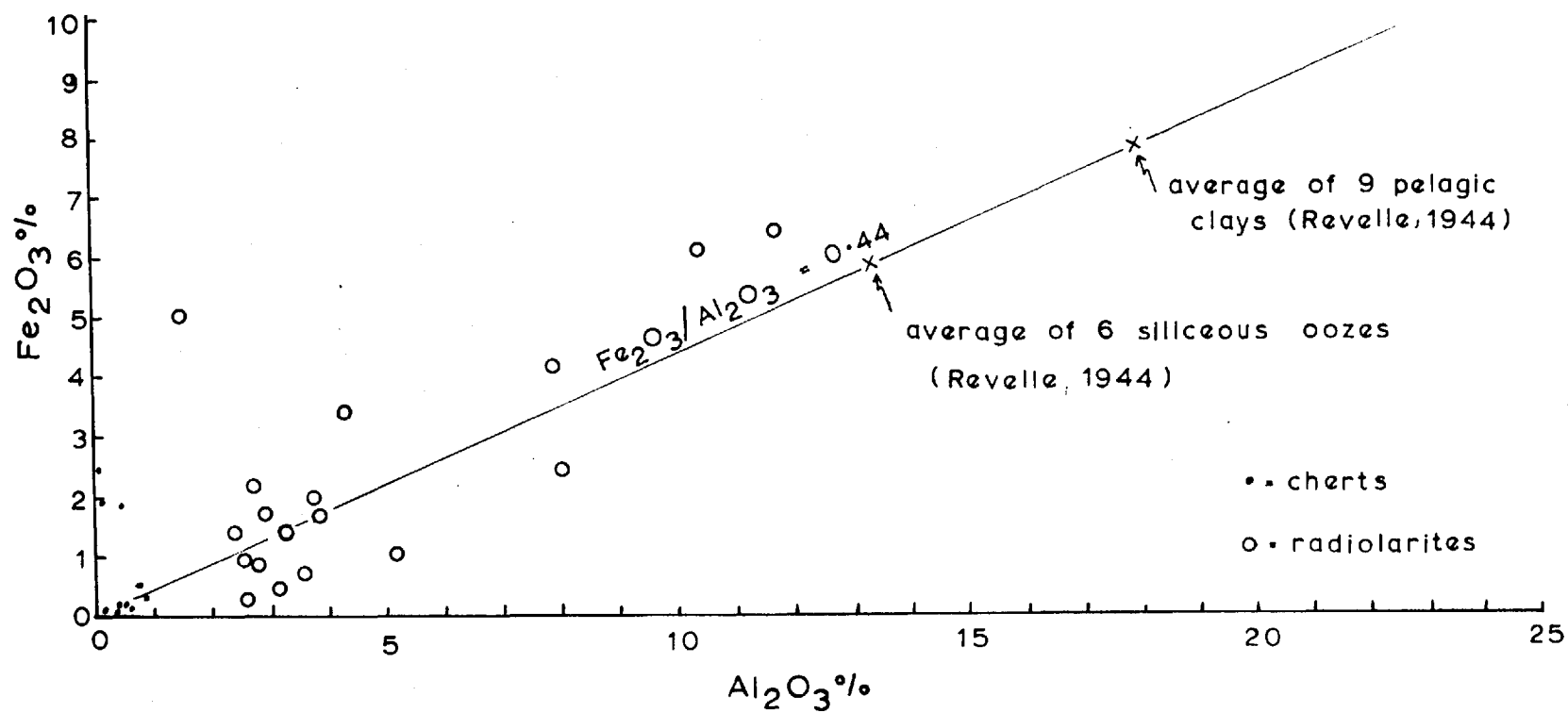


FIG. 2

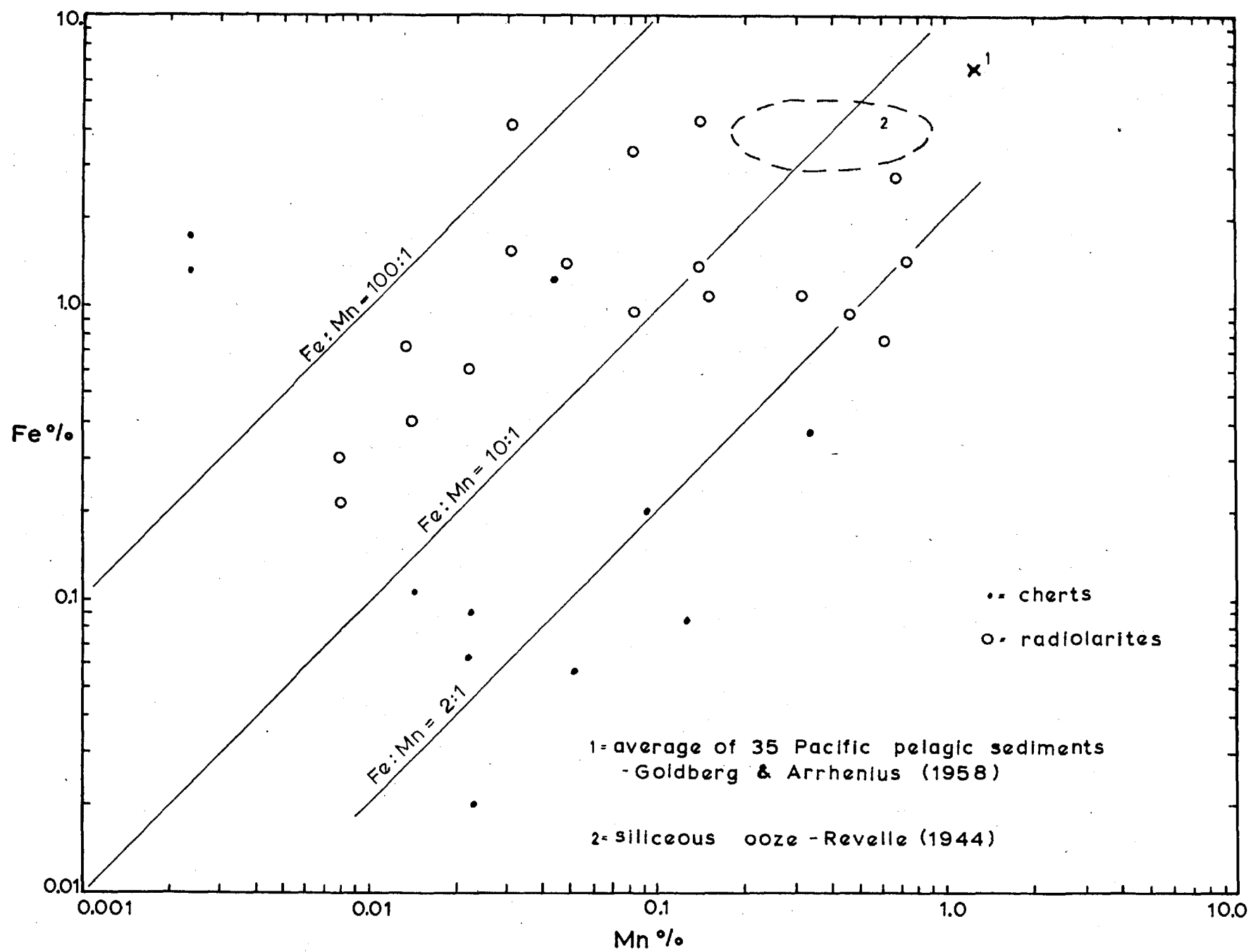


Fig. 3

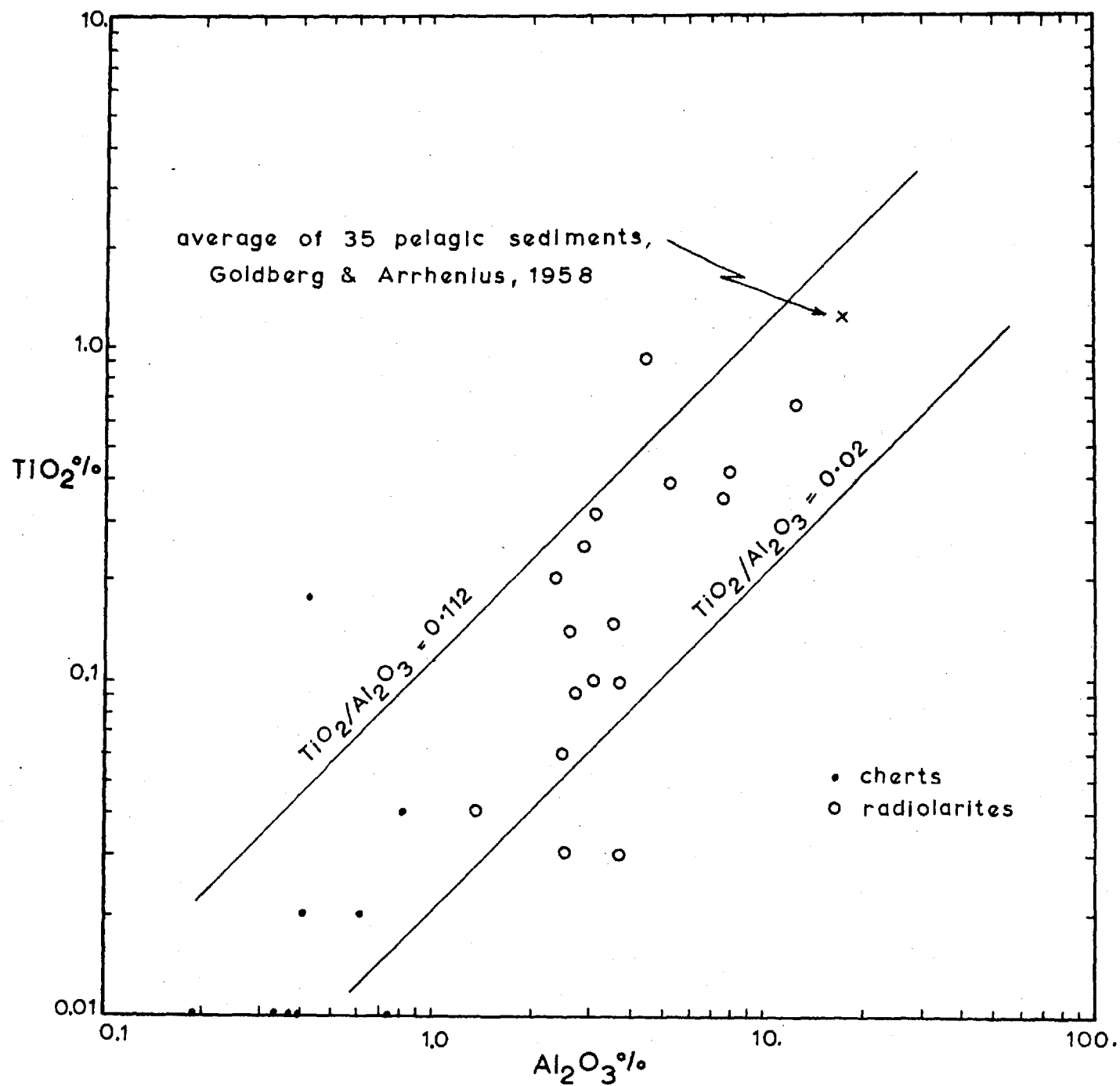


Fig. 4

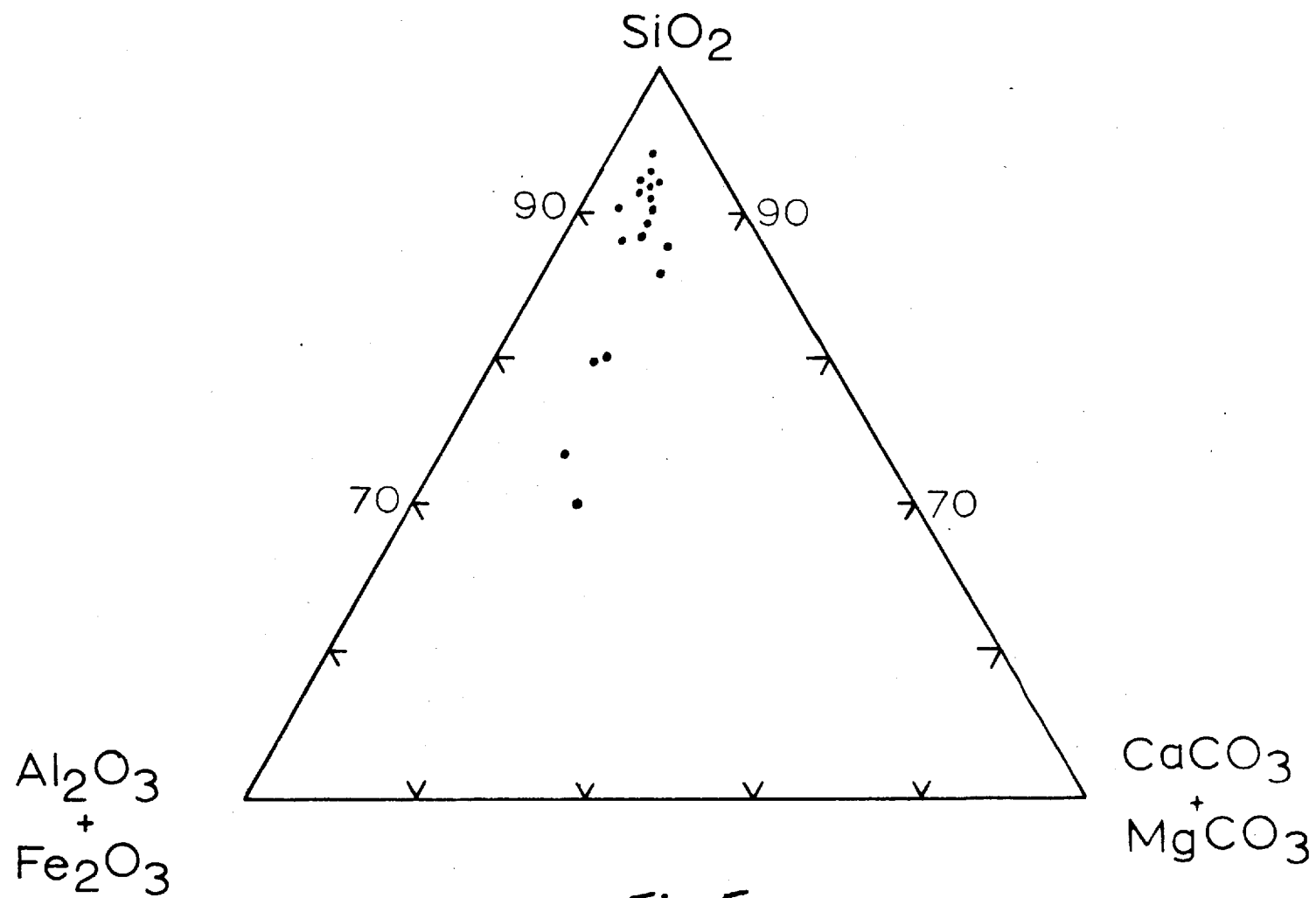


Fig. 5

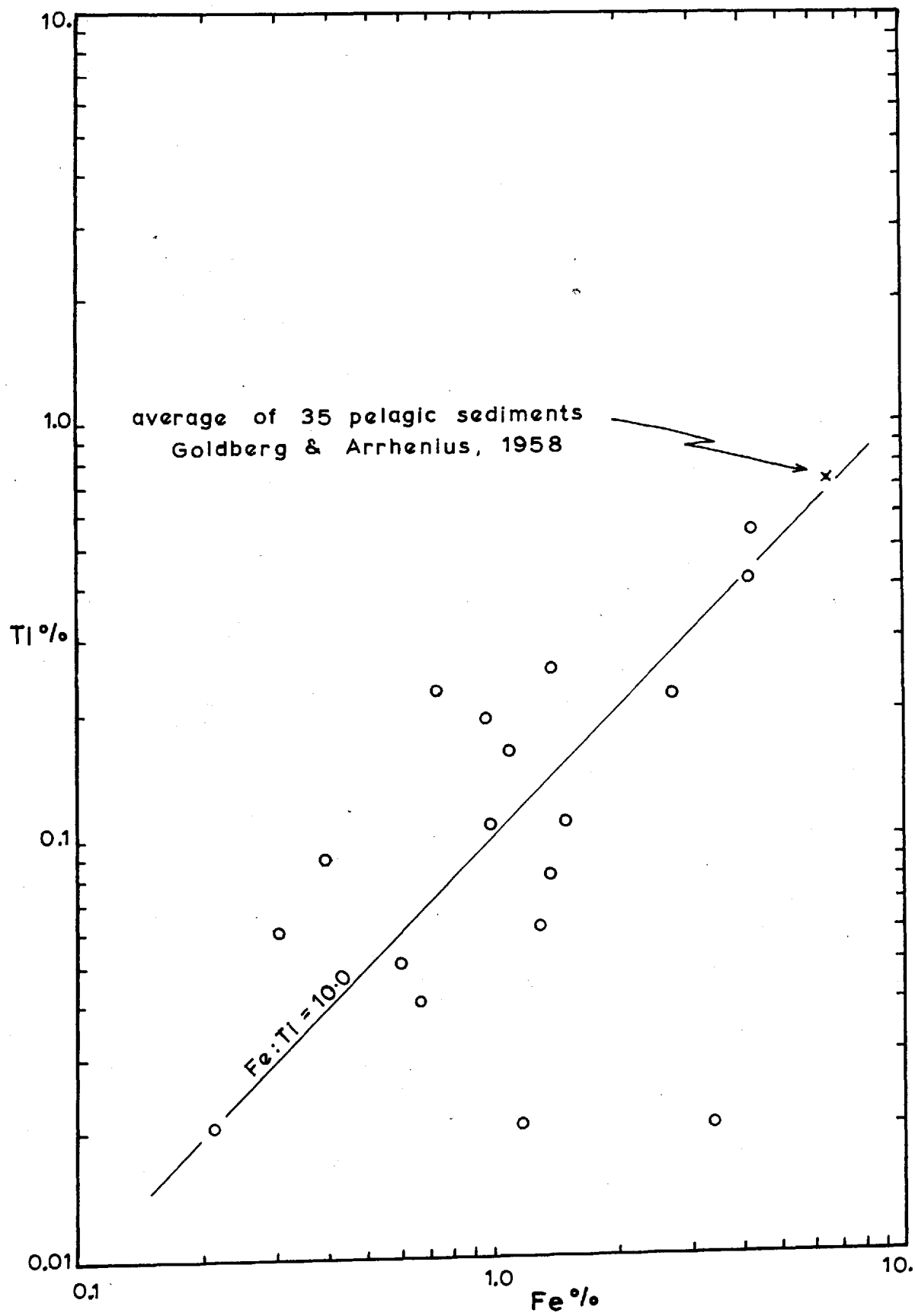


Fig. 6

APPENDIX II

A GEOCHEMICAL STUDY OF CRETACEOUS FERROMANGANIFEROUS SEDIMENTARY ROCKS FROM TIMOR.

ABSTRACT.

Seven manganese nodules, eight ferromanganiferous shales from the Cretaceous Wai Bua Formation of Timor, and a pelagic limestone with four ferromanganese enriched layers from the Middle Eocene of Timor have been analysed. The nodules are compared with modern deep-sea nodules, and the ferromanganiferous shales are contrasted with relatively shallow marine manganiferous shales. The conclusion is reached that these rocks from Timor were probably deposited in a bathypelagic environment. There is a total absence of any indication that volcanic material has contributed to these deposits.

The chemical composition of the ferromanganiferous rocks are discussed and some indications of biogenic influences are noted.

The Middle Eocene pelagic limestone is compared with a similar modern sediment described from the Easter Island Rise in the Pacific.

INTRODUCTION

Molengraaff (1916) reported the presence of Mesozoic sedimentary rocks unusually high in manganese from the islands of Borneo, Timor and Rotti. He described four principal types of manganiferous deposit from western (formerly Dutch) Timor, namely:

- (i) Finely disseminated small grains in red shales.
- (ii) Manganese nodules.
- (iii) Slabs and flat concretions.
- (iv) Secondary features such as films deposited by ground waters.

Later Molengraaff (1922) described in some detail the physical and chemical aspects of two distinct types of manganese nodule from western Timor (described by Molengraaff as "Central Timor"). These manganese nodules are embedded in a red clay with numerous sharks teeth, fish teeth and other bones of Upper Cretaceous age. Molengraaff considered these deposits to be analogous to the red clay with manganese nodules and sharks teeth, that predominate in large parts of the modern Pacific Ocean. Brouwer (1925) was of the same opinion. El Wakeel and Riley (1961a) analysed the micro-nodules disseminated in these red clays of western Timor. These workers agree with Molengraaff's (1922) theory that the sediments were deposited in a Cretaceous deep sea, analogous to the environment of modern deep-sea manganese nodules.

In eastern Timor (Portuguese) there are two well developed Upper Cretaceous pelagic facies, one a predominantly radiolarian facies called the Wai Bua Formation and the other mainly foraminiferal limestones. The Wai Bua Formation succession contains two distinct types of manganese

nodule (both of which are different from the nodules found in western Timor), as well as manganiferous shales, highly manganiferous siliceous beds, and iron rich shales in which manganiferous shales are interlaminated.

In this paper the chemistry of representative samples of these sedimentary rocks is described together with the chemistry of a laminated pelagic limestone of Middle Eocene age, whose fine laminae are enriched in iron and manganese minerals. In addition three manganese nodules from the Upper Cretaceous of western Timor have been analysed.

The close association of bedded cherts, particularly radiolarian cherts, with manganese rich sediments has been reported from many parts of the world, e.g. Miser (1917). Some workers have stressed the association of manganese and cherts with volcanic activity (Taliaferro and Hudson, 1943; Park, 1946; Tromp, 1948; Stephens, 1956; Takabatake, 1956). There is, however, no indication that volcanic activity has been associated with the various manganese rich sedimentary rocks intimately associated with cherts and radiolarites in eastern Timor.

The rocks that have been analysed will for the convenience of discussion be considered separately in three parts: Part I, the laminated shaly deposits; Part II, the nodules; and Part III, the Eocene pelagic limestone.

PART I

THE LAMINATED SHALY FERROMANGANESE ROCKS.

1. GENERAL DESCRIPTION.

(A) Iron rich shales with interlaminae of manganiferous shale.

These shales, typically reddish brown with thin black laminae generally 0.5 - 2.0 cm. thick are found as very rare sequences interbedded with cherts and radiolarites. The ferromanganiferous shales usually form a unit less than three metres thick, the bulk of which is iron rich, they are various shades of red and yellow, and often cut by thin calcite veins. The manganese rich layers are black, soft and sooty.

The minerals present include quartz, calcite, goethite, pyrolusite and a consistently small quantity of clay minerals.

No trace of organic skeletal remains could be detected in these rocks, but it is possible, having regard to their intimate association with rocks composed predominantly of Radiolaria and pelagic Foraminifera, that some of their silica and calcium carbonate may have been derived from these organisms. The four samples of this group (Nos. 7806-9) represent separate laminae one 10 cm. thick unit.

(B) Manganiferous siliceous shales.

These soft, black, often sooty shales have two modes of occurrence. One type (Nos. 7887 & 7820) occurs as

predominantly manganiferous units up to 25 cm. thick within a larger ferromanganese shale unit such as is described under "(A)" above. The other mode of occurrence (No. 7888) is less common, and forms firmer black shales not interbedded with ferromanganese shales, but directly with radiolarites and cherts; it appears as an occasional isolated bed seldom more than 5 cm. thick.

There are two predominating minerals present namely pyrolusite and chalcedonic silica. Some quartz grains always very small have also been found in these beds. Very little clay is present. The pyrolusite is present mainly in the form of microcrystalline aggregates.

There is no direct evidence of organic skeletal material in either type despite the high proportion of silica.

(C) Dense manganiferous beds (slabs).

These have a much rarer field occurrence than the two varieties of shale discussed above. They are readily distinguished from the others by their metallic appearance, and by being hard and dense. These slabs have not been found more than 3 cm. thick. When found they are always interbedded in the manganiferous section of the ferromanganese shale units. The physical properties of these slabs are in marked contrast to the very soft, powdery, sooty shales.

Two minerals predominate namely pyrolusite and chalcedonic silica. The pyrolusite locally forms subhedral crystalline mosaic intergrowths, but is generally seen as fine-grained microcrystalline aggregates. The pyrolusite shews prominent banding with alternate horizons of

chalcedonic silica. Dr. A.P. Millman (personal communication, 1964) considers this banding is probably an original syngenetic feature.

No evidence of any organic skeletal features were found in these slabs. One sample (7821) represents this type of deposit.

2. DISCUSSION OF CHEMICAL COMPOSITION

Table I shews the chemical analyses of the samples mentioned above. Table II lists various ratios that have been calculated from these analyses. Table III lists data culled from the literature that enable comparisons to be made with other deposits.

(A) Iron rich shales with interlaminae of manganiferous shale.

(i) Major constituents.

The four samples in this group are divisible into three that are iron rich and one that is manganese rich. The latter may be compared with the manganiferous siliceous shales, but is considerably richer in CaCO_3 as are the iron rich shales.

Compared with Clark's average shale (Clarke, 1924) these shales are richer in CaCO_3 , poorer in Al_2O_3 and SiO_2 and richer in Mn. The iron rich shales are, of course, richer in Fe, but the manganese rich example is not. Compared with the Cambrian Manganese Shales of the Harlech Dome, North Wales (Mohr, 1959), the Timor shales are richer

in CaCO_3 and P_2O_5 , which may indicate a biogenic contribution to their composition. They are also richer in Mn. The manganiiferous shale from Timor contains less iron and has a distinctly lower Fe/Mn ratio than the average Manganese Shale from North Wales, but the ferriferous shales contain more Fe and Fe/Mn ratios of the order of, or greater than, those in the Harlech rocks .

With regard to the relative impoverishment of SiO_2 and Al_2O_3 of the Timor shales it may be seen from Table I and Table III that if the iron and manganese values of the Timor shales were reduced to average shale values, and the composition adjusted to 100%, that their SiO_2 and Al_2O_3 values would remain well below average, particularly the Al_2O_3 even allowing for wide inaccuracies in the analytical values of Al_2O_3 . Yet Mohr (1959) found that the Manganese Shales of the Harlech Dome were relatively high in Al_2O_3 and TiO_2 , and considered that they might be related. He quoted Goldschmidt (1954) as giving a value of 20 for the normal Al/Ti ratio in marine hydrolysates. The Timor ferriferous shales (Table III) agree exactly with Goldschmidt's figure, whilst the other is a little low (13). Mohr obtained a value of 16.6 for the Al/Ti ratio of the Manganese Shales. The value for the Timor Manganiiferous shale is 4.4. As no detrital ilmenite (such as Mohr found) or titania rich mineral could be found in thin section, the low value of Al/Ti cannot be explained in terms of detritus.

The conclusion reached by Mohr (1959) was that the high Al_2O_3 values in the Manganese Shale signify "that the sediments were deposited from waters carrying comparatively large amounts of clay minerals". It seems reasonable to deduce that the environment in which these Timor rocks were

deposited was exceptionally poor in clay minerals.

The MgO content seems to have no relation to CaCO_3 . Despite the much higher values of CaCO_3 relative to the average shale, the MgO content of all four samples (7806 - 7809) is less than that of the average shale. Presumably a large part of the MgO in the average shale is associated with the clay minerals, while in these Timor rocks clay minerals are relatively much more reduced in importance. Mohr (1959) found that the MgO values in the Manganese Shales were relatively low, showed that they were related to the total iron present, and claimed this indicated a common mode of transport for Mg and Fe as bicarbonates. There is no relationship apparent between Mg and total Fe in these Timor shales.

One means of comparison is seen in figure 1., where the values for three major constituents Fe_2O_3 , MnO_2 and SiO_2 are plotted as though they totalled 100%. Figure 1 shows that all these Timor rocks fall into one of the four distinct fields that may be described: - manganese poor, iron poor, silica poor and iron-manganese rich.

Figure 1 results in the manganiferous shale (7806) falling into the iron poor field, while the ferriferous shales and the average of the Manganese Shales of North Wales (average of 7 samples Mohr, 1959) all fall in the manganese poor field. Figure 1 also suggests comparison of the ferriferous shales with the iron rich manganese nodule (7823). It is interesting in this respect to note the similar Fe/Co ratios of the ferriferous shales and this nodule (7823) in contrast to the ratios of the other shales and nodules.

(ii) Trace elements

Copper.

The copper content of the manganiferous shale (7806) is of the same order as Mohr's (1959) average value of 70, while as is to be expected there is no comparison with the ferriferous shales. No covariance between copper and manganese, as is mentioned by Goldberg (1954), and Goldberg and Arrhenius (1958) in their studies of deep-sea sediments, is apparent in the ferriferous shales. The increase in copper content with increase in manganese content although suggested by 7806 and the manganiferous siliceous shales is very poorly defined. The higher copper value of 7806 together with high P_{2O_5} may indicate a common organic origin (cf. Schubert, 1954; Arrhenius, Bramlette and Piccioto, 1957; and Goldberg and Arrhenius, 1958). The much higher value of strontium in this manganiferous shale may also indicate a biogenic influence. Goldberg and Arrhenius (1958) state that high concentrations of strontium are found in the apatite phase of fish debris, and in the calcite of pelagic planktonic fossils. Even so the actual value of copper (60 p.p.m.) in this shale is considerably lower than one would expect. In this context it should be recalled that Hutchinson et al. (1955) found that the nickel, copper and cobalt content of pelagic sediments varies along the length of the core and that copper was distributed most irregularly.

Cobalt and Nickel.

These two elements especially nickel vary considerably in concentration, and this makes comparison difficult. The average values obtained by Mohr were 27 p.p.m. cobalt,

68 p.p.m. nickel, with an average Ni/Co ratio of 2.5. The variations between the Timor shales are apparent in Table II. The values for the average shale are difficult to determine from the literature since the differences obtained by different workers are so great (cf. Rankama and Sahama, 1950; and Shaw, 1954).

It is difficult to draw any deductions from the Fe/Co, Fe/Ni, Mn/Ni and Ni/Co ratios in Table II except that the manganiferous shale 7806 is distinct from the ferriferous shales. An anomalous feature is the nickel value of 630 p.p.m. in one of the ferriferous shales (7809). An explanation of this might be a contribution from cosmic particles. Pettersson and Rotschi (1952) noted the considerable variation in the nickel contents of deep-sea deposits below the sediment surface, and suggested tentatively that the abundance of abyssal nickel might be partly derived from cosmic dust. Smales and Wiseman (1955) criticised this view on the basis of absence of agreement with the cobalt and copper contents. Pettersson (1959) reaffirmed his earlier view that the nickel content of deep-sea sediments is largely due to contribution from the cosmos. By quantitatively estimating the weight of cosmic spherules in modern deep-sea sediments Pettersson (1960) considered he could completely account for their average nickel content. Serious objections remain such as those of Smales and Wiseman (1955) and that of the effect of variations in the rate of sedimentation of terrestrial material.

Vanadium.

The manganiferous shale (7806) is much poorer than the ferriferous shales in vanadium. In this it is comparable

to the manganiferous siliceous shales (of "B" below). The value of 165 p.p.m. was obtained by Mohr (1959) for the Manganese Shales of North Wales, while for the average shale Rankama and Sahama (1950) quote 120 p.p.m., Shaw (1954) quotes 109 p.p.m., and Goldschmidt (1954) 200 p.p.m. Thus while the manganiferous shale is impoverished the ferriferous shales are enriched. Goldberg and Arrhenius (1958) state that a large fraction of the vanadium is found in the finest grain size fraction of pelagic sediments. They suggest it is distributed "between the clay minerals, the iron oxide minerals and possibly the authigenic titanium minerals". They found a definite indication of a concentration in the iron oxide minerals. Another important source of vanadium in Pacific sediments they found to be basic pyroclastic material.

Mohr (1959) found that authigenic magnetite was enriched in vanadium by a factor of x20 compared with its matrix.

The sorption of vanadium on clay minerals mentioned by Goldschmidt (1954) is not likely to be a major factor in these Timor sedimentary rocks since the clay mineral content is so low. It would therefore seem to be directly related to the iron oxide minerals, since there is no evidence of basic pyroclastic material being an important constituent.

Molybdenum.

The molybdenum values appear to be more closely related to the iron content than the manganese, as Goldberg and Arrhenius (1958) suggested from their studies of modern Pacific pelagic sediments. Kuroda and Sandell (1954) noted

that in shales molybdenum and copper increase together, possibly due to organic matter. The ferriferous shales do not contradict this, while the manganiferous shale (7806) and those of group "B" appear anomalous.

Zirconium, yttrium, rubidium and chromium.

The low values for zirconium (50 p.p.m. or less), yttrium (less than 50 p.p.m.), and rubidium (less than 40 p.p.m.) in these sediments accords with the other evidence (discussed earlier) that indicates a very low proportion of detrital minerals. Mohr (1959) found by contrast an average value of 230 p.p.m. for zirconium. The low values of chromium support the hypothesis that there has been no important contribution from basic pyroclastic material.

Barium and strontium.

The low content of barium (less than 100 p.p.m.) distinguishes all the ferromanganese shales from the nodules. The Ba/Sr ratios contrast with the manganese shales of Mohr (1959) that are richer in barium and poorer in strontium.

SUMMARY

It must be pointed out that these ferromanganese shales form a very small (quantitatively negligible) fraction of the whole Cretaceous section in Timor. Another factor to be borne in mind is that the geochemical, petrological and field evidence all support the view that the Cretaceous radiolarites and cherts (with which these ferromanganese shales are interbedded) were deposited in bathypelagic environment. The chemistry of these ferromanganese shales

accords with this independent evidence in the following ways: -

- 1) Low Al_2O_3 , and the conclusion that the clay mineral content of the water from which these shales were deposited was very low.
- 2) The high CaCO_3 and P_2O_5 suggest that living organisms may have played an important part in the genesis of the sediment.
- 3) The high value of strontium in the manganiiferous shale suggests some contribution from organic matter either as fish debris or from planktonic Foraminifera or Radiolaria.
- 4) The fundamentally different chemistry of these shales from the Manganese Shales of the Harlech Dome suggest that each group was deposited in a very different environment.
- 5) The very low values obtained for yttrium, zirconium and aluminium suggest that land derived detritus has not played an important part.
- 6) Despite the high ferromanganese and vanadium values, the low chromium and TiO_2 values indicate that an important contribution of pyroclastic material is highly improbable. This accords with the conclusion reached from studying the associated radiolarites and cherts.
- 7) The irregularity of the copper, cobalt and nickel content, together with the absence of any discernible covariance between manganese and copper, as well as barium remaining below detection limit (100 p.p.m.) is analogous

to variation in modern deep-sea sediments and suggest some important diagenetic changes may have taken place. The variation in the strontium values may point to the same conclusion.

8) The clearly differentiated laminations of iron rich and manganese rich composition in immediate contact, together with the exceptionally low Al_2O_3 , low SiO_2 and high CaCO_3 suggest a syngenetic origin that is consistent with all field and petrological observations. This is not however to deny the importance of some diagenetic change. What is important and must be stressed is that the evidence offers no suggestion of a later addition of iron and manganese to a clay.

9) The relatively much smaller quantity of manganese shale that is so intimately associated with the much greater quantity of iron rich shale accords with the general principles of Krauskopf (1957) concerning the inorganic precipitation of iron and manganese from a solution containing them both. But as Lepp (1963) pointed out, diagenetic modifications could be responsible for influencing the Fe/Mn ratio.

(B) Manganiferous siliceous shales.

Chemically one sample (7888) is similar to the manganiferous shale (7806) discussed above. The major difference is the increase in the SiO_2 and the decrease in the CaCO_3 content of 7888. This is readily understood in relation to the field association of 7888 being interbedded directly in the radiolarites.

Comparison of 7888 with 7806 reveals: -

- i) Both fall in the iron poor field of figure 1.
- ii) Similar Fe/Mn ratio (factor of x2)
- iii) Similar Ni/Co ratio (factor of x2)
- iv) Similar Mn/Cu ratio
- v) Comparison can be made between other element ratios particularly Fe/Ni, Fe/Ti and $\text{Al}_2\text{O}_3/\text{TiO}_2$.
- vi) The P_2O_5 values are remarkably similar and stand out relative to all the other rocks under discussion.
- vii) The trace element composition is quite similar.

The presence of high strontium and high P_2O_5 in these two samples may be significant in relation to the CaCO_3 content being biogenic. Contrast the high strontium values with relatively low P_2O_5 content in the nodules that have lower CaO values.

The other two samples in this group (7820, 7887) are very similar to each other in most respects. Their very high MnO_2 content tends to differentiate them from the other shales considered so far. Their very low Fe/Mn ratios are noteworthy. In figure 1 they fall in the same part of the field as the brown manganese ore associated with the cherts described by Taliaferro and Hudson (1943).

Their Al_2O_3 and SiO_2 contents, and their $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratio suggest comparison with the shales described above.

An important point of departure in major constituent composition is their very low CaO values. In this respect they resemble the Manganese Shales of Mohr (1959).

As in the ferromanganese shales these two samples also have low TiO_2 values. The Fe/Ti ratios suggest comparison with the mangiferous shale 7806, while the $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios fall within the range of the ferromanganese shales.

Trace element composition.

The trace elements shew a number of interesting trends. The Mn/Cu ratios are very consistent in these high manganese shales. This covariance between Mn and Cu was noted by Goldberg (1954) in modern deep-sea sediments. (But Riley and Sinhaseni (1958) who made a statistical study of Goldberg's (1954) data deny there is evidence of this relationship).

The Mn/Ni and Mn/Mo ratios shew a closer agreement than do the Fe/Ni and Fe/Mo ratios. This accords with the suggestion of Goldberg and Arrhenius (1958) that Ni and Mo tend to associate with Mn in marine pelagic sediments and manganese nodules. The Fe/Co and Mn/Co ratios are very similar in these shales.

The low values for chromium are consistent and were discussed earlier.

The below sensitivity level of barium (100 p.p.m.) suggests comparison with the ferromanganese shales. Strontium is notably variable.

The higher values of copper, nickel and to a lesser extent cobalt, as compared with the values obtained by Mohr (1959), although not of the same order of enrichment as in modern manganese nodules from the deep-sea, do nevertheless

follow this trend. Figure 1 suggests that on the basis of three major components, these manganiferous shales are as different from the Manganese Shales of North Wales, as they are from the ferriferous shales of Timor (with which they are closely associated in the field), the nodules from western Timor (from the same formation) and modern Pacific deep-sea nodules (Mero, 1962). In the light of this it is hardly surprising that there are large differences in trace element concentration.

SUMMARY

- 1) One conclusion to be drawn from the comparison of these three manganiferous shales is that their chemical composition indicates a number of important conclusions that were arrived at for the ferromanganese shales discussed earlier, namely the conclusions numbered: - 1, 4, 5, 6 and 8.
 - 2) A major difference is the great reduction in CaCO_3 in the two samples that have a greatly increased MnO_2 content.
 - 3) The two samples very high in MnO_2 shew a much closer agreement to the general principles of element relationships discussed by Goldberg (1954) and by Goldberg and Arrhenius (1958). In this these two samples tend to exhibit the same trends as modern deep-sea manganese rich sediments.
- (C) Dense manganese beds (slabs).

From the point of view of major constituents the sample 7821 (that represents the present group) is very similar to the manganiferous shales 7820 and 7887 described above.

The similarities may be summarised as follows: -

- i) In figure 1 it shares a close part of the iron poor field with the other two, having also a very similar SiO_2 content.
- ii) Low values for Al_2O_3 , CaO and MgO .

In many ways sample 7821 seems to bridge the gap between the ferromanganese shales and the manganese nodules. In particular the trend in trace element enrichment is more pronounced in this bed than the other shales (cf. the Cu, Ni and Mo values). However, the cobalt value it should be noted is reduced. Mohr (1959) found a very close covariance of Co and Fe in the Manganese Shales of North Wales. Goldberg (1954) also pointed out this correlation of cobalt with iron, and Riley and Sinhaseni (1958) acknowledge this relationship. The lower value of cobalt with the reduced concentration of iron in 7821 is therefore in accord with this principle.

Likewise it is seen that the vanadium content is low, very low in relation to the copper, nickel and molybdenum. Here is another indication of what was seen in the ferromanganese shales, namely that the vanadium is related to the iron oxide minerals. Low chromium and very low TiO_2 strengthens the affinity with the other shales. Similarly the rubidium, yttrium and zirconium contents remain low.

A major change in trace element composition is the presence of barium (7500 p.p.m.). Goldberg and Arrhenius (1959) indicate that the barium in modern pelagic sediments

is probably biogenic. This relatively high value of barium may therefore indicate an important biogenic contribution. In the light of this it should be recalled that Revelle et al.(1955) found a strong covariance between biogenous copper and barium. Another possibly biogenous element strontium, present as 460 p.p.m., may seem low compared with the others, although CaO and P_2O_5 are relatively low. Mohr (1959) noted that the Manganese Shales of the Harlech Dome are richer in barium and poorer in strontium than most other shales. He considered the inverse relationship between barium and strontium which he attributed to their different sedimentary cycles. He suggested that "strontium follows calcium to a certain extent occurring in the carbonate precipitate". A liberal view of the Ca/Sr relationship in the ferromanganese shales would perhaps concur with Mohr's comment.

SUMMARY

The major chemical features of the shales seem to be present in this slab, while at the same time the trend of the trace elements towards greater concentration, that typifies the modern deep-sea manganese nodules, is carried further than in the shales.

An important factor, that of the biogenous aspect of some elements is prominent, despite the very low value of CaO, that in the shales seemed attributable to biogenesis.

A highly significant feature of this sample 7821 is its similarity with the manganese nodule 7827, notwithstanding the major difference in their silica contents (see figure 1). Reference to the ratios in Table II shews how similar some of their element relationships are.

PART II

THE MANGANESE NODULES.

1. GENERAL DESCRIPTION OF NODULES FROM TIMOR.

(D) Manganese nodules (manganese rich).

These nodules are found at certain very rare horizons in the Wai Bua Formation. They are isolated and not found with other ferromanganese sediments. Unlike the nodules described from western Timor by Molengraaff (1916 and 1922), they are not associated with sharks' teeth and bones.

These nodules are small (about 1.5 to 5.0 cm. max. diam.) having a smooth black skin and slightly nobbly surface. They are globular in form. They have an essentially metallic appearance being hard and dense. They seem to lack the concentric banding that is so characteristic of modern nodules from the deep-sea, shallow seas and lacustrine environments. These nodules consist predominantly of pyrolusite (sample 7827) contains more than 80% MnO_2) that takes the form of fine-grained microcrystalline aggregates.

There is no evidence of any organic skeletal structures in these nodules. One sample 7827 represents this type of nodule.

(E) Manganese nodules (iron rich).

These nodules like the manganese rich nodules are very rare and occur isolated within the Wai Bua Formation

They are readily distinguished from the manganese rich nodules by their shape, colour and greater size. These nodules have their maximum diameters between 5 and 15 cm. They are a dark red, rusty colour and have an irregular shape. Concentric banding is very strongly developed in these nodules. In contrast to modern deep-sea nodules these are hard and dense,

The principal iron mineral present is goethite. Of the manganese minerals pyrolusite predominates; it is intimately intergrown with hausmanite (or the partially hydrated sub-variety, hydrohausmanite). A secondary manganese mineral showing colloform banding is present, occurring as simple infilling, but also as a replacement boxwork, after pyrolusite by guided metasomatic diffusion along cleavage planes and crystal boundaries. Dr. A.P. Millman (personal communication, 1964) considers this mineral is probably cryptomelane.

At the core of this nodule (7823) is a relic of what may have been a small chambered shell.

(F) Manganese nodules (nickel-cobalt rich).

The nodules in this group come from the Upper Cretaceous of western Timor and were not collected by the writer. Two of the nodules analysed were provided from the collection in the Museum of the Department of Geology, Imperial College of Science and Technology, and one nodule was made available by the University of Amsterdam.

Unlike the other nodules discussed above, these have a distinct core and corona that are clearly seen on cutting

the nodules in half. They are also readily distinguished from the other nodules by their light earthy colour, low specific gravity, and very soft, easily scratched surface. Physically they are indistinguishable in the hand specimen from modern deep-sea nodules. The centre of the cores of these nodules failed to reveal any recognisable nucleus.

These nodules from western Timor are found in a red clay shale matrix. Similar nodules and similar clay shales have not been found in eastern Timor.

These nodules are mineralogically more complex than those from eastern Timor. They contain about 20% clay, 20% chalcedonic silica and about 40% complex iron-manganese minerals. A little quartz is present as very small grains. Some of the chalcedonic silica may have been derived from Radiolaria.

This type of nodule is represented by five samples as follows: -

7889 - core) - nodule 1
7890 - corona)
7891 - corona)
7892 - core) - nodule 2
7893 - undivided nodule 3

3. DISCUSSION OF THE CHEMICAL COMPOSITION OF THE TIMOR NODULES.

(D) Manganese nodules (manganese rich)

One sample 7827 represents this group, and as may be seen from Table I it consists of 82.5% MnO₂. The very low

values for SiO_2 , TiO_2 and the value of Al_2O_3 suggest that clay minerals and detrital materials were relatively impoverished in the waters from which the nodule formed. The relatively high values of Cu, Ba, Sr, and V together with the presence of CaO suggest that biogenic contribution may have been important.

Apart from the very low SiO_2 content, and consequently unique position this nodule occupies in figure 1, it shows a number of important similarities with the shale 7821 (e.g. the Fe/Mn ratio).

The zirconium level is low (130 p.p.m.) and the Ti/Zr ratio (2.3) is very similar to that of sample 7821. Goldberg (1954) was of the opinion that the Ti/Zr ratio "is indicative of the past history of the sedimentary matter". He quotes a figure of 150 as the average Ti/Zr ratio of modern manganese nodules, that as he comments "are presumed to be almost entirely hydrogenous". He contrasts this value with that of 20 as the average for igneous rocks, and considers that values of this order suggest the presence of lithogenous matter.

If the composition of this nodule is compared with that of modern deep-sea nodules from the Pacific, as listed by Mero (1962), it is seen that while SiO_2 and Al_2O_3 values of the same order as those of 7827 do occur in modern nodules, they are not common. What is singular is the very high MnO_2 content and extremely low Fe/Mn ratio of 0.002. Figure 1 reveals the unique position of this nodule, and its relation to the average Pacific nodule. In this respect the question posed by Goldberg (1954) is recalled "why do manganese nodules close to coastal areas

contain extremely high manganese concentration compared with iron?". He describes a nodule from the Gulf of California that contained essentially pure MnO_2 , and was devoid of normally associated metals such as Ni, Co, Cu, and Zn.

(E) Manganese nodules (iron rich)

In a number of respects the nodule 7823 has a chemical composition fundamentally different from that of the manganese nodule 7827 (see figure 1 and Table I and II). In particular, contrast the Fe/Mn ratio and the trace elements Cu, Ni, V and Mo. But what is equally interesting is the similarity between these two nodules. Note for instance low SiO_2 and the similar Al_2O_3 and CaO contents. P_2O_5 it is noted is negligible. This contrasts with the ferromanganese shales where high Sr values are accompanied by high P_2O_5 .

In figure 1 this iron rich nodule appears isolated, but the same silica poor field is shared with the manganese rich nodule and one of the ferriferous shales.

If it is accepted that the metallic cations are related to the ferromanganese minerals as Goldberg (1961b) suggests, then the difference in concentration of these cations in these two nodules 7827 and 7823 can be related to the very different Fe/Mn ratios. Since they both occur in the Wai Bua Formation and were deposited in the same locality, this suggests they formed either by different mechanisms or else the Fe/Mn ratio of the environments was radically different. The activity of submarine volcanic emanations it might be argued could effect such local changes in the Fe/Mn ratio. Yet the testimony of all the

ferromanganese sediments that form the basis of the present study, together with that of the radiolarites and cherts with which they are associated in space and time, is that there is no evidence of volcanic contribution in any form.

The iron rich nodules from the modern deep Pacific (Mero, 1962) are usually found along the continents that border the Pacific. Although modern nodules as low in iron as 7827 have been found (e.g. Goldberg, 1961a; and Willis and Ahrens, 1962) there does not appear to be any record of an iron rich nodule containing 35% Fe, and having an Fe/Mn ratio of 2.65. The highest value for iron appears to be 26.6% in a Pacific nodule (Mero, 1962). This limits the extent to which direct comparison with modern nodules can be made. Certainly the iron rich nodules analysed by Goldberg (1954), Mero (1962) and Willis and Ahrens (1962) are not greatly impoverished in trace cations, as is the Timor nodule.

(F) Manganese nodules (nickel-cobalt rich).

These nodules from western Timor are very similar to each other, and their cores are very similar to their coronas (see figure 1). Table I and II, and figure 1 allows the marked differences between these nodules and all the other sediments under discussion to be seen.

The basic characteristics that distinguish these nodules from all the other nodules and shales may be enumerated as follows: -

- 1) The Fe/Mn ratios vary closely about 1.0. This coincides with the value for modern manganese nodules quoted

by Goldberg (1954).

- 2) Consistently high SiO_2 and Al_2O_3 that are closely comparable with modern deep-sea nodules from the Pacific (Mero, 1962).
- 3) Relatively high TiO_2 values that compare with the higher values found by Willis and Ahrens (1962) in Pacific nodules, and higher values found by Goldberg (1954).
- 4) The CaO content of these nodules is usually lower than the ferromanganese material, but higher than the manganese rich deposits of eastern Timor. These CaO values are closely comparable to the values in modern deep-sea nodules (cf. Mero, 1962).
- 5) Thus as is illustrated by figure 1 the manganese nodules from western Timor have a major element composition that is comparable with the composition of the average deep-sea Pacific nodule, while the nodules from eastern Timor fall at the two extreme ends of the composition scale of modern nodules.
- 6) The trace element composition of the nodules from western Timor is consistently higher than all the other Timor sediments under consideration (hence the term "nickel-cobalt rich"). These higher trace elements contents compare with the values for modern deep Pacific nodules (cf. Mero, 1962). The values of the western Timor nodules fall into the following categories for Pacific nodules: -

Ni - minimum; Co - between minimum and average; Cu - between minimum and average; V - between average and maximum;

Mo - between minimum and average; Ba - about average;
Sr - about x2 maximum; Zn - about x0.5 minimum; Zr - between
minimum and average.

7) The higher values for barium in the nodules from eastern Timor that conform approximately with the maximum values found by Mero (1962) are notable. The fact that barium values are less than 100 p.p.m. in all the shales forms a marked distinction that cannot be explained, except in so far as Table II shews that when barium is present it has a covariance with manganese. This suggests that the nodules and shales may have had their manganese concentrated by fundamentally different mechanisms, unless it is supposed that barium was not available.

SUMMARY.

1) The first conclusion which is unassailable is that the nodules from western Timor are very similar to the average deep-sea nodule from the Pacific. This conclusion was also reached by El Wakeel and Riley (1961a) for a different kind of nodule from western Timor. Their nodules, "micronodules", were very small (average 2 - 3mm.) and had to be hand picked from the red clay matrix, and differ chemically in some respects from the larger nodules (see Table III).

2) There are therefore four different kinds of manganese nodule in the Cretaceous rocks of Timor, two of which occur in the western and two in the eastern part of the island.

3) The nodules from eastern Timor are distinctly different from those of western Timor and from each other,

and from the average deep-sea modern nodule. Although they exhibit some similarities with the more extreme type of modern deep-sea nodule, they seem to have a composition intermediate between modern deep-sea and modern shallow marine nodules (Manheim, 1961).

4) None of the manganese nodules from Timor suggest any relation with volcanic material.

5) The wide variation in composition shewn by modern deep-sea nodules, and in the various Cretaceous nodules from Timor, together with the existence of manganese nodules of different composition in shallow seas such as the Baltic (Manheim, 1961), and in some fresh-water lakes (Kindle, 1932), suggest there are a number of different mechanisms that are able to concentrate iron and manganese on the sea floor.

PART III

THE FERROMANGANIFEROUS LIMESTONE OF EOCENE AGE

1. GENERAL DESCRIPTION

These limestones have been included in this study because they provide (by analogy with a modern deposit from the central Pacific) further evidence of the existence in the Timor region during the Upper Cretaceous and early Tertiary of conditions that today seem to be confined to major oceanic areas distant from land.

These pelagic limestones of the Middle Eocene Seical Formation are interbedded with radiolarian shales and limestones outcrop on the north coast of eastern Timor

(east of Baucau). The field relations are uncertain because the base is not seen, and they are overlain unconformably by an Upper Miocene block clay.

The limestone is very finely laminated. The individual laminations are coloured different shades of red with an occasional thin black layer. This colouration is due to ferric oxide and pyrolusite. The pyrolusite is in the form of a fine grained microcrystalline aggregate, that coats the inside and outside of the tests of the pelagic Foraminifera that make up most of the limestone. The ferric oxide behaves in the same way.

In the iron rich layers clay is an important constituent that forms up to about 50% of the layer. In the pyrolusite rich layers clay is always quantitatively unimportant.

Radiolarian skeletons are present in varying proportions and are composed now of chalcedonic silica.

El Wakeel and Riley (1961b) described from the Easter Island Rise in the Pacific a "calcareous manganiferous mud" that offers a most striking resemblance to the Eocene limestone in Timor.

The Timor limestone is represented by four samples, each one from a layer about 0.5 cm. thick, that are in immediate contact with each other. These samples are 7814, 7815, 7816 and 7817.

2. DISCUSSION OF THE CHEMICAL COMPOSITION

As will be expected figure 1 separates the two iron

rich layers from the two manganese layers. The manganese rich layers have a different trace element content from the iron rich ones (see Tables I and II).

Comparisons between the modern deposit from the Easter Island Rise and the Timor limestone are difficult to make because of the wide variation between the various layers of the Timor sample. Confining attention to the manganese rich layers it can be seen that the modern sediment is richer in CaCO_3 and poorer in SiO_2 . This may be a reflection of the difference in the Foraminifera/Radiolaria ratio. The iron content of the modern deposit is much higher, and the manganese content much lower, than the manganiiferous layers of the Timor limestone. In this respect comparison is perhaps closer with the iron rich layers, although the Fe/Mn ratio is different.

Without attempting a detailed discussion of the trace element composition, it is apparent from the analytical data, in the light of the arguments presented earlier in this essay, that there is no evidence of an important contribution from volcanic material or from land derived detritus. These factors taken together with the observation that the Fe/Mn ratios of the thin layers of limestone, that are closely related in space and time, are markedly different, suggest comparison with the Upper Cretaceous Wai Bua rocks.

CONCLUDING NOTE

Murray and Renard (1891) in discussing the deep-sea deposits in the 'Challenger' report are very sceptical about finding any real deep-sea deposits in a supramarine position today. Later Chamberlain (1914) strongly supported this

view. Molengraaff (1916 and 1922) challenged this idea, and argued that some Triassic and Jurassic radiolarites from the Alps, together with similar sediments in Borneo, Rotti and Timor were deposited in a deep-sea analogous to that in modern oceans. A conclusion reached in this essay is that the chemistry of the manganese nodules from western Timor supports Molengraaff's view, while the chemistry of the nodules and the shales from eastern Timor suggests a neritopelagic or bathypelagic environment, that is an intermediate depth between the deep bathyal environment of the modern deep-sea nodules and the shallow marine (e.g. Baltic) conditions. How far the chemical composition may be used as a paleoenvironmental indicator cannot be determined until more is known of the relative importance to the genesis of manganese nodules of (a) actual depth of water and (b) the absence of detrital sediment.

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Method of analysis.

SiO_2 was determined by a combined gravimetric and colorimetric method except for concentrations below 5% when an optical spectrographic method (after Bray, 1942) was used. R_2O_3 was determined gravimetrically. Mn, Ti, & P were determined colorimetrically when the ratio Mn/Fe was below 5; in the (seven) samples where this ratio was exceeded Fe was determined by an X-ray fluorescence method using Mn as a (variable) internal standard. Al_2O_3 was determined as the difference between R_2O_3 and the sum of Fe_2O_3 , TiO_2 , & MnO_2 ; data for Fe & Ti in the sample were used for calculating the contribution of these elements to the R_2O_3 precipitate on the assumption that all Fe & Ti were precipitated with the sesquioxides; the precipitation of Mn with the sesquioxides is known to be incomplete for Mn-rich specimens and therefore Mn was separately estimated on the R_2O_3 precipitate and this figure used in calculating

Al_2O_3 by difference. Ca & Mg were determined by complexometric titration when above 1%; they were determined by an optical spectrographic method when below 1% with an estimated standard deviation of $\pm 10\%$. V, Cr, Co, Ni, Cu, Mo, & Ba (when below 500 p.p.m.) were determined by a similar optical spectrographic method (after Bray, 1942) and with similar percentage standard deviations down to concentrations 4 times the sensitivities (given in Table I); standard deviations increased to $\pm 25\%$ as the sensitivity limit was approached. Zn, Rb, Sr, Yt, Zr & Ba (when above 500 p.p.m.) were determined by an X-ray fluorescence method (after Andermann & Kemp, 1958); estimated standard deviations were $\pm 20\%$.

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Table 1. Composition of ferromangiferous sediments from Tabor

Sample No.	FeO ₂	Fe ₂ O ₃	SiO ₂	Al ₂ O ₃	TiO ₂	CaCO ₃	MgO	P ₂ O ₅	Cu	Mn	Co	V	Na	Cr	Zn	Ba	Sr	Rb	Na	K	Total	
I																						
7807	4.2	38.5	25.3	6.0	0.24	15.0	0.6	0.92	20	530	35	350	25	50	250	*	*	*	1	1.5	99.40	
7807	3.2	56.4	10.6	7.4	0.22	14.5	0.8	0.31	25	180	35	340	50	40	400	*	140	*	*	4.0	99.44	
7808	7.5	34.6	22.2	6.6	0.12	25.2	1.0	0.17	15	85	10	300	25	25	200	*	110	*	*	1.0	99.37	
7806	21.2	4.3	29.6	7.8	0.78	25.3	1.8	3.12	60	95	70	90	10	15	200	*	650	*	*	20	99.40	
II																						
7885	14.1	5.6	50.8	6.6	0.57	11.1	1.8	3.36	50	160	55	70	10	15	150	*	520	40	80	4.0	99.83	
7887	51.2	1.9	33.2	7.7	0.70	0.5	1.3	0.24	200	190	35	140	20	15	450	*	230	40	30	4.0	99.14	
7820	61.9	0.8	23.2	7.8	0.13	1.4	1.1	0.13	280	300	35	110	40	15	450	*	190	*	*	70	99.36	
III																						
7821	57.5	0.1	33.6	6.6	0.03	1.3	0.5	0.16	800	360	15	80	200	15	350	7500	460	*	*	70	100.89	
IV																						
7827	82.5	0.1	1.1	9.3	0.06	4.3	0.2	0.01	4500	280	85	580	270	15	75	5500	700	*	100	140	1.0	99.37
V																						
7823	21.3	46.1	3.6	11.1	0.09	3.4	0.8	0.01	40	80	50	*	10	15	50	4000	1000	40	50	12.0	99.00	
VI																						
7889	20.9	16.8	29.7	14.8	1.46	3.4	1.8	0.18	2600	2300	1400	700	500	15	350	1500	3800	40	*	250	10.0	99.84
7890	16.4	17.9	33.4	14.7	1.64	3.0	1.4	0.17	2000	1300	680	760	370	15	200	1500	2900	*	*	920	10.0	99.21
7891	21.3	20.3	28.3	10.9	2.02	3.6	1.5	0.01	2600	1600	1250	800	250	15	250	2000	2900	*	50	230	10.0	99.73
7892	20.6	22.4	28.7	9.1	2.14	3.0	1.6	0.18	1800	1700	950	800	290	15	250	1800	2800	*	*	180	11.0	99.22
7893	20.2	17.6	29.8	13.8	1.76	2.9	1.7	0.22	2300	1450	950	720	560	15	250	1500	3400	*	50	120	11.1	99.08
VII																						
7817	20.9	0.9	11.2	2.7	0.19	62.8	1.0	0.01	600	80	60	380	20	15	*	270	500	*	*	*	1.0	100.70
7816	10.7	0.7	16.5	4.0	0.37	64.5	1.1	0.15	400	120	*	300	15	15	50	700	460	*	*	90	0.5	99.62
7815	3.1	14.6	23.3	3.0	0.85	55.5	0.8	-	70	*	*	700	20	55	50	*	330	*	80	60	0.5	100.05
7814	1.0	6.9	21.2	2.6	0.67	67.3	0.7	-	20	*	*	600	20	35	50	*	420	40	50	90	0.7	101.07
VIII																						
									2	5	5	15	10	10	50	50	40	40	40	55		

NOTE:

* Not reported

* Not listed in.

* Sensitivity

Fe₂O₃, H₂O, CO₂, NaO₂, Fe₂O₃, SiO₂, Al₂O₃, TiO₂, CaO, MgO, are in weight percent, all others in p.p.m.

Table II. Some element ratios of the ferromanganiferous sediments from Timor

Sample No.	Fe/Mn	Mn/100Ni	Mn/100Cu	Mn/100Ba	Mn/100Mo	Fe/100Co	Fe/100Ni	Fe/Ti	Ni/Co	Ba/Cu	Ti/Zr	Al ₂ O ₃ /TiO ₂
<u>A</u>												
7809	35	0.1	3.8	-	3	77	4.3	200	18	-	-	25
7807	20	1.1	8.0	-	4	120	23	300	5.1	-	-	34
7808	5.1	5.5	31.3	-	19	240	29	350	8.5	-	-	55
7806	0.2	14.1	22.3	-	130	4.3	3.2	6	1.3	-	95	10
<u>B</u>												
7888	0.44	5.5	18	-	89	7.1	2.4	11	2.9	-	-	12
7887	0.04	17.5	16	-	160	2.5	0.5	2	5.3	-	-	11
7820	0.014	12.6	14	-	98	1.7	0.2	7	8.9	-	11	60
<u>C</u>												
7821	0.002	10.1	4.5	4.9	18	0.6	0.03	4.5	24	9.3	2.2	200
<u>D</u>												
7827	0.001	18.6	1.2	9.5	19	0.1	0.04	3.3	33	1.2	2.3	155
<u>E</u>												
7823	2.4	17.0	34	3.3	135	72	45	700	1.6	100	-	123
<u>F</u>												
7889	0.89	0.57	0.5	8.8	2.6	0.9	0.51	13.4	1.7	0.58	35	10
7890	1.21	0.79	0.5	7.0	2.8	1.8	0.95	12.8	1.9	0.75	23	9
7891	1.06	0.85	0.5	6.7	5.5	1.1	0.89	11.7	1.3	0.77	52	5.4
7892	1.21	0.78	0.7	7.2	4.6	1.7	0.94	12.3	1.8	1.00	71	4.3
7893	0.97	0.89	0.6	8.5	2.3	1.3	0.86	12.0	1.5	0.65	87	7.8
<u>G</u>												
7817	0.05	16.5	2.2	50	66	1.0	0.80	5.4	1.2	0.45	-	14
7816	0.07	5.7	1.7	10	45	-	0.41	2.2	-	1.7	24	11
7815	14.8	-	0.9	-	3.4	-	-	20	-	-	85	3.5
7814	7.7	-	1.3	-	3.3	-	-	12	-	-	44	3.9

Table III. Data for comparison with ferromanganiferous sediments from Timor

Sample No.	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MnO	ZnO	CaO	MgO	P ₂ O ₅	Ba	Sr	Co	Cu	Mo	Ni	V	Zr	Cr
1.	60.15	0.76	16.45	4.04	2.90			1.41	2.32	0.15	360								
2.	55.43	0.46	13.84	4.00	1.74			5.96	2.67	0.20	540								
3.	59.07	1.73	18.75	2.45	6.07	1.52		0.76	1.81	0.03									
4.	12.75		12.50	13.74	7.70	36.08		1.62	0.58										
5.	33.25	1.55	12.25	17.75		7.32	0.31	10.20		0.43	1150	150	1900	1600	100	3400	320	75	
6.	29.90		1.50	1.35		48.70		0.90	1.98	0.06									
7.	33.65		1.70	1.46		40.22		1.10	1.77										
8.	3.32	0.07	0.64	13.88		4.80		42.61	1.96	0.13	800	1300	170	280	70	470	30	130	8

NOTE: SiO₂, TiO₂, Al₂O₃, Fe₂O₃, FeO, MnO, ZnO, CaO, MgO and P₂O₅ are in weight percent, all other elements expressed in p.p.m.

Some determinations such as H₂O, CO₂ have been omitted.

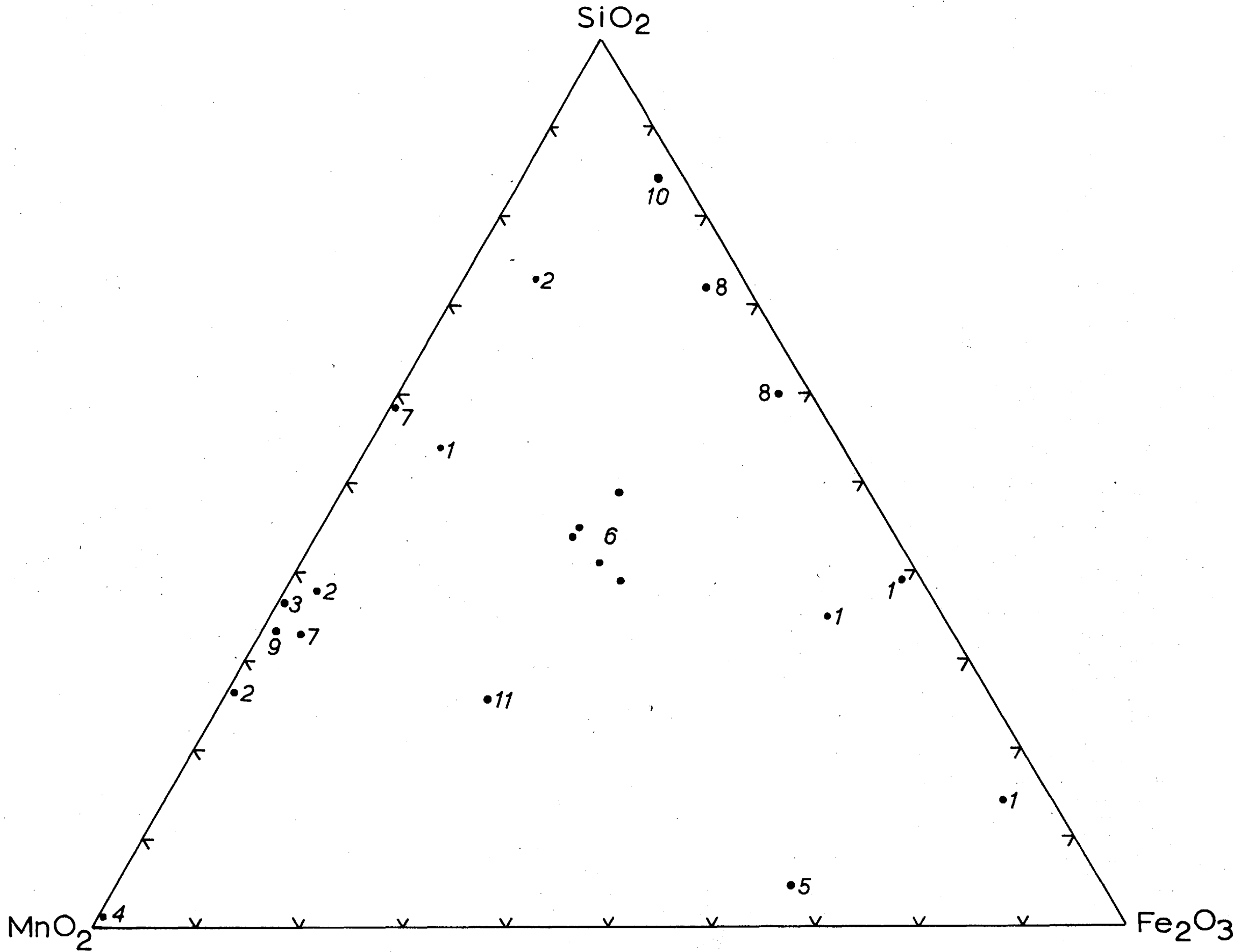
NOTES: (1) Clarke (1924). Composite analysis 51 Palaeozoic Shales. (H.N. Stokes).
 (2) Clarke (1924). " " 27 Mesozoic and Cenozoic Shales. (H.N. Stokes).
 (3) Mohr (1959). Average of 7 Manganese Shales.
 (4) Kindle (1932). Lacustrine Manganese Nodule from Canada.
 (5) El Wakeel and Riley (1961a). Micronodule from western Timor.
 (6) Taliaferro and Hudson (1943). Manganese-ore in chert from California.
 (7) Taliaferro and Hudson (1943). " " " " " "
 (8) El Wakeel and Riley (1961b). Calcareous Manganiferous Mud from Easter Island Rise in the Pacific.

LEGEND FOR FIGURE I

Title: Compositional diagram of various ferromanganiferous deposits from Timor and elsewhere.

Legend:

1. Ferromanganiferous shales from eastern Timor (Nos: 7806-7809 incl.).
2. Manganiferous siliceous shales from eastern Timor (7887, 7820, 7888).
3. Dense manganese bed from eastern Timor (7821).
4. Manganese nodule (manganese rich) from eastern Timor (7827).
5. Manganese nodule (iron rich) from eastern Timor (7823).
6. Manganese nodules (nickel-cobalt rich) from western Timor (7889- 7893 incl.).
7. Pelagic limestone (manganiferous) from eastern Timor (7816, 7817).
8. Pelagic limestone (ferriferous) from eastern Timor (7814, 7815).
9. Manganese ore from California (Taliaferro and Hudson, 1943).
10. Average of seven samples of the Manganese Shales from North Wales (Mohr, 1959).
11. Average of fifty two manganese nodules from the Pacific Ocean (Mero, 1962).



APPENDIX III

LIST OF UNPUBLISHED REPORTS REFERRED TO IN THIS THESIS.

- Audley-Charles, M.G. 1960. Final report on gravity surveys carried out in Portuguese Timor from June to November. 1-36, 15 maps.
- Audley-Charles, M.G. 1961. The geology of western Portuguese Timor. 1-40, 14 maps.
- Audley-Charles, M.G. 1962. The geology of Portuguese Timor. 1-233, 32 maps.
- Belford, D.J. 1960. Micropalaeontology of samples from Ossulari No.1 and No.1A Bores, Portuguese Timor. Rec. Bur. Min. Resour. Austr., 1960/33, 1-2.
- Belford, D.J. 1960. Micropalaeontology of samples from Portuguese Timor. Rec. Bur. Min. Resour. Austr., 1960/98, 1-6.
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- Crespin, I. 1956. Micropalaeontological examination of rock specimens from Portuguese Timor. Rec. Bur. Min. Resour. Austr., 1956/65, 1-3.
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- Crespin, I., & Belford, D.J. 1959. Micropalaeontology of further rock samples from Portuguese Timor. Rec. Bur. Min. Resour. Austr., 1959/118, 1-3.

- Crespin, I. 1961. Microfossils in rocks from Portuguese Timor. Letter to Timor Oil Limited.
- Dickins, J.M., & Skwarko, S.K., 1961. Quoted in letter to Timor Oil Limited by Dr. N.H. Fisher.
- Freytag, I.B. 1959. Regional geology and potential oil drilling areas of central southern Portuguese Timor. 1-32 , 3 maps.
- Lloyd, A.R. 1962. Micropalaeontological examination of samples from Portuguese Timor. Report to Timor Oil Limited from the Bureau of Mineral Resources, 106F/1, 1-4.
- Schneeberger, W.F. 1961. Interpretation of Aliambata No.1 Bore. Letter to Timor Oil Limited.
- Skwarko, S.K. 1961. Quoted in letter to Timor Oil Limited by Dr. N.H. Fisher.