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—A SYMPOSIUM

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— A SYMPOSIUM —

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Preface

On the occasion of the Annual Meeting of the Palaeontological Society of Japan on January 27, 1968, at Kyushu University, Fukuoka, a symposium was held on litho- and bio-facies of the carbonate sedimentary rocks, for which Dr. K. KANMERA and K. KONISHI acted as conveners. The invited members orally communicated the results of their works, which were immediately open to discussion. On closing the symposium I suggested that their researches were so important that the results should be published in English with some necessary refinement and that it would be desirable to assemble the contributions in one volume. This has now been realized herein.

The presented papers do not comprehensively cover various sorts of carbonate sediments and sedimentary rocks, but they show representative works which have recently been undertaken by some active geologists and palaeontologists in Japan.

The carbonate sedimentary rocks in Japan and adjacent regions are unique in that they occur in piles of geosynclinal deposits. They are, however, by no means simple, and various kinds of bio- and litho-facies are distinguished in accordance with the conditions in the mobile belt and with the stages of the tectonic development. The paper by N. OTA et al. and that by K. KANMERA are concerned with relevant examples in Southwest Japan, giving valuable information on the problem. The researches in our country are in progress and these papers are only a fraction of the results. I know, for example, another paper by T. MIKAMI in press (*Mem. Fac. Sci., Kyushu Univ.*, Ser. D, **19**, no. 3), which deals with another type of limestone in the Lower Permian Sakamotozawa formation of Northeast Japan.

The paper by K. ISHII et al. deals with the Permian Sisophon limestone, which was formed in a tectonically less deformed area in Southeast Asia. This exemplifies a more stable condition than the geosynclinal one but is less stable than a more extensive shelf.

H. IGO and T. KOIKE give descriptions and comments on some carbonate rocks of Japan and Southeast Asia from the standpoint of fossil conodonts, giving a hypothetical view on the mode of life in conodont-bearing animals.

Prior to these works S. HANZAWA (1961) published a magnificient monograph entitled "Facies and microrganisms of the Paleozoic, Mesozoic and Cenozoic sediments of Japan and her adjacent islands" (*International Sedimentary Petrographical Series*, **5**, Leiden), in which micrographs of limestones or calcareous sediments are illustrated, with some geological explanation.

The above researches are all based on microscopic observations. R. SHOJI and R. L. FOLK (1964: *Jour. Sed. Petrol.*, **34**, 144–155) attempted the examination of limestones by electron microscope. They gave a description of surface morphology of various limestone types but the results obtained seem to show some apparent features. No microrganisms were identified in that study. In the same year S. HONJO (1964, *Science*, **144**, 837–839) preliminarily gave a fine illustration of fossil coccoliths in limestone examined by electron microscopy. S. HONJO and A. G. FISCHER (1965 *in* B. KUMMEL and D. RAUP; *Handbook of Paleontological Techniques*) explained at length the methods and techniques in the palaeontological investigation of limestone by electron microscope. Subsequently A. G. FISCHER, S. HONJO and R. E. GARRISON (1967) published a fine book, "Electron micrographs of limestones and their nannofossils" (*Monographs in Geology and Paleontology*, **1**, Princeton). In addition to several other papers HONJO has further contributed another interesting paper to the present issue of the *Special Papers*.

Geochemical study of carbonate rocks is important. In fact a symposium was held in 1966 by a group of geochemists in Japan on the geochemical problems of carbonates. T. FUJINUKI, among many others, attempts a series of geochemical investigation of limestone from various geological formations in Japan. As Part I, FUJINUKI (1968: *Bull. Geol. Surv. Japan*, **19**, 603-624) published a result of his study on the minor elements of the Permian Akasaka limestone, suggesting the close relation between the contents of certain minor elements (e. g. strontium) and the abundance of certain kinds of organic remains (e. g. calcareous algae and corals).

Prior to this H. IGO (1960) studied the carbonate rocks in the Permian Nyukawa group in central Japan to see the relation between their chemical composition and bio- and lithological characters and eventually to know the paleoenvironments. The result of his study was briefly written in Japanese (*Kaseki*, no. 1, 63-71) and seems to have been overlooked.

In our symposium of the last year K. KONISHI orally delivered a result of his study on the Cenozoic Ryukyu limestone, giving the details of the shallow sea sedimentary facies. On this and other occasions he attempted to coordinate geochemical approaches with the palaeontological facies analysis. For some reasons KONISHI postponed the presentation of the final paper, which accordingly is not included in this volume.

I hope that the five symposium papers compiled in the present issue of the *Special Papers* would contribute not only domestically but also internationally to the knowledge of carbonate sedimentary rocks and would give stimulation for further improvement of our researches.

Finally I am indebted to Dr. K. KANMERA for his cooperation in collecting manuscripts and to Mr. T. OZAWA and Miss Yuko WADA for their assistance in editorship. Acknowledgements are extended to the Geological Society of Japan under whose cosponsorship with the Palaeontological Society of Japan the symposium was held.

July 30, 1969.

Tatsuro MATSUMOTO
Department of Geology
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(Editor)

REEF DEPOSITS IN THE *MILLERELLA* ZONE OF THE AKIYOSHI LIMESTONE GROUP

By

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1. Introduction

The Carboniferous and Permian Systems of Japanese Islands are composed of a heterogeneous lithologic assemblage, typified by predominant sandstone of wacke-type and mudstone (converted to slate or phyllite) and subordinate chert, volcanic sediments and limestone. Limestones are mostly of lenticular masses of various thickness and extension, and are often associated with basic volcanic sediments.

In the Chugoku region of the Inner Zone of Southwest Japan there are some extraordinary large, (compared with other bodies) isolated limestone masses which lie on basic volcanic rocks and are surrounded by non-calcareous, mostly clastic sedimentary rocks of Permian age. They are massive and several hundreds meters thick, and range in age from upper Lower Carboniferous (Visean) to Upper Permian. These limestones have been intensively studied from the palaeontological and/or biostratigraphical view points and the detailed zonation has been accomplished mainly by fusuline fossils and subordinately by corals and microforaminifers (OZAWA, 1923, 1925; TORIYAMA, 1954, 1958; HASEGAWA, 1958; MURATA, 1961; NOGAMI, 1962; OKIMURA, 1963, 1966; SADA, 1965). Little attention, however, has been focussed until very recently to the sedimentological features of the limestones. They are structurally very much complicated by a number of faults and folds including recumbent ones. Regarding its geotectonic setting there are two diverse opinions, one of which is that they form a large Klippe derived far from the north lying on the noncalcareous autochthonous groups (KOBAYASHI, 1941) and the other is that they are autochthonous, although the original structural relation to the surrounding sedimentary rocks is largely modified by later thrusting (TORIYAMA, 1954, 1958; HASEGAWA, 1958; MURATA, 1961; KAWANO, 1961; OTA, 1968). The general mode of their occurrence is, however, like a knoll-limestone or a biohermal limestone surrounded by clastic sediments, although they form a much larger mass than the latter. On the other hand their configuration on volcanic sediments recalls us the coral reefs in the equatorial Pacific

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which are developed on volcanoes.

Our knowledge on the sedimentary facies and lithologic features of bioherms and well-bedded limestones on the epicontinental stable area has recently been much improved and expanded, but that of large, isolated block-form massive limestones in the thick pile of eugeosynclinal sediments is still insufficient.

OKIMURA (1963, 1966) was the first who pointed out the existence of reef type deposits in the lower part of the Akiyoshi Limestone Group. ETO (1967) made a lithofacies analysis of the lower part of the Akiyoshi limestone Group in the south-eastern part of the limestone plateau, and showed the depositional pattern of the basic pyroclastic rocks and the successive limestones and also the vertical changes of organic communities in accordance with the stratigraphic sequence.

One of the writers, M. OTA (1968), treated the Akiyoshi limestone Group as a geosynclinal organic reef complex. His view was originally based on the fossiliferous reef limestones found in several areas on the Akiyoshi limestone plateau. He outlined the geologic history of the Akiyoshi limestone Group from sedimentological and palaeoenvironmental standpoints. He concluded that the sedimentation of the Akiyoshi limestone Group followed the submarine volcanic activity and that after forming an organic reef on the basic tuffaceous sediments it developed to an atoll in the upper Lower Carboniferous Period.

To make clear the sedimentological features of such a large eugeosynclinal limestone we are investigating the Akiyoshi Limestone. It requires much time to know the details of the bio- and lithofacies in every part of the limestone group. But in the course of study we have found a especially clear reef-limestone at the Sumitomo-Quarry area in the eastern part of the Yowara (Yobara) limestone plateau.

In this paper we describe in detail bio- and lithofacies of the reef limestone at the Sumitomo-Quarry area to know the characteristic features of the reef deposits. In this connection we have considered about the organic reef environment with relation to the direction of wave action. We have distinguished two types of limestone each of which is characterized by a particular bio- and lithofacies. It is concluded that one was acted as the wave registant mass and the other was subject to the action of wave and current.

In this research the field survey has been carried out in collaboration by all of us. Akihiro SUGIMURA has prepared hundreds of thin sections of limestones for microscopic study. Nobuki OTA has petrographically and sedimentologically examined thin sections and written the first draft of this paper. Masamichi OTA generalized our research.

Acknowledgements:—We wish to express our sincere gratitude to several persons who aided us in the course of our work. Dr. Kametoshi KANMERA of Kyushu University has read the first draft of this paper and given valuable advices and encouragements. Professor Tatsuro MATSUMOTO read the draft of this paper with instructive advices. Drs. Tsugio SHUTO, Juichi YANAGIDA, Itaru HAYAMI of Kyushu University, Kenji KONISHI of Kanazawa University and Mr. Tadashi KURAMOTO of Akiyoshi-dai Science Museum provided many helpful suggestions. Mr. Yoichiro MORINAGA of Sumitomo Coal Mine Company showed us the drilling data which are very useful for the analysis of the geologic structure. Mr. Terutsugu SHIMODA of

Sumitomo Cement Company gave us sincere support in collecting samples. Miss Seiko HAYAKAWA prepared the typescript. Finally, we heartily thank to Professor Ryuzo TORIYAMA who gave us valuable suggestions, and willingly lent us his numerous thin sections of limestone for this study.

2. General Lithographic Features of the Akiyoshi Limestone

The Akiyoshi Limestone comprises a nearly flat-lying plateau occupying an area about 130 km^2 with an approximate dimensions of 17 km in the northeast-southwest and 7 km in the northwest-southeast direction. Its surface elevation ranges 200 m to 300 m from the bottom of the dissected valleys. Stratigraphically it ranges in age from Visean to Upper Permian, although the Upper Carboniferous *Fusulina* and *Triticites* zones are in part lacking. Its total thickness attains about 650 m (OTA, 1968). It rests on calcareous, basic volcanic sediments—olivine basaltic tuff breccia, olivine basaltic tuff, volcanic conglomerate and tuffaceous shale—containing some lenses of limestone. It is along with the underlying volcanic sediments, in fault relation to the surrounding clastic sediments of Carboniferous to Upper Permian in ages.

The Akiyoshi Limestone is massive, having no distinct stratification plane. It is grey to slightly brownish white-grey and is devoid of terrigenous matter. The limestone as a whole is characterized by coarse grained bioclastic limestone. The constituent particles are crinoids, bryozoa, foraminifers, brachiopods, rugose and tabulate corals and some cephalopods, gastropods and pelecypods. Fusuline fossils are abundant at many horizons, by which precise biostratigraphical succession can be established. Codiacean and dasycladacean algae are also abundant throughout the thickness of the limestone of the Permian in age. Crinoids, together with oolite, are predominant in the Carboniferous section, in particular in the pre-*Millerella* Zone, the lowest part of the limestone. No prominent dolomite beds or bodies have been found.

It is worthy to note that a remarkable change of general lithology is recognized between the limestones of the pre-*Millerella* Zone and those of the overlying zones of the Carboniferous (i. e. *Millerella*, *Profusulinella* and *Fusulinella* Zones). The limestones of the pre-*Millerella* zone are densely packed with fragments of crinoids, bryozoa, brachiopods and some subordinate compound rugose corals. Oolite limestone is also well developed in them. Their matrix is generally narrow and comprises sparry calcite. The limestones are referred to typical grainstone, and no remarkable vertical and lateral changes in the rock type have been recognized. The limestone sequence of the pre-*Millerella* Zone is about 250 m in the Okubo area (ETO, 1967, fig. 9) although it includes tuffaceous shale beds in the lower part. On the other hand, the limestones of the *Millerella* Zone and the overlying two zones considerably vary in rock type from place to place, including reef limestone and poorly sorted packstone in addition to grainstone. The lateral change of limestone facies in the *Millerella* Zone is probably due to an environmental control caused by the development of reef-masses, as will be discussed later.

3. Brief note on stratigraphy and geologic structure of the Yowara area

The area dealt with in this paper is the eastern part of the Yowara (Yobara) limestone plateau which is separated by a narrow valley from the main Akiyoshi plateau (Fig. 1). The geologic map and profile of the area are shown in Figs. 2 and 3. The stratigraphic sequence of the limestones exposed in the area is as follows.

	zone	thickness
P_{III}	*Yabeina shiraiwensis* zone (with slate at the uppermost part) *Neoschwagerina douvillei* z. *Verbeekina verbeeki* z. *Neoschwagerina craticulifera* z.	40 m+
P_{II}	*Parafusulina kaerimizensis* z.	30 m+
$P_{I\beta}$	*Pseudofusulina ambigua* z. *Pseudofusulina vulgaris* z.	50 m+
$P_{I\alpha}$	*Triticites simplex* z.	60 m+
	unconformity	
C_{IV}	*Fusulinella biconica* z.	35 m+
C_{III}	*Profusulinella beppensis* z.	50 m+
C_{II}	*Millerella* sp. α z.	60 m
C_{I}	limestones without fusulinaceans (and basaltic pyroclastic rocks at the lowermost part)	130 m+

Fusulinacean zonation is based on TORIYAMA's scheme (1958). The limestones of the area are structurally very much complex, and belong to a part of an overturned limb (TORIYAMA, 1954a, pp. 89–90). They constitute an imbricated structure with overturned synclines and incomplete anticlines which were sliced by several subparallel, northwesterly inclined thrusts with moderate dips of 30° to 50°.

The geologic structure of this area was attributed from the zonal determination of beds by the contained fusuline fossils at 130 localities in addition to the drilling data.

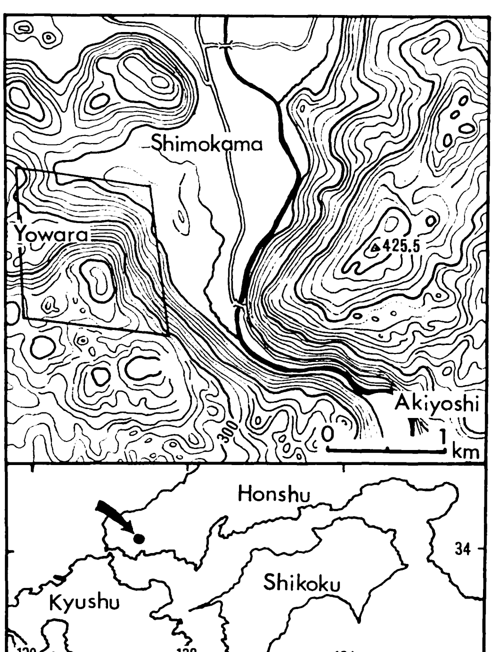

Fig. 1. Index map showing the surveyed area.

4. Description of bio- and lithofacies of the *Millerella* sp. α zone

General remarks.—The investigated limestone occupies an area of 370 m by 230 m in bench-cut quarries of the Sumitomo Co. Ltd., where outcrops were precisely inspected and

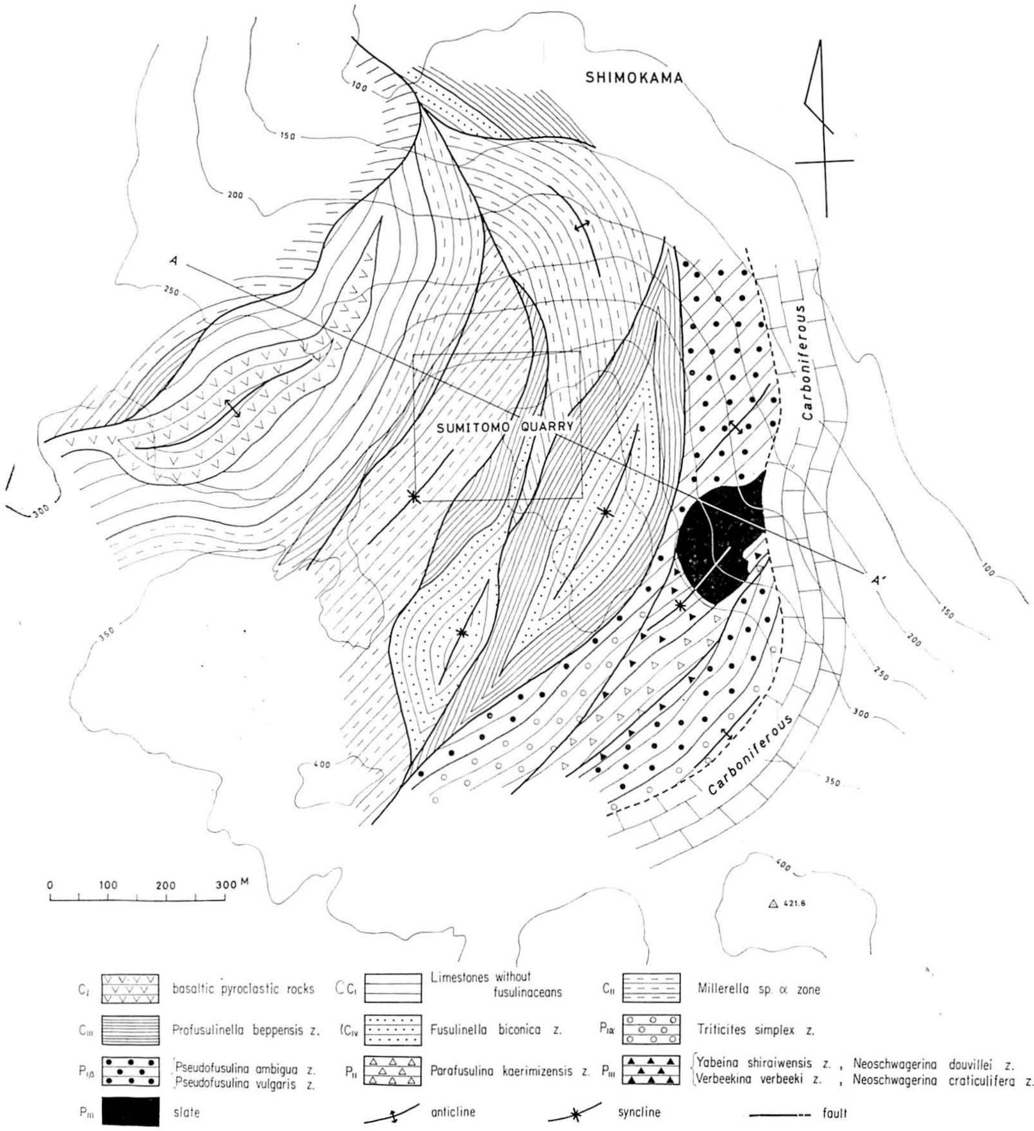

Fig. 2. Geologic map of the eastern Yowara plateau (By N. OTA, A. SUGIMURA, M. OTA and Y. MORINAGA).

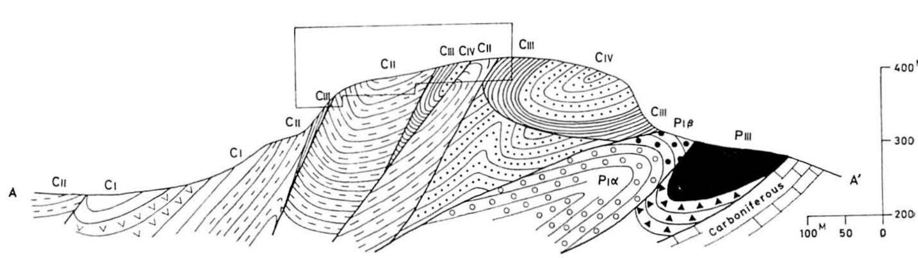

Fig. 3. A–A′ section of the eastern Yowara Plateau (By N. OTA, A. SUGIMURA, M. OTA and Y. MORINAGA).

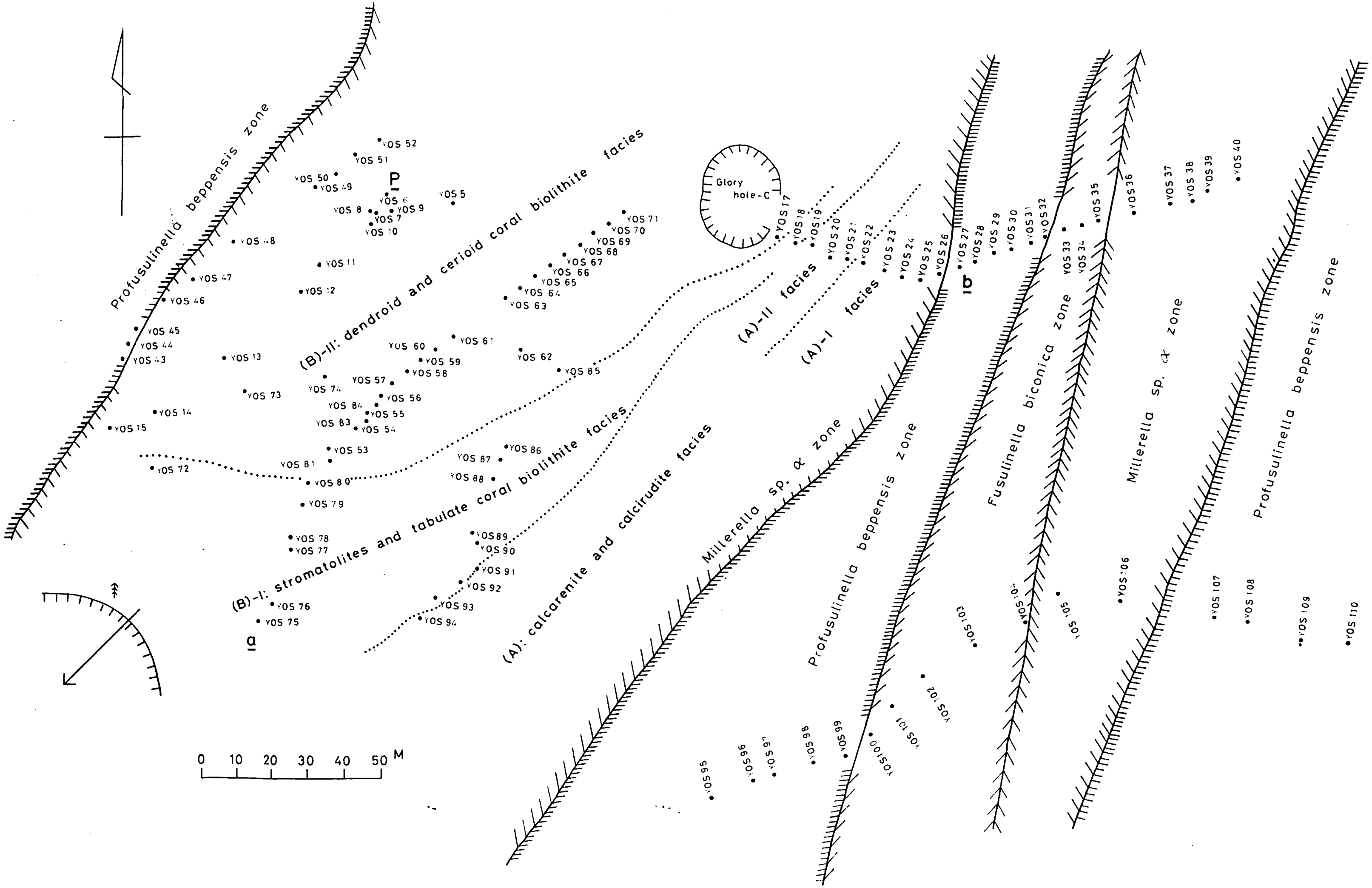

Fig. 4. Reef facies in the *Millerella* sp. α zone in the Sumitomo Quarry area.

numerous samples were collected. The samples were systematically collected at 5-meter intervals along several routes and supplimentary collections were made at random.

At least two thin sections were prepared for each of 110 samples. Their size is about 27 cm^2 (ca. 6 cm$\times$4.5 cm). Microscopic study was made by these thin sections to elucidate lithologic features, and volumetric analysis was made by a point counting method to get the quantitative data of the constituents.

On the basis of both the outcrop observation and the thin section analysis the limestone of this area is classified into the following two major lithologic facies, each of which is further subdivided into two subordinate facies:

(A) Calcarenite and calcirudite facies
- (A)-I : Facies mainly composed of well sorted skeletal grains
- (A)-II: Facies mainly composed of poorly sorted angular skeletal debris

(B) Reef limestone facies
- (B)-I : Stromatolites and tabulate coral biolithite facies
- (B)-II: Dendroid and cerioid coral biolithite facies

(A) Calcarenite and calcirudite facies

(A)-I facies

Main constituents of the limestone in this facies are crinoids, bryozoa, branching red algae and nigriporellids fragments. They are accompanied with foraminifers (*Millerella* sp. etc.). The crinoid ossicles are angular to rounded. Nigriporellids often encrust the crinoids, bryozoa and other fragments together with a large number of their own fragments of irregular forms. Bryozoan fragments are mostly those of fenestellids and acanthocladids. Fragments of branching red algae fill up the interspace among bryozoan and crinoid fragments. The tests of foraminifers are commonly broken. The ooliths which show clear concentric layers are also found sporadically. According to the scale of grain size of carbonate rocks by FOLK (1959, p. 56) these constituents range from arenite- to fine rudite-size. Along with crinoid fragments a large number of fragments of bryozoa and branching red algae significantly characterize this facies. Crinoid fragments are most abundant and come up to about 40% in several specimens of certain localities.

Most of the limestones of this facies are petrographically characterized by grainstone but some are assigned to other rock types. For example colonial mass of *Chaetetes* is observed at Loc. YOS 26.

The limestone of this facies is distributed in NE-SW direction and has width of about 25 m. Easterly it is overlain by the limestones of *Profusulinella* Zone.

(A)-II facies

The limestone of this facies is composed of angular fragments of stromatolites, *Chaetetes* and branching red algae (Pl. 2, Fig. 2), of which the last one is the most abundant. They range from medium arenite- to coarse rudite-size and are poorly sorted. The matrix is characterized by lime-mud which is probably finally disintergrated bioclasts. The distribution of the limestone of this facies is less extensive than the others and its width is about 15 m.

(B) Reef limestone facies

(B)-I facies

The limestone of this facies is composed of frameworks of stromatolites and *Chaetetes*, with interspaces filled by bioclasts. Cerioid rugose corals and fistriporoid bryozoa are also the minor elements of the frame-builders. The frame-building organisms are of various sizes. The largest colony which consists of both stromatolites and *Chaetetes* has the dimensions of 8 m length and 1.5 m width. *Chaetetes* colonies generally form sheet-like masses and are commonly vertically ramified. Stromatolites are usually associated with *Chaetetes* and similarly make a pattern of undulating sheet-form (Fig. 5). They often cover other frame-builders, forming superimposed sequences by themselves. The stromatolites are mainly composed of the "family" Spongiostromata. Interspaces among frame-builders are filled up with various kinds of bioclasts of arenite- to rudite-size. They are mainly fragments of nigriporellids, crinoids, bryozoa, foraminifers and brachiopod shells.

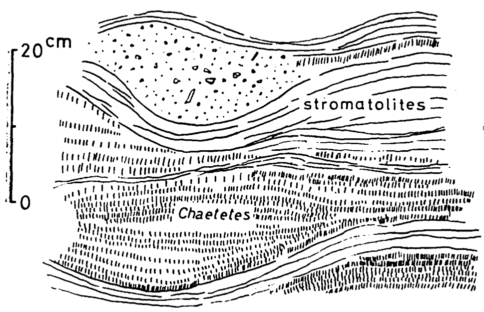

Fig. 5. Sketch showing the detail of alternate occurrence of stromatolites and *Chaetetes*. Locality YOS 72.

The distribution of the limestone of this facies decreases its width from southwest toward northeast with the largest width of 40 m. This character may be attributable to either the inequality of the width in a depositional environment or the modification by the later structural disturbance.

(B)-II facies

The limestone of this facies is composed of the frameworks mainly of dendroid corals (Pl. 1, Fig. 5; Pl. 3, Fig. 4), cerioid corals (Pl. 3, Fig. 3) and *Chaetetes* (Pl. 1, Fig. 3) with subordinate stromatolites. The hexagonellid bryozoa are found commonly as one of the framework builders, covering the coralla of the cerioid corals, but they are in a subordinate amount. *Chaetetes* forms large irregular, hemispherical colonies and does not take a sheet-like growth-pattern. The interspaces of the frameworks are filled up with debris of corals which are of the same group as those of the frame-builders. In addition there are debris of nigriporellids, crinoids, bryozoa, brachiopod shells and foraminifers. The taxonomic assignment of the particles smaller than fine arenite-size is hardly determined. The nigriporellids are more common than the crinoids as the constituents. The former is about 10 percent and the latter about 5 percent in volume. The nigriporellids are variable in form and some of them show encrusting form covering the debris of crinoids and corals. The crinoid fragments are abraded, being rounded to subrounded. The tests of foraminifers are usually more or less waterworn but some of them are nearly complete. *Komia* like algae is also commonly found.

Using the limestone of Loc. YOS 8, where dendroid corals are remarkably developed on the colonies of *Chaetetes*, the proportion between reef builders and the remainder was measured as follows. The dendroid corals and *Chaetetes* respectively occupy 8.3% and 11.8% in area of 0.58 m^2 ($58 \times 100\ cm^2$). The remainder accounts at 79.9%.

The limestone of this facies is distributed by the width of about 70 m and the length of 150 m.

5. Configuration of the facies

Fig. 4 is the generalized distribution map of the four types of facies described above. The map is indeed preliminary, because the examined localities are not sufficiently numerous due to the limited location of well exposed trenches, but it seems to give a general view of the palaeoenvironments in the Yowara area at the time of the *Millerella* sp. α zone.

The four types of facies are arranged in the order of (A)-I, (A)-II, (B)-I, and (B)-II. The boundary lines, which are still preliminary, are more or less oblique to the boundary of the biostratigraphic zones. In other words they may show the penecontemporaneous change of facies rather than strictly vertical change within the zone of *Millerella* sp. α. Structurally the area of facies (B) is on the axial part of a syncline.

The frequency data of various kinds of organisms obtained through thin section analysis are plotted in Fig. 6, which is taken along a profile connecting the points a,

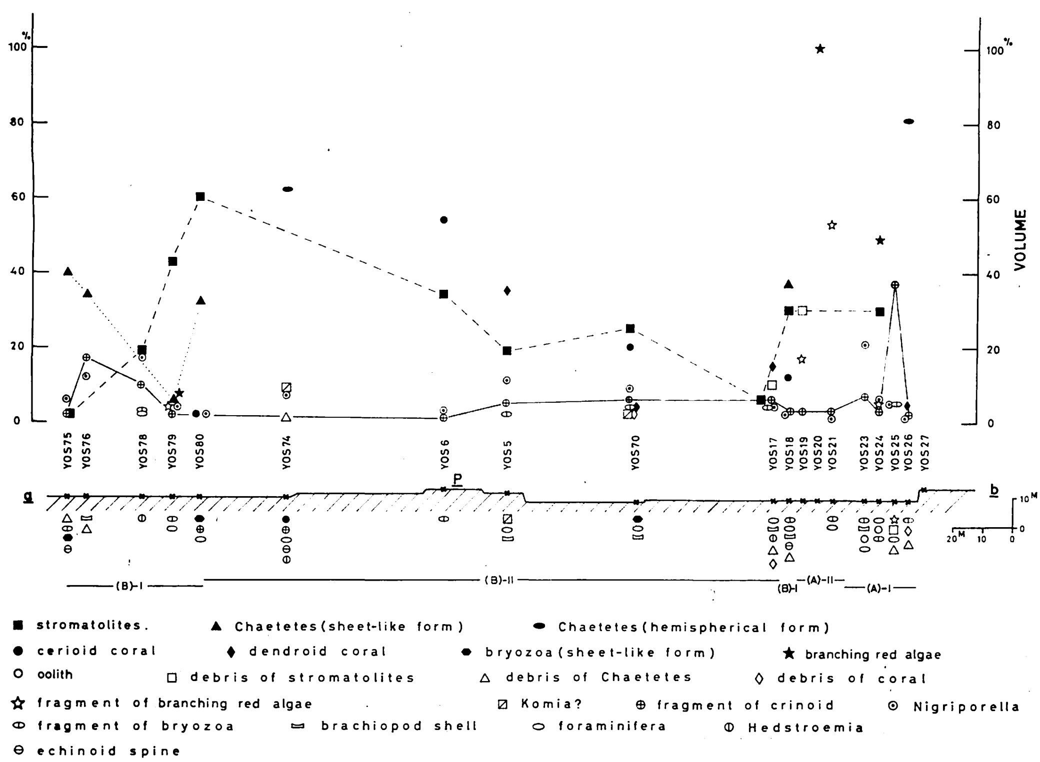

Fig. 6. Organic analysis of the reef deposits based on point counting method.

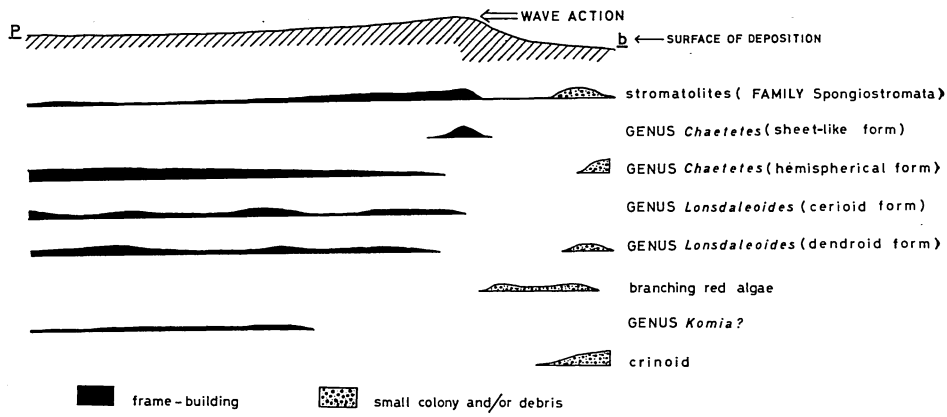

Fig. 7. Assemblage and relative abundance of reef-building organisms.

P and b indicated in Fig. 4. This is to some extent generalized in Fig. 7 and distribution of reef building organisms along the profile. The three figures, Figs. 4, 6, and 7, altogether show that the facies (B), which occupies the northwestern part of the *Millerella* sp. α zone, certainly indicates a reef* environment and that the facies (A), which is distributed in the southeastern part, probably represents the environment in front of the reef.

Stromatolites and the sheet-like formed *Chaetetes*, which are the reef builders of the facies (B)-I, have crusty forms. The crusty forms are one of the most important features of reef-building organisms. In the facies (B)-II dendroid corals play the important roles as reef-building organisms.

As is summarized in Figs. 6 and 7, crinoid fragments remarkably increase in number in the facies (A)-I, which was probably a niche of the crinoids. The local abundance of *Chaetetes* and other reef-building organisms in a portion of the (A) facies may need a special explanation. Possibly this could mean that they have been derived from the reef of the facies (B), since some of them occur as fragments, but small colonies may have existed in situ.

6. Summary of results

Generally speaking, the lithologic character of the Carboniferous limestones of Akiyoshi, Inner Zone of Southwest Japan, is grouped into two main parts, one is those of the pre-*Millerella* zone and the other those of the *Millerella* and the overlying zones. The former is represented by clean grainstone and the latter, on the other hand, is commonly characterized by dirty limestone, consisting of reef limestone, packstone and subordinate grainstone.

In the Sumitomo Quarry area in the eastern part of Yowara (Yobara) limestone plateau of the Akiyoshi district limestones of a reef facies are found. They are exposed in the area of about 100 m width and about 150 m length. Geologically the Akiyoshi limestone Group is strongly folded in this area. The limestone of the reef

* In this paper we use the term "reef" in the concept of LOWENSTAM (1950, p. 430).

facies is distributed in the *Millerella* sp. α zone and is located nearly at the axial part of a synclinal structure.

The limestones of the zone of *Millerella* sp. α are classified into four facies as follows.

(A) Calcarenite and calcirudite facies
- (A)-I : Facies mainly composed of well sorted skeletal grains
- (A)-II : Facies mainly composed of poorly sorted angular skeletal debris

(B) Reef limestone facies
- (B)-I : Stromatolites and tabulate coral biolithite facies
- (B)-II : Dendroid and cerioid coral biolithite facies

Among four lithologic facies, (B)-I and (B)-II facies clearly indicate the organic reef environment.

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Plates 1 – 3

Nobuki OTA, Akihiro SUGIMURA and Masamichi OTA

Reef Deposits in the *Millerella* Zone of the Akiyoshi Limestone Group

Explanation of Plate 1

Fig. 1. An outcrop of biolithite, (B)-I facies. Locality YOS 93.

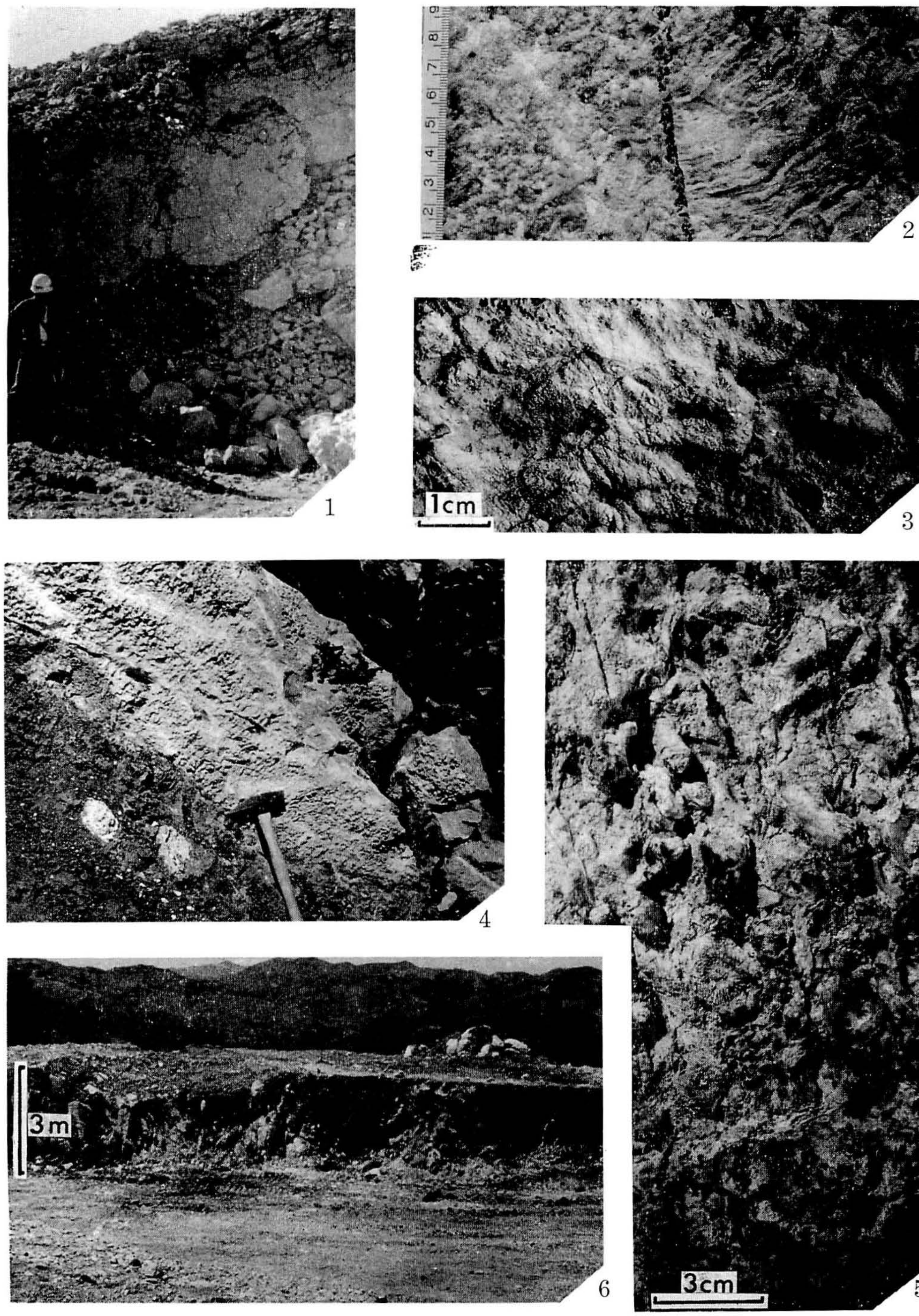
Fig. 2. Layered structure of stromatolites clearly exposed on the weathered surface, (B)-I facies. Locality YOS 87.

Fig. 3. A part of a colony of *Chaetetes* sp., (B)-II facies. Locality YOS 8.

Fig. 4. A part of a large colony of dendroid coral (*Lonsdaleoides* sp.), (B)-II facies. Locality YOS 5.

Fig. 5. Enlarged part of the weathered surface of Fig. 4 showing the occurrence of dendroid coral.

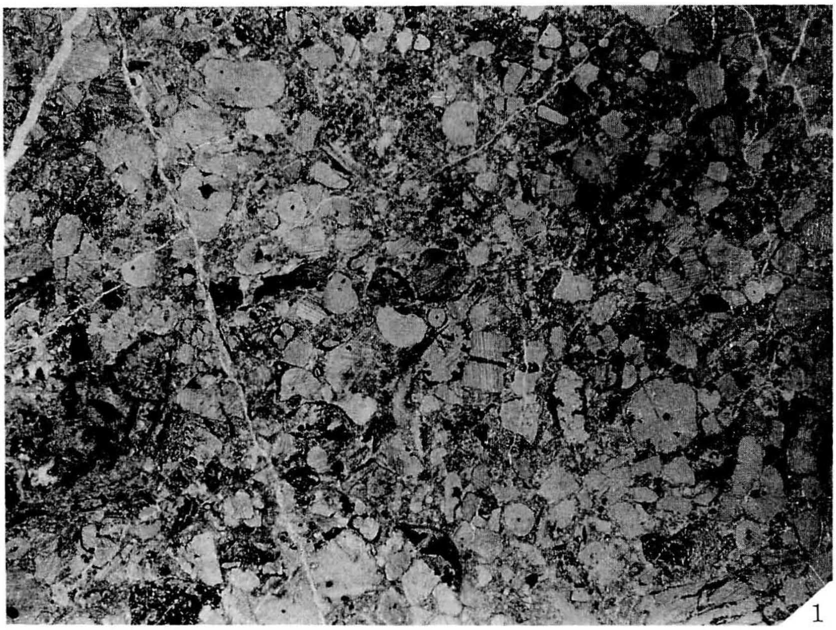
Fig. 6. Distant view of a quarry characterized by biolithite, (B)-II facies.



N. OTA *et al.*: Reef Deposits of the Akiyoshi Limestone

Explanation of Plate 2

Fig. 1. Crinoidal grainstone, (A)–I facies. Locality YOS 25. ×4.
Fig. 2. Branching red algae, (A)–II facies. Locality YOS 20. ×10.
Fig. 3. Packstone consisting of angular debris derived from reef, (A)–II facies. Locality YOS 19. ×4.



1

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N. Ota *et al.*: Reef Deposits of the Akiyoshi Limestone

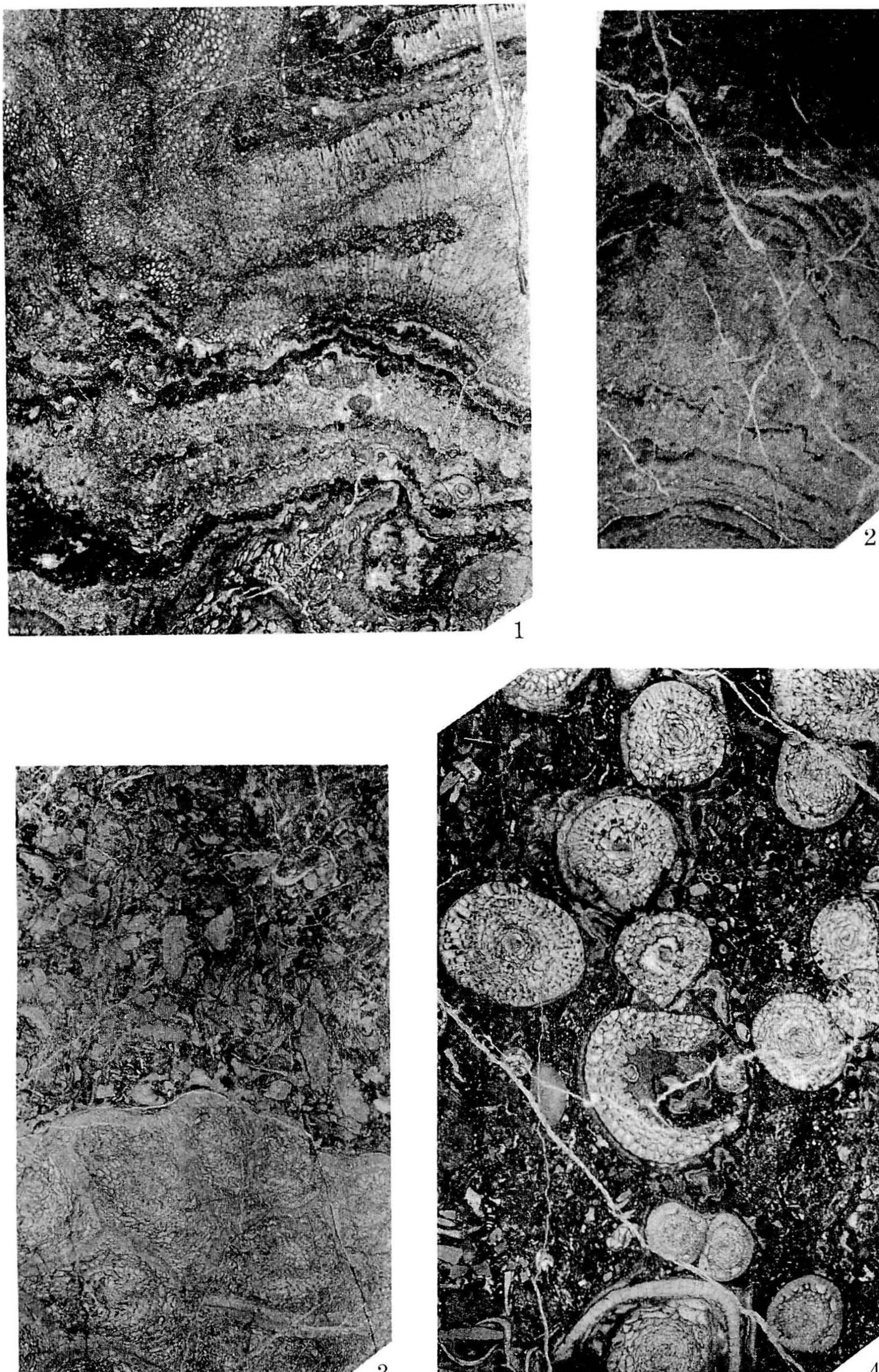
Explanation of Plate 3

Fig. 1. Stromatolites and sheet-like *Chaetetes* sp. developed on cerioid coral, (B)-I facies. Locality YOS 18. ×2.

Fig. 2. Stromatolites, (B)-I facies. Locality YOS 93. ×2.

Fig. 3. Cerioid coral (*Lonsdaleoides* sp.) and bioclasts filling the interspace, (B)-II facies. Locality YOS 81. ×2.5.

Fig. 4. Transverse section of a colony of dendroid coral (*Lonsdaleoides* sp.). Locality YOS 5. ×2.5.



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LITHO- AND BIO-FACIES OF PERMO-TRIASSIC GEOSYNCLINAL LIMESTONE OF THE SAMBOSAN BELT IN SOUTHERN KYUSHU

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1. Introduction

It is well known that very fine-grained limestone with abundant planktonic organisms is extensively developed in the Upper Jurassic and Cretaceous Systems of the Alpine Geosyncline which extend from the Circum-Mediterranean region to the Himalayas (STEINMANN, 1905; ANDRUSOV, 1950; COLOM, 1955; CUVILLIER, 1961; TRÜMPY, 1960; MISIK, 1966; GARRISON, 1967 and others). Similar limestones are also distributed in the West Indies, Central America (BRONNIMAN, 1952, 1955; COLOM, 1955, and others), and Indonesia (WANNER, 1940; COLOM, 1955).

They are comparatively thin, micritic or in part marly, commonly accompanied with chert or jasper, and contain abundantly planktonic microorganisms such as Radiolaria, Tintinnids, Globotruncanid foraminifers, Coccolithophorids and other microscopic algae, and also some smooth-shelled ammonites, etc. They have been considered to be deep-sea, essentially pelagic sediments.

Limestones of a similar facies are found in the Permo-Triassic Sambosan Group of the Outer Zone of Southwest Japan. They resemble in the general lithofacies to those of the Tethyan geosyncline, but they differ not only in geologic ages but also in the assemblage of microorganisms and accompanying rocks. One of the most remarkable differences is in their close association with volcanic sediments. In this respect they are similar to the Calera and Laytonville type limestones of the Franciscan Group of California.

This paper gives descriptions of litho- and bio-facies of the limestones of the Konosé Group in southern Kyushu, a representative formation of the Sambosan belt. An interpretation on the sedimentary environment of the group is also presented.

2. General accounts of the Konosé Group

Geological setting.—As shown in Fig. 1, the Sambosan belt is narrow but long (maximum 5 km in width, more than 600 km in extension, although in part tectonically discontinuous). Geotectonically it occupies the southern marginal part of the

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Chichibu terrain of the Outer Zone of Southwest Japan, which extends from the western extremity of Kyushu through Shikoku to the Kii Peninsula with NEE-SWW direction. Its northeastern extension appears in the Akaishi and Kwanto Mountains in central Honshu. To the south it extends to the Ryukyu Islands.

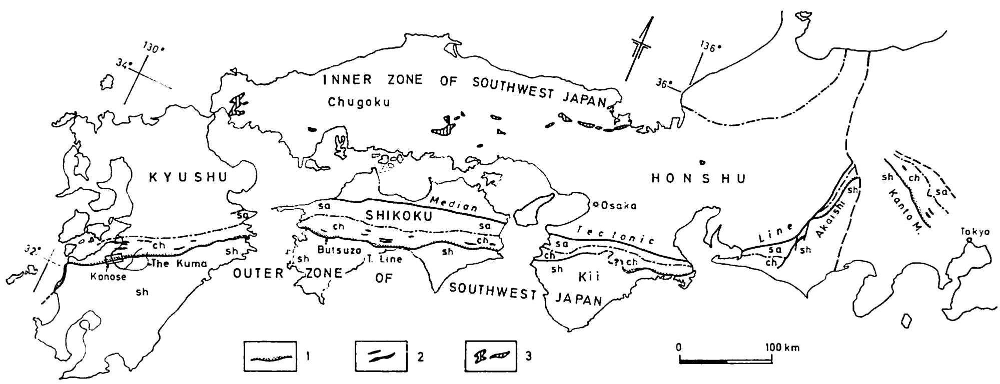
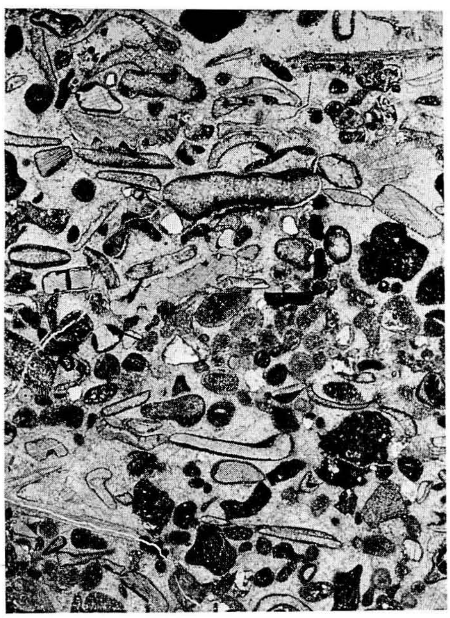


Fig. 1. Outcrop map of the Triassic sediments in Southwest Japan. 1, eugeosynclinal Sambosan facies in the southern margin of the Chichibu terrain (ch) ; 2, neritic facies in the northern and central parts of the Chichibu terrain of the Outer Zone; 3, neritic to deltaic facies in the Inner Zone.

The strata of the Sambosan belt are currently called the Sambosan Group (KOBAYASHI, 1941). The best display of the group is seen in the middle course of the Kuma river in southern Kyushu, where the group is locally called the Konosé Group. It is a thick conformable series (about 1300 m) of Upper Middle Permian to Upper Triassic, but the most of it belong to Triassic. So far as is known, it is the southernmost representative of the Permian and Triassic sediments in the Japanese Islands.

General sedimentary facies.—The lithologic assemblage of the Triassic part of the Sambosan belt is remarkably different from that of the coeval strata which are zonally distributed to the north of the belt (Fig. 1). The Triassic sediments of the northern and central parts of the Chichibu terrain to the north of the Sambosan belt are of a shallow neritic facies, composed of grey to dark-grey sandstone and shale with some small lenses of molluscan limestone in the Scythian, and grey sandstone and shale with some beds of intraformational conglomerate and some small lenticular bodies of sandy or clayey bioclastic limestone in the Middle and Upper Triassic. Those of the Inner Zone are of a shallow neritic to deltaic facies consisting of conglomerate, sandstone and shale in the lower series and a molasse type extremely thick, very coarse-grained, clastic sediments with some shale and coal seams in the middle and upper series, which contain shallow sea mollusks, estherians and fossil plants. They are almost devoid of volcanic material throughout the whole series, except for a few, locally intercalated thin beds of fine-grained acid tuff. Siliceous sediments are also entirely lacking.

In contrast to these, the Triassic strata of the southern zone of the Chichibu terrain, the Sambosan Group, are of a thick conformable series of eugeosynclinal lithologic assemblage characterized by a large quantity of volcanic breccia, tuff, tuff breccia, and lava of basaltic composition, a number of limestone bodies of various dimensions, and thin-bedded chert, with subordinately intercalated mudstone (converted to slate) containing lenticular thin beds of sandstone and cannibalic chert-conglomerate. Thus the Sambosan belt was the scene of submarine volcanic outburst during the Triassic times, particularly in the upper. The limestones occur mostly in association with volcanic sediments and consist of several lithologic types. The most predominant type is micritic limestone with abundant planktonic microorganisms and is distinctly different in litho- and bio-facies from that of the equivalent ages in the Inner Zone and the main part of the Chichibu terrain of the Outer Zone, which is, in turn, coarse-grained, sandy or clayey bioclastic and/or oolitic limestones mostly with a sparry calcite matrix (Fig. 2).



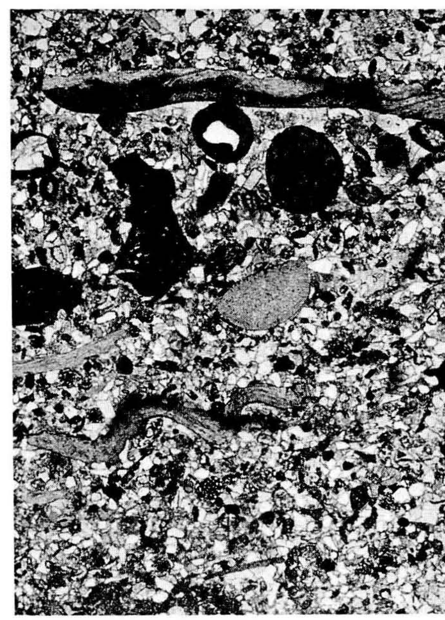


Fig. 2. Examples of Triassic limestones in the central part of the Chichibu terrain. Carnian Tanoura Formation in the lower course of the Kuma river, southern Kyushu. Left: Oolitic biosparite containing crinoids, algal debris, brachiopod shells and a few quartz grains. Right: Highly arenaceous biosparite containing abundant foraminifers, algal debris of various sizes, crinoids, brachiopod shells and a small amount of ooids (some of which are fragmentary). ×8.

Brief notes on the stratigraphy.—Before entering into the petrography of the limestones, the stratigraphy and general lithology of the Konosé Group is briefly given here. For details of the stratigraphy and palaeontologic descriptions of corals from the group the reader may refer to the previous papers (KANMERA and FURUKAWA, 1964; KANMERA, 1964).

The Konosé Group occupies a belt with the maximum width of 4 km, and is bordered, as in other areas of the Sambosan belt, on the south by the Butsuzo thrust against the Shimanto terrain consisting of Cretaceous and older Tertiary ages (Fig. 1), and on the north by another fault against the Carboniferous rocks. It is separated into the southern and the northern tract by a thrust which runs along the

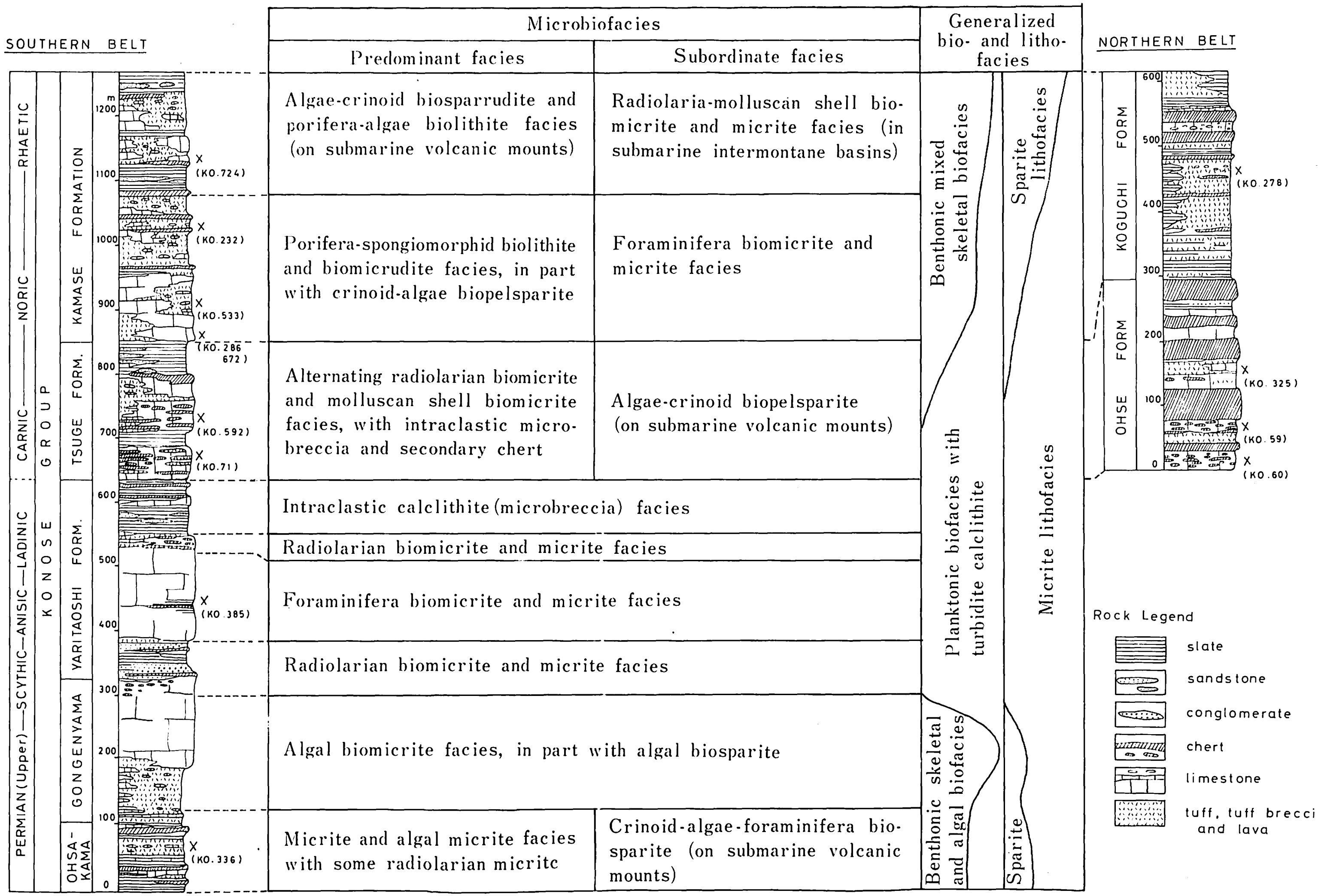


Fig. 3. Generalized stratigraphic sequence of the Konosé Group in the type section along the Kuma river and the summary of litho- and bio-facies of the limestones of the group. For the geological map of the group the reader may refer to the previous paper (KANMERA and FURUKAWA, 1964).

central part of the belt. Fig. 3 shows a generalized stratigraphic sequence and subdivisions in these two tracts, mainly based on the type section along the Kuma river.

On the fossil evidence (Fig. 3) the Konosé Group ranges in age from upper Middle Permian (*Yabeina globosa* zone) to Upper Triassic (probably to Rhaetian). Although the exact boundary between stages cannot be determined owing to scarcity of index species. Recent finding of conodont *Epigondolella abneptis* (HUCKRIEDE) (personal communication from T. KOIKE) from the Tsugé and Ohsé Formations confirms the upper Carnian age of the two formations.

As is shown in Fig. 3, the Konosé Group (1300 m thick) consists of two-fold lithologic assemblages. One is a set dominantly of basic volcanic sediments accompanied by many bodies of limestone, bedded chert of various thicknesses, and the other is that of mudstone (converted to slate) with some lenticular bodies of sandstone and cannibalic chert-limestone conglomerate. The latter is subordinate to the former and is intercalated as a wedge bed or in alternation.

Volcanic sediments occur at many horizons of the group, particularly in the upper Triassic part. They consist of dark reddish or dark greenish agglomerate, volcanic breccia, tuff breccia and tuff. Lavas are dark greenish augite basalt or dolerite, showing partly a pillow structure. They are mostly altered to spilite. The pyroclastic rocks mentioned above are characteristically calcareous and often contain a great number of lenticular bodies of limestone of various sizes, usually 50 m to 1 m in thickness. The lavas and breccias of the pyroclastic rocks are coarsely amygdaloidal and those which accompany limestone and chert in the same layer exhibit a palagonitized texture of primary basalt glass. The amygdales are filled mostly with calcite and sometimes zeolites. These volcanic matters are the products of submarine volcanism.

Sandstone includes two types: One is chert arenite consisting mostly of coarse- to medium-grained angular chert (>94% excluding the matrix) with a few amount

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List of fossils from the Konosé Group

Corals (by KANMERA, 1964):

Ko. 724—*Oppelismilia* ? sp.; Ko. 232—*Thecosmilia* sp.; Ko. 278—*Montlivaltia* cf. *norica* FRECH, *M.* cf. *stylophylloides* VINASSA, *Thecosmilia eguchii* KANMERA, *Elysastraea* ? sp.; *Procyclolithes* cf. *triadicus* FRECH, *P.* ? sp. aff. *P. timoricus* VINASSA, *P.* ? sp.; *Conophyllia* ? sp.; *Thamnastraea* (s.l.) *furukawai* KANMERA, *Th.* (*Th.*) sp.; Ko. 325—*Montlivaltia* cf. *timorica* VINASSA, *Volzeia konosensis* (KANMERA);

Ammonites (by KANMERA, 1964):

Ko. 533—*Cycloceltites* ? sp.; Ko. 385—*Balatonites* ? sp.

Fusulines (by KANMERA, 1964):

Ko. 336—*Yabeina columbiana* (DAWSON), *Neoschwagerina margaritae* DEPRAT, *Verbeekina* sp., *Schwagerina* sp.

Conodont (personal communication from T. KOIKE):

Ko. 592, 71, 59, 60—*Epigondolella abneptis* (HUCKRIEDE).

Calcareous algae (by ENDO and HORIGUCHI, 1967):

Ko. 278—*Petrophyton tenui* YABE, *Solenopora kumensis* ENDO and HORIGUCHI, *Pycnoporidium elongatum* ENDO and HORIGUCHI, *Nipponophycus kanmerai* ENDO and HORIGUCHI, *Diplopora* sp., *Stenoporidium chaetetiforme* YABE and TOYAMA.

Sponges, Stromatomorphids:

Ko. 286, 672—gen. et sp. indet.

of fine-grained, rounded quartz (<3%). It occurs as a lenticular bed less than 3 m in thickness usually at the same horizon as chert-comglomerate mentioned below. The other type of sandstone is grey to dark-grey quartzose wacke consisting of medium- to fine-grained, single or polycrystalline quartz, K-feldspar, plagioclase, microcline and perthite. The mineral assemblage of the main constituents and heavy minerals suggests acid plutonic rocks for the main source.

Conglomerate occurs as intraformational lenticular bodies usually of 1-2 m, rarely up to 4.5 m thick. It consists chiefly of angular pebbles and granules of chert (>80% excluding the matrix) with subordinate limestone and basic volcanic rocks, but locally contains abundant angular fragments of black mudstone, limestone or basaltic rocks. Its matrix is narrow and cemented by sparry calcite. The conglomerate merges laterally into mudstone with some isolated pebbles and granules of the same kinds or into the chert-sandstone mentioned above. The material of the conglomerate as well as of chert-sandstone are almost all common to the constituents of the Konosé Group, and they are considered to have been derived from geanticlinal uplifting areas within the same sedimentary basin by cannibalic contemporaneous erosion. In the Yaritaoshi Formation chert-conglomerate beds directly overly radiolarian limestone and may probably be referred to beds of slump masses.

Chert comprises about 10 percent of the total volume of the Konosé Group in the type section and occurs as a thin-bedded form and secondary nodules in limestone. Bedded chert is well stratified in commonly 2 to 5 cm thickness, variegated in colour, and is in part intercalated with a clayey parting (mainly illite). It is usually 10 to 20 m, rarely attaining 50 m in thickness and is extended for a long distance. It is made up of microcrystalline quartz and often contains abundant radiolarian tests and their debris. There are some massive chert mostly of white to brownish white colour which are composed of much crystalline, coarse mosaic quartz.

Chert in limestone occurs as a nodular, ribbon-shaped, lenticular or irregular form and usually shows an uneven boundary. The limestone containing chert of this type are almost always rich in radiolaria.

Detailed comments on the mode of occurrence, the lithologic features, the origin, the diagenetic processes and the epidiagenetic recrystallization of chert have already given in the previous papers (KANMERA, 1968; NAKAO, 1968).

3. Petrography of Limestones

Method of study and terminology of limestone.—Samples were systematically collected from limestones of the type section along the Kuma river. Supplementary samples were taken from the sequence along several other routes to see the lateral change.

More than 400 thin sections were prepared. Their size is various according to the lithologic features, and for the samples which contain large biogenic component the sections were made as large as 6×10 cms. In several cases two or more sections were taken from one and the same sample.

Microscopic observations were made on these samples to know the petrographic features of the limestones. Volumetric analysis of the constituents was made by a lineal analysing method.

The limestones here dealt with are generally more or less recrystallized. Electron microscopic study was preliminary attempted on apparently less crystallized aphanitic samples, but no ultramicroscopic organic elements such as coccoliths have been detected. Even if they were primarily contained, they have probably been vanished due to recrystallization. Therefore this study is entirely based on microscopic observation of less than 1000 times magnification.

Limestone classification and terminology essentially owe to FOLK's (1959, 1962) with some supplementary modifications.

General remarks.—Little attention has hitherto been paid for the limestones of the Sambosan belt on account of the so-called " non-fossiliferous " state. In fact they are rather poor in easily determinable megafossils and are predominantly very fine-grained. In this respect it is significant to study the petrography of the limestone.

In the Konosé Group several types of limestone are recognized, but the dominant type is very fine-grained aphanitic micrite. This type of limestone is particularly significant in the lower and middle part of the group. Especially the limestones of the upper part of the Gongenyama Formation and the Yaritaoshi, Tsugé and Ohsé Formations contain abundant planktonic organisms such as radiolaria, extremely thin-walled shells, foraminifers of a particular assemblage in a homogeneous micrite matrix. These limestones mostly occur as an extensive body as thick as 80 to 100 m and more than 20 km long within the surveyed area and are dark grey to black. They are assumed to be of fairly deep water sediments, as will be discussed later. The limestone rich in radiolaria is characteristically associated with secondary chert of nodular to irregular forms, and the contained radiolarian remains are completely replaced by sparry calcite.

In the upper part of the group, i. e. Kamasé and Koguchi Formations, occur also the micritic limestone of almost the same type as above, but more commonly the limestone containing benthonic megafossils such as calcisponges, spongiomorphids, crinoids, calcareous algae, some thick-walled gastropods and brachiopods, in a micritic or spar matrix. The latter type of limestones occur as lenticular bodies of various sizes (up to 70 m thick and 2 km long to only 50 cm thick and several meters long) in a thick pile of pyroclastic rocks and lavas. The constituents and lithologic features of these limestones indicate sediments in shallower environments on the ridges or the side slopes of submarine volcanic mounts. Furthermore in the upper part limestone-boulders or -blocks of various forms and sizes, ranging usually from 5 to 50 cm, sometimes as large as 2 m, are locally but not occasionally contained in unstratified, heterogeneous chaotic volcanic sediments (Fig. 8). Such angular blocks occur usually as swarms, sometimes scattered or isolated, and lithologically belong to sparrudite containing coarse debris of calcareous algae and reefal biolithite with abundant coralline algae and some compound corals. These limestone blocks and the enclosing volcanic sediments are referred to slump masses or blocks derived from the sediments of very shallow levels.

Thus the limestone of the upper part of the group includes several different lithologic types as exemplified by a radiolarian biomicrite on one hand and a reefal biolithite on the other. This fact indicates the difference of the depositional environments produced by a remarkable lateral change in the thickness of volcanic accumulation which must have provided a considerable topographic relief.

Throughout the Konosé Group neither oolitic nor fecal pellet limestones have been found, and either no admixture of sand- and silt-size terrigeneous material such as clastic quartz and feldspar can be detected. However microbreccia or intraclastic calclithite which is usually associated with radiolarian biomicrite as a kind of turbidite commonly contains volcanic rock fragments which show almost the same lithologic nature as those of the members of the group. Clay size terrigeneous material may be contained, but if present, it must be quite insignificant in all the samples collected. However, the black to dark grey micrite of the Yaritaoshi Formation contains an appreciable amount of carbon, and a small amount of illite, kaolinite and quartz.

In the following pages the lithologic features and microbiofacies of the limestone rock-type are described.

A. Micrite group

1) *Homogeneous micrite.*—This is grey to dark grey, consisting of homogeneous microcrystalline calcite without significant coarse bioclasts (Pl. 4, Fig. 5). Microcrystalline calcite crystals are uneven, blocky or interlocking, ranging in size mostly from 4 to 8 microns. There are in patches amoeboid coarser, recrystallized mosaics of 10 to 12 microns (Pl. 4, Fig. 6), which have intricate boundaries.

This type is common in the thick main limestones of the Gongenyama and Yaritaoshi Formations and also found in the Tsugé and Ohsé Formations.

2) *Fossiliferous micrite and biomicrite.*—Fossiliferous micrite implies the limestone which contains fossil grains less than 20 percent of the volume of a given sample in a predominantly micritic matrix, and biomicrite is used for that with more than 20 percent fossil grains in the matrix of the same kind. They are, thus, artificially classified by the quantity of the contained fossils and bioclasts, but have no essential difference in litho- and bio-facies. Emphasis is to be placed primarily on the kinds of the contained fossils.

a) *Radiolarian micrite and biomicrite.*—These are white grey to grey, composed of microcrystalline calcite and characteristically contain radiolarian remains (Pl. 5, Figs. 1-3). In some samples the contained radiolaria are innumerable, attaining as much as 50 percent (radiolarian biomicrite), but in many others less abundant, being usually 5 to 20 percent (radiolarian micrite). Matrix is the same as the homogeneous micrite mentioned above, consisting of mosaic calcite smaller than 10 microns.

In most cases the radiolarian tests are completely replaced and filled by sparry calcite, having lost detailes of their original structures. Therefore the specific identification of them is hardly done, but their molds suggest that they include Archipillicae, Cenodiscicae and Liosphaericae.

The limestone of this type is almost always associated with secondary chert of a nodular or small lenticular form or of irregular band-shape. The silica of the radiolarian tests was removed by the replacement of calcite in early diagenetic processes and formed chert nodules or bands in the limestone. The processes of chert formation has already been discussed in the writer's previous paper (KANMERA, 1968).

Examples are found in the upper part of the Gongenyama and the Yaritaoshi Formation, the Tsugé, Ohsé and Koguchi Formations.

b) *Molluscan shell micrite and biomicrite.*—These are grey to dark grey, often constitute a distinct bed thinner than 15 cm, usually 2 to 7 cm, containing a great number of thin shells and their fragments as much as 20 to 40 percent of a given sample (shell biomicrite; Pl. 6, Figs. 1-6). Occasionally fragmentary shells are so densely swarmed as to attain 60 percent (Pl. 6, Fig. 2). Radiolarian remains are common, occasionally so abundant as to occupy quantitatively nearly equal to the shells. Shell micrite with scattered shells are also commonly found. Matrix consists of microcrystalline calcite smaller than 12 microns.

The contained shells are extremely thin or filamentous, mostly 15 to 20 microns in thickness; the thickest one attains 40 microns, the thinnest less than 10 microns. They are more or less fragmentary, of various sizes, but usually 3 to 5 mm in length, rarely over 7 mm. They are mostly disposed parallel to each other and two valves of individuals are often detached.

Shell micrite and biomicrite are so packed and hard that the shells cannot be separated to free specimens. Therefore they are hardly identified with any accuracy, but at least four types of shell form can be discriminated: flat equivalves; slightly convex-concave, nearly equivalves; flat convex inequivalves; thickly convex, comparatively thick-walled ones. The first (Pl. 6, Figs. 4-6) may be referable to a pelecypod such as *Halobia*, *Daonella* or *Bositra* (=" *Posidonia* ") and is very similar to the *Halobia* shells of the Triassic limestones of British Columbia illustrated by DANNER (1965): the third (Pl. 6, Figs. 1, 3) to a monotid such as *Otapira*; the second and the fourth to other pelecypods. Besides them ostracod shells are occasionally found. Some shell beds show a grading in terms of shell-size.

These form almost always thin bedded alternation with radiolarian micrite and biomicrite described in (a). Examples are found frequently in the Tsugé and Ohsé Formations, less commonly in the Yaritaoshi and Koguchi Formations. More detailed mode of occurrence is mentioned in later pages (p. 30-31, Fig. 6).

c) *Foraminifera micrite and biomicrite.*—In general foraminifera are not common in the Konosé Group, but the major part of the main limestone of the Yaritaoshi Formation and some beds of the Kamasé Formation are composed of foraminifera micrite and biomicrite (Pl. 4, Figs. 1-3). The former is characterized by fairly abundant *Aulotortus* (=*Angulodiscus*) sp. and extremely small and elongate *Frondicularia* sp. As they are mostly replaced or filled by sparry calcite, detailes of their internal structures are largely obliterated. Their contents are usually as much as 5 to 20 percent, rarely 50 percent, and besides them there are not a few completely crystalline, indeterminable foraminifera-like particles (usually 5 to 15%). Associated with them are contained tiny thin-walled shells, probably of ostracods, a few crinoid ossicles and echinoderm spines, and indeterminable sparite-filled bioclasts. Crinoid ossicles are smaller than 0.7 mm in size.

Matrix is mostly microcrystalline mosaic calcite, but is in part recrystallized to more than 20 microns.

d) *Algal micrite and biomicrite.*—They are characterized by preponderance of algal debris and micritic matrix (Pl. 7, Figs. 5-7). The algal debris are generally subrounded to subangular, ranging in size mostly from 0.2 to 1.5 mm, rarely up to 2.5 mm. Not a few of them internally show a definite algal structure consisting of bundles of well-defined tubules, but many others only show faint vestiges of algal filaments or entirely micritic texture. All gradations from the former to the latter are recognized. This change corresponds to what is known as grain diminution (ORME and BROWN, 1963; WOLF, 1963 and others) or degradational recrystallization (FOLK, 1959; DUNHAM, 1962; ORME and BROWN, 1963). Small grains tend to be completely diminished and can be referred to algal pellets of WOLF (1965). In the samples which have a recrystallized microsparite matrix algal grains are sometimes internally recrystallized to coarse sparry mosaics, leaving a micrite rim.

They are a dominant rock type of limestones of the Gongenyama Formation, most part of which are referred to algal biomicrite (Pl. 7, Figs. 5, 6). Algal debris are mostly those of codiaceans, commonly as much as 25 to 50 percent, occasionally up to 65 percent of a given specimen.

Matrix is composed of fine-grained particles of the same kind as algal debris and microcrystalline calcite which may probably be disintegrated products of algal films.

e) *Porifera micrite and biomicrite.*—This consists mainly of skeletons of calcisponges and spongiomorphids (?) and micritic matrix (Pl. 8, Fig. 2). In not a few samples skeletal components occupy 30 to 60 percent of a given sample and are disposed commonly in roughly parallel or upward radiating growth pattern or superimposed sequences. Interspaces are filled with micrite, generally with a few, scattered fine-grained crinoid debris, micritic pelletoid lumps, foraminifers, and some other indeterminable particles. As it is difficult to clearly distinguish skeletal part from interspace fillings on weathered surfaces of outcrops, it cannot be decided whether or not they have primarily constituted frame-works of limestone at their living sites at the time of deposition. In other samples poriferan skeletons occupy 20 to 50 percent, and are disposed haphazardly. Interspace fillings are mixed biomicrite containing poriferan debris, spine-like tubules filled with sparite, pelletoid micritic lumps of various shapes and sizes, and some crinoid debris and foraminifers.

The calcisponges and spongiomorphids are largely recrystallized or replaced by coarse-grained sparry calcite, partially leaving their original structures, so that it is difficult to determine their definite specific names.

Limestones of this type are found in the lower and upper parts of the Kamasé Formation, and the first type is dominant in the lower and the second one common in the upper.

Further remarks on micrite and micrite matrix.—Very fine-grained, aphanitic or structureless limestones are certainly not a single origin as already discussed by WOLF (1965a, b), WOLF and CONOLLY (1965), FLÜGEL (1967) and some others.

The micritic limestone of the Konosé Group, described above, is unfortunately more or less recrystallized into relatively coarser, more or less equigranular mosaic calcite and/or solution-welded amoeboid unequal mosaics (FISHER *et al.*, 1967), but many of them may have primarily been more fine-grained than they are seen at present. The unsettled question is whether they were originally accumulations (lime-ooze) of nannoplanktonic microorganisms or they were mechanically abraded fine-biogenic detritus or a chemical or biochemical minute precipitates of calcite or aragonite needles including "algal dust" (WOOD, 1941).

The micritic matrix of algal biomicrite exclusively consisting of algal debris of the Yaritaoshi, Kamasé and Koguchi Formations is probably made up of disintegrated fine particles of algal films, and that of algae-porifera biomicrite and other micritic limestones containing various kinds of bioclasts in the latter two formations may be a mixture of fine-grained biogenic detritus. On the other hand the homogeneous micrite and the micritic matrix of radiolaria, shell, and foraminifera biomicrite and micrite are apparently more uniform in texture than in other types of micritic limestone, and may contain chemically precipitated calcite or aragonite and nannoplanktonic microorganisms. These micrites are, however, so fine-grained that the fabrics such as their size, shape and arrangement of the constituents cannot be precisely resolved by ordinary light microscope.

It has been well known since STEINMANN (1925) that the micritic limestones of the Alpine geosyncline of the Mediterranian-Alpine region and Central America and the chalk of West Europe and North America contain abundant pelagic nannoplanktonic fossils such as coccolithophorids and their discrete particles. The coccolithophorid limestones of these regions are of Middle and Upper Jurassic, Cretaceous and Cenozoic ages, but it has been uncertain whether coccolithophorids were flourished also in the Triassic and older ages. Recently FISHER *et al.* (1967, p. 25, figs. 76, 77, 79-82) have found particles which show a coccolith-like outline in some Norian limestones of the Hallstatt facies of Austria.

The writer has attempted electron microscopic studies on several aphanitic micrite of the Konosé Group, but no signs of coccoliths have obtained. At the present, therefore, definite conclusions regarding the genesis of the micrite in question cannot be given.

B. Biosparite and biosparrudite group

Limestones of this group mostly occur in the Kamasé and Koguchi Formations of the upper part of the Konosé Group as lenticular bodies of various sizes. They consist predominantly of biogenic or skeletal debris with a sparry calcite matrix. They are rather limited in the kinds of constituents and are microscopically grouped into some rock-types according to the assemblage and prevalence of constituents.

1) *Algal biosparite and biosparrudite.*—These consist of abundant algal debris and micritic particles of arenite (0.1-2 mm) and rudite (>2 mm) size and a rather wide matrix (Pl. 7, Figs. 1, 2, 4). Algal debris mostly belong to codiacean and solenoporacean algae and in part show a grain diminution. Micritic particles seem to have been originally algal remains, because faint vestiges of a thalloid structure are not uncommonly recognized. They are varied in shape and size. In some samples rounded ones are common, but even in such a case they are not so uniform in shape and size as ooids or fecal pellets. Some others commonly contain short tubular, ovoid or subrounded particles which have a micritic outer rim and sparite or pseudosparite fillings. These are also referred to algal remains. Algal debris combined with the micritic debris attain as much as 40 to 65 percent of a given sample.

Associated biogenic remains are crinoid ossicles, echinoderm spines and small foraminifers. Of these crinoid ossicles are rather common, as much as 2 to 5 percent in a few samples, but usually less than 1 percent. Others are very few.

Matrix, mostly 35 to 60 percent of a given specimen, is composed of medium- to fine-grained mosaic calcite. But when the interparticle space is relatively wide (mostly in algal biosparrudite), sparite matrix is commonly made up of fibrous calcite which is arranged perpendicular to the wall of particles.

In most of algal sparite and biosparrudite, secondary idiomorphic quartz-crystals are developed often showing double- to multiple-layered zonal structure. In some samples they occur abundantly. They mostly occur within micritic debris, but some of them transect adjoining debris or a debris and sparite matrix. It is not clear from what part silica of these diagenetically produced quartz crystals have been derived. A remark to be mentioned here is that such secondary quartz is quite rare or absent in the algal micrite mentioned before, notwithstanding the contained algae belong to the same or similar groups.

2) *Algae-crinoid biopelsparite*.—The contained grains are composed of well-sorted micritic to very fine-grained pseudosparitic pellets and subordinate crinoid debris (Pl. 7, Fig. 3). Brachiopod shell fragments are rarely found. The matrix is medium-grained sparry calcite.

The pellets include at least three kinds. One is of dark, structureless micrite; another less dark, slightly coarser micrite with a darker rim; and the rest recrystallized fine-grained pseudosparite leaving a dark rim. All gradations can be recognized from the first to the third type. They are mixed together haphazardly in the same section. They are not uniform in shape, usually a subspherical, ellipsoidal, discoid or a platy shape and range usually from 0.1 to 0.5 mm in size, occasionally up to 0.8 mm. They attain 40 to 50 percent of a given sample and the associated crinoid less than 10 percent.

They may not be of the same origin, but not a few of them are probably algal debris which were subject to "grain diminution". Actually the pellets of the second type occasionally show faint vestiges of a thin thalli-like structure similar to that of codiacean algae, and some sections contain, besides the above mentioned pellets, larger grains which show an apparent algal structure. These approach the algal biosparite in texture and constituents.

C. Biolithite group

This is represented in the Konosé Group by the coralline algae-porifera biolithite. Its frame-builders are solenoporacean, spongiostromatan calcareous algae, calcisponges and some scleractinean corals (Pl. 8, Figs. 1, 3-5). Many of the algal bodies show a digitate or humpy upward radiating pattern, or overlapping or superimposed sequences, or occasionally an anvil-like form. Poriferan colonies also show a similar growth form. Attached to them, small bunches of codiacean algae, and serpulid (?) warm tubes are commonly found.

The interspace fillings greatly vary from part to part. In some parts they are fine-grained, fairly well-sorted, but in many other parts coarse- to fine-grained and poorly sorted. Narrow pocket fillings often show a rough lamination which meets at right to large angles with the wall of the frame-builders, sometimes leaving a sparite filled void above the pocket fillings. The interspace fillings are mainly composed of algal debris and " pellets ", subordinately of debris of crinoids, sponges, corals and brachiopod and gastropod shells. Algal oncolites are abundantly found in part. Besides these interspace fillings, there are not uncommonly void fillings which are composed of fibrous calcite oriented perpendicular to the wall of frameworks and predeposited interspace sediments. In some sections void fillings show two phases of generation, the first is the growth of fibrous calcite which have grown perpendicular to the void wall and the second is that of the filling of volcanic or carbonate sediments (Pl. 8, Fig. 4). This fabric indicates that the fibrous calcite was formed penecontemporaneously with the growth of the frame-builders and that the limestone under consideration was deposited as a rigid reefal mass.

Besides the above mentioned void fillings, there are a number of patchy cavities which are filled with mosaic sparry calcite. They are disharmonious to the surrounding sediments and very much irregular in size and shape, and are considered to be solution-and-secondary filling by diagenetic processes.

D. Intraclastic limestone group

1) *Microbreccia* (fine-grained calclithite).—The alternating beds of the above mentioned radiolaria biomicrite, molluscan shell biomicrite and nodular to banded chert are characteristically accompanied by limestone of microbreccia or microclastic structure.

The microbreccia consists of obviously intraclastic, subangular to angular or irregular shaped, mostly sand-size grains or breccias of limestone of several kinds, and includes three varieties (Pl. 5, Figs. 4-6). The most common type has a wide and rather heterogeneous micritic matrix and contains abundant breccias of radiolarian biomicrite with some thin-walled shells, and common crinoid ossicles, some tests of a thick-walled nodosariid, and a few echinoderm spines, sponges and fragments of calcareous algae. It is interesting that not a few of the radiolarian micrite breccias have a partial outer cover of a thin convex shell (Pl. 5, Fig. 6). This demonstrates that the convex shell worked not only as an easily detachable plane along its outer surface for brecciation but also as a shield from further fragmentation and that the brecciation had taken place before the radiolarian micrite was consolidated to a hard rock. The breccias range in size from 0.5 to 2 mm.

Another less common type of microbreccia has a little matrix and consists of medium- to coarse-grained lumps of limestone with a pseudosparite matrix, some of which contain coralline calcareous algae or crinoid ossicles. The breccias range in size from 0.2 to 1 mm, and they are usually in stylolitic contact.

Another rare type has a coarse-grained pseudosparite matrix and contains almost exclusively dense and sharply angular breccias.

The micritic and/or radiolarian micrite breccias mentioned above are very similar to or almost the same in the texture and fossil assemblage as the non-brecciated main limestone of the same and lower horizons, although it is impossible to identify their original stratigraphic position on account of the lack of fossils which show definite ages. The breccia which has a sparite matrix and crinoids, algae, lumps and so on as the main constituents cannot be considered to have deposited in the same or nearby environments as the micrite mentioned above, but is probably the sediments of shallower depths. The microbreccias under consideration also often contain angular fragments of basic tuff and volcanic fragments of a similar size to the limestone breccias (Pl. 5, Fig. 5), but have no land-derived detritus such as quartz and feldspar. Many of the microbreccia beds exhibit a grading in grain size. These facts suggest that the microbreccias are probably a kind of turbidites which have been brought by submarine slumping of the contemporaneous and penecontemporaneous sediments at shallow depths probably on the flanks of submarine volcanoes and have been mixed with micritic sediments at deeper places where the radiolarian and planktonic shell micrites were deposited.

2) *Megabreccia* (coarse-grained calclithite).—In volcanic sediments of the Kamasé and Koguchi Formations there are some lenticular bodies or tongues of coarse limestone breccia of several to 30 m thickness. The contained breccias greatly vary in size, being pebbles in a part and boulders in another part. They are those of coralline algal and lumpal sparite, crinoid lumpal sparrudite, mixed skeletal biosparite, intrasparite, etc. Besides them isolated crinoid ossicles are not uncommonly found. Many of the individual breccias have a sparite or pseudosparite matrix. The breccias are of remarkably uneven angular shape and commonly in stylolitic contact along which dark reddish tuffaceous or ferruginous film is formed. They are entirely chaotic in most parts, but show a roughly stratified structure in some parts, usually in the case of fine-grained breccia.

The matrix which fills interspaces of breccia is usually very narrow in pebble-size breccia beds, but wider and very much uneven in coarser ones. It consists largely of dark reddish volcanic matter containing angular fragments of altered amygdaloidal basalt and basaltic tuff, and in part of coarse-grained sparry calcite.

These breccia beds merge laterally into tuff breccia and tuff which also often contain isolated or chaotic limestone blocks or breccias of various sizes, usually 30 to 50 cm, sometimes more than 1 m across (Fig. 8). The isolated breccias have a sharp boundary to the surrounding volcanic rocks and consist of crinoid-lumpal biosparite, algal biosparite and biosparrudite, coralline algal intrasparrudite with some brachiopod shell debris, algae-spongiomorphid biosparrudite, algae-coral biosparrudite, etc. They have a sparite matrix and are almost the same in lithology and biogenic constituents as that of the main breccia beds.

The lithologic features and constituents of the megabreccia and isolated blocks suggest that the breccias were originally of shallow water sediments including those of a reef facies. They are probably talus deposits or submarine slump masses which were derived from sediments deposited on the flanks or ridges of submarine volcanoes which reached near the sea level. It should be noted here that no micrite breccias such as radiolarian micrite have been found in the megabreccia. This suggests that the megabreccia did not reach so deep places as the radiolarian micrite deposited.

4. Litho- and bio-facies of the Konosé Limestones

The limestones of the Konosé Group include several different kinds as mentioned above and are, unit by unit, represented by a certain kind or a particular assemblage of two or three kinds. In the following pages the general and diagnostic features of the limestone facies of individual formations are summarized with interpretation of the sedimentary environments.

1) *Osakama Formation* (80–150 m).—This formation consists of black slate, chert, basic tuff, tuff breccia and lenticular limestone. The limestone of the lower part is radiolarian micrite with nodular to thin lenticular bands of chert. That of the upper part is also micrite without discernible biogenic constituents. However, a tuff breccia bed of the middle part locally contains blocks (huge boulder to granule size) of biosparrudite consisting of fusulinaceans (*Yabeina* and *Neoschwagerina*), small foraminifera (mostly thick-walled archidiscid), and algal and crinoid debris. In addition there occur lenses of microbreccia composed mostly of sand- to granule-size breccia of micrite and radiolarian micrite with admixture of algal biopelsparite and chert.

Thus the limestone of the formation is characterized by micrite, but include some penecontemporaneous allochthonous slump masses, some of which have mixed with radiolarian micrite. The depositional environment is presumed to have been along a submarine volcanic belt which have provided some topographic uplift in a fairly deep submarine trough. The fusulinacean biosparrudite and algal pelsparite were formed in a shallow water on such volcanoes and were redeposited en block by slumping into a deeper place where micritic limestones were predominantly deposited. A similar sedimentary framework is well exemplified in the upper formations mentioned below.

2) *Gongenyama Formation* (80–200 m).—This consists mainly of a very thick limestone which is accompanied locally by moderately thick beds of tuff breccia and basic lava (spilite), with some lenticular limestones in the lowest part and nodular thin bands of chert in the uppermost part and a chert bed at the top.

The main limestone is massive, grey to white grey and dominantly algal micrite and biomicrite, with homogeneous micrite and algal biosparite at some horizons (Fig. 4). The contained algae are mostly codiaceans. In the recent sea the codiacean algae flourish in the photic zone, usually up to 50 m deep, although the maximum recorded depth is 120 m (LEMOINE, 1942 in KONISHI, 1961) and their debris can be delivered to bottoms of deeper water. As the contained algae are mostly very much fragmentary and smaller than 1 mm in size, they must have been transported for some distance from their living places. Besides the algal remains, very small crinoid ossicles (<1.5 mm in size; <0.1% in volume), small foraminifers, highly cellular sponges, and small, filamentous shells probably of ostracods are rarely found at some horizons of the lower part. The matrix is for the most part micrite. Thus the contamination of primarily thick skeletal remains are quite rare and if present they are very small and fragmentary. The limestone containing nodular chert in the uppermost part is characterized by homogeneous micrite in the lower and by radiolarian micrite and biomicrite described in A-1 and -2a of the preceding chapter in the upper, and is accompanied in part with some filamentous shell fragments and sponge spicules.

The limestone under consideration are entirely massive, neither stratification plane nor laminae are discernible. These facts suggest that the main limestone was deposited in an off-shore or pelagic environment in the water depth below the wave

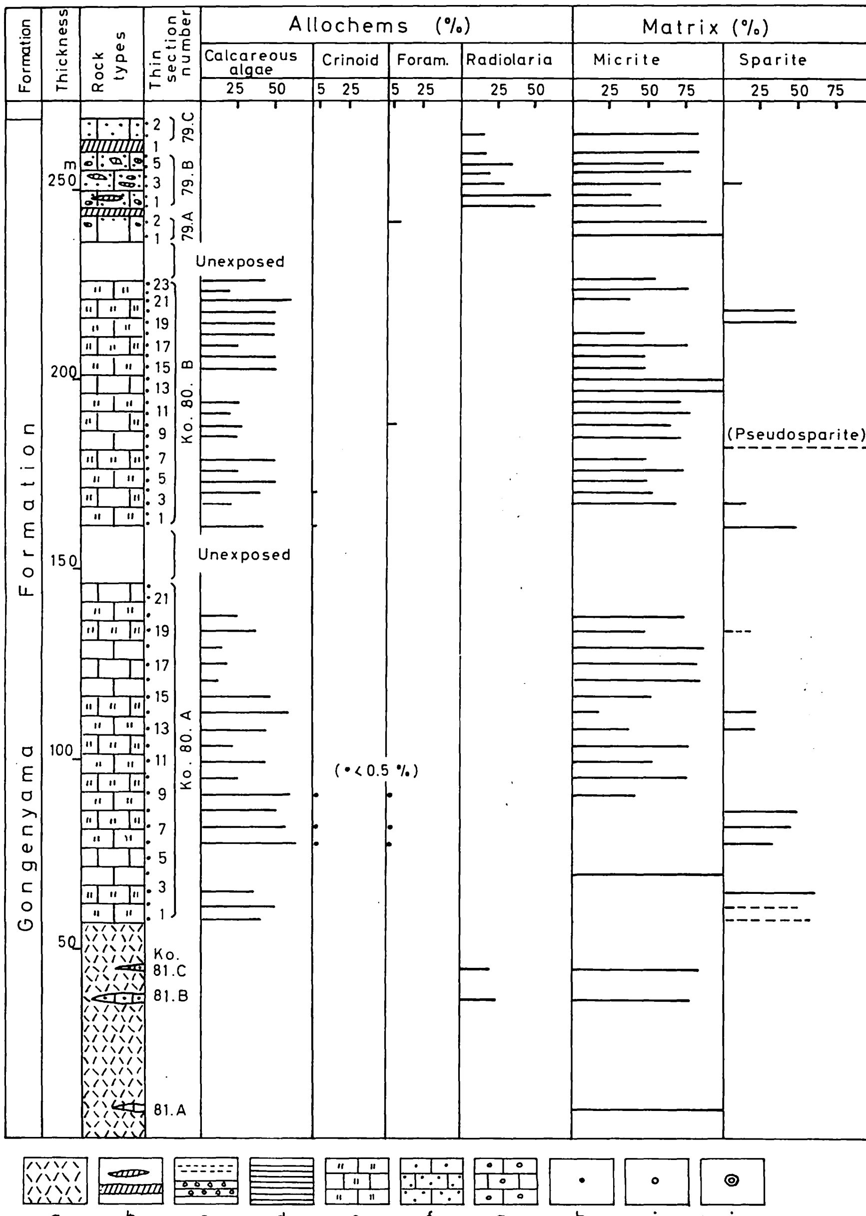


Fig. 4. Constituent diagram of the limestones of the Gongenyama Formation. a, basic volcanic sediments including tuff, tuff breccia, volcanic breccia and lava; b, chert; c, conglomerate (chert-limestone breccia) and sandstone; d, black slate; e, algal limestone; f, radiolarian limestone; g, foraminiferal limestone; h-j, volume of content of fossils and bioclasts, less than 0.5%, 0.5~1%, 1~2%, respectively.

base where heavy skeletal grains could not reach but only porous algal debris of a relatively small specific gravity and planktonic organism were delivered and that the depositional environment became deeper in the upper part than in the lower part.

3) *Yaritaoshi Formation* (230-300 m).—The formation is subdivided into three members: Lower member (Y_1, 20-60 m) mainly of black slate with some beds of chert

conglomerate and sandstone; Middle member (Y_2, 80–170 m) of dark grey to black, thick, massive limestone partly with thin bands of slate and chert in the middle part and with nodules and bands of chert in the upper; Upper member (Y_3, 60–90 m) mainly of black slate with some lenses or beds of black limestone and chert.

The thick limestone of the middle member consists mainly of foraminifera micrite and biomicrite in the lower part and of foraminifera-radiolarian and radiolarian micrite in the upper (Fig. 5). Homogeneous micrite which are devoid of bioclasts are found at some horizons. The contained foraminifera (*Aulotortus* and *Frondicularia*) and radiolaria are largely or completely replaced and filled with sparry calcite. Most of them are complete in outline and fragmentary specimens are extremely rare. In association with them there occur not a few, small subspherical particles which are almost completely replaced by sparry calcite. Their outline and faint vestiges of a cellular structure demonstrate that they are probably foraminifera. Besides them, crinoid debris are found at many horizons but they are small (<1 mm in size) and very much fragmentary. Echinoderm spines are rarely met with. So far as the collected samples are concerned, these skeletal grains, including some other indeterminable ones, never exceed 0.5 percent of the total volume of a given sample, but in only one bed of the upper part there occur fairly abundant thick-walled pelecypods and gastropods, and crinoid ossicles (in total about 5%). Calcisphere-like small

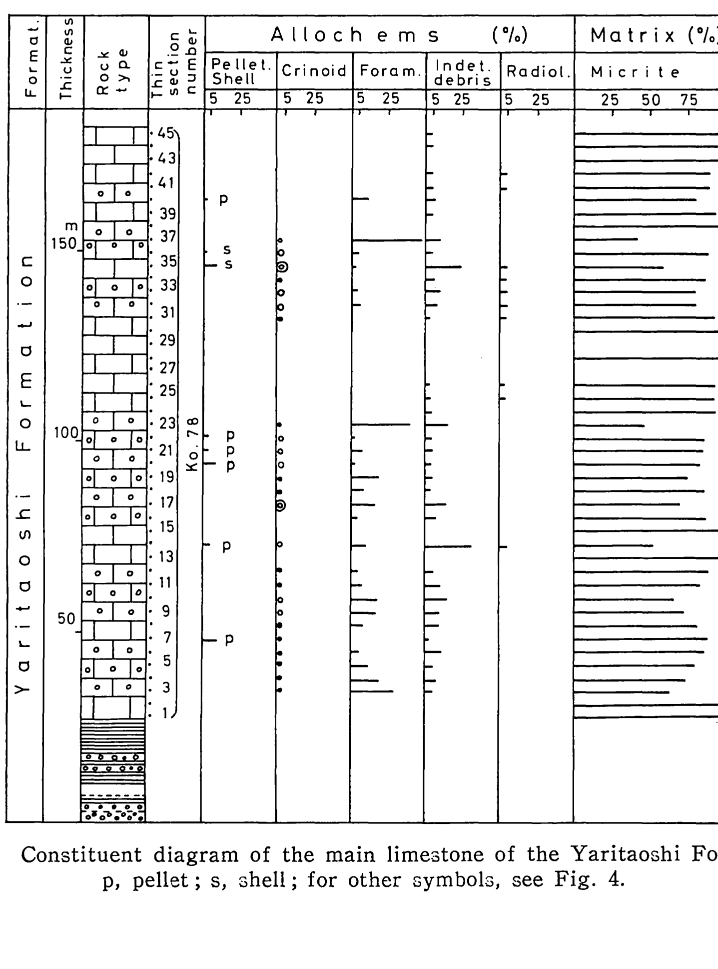


Fig. 5. Constituent diagram of the main limestone of the Yaritaoshi Formation. p, pellet; s, shell; for other symbols, see Fig. 4.

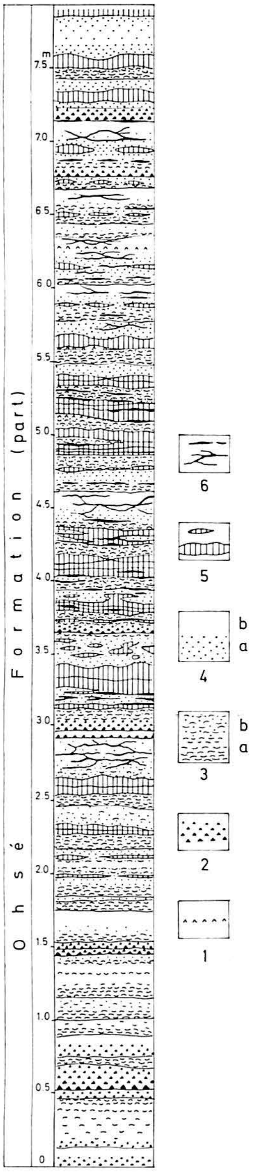
spherical particles which have a dark, thin micritic outer rim and sparry calcite fillings are found in a few beds. Biogenic remains are embedded haphazardly in the matrix. The matrix consists of microcrystalline calcite mostly of 6 to 10 microns in size and partly is recrystallized to mosaic calcite of 12 to 20 microns. It occupies more than 80 percent of the total volume of a given sample. Thus the limestone under consideration is characterized by micrite with a restricted microfossil assemblage. There is no remarkable vertical change in lithologic features and constituents. It is massive throughout the thickness of about 100 m except for a locally developed, 2 m thick sooty black, laminated, highly carbonaceous micrite with abundant ammonite shells (*Balatonites* ? sp.) in the middle part. These litho- and bio-facies indicate that the limestone is pelagic deposits accumulated in a relatively deep quiet environment and that the limestone was not affected at the time of deposition by appreciable bottom currents.

In the upper member limestone occurs as lenticular bodies of 2 to 10 m thick at a few horizons in a dominantly shale sequence. That of the lower part is calclithite consisting of intraclasts of granule- to silt-size. The intraclasts are those of micrite, algal biomicrite and pelmicrite, radiolarian biomicrite, shell micrite and chert, accompanied with a few isolated crinoid debris. In some bodies the matrix is wide and comprises lime mud, but in some others it is very narrow and the grains are often in stylolitic contact. The calclithites of the lower part contain pebbles of chert-bearing radiolarian biomicrite and chert. Their matrix is lime mud, and commonly contains radiolaria, sponge spicules and thin molluscan shells. The intraclasts under consideration all exhibit almost the same lithologic features and biogenic assemblages as the limestones of the upper part of the middle member of the Yaritaoshi Formation. This fact suggests that the intraclasts were derived by local cannibalic erosion of the older or the penecontemporaneous beds within the same depositional area.

4) *Tsugé Formation* (200–300 m) and *Ohsé Formation* (200–300 m).—The Tsugé Formation comprises four members of two assemblages of sediments in alternation: the first (T_1) and the third (T_3) member in the type section along the Kuma consist of limestone with frequent intercalations of chert of nodular, lenticular, or irregular forms and with some beds or partings of red tuff. These sequences change laterally westward into agglomeratic volcanic breccia, tuff breccia and lava with some small lenticular or blocky bodies of limestone; the second (T_2) and the fourth (T_4) are black slate with some lenticular bodies of sandstone.

The Ohsé Formation in the northern belt, which is correlated with the Tsugé Formation, comprises at least five thick beds of chert alternating with limestone, which, in turn, is often accompanied with bands and nodules of chert and with some beds of tuff and tuff breccia, as in the Tsugé Formation.

The limestone of the above mentioned interlacing limestone and chert sequence is, as well as other examples, composed characteristically of radiolarian micrite and biomicrite and thin molluscan shell biomicrite with some intercalations of microbreccia. To understand the mode of occurrence of these rocks an example of their sequence in the lower part of the Ohsé Formation is shown in Fig. 6. The bed (9 m) lies on a tuffaceous microbreccia (2 m), which is underlain by a dark reddish calcareous tuff with some small lenses of tuffaceous microbreccia in the upper part, and is



succeeded by a massive brownish white chert bed. As shown in Figs. 6 and 7, it comprises alternating beds of radiolarian biomicrite or micrite, shell biomicrite and chert, and is accompanied with microbreccia in the lower part. In addition, a dark reddish or greenish tuff partings (thinner than 1 cm) may be intercalated between a shell biomicrite and chert. In the bed under consideration there are 34 layers of shell biomicrite and at least 17 layers of microbreccia. A set of succession of radiolarian biomicrite, shell biomicrite and chert in ascending order is most common. A microbreccia, if present, usually underlies a shell biomicrite.

←— Fig. 6. An example of alternating succession of radiolarian biomicrite and molluscan shell biomicrite with some beds of microbreccia and many beds or nodules of secondary chert. Lower part of the Ohsé Formation. Loc. Ko. 59, 800 m north of Ohsé along the highway no. 219. 1, lapilli tuff; 2, microbreccia; 3a, filamentous molluscan shell biomicrite; 3b, radiolaria-molluscan shell biomicrite; 4a, radiolarian biomicrite; 4b, homogeneous micrite; 5, chert; 6, dolomite. Chert and dolomite are of secondary origin produced by diagenetic processes.

Fig. 7. An exposure of alternating beds of radiolarian biomicrite and molluscan shell biomicrite shown in Fig. 6.

The lithologic features of the limestone of the above mentioned three kinds are already noted (p. 20, 21, 25), but some remarks is given here regarding chert. Chert is mostly milky grey to light brownish grey and occurs as a lenticular or bed-form, being roughly parallel to the shell biomicrite beds, but sometimes nodular to irregular, and obliquely intersects the overlying and/or underlying beds. It is essentially a product of secondary replacement of limestone by silica derived from the contained radiolaria and other siliceous organic remains in the early diagenetic processes (see KANMERA, 1968). The limestone and chert are also commonly in stylolitic contact along which dark brownish fillings are developed. Furthermore along and near the boundary zone there commonly occur veinlets or disseminated crystalls of coarse-grained euhedral dolomite, which is also of a diagenetic product.

There is no need to dwell upon the planktonic nature of radiolaria. With respect to the mollusks of the shell biomicrite, the extreme thinness, extraordinally swarmed or packed occurrence of the shells and their common association with radiolaria suggest that they are of a planktonic habit. The microbreccia bed is most coarse-grained at the bottom and often shows an upward grading with a sharp uneven boundary with the underlying radiolarian biomicrite or shell biomicrite. This fact and the lithologic features of the microbreccia suggest the turbidite origin of this kind of limestone sequence under a fairly deep sea environment.

As mentioned above the limestone and chert sequence under consideration merges laterally westward into the volcanic and tuff breccia sequence. The mode of lateral change of lithofacies and lithologic assemblage between the two coeval sequences is well exemplified in the third member (T_3) of the Tsugé Formation as shown in the writer's previous paper (KANMERA, 1968, fig. 1). The lenticular or blocky limestones contained in the thick pile of volcanic sediments in the western area are composed of algae crinoid biosparite and biomicrite, which suggest a primarily shallow water origin. Going eastwards the limestones assume a more elongate lenticular to bed form with intertongues of volcanic sediments and become more micritic with gradual increase of the contents of radiolaria and thin shells. Assuming that the basal bed of this member was in the same level at the time of deposition, the relative height between the level of the western volcanic sediments area and that of the eastern limestone and chert area is measured about 80 m in the distance of 2000-2500 m. Although there exists a remarkable difference in litho- and bio-facies of the limestones of the two areas, the above mentioned fact suggests that the limestones of the Tsugé Formation are not deep water deposits, but shallow water one, at most not more than 300 m (see chapter 5).

5) *Kamasé Formation* (400-500 m) and *Koguchi Formation* (200-320 m).—The Kamasé Formation of the southern belt comprises four members: the first (200-300 m) and the third (80-150 m) of dark green to dark reddish agglomeratic tuff breccia, lapilli tuff and lava with many lenticular bodies of limestone of various thickness and extent, some beds of chert and a few thin intertongues of slate; the second (40-100 m) and the fourth (50-70 m) of black slate with some lenses of sandstone. The Koguchi Formation of the northern belt is correlated with and is in lithologic assemblage and facies quite similar to the Kamasé although it is fairly different from the latter in the detailed stratigraphic succession as shown in Fig. 3. The volcanic sediments of these formations contain, besides the intercalated lenticular bodies of limestone, some beds of megabreccia and a number of isolated limestone blocks of a boulder to cobble size.

The lenticular limestone of the lower part of the Kamasé Formation is predominantly composed of poriferan biomicrite containing abundant calcisponges and some spongiomorphids (?). In many sections taken from the limestone a digitate or roughly parallel, or upwardly radiating growth pattern of the spongeframe work is recognized. In such a part interspace fillings are micrite with only a small amount of fine-grained debris of crinoids, pelletoid micritic particles and some other indeterminable sparite-filled remains. These features indicate that the limestone under consideration contains a considerable amount of framework constituents which accumulated at their living sites in a quiet water environment, where there were no significant bottom currents and agitation of water.

Besides the poriferan biomicrite, pelletoid lumpal micrite, foraminifera (*Frondicularia*) biomicrite, micrite containing a few skeletal debris and fine indeterminable sparite-filled particles, and crinoid-algal pelsparite are also met with.

In the middle part of the Kamasé Formation poriferan biomicrite is again found, but the contained porifera are mostly fragmentary and haphazard in disposition. The common kind is micrite with a few fine bioclasts including calcareous algae, crinoids, foraminifers, radiolaria and pelletoid micritic particles. The last is occasionally very abundant in some limestones.

The limestones of the upper part of the Kamasé Formation are generally of smaller dimentions than those of the underlying formations and are mostly referred to algal biosparite, algal biosparrudite, and crinoid-algal pelsparite.

In the Koguchi Formation limestone occurs at one horizon in the lower part and at a few levels in the upper. That of the lower part is micrite with a small amount of crinoids, foraminifers, and pelletoid micritic particles. Those of the upper part contain radiolarian biomicrite, shell micrite at one horizon, and crinoid-algal pelsparite and algal biosparite at others.

Thus the limestones of the Kamasé and Koguchi Formations are again predominantly micrite and biomicrite and subordinately biosparite in some part. Compared with those of the underlying Tsugé, Ohsé and Yaritaoshi Formations their biogenic constituents are much mixed and the matrix is more heterogeneous. The occurrence of calcisponges, spongiomorphid (?), calcareous algae, large crinoid debris and well-sorted pelletoid particles and the association of biosparite suggest their deposition in a shallower water environment than the underlying formations.

Another important fact to be mentioned is the common occurrence of megabreccia limestone and isolated limestone blocks in the middle and upper part of the Kamasé Formation and the upper part of the Koguchi Formation (Fig. 8). They sporadically occur in a thick pile of volcanic sediments, particularly at its sidewise thinning parts. Megabreccia consists angular limestones of various sizes ranging from a boulder- to granule-size. The limestone includes abundant algal biosparite, crinoid-algal biosparite, pelletoid or lumpal intrasparite, and some oosparite. Isolated limestone blocks also vary in size, usually 5 to 50 cm, occasionally more than 1 m, and are mostly composed of algal biosparite, crinoid-algal pelsparite and also algae-poriferan biolithite. The corals described by the writer (KANMERA, 1964) and calcareous algae by ENDO and HORIGUCHI (1967) were obtained from some of these blocks from the Kamasé and Koguchi Formations. The majority of the limestone breccia and isolated blocks are primarily of the shallow water origin including some reefal sediments. They are considered to have been derived by submarine sliding or slumping from a shallow place probably on the summits or the side slopes of submarine volcanoes.

The volcanic sediments greatly vary in thickness. The variation of the thickness, which may reflect that of relative height of the volcanic mounts, is related with the lateral change of the volcanic sediments from coarse-grained ones (volcanic breccia or tuff breccia) to fine-grained ones (lapilli-tuff) or further to shale. It is measured

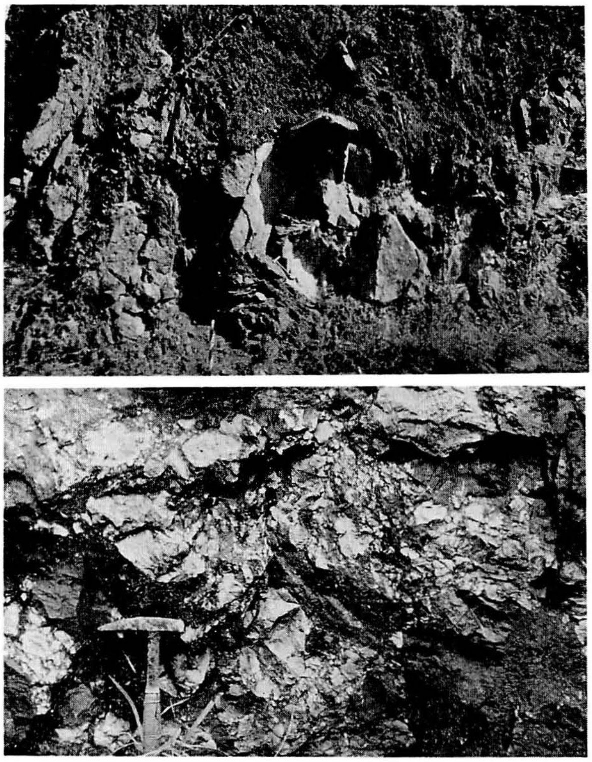


Fig. 8. Exposure of isolated limestone blocks in volcanic sediments in the upper part of the Kamasé Formation. Loc. Ko. 61, 600 m north of Ohsé along the highway no. 219. Above: isolated limestone blocks (large one about 1.5 m in size) in chaotic basaltic tuff; Below: limestone breccias in basaltic tuff breccia. These limestone are mostly algal biosparrudite and biosparite.

100–150 m in a distance of 500–700 m in some samples and 200–300 m in that of 1500–2000 m in others, resulting in general slopes of 10–20°. The rapid lateral changes in the thickness and facies of the volcanic piles signify a remarkable difference of the depth of water in a short distance between a volcanic sea-mount or island and an intermontane furrow or basin. This is accompanied with the difference in litho- and bio-facies of the limestones, which are actually shown by radiolaria-, pelagic shell-, and foraminifera-biomicrite on one hand, and algal biosparite and reefal biolithite containing coralline algae, calcisponges and compound corals on the other.

To sum up, the limestones of the Konosé Group are the deposits within and along a submarine volcanic belt which was situated far off from the coast of a mountainous land and are predominantly composed of micrite and biomicrite, but show a considerable vertical and lateral changes in biogenic constituents. The variations of litho- and bio-facies of the limestones are eventually related to the submarine volcanism which could, according to the intensity of its activity, give rise to a considerable topographic relief, in other words, the variation in the depth of water and accordingly that of currents under which the limestone were deposited.

The limestones of the middle part of the group which are independent of volcanic sediments are distributed extensively and composed dominantly of micrite and biomicrite characterized by an appreciable amount of planktonic organisms and/or foraminifera of a particular assemblage and a wide homogeneous micrite matrix. Furthermore thin beds of intraclastic microbreccia which often show a graded bedding are locally associated with them. These features suggest a pelagic, fairly deep water deposition.

On the other hand, the limestones of the lower and the upper part of the group are closely associated with basic pyroclastics and lavas and are discontinuous and lentiform. They are predominantly micrite, but include a considerable number of bands and laminae of biosparite and pelsparite. Many of the micrite contain benthonic megafossils commonly of mixed assemblages. The matrix is heterogeneous and often shows evidence of the sorting by currents. Besides the above mentioned, there are some beds of biomicrite characterized by planktonic fossils, more or less contaminated with fragmentary remains of benthonic organism. In addition, there sporadically occur fairly numerous masses of limestone megabreccia and isolated limestone blocks which were primarily originated in shallow water on the ridges or side slopes of submarine volcanoes and were displaced into deeper water through the action of submarine slides. They are particularly common in the upper part which contains thick piles of volcanic sediments.

Thus the litho- and bio-facies of the limestones of the lowest and the upper part, particularly of the latter, greatly vary in accordance with the site of deposition which is either on the ridges or side slopes of submarine volcanic uplift or islands, or instead adjoining intermontane basins.

5. Depth of submarine volcanism and sedimentation

As mentioned above, many bodies of limestones of the Konosé Group occur in close association with submarine volcanic sediments and lavas. The nature of submarine volcanism must be governed by the physical conditions at the site of eruption or emplacement. One of the important factors influencing the nature of volcanic activity is the pressure at various depths below the sea level.

With respect to the depth of water in which the limestones in question were deposited we can also refer to a recently introduced knowledge on the vesicularity of pillow lavas as a depth indicator. According to MOORE (1965) and JONES (1969), submarine pillow basalts show a systematic vertical change in the abundance and size of vesicles, and those collected from progressively deeper water contain fewer and smaller vesicles. Although further data are needed for assurance, the vesicle size and abundance can be related to inferred depth of water at the site of emplacement of lavas at the time of consolidation. In the dredge samples of basalt pillow lavas from the submarine part of the east rift zone of Kilauea volcano, Hawaii and the Iceland interglacial pillow lavas, the vesicularity of more than 1 mm in diameter and more than 5 percent in volume are almost confined to the lavas in the depth shallower than 500 m.

In the Konosé Group there occur fairly numerous beds of amygdaloidal basalt, although a pillow structure is not distinct in most of them. The amygdales are often as large as 1 mm or more in diameter and more than 10 percent in volume. In addition there are a number of beds of volcanic breccia and tuff breccia containing large blocks or bombs which are also highly amygdaloidal and apparently exhibit a concentric structure with a chilled rim. No systematic studies on the vesicularity of basaltic bombs and breccias in the submarine pyroclastic rocks have been made, and the vesicle size and abundance of them do not necessarily give a measure of the depth of emplacement, but it is considered that the relation is not much different from that in the case of submarine lava flow, because the bombs cannot be brown up so high as in the subaerial condition due to the resistance of water.

Another point to be considered in relation to the nature of submarine volcanic activity is whether the explosive eruption which produces pyroclastic rocks could be possible or not in the deep sea floor. On this respect McBIRNEY (1963) concluded, from the examination of the volumetric expansion of vesiculating water vapor at temperatures and pressures corresponding to those of basaltic and rhyolitic magmas erupting under various depths of sea water, that the explosive ash formation is unlikely at depth greater than 500 meters. Volcanic eruption at deep sea floor probably gives rise to quiet extrusion of lavas on the floor so as to make a sea mount of lavas with hyaloclastites on their surfaces by the chilling effect of cold water or intrusion into soft sediments as sills.

Further systematic investigations are needed with respects to the features of modern submarine volcanic sediments and physical factors influencing the nature of volcanic activity at various depths below sea level before the valid interpretation on features of ancient submarine volcanic products is achieved. It is, however, highly probable that the basaltic lava and pyroclastics of the Konosé Group were erupted and settled at the depth of water shallower than 500 m so far as the available factors are taken into consideration.

Another remark to be given in connection with the depth of water is the occurrence of megabreccias and blocks in the upper formations which consist of algal biosparrudite, algae-porifera-coral biolithite of a reefal facies and other similar rock-types. As mentioned before, they are considered to be slump masses or blocks originated from a very shallow environment on submarine volcanoes, and some of them are found along with radiolarian- and planktonic shell-biomicrite which were probably accumulated in the deeper intermontane basins among submarine volcanic mounts. The volcanic sediments greatly vary laterally in thickness. The thickness of the exposed volcanic accumulations does not necessarily indicate the real maximum thickness of them, which, in turn, approximately indicates the minimum height of the volcanoes at the time of eruption. So far as their exposures are concerned, the thickest part of a single volcanic series which contain the reefal biolithite blocks and/or algal biosparrudite in their flanks attain 100 to 350 m. As the reefal biolithite must had been deposited at and/or near the sea level, the largest depth of water at the time of deposition are estimated to be approximately not more than 350 m. This depth of water is not inconsistent with the deposition of porifera-spongiomorphid biomicrudite and other kinds of limestone.

In short, the depth of water in which the limestones of the upper part of the

Konosé Group were deposited was not so great as the ocean floor or deep sea trench of the present days, and the radiolarian, foraminiferal, and planktonic shell biomicrite of the lower and middle part were probably formed at depths not much different from that of the upper formation.

Limestones of the Konosé Group is very similar to those of the Franciscan Group (Upper Jurassic-Cretaceous) of western California not only in the lithofacies and biofacies but also in their close association with submarine volcanic matter. According to BAILEY *et al.* (1964), the Franciscan limestones include several rock-types, but the most common kinds are 1) light- to dark-grey, massive limestones of the Calera type and 2) pink to deep-red, small lenticular limestones of the Laytonvill type, both of which are characteristically micritic and locally contain abundant globotruncanid and globigerinid foraminifers and/or radiolaria.

Besides these types, there are glauconitic limestone, oolitic limestone, and organic detrital and pelletal limestones in a subordinate amount. The limestones of these less common kinds are similar to those of the upper part of the Konosé Group which usually occur as lenticular or blocky bodies usually embedded within the thick piles of volcanic sediments.

The Franciscan limestones are commonly accompanied with lenticular beds or isolated, generally loaf-shaped nodules of chert which in places constitutes 30 percent or more of the total volume of the limestone and chert sequence. They are closely associated with basic volcanic rocks. The Calera type limestone occurs most commonly in the pyroclastics, locally interbedded with each other. The Laytonville type limestone invariably is associated with pillow basalt, which are draped on top with the limestone, or interbedded with red radiolarian chert in a volcanic rock-chert sequence.

The close similarity in occurrence, lithologic assemblage and general litho- and bio-facies suggest that the Franciscan and the Konosé limestones were deposited under similar sedimentary environments with particular relations to the submarine volcanism, although the two formations are not coeval.

BAILEY *et al.* (1964) considered that the bulk of the Franciscan limestones appears to be chemical precipitate in deep water, perhaps bathyal, genetically associated with submarine volcanic eruptions which caused the heating and agitation of water, and that differences in the environment of deposition led to either the formation of the light-coloured, iron-free Calera type limestone, or to the red iron-rich Laytonville type. Recently, however, FISHER *et al.* (1967) clarified that the latter contain abundant coccoliths and are only slightly recrystallized and the former, in contrast, have been largely recrystallized to pavement mosaics, but contain a few fragments of coccoliths and some other relicts of the problematical nannofossils, suggesting that they may have once been coccolith limestones.

BAILEY *et al.* (1964) believe the Franciscan bedded-chert to be also chemical sediments formed with silica released by the reaction of hot magmas and heated sea water under considerable hydrostatic pressure and volcanic eruption would have occurred in the oceanic depth as deep as 3900 m. The associated greenstones contain, besides pillow lavas, thick sequences of tuff, tuff breccia, and agglomerate, and some of them are vesicular. As mentioned in the foregoing pages, however, explosive volcanic eruption which produced pyroclastic rocks unlikely took place in such a deep oceanic floor, and no appreciable chemical reactions between hot lavas and sea water are taken place (MOORE, 1965, 1966).

Regarding the association of oolitic and organic detrital limestones with the Calera type BAILEY *et al.* (1964) referred to redeposition of primarily shallow water deposits perhaps in the vicinity of seamounts or islands into deeper water through the action of submarine slides or turbidity currents. Almost the same conclusion can be led also as for the megabreccia, microbreccia and blocky limestones of the Konosé Group as has been discussed above.

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Plates 4–8

Kametoshi KANMERA

Litho- and Bio-facies of Permo-Triassic Geosynclinal
Limestone of the Sambosan Belt in Southern Kyushu

Explanation of Plate 4

Figs. 1–3. Foraminifera biomicrite .... p. 21

1, containing abundant *Aulotortus* (large, discoidal to spherical specimens) and some *Frondicularia* (small, tapered subcylindrical specimens—longitudinal sections and small spherical specimens—transverse sections), with a micrite matrix. Ko. 78–37. 2, mainly consisting of *Frondicularia* and *Aulotortus*, and a few thin shells (Ostracods ?), with a micrite matrix. Ko. 78–10. 3, containing some large *Aulotortus*. Ko. 800.

Foraminifers are mostly filled by sparry calcite. All ×10, Yaritaoshi Formation, Y_2 Member.

Fig. 4. Micrite with a few, small echinoderm debris, thin shells and indeterminable fragmentary particles .... p. 20

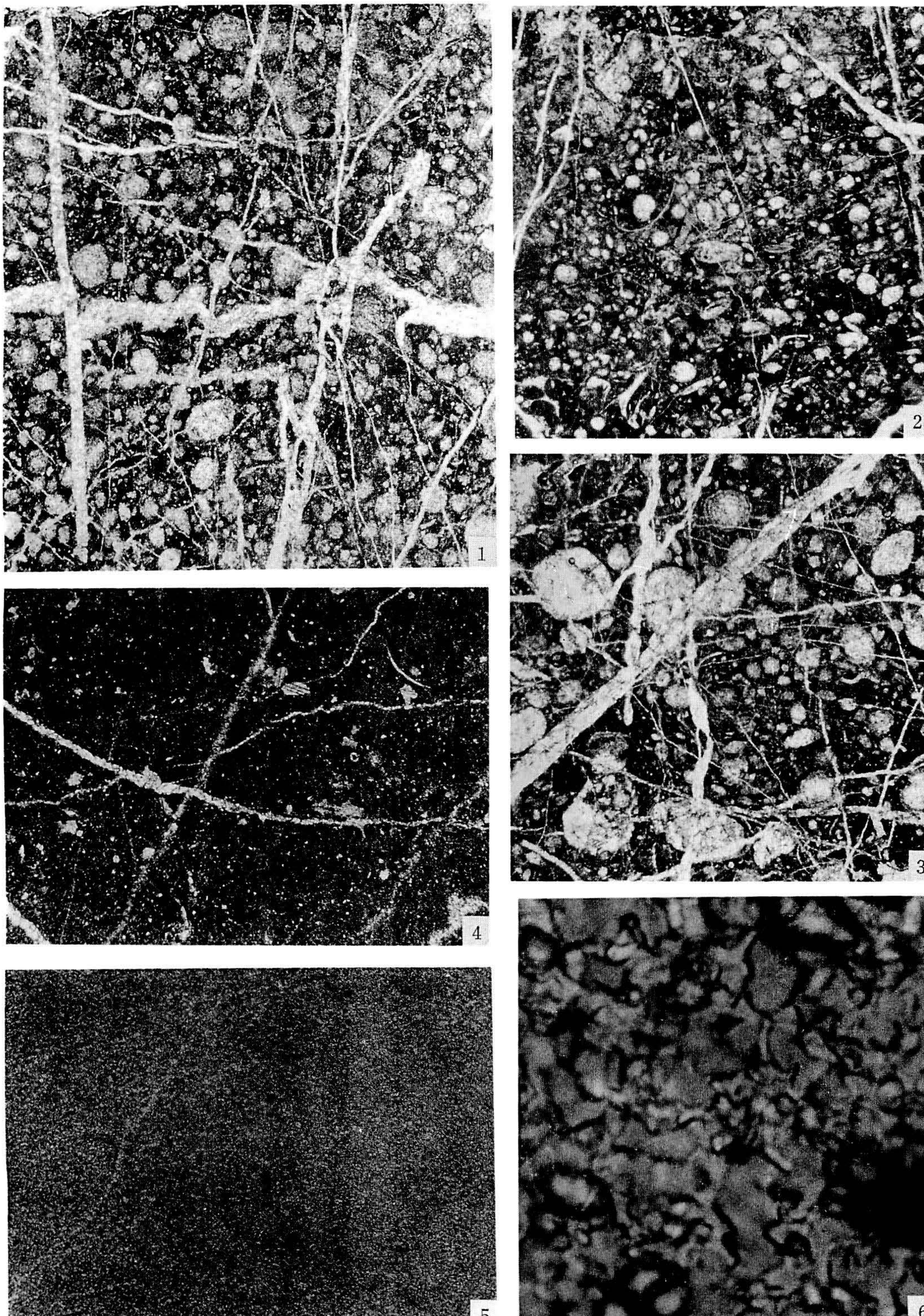
×10, F–8038, Yaritaoshi Formation, Y_2 Member.

Fig. 5. Homogeneous micrite.. p. 20

×40, Ko. 78–30, Yaritaoshi Formation, Y_2 Member.

Fig. 6. Enlarged figure of homogeneous micrite .... p. 20

×1650, negative replica, Ko. 59–3b, Ohsé Formation.



K. KANMERA: Geosynclinal Limestone of the Konosé Group

Explanation of Plate 5

Figs. 1–3. Radiolarian biomicrite and micrite .... p. 20

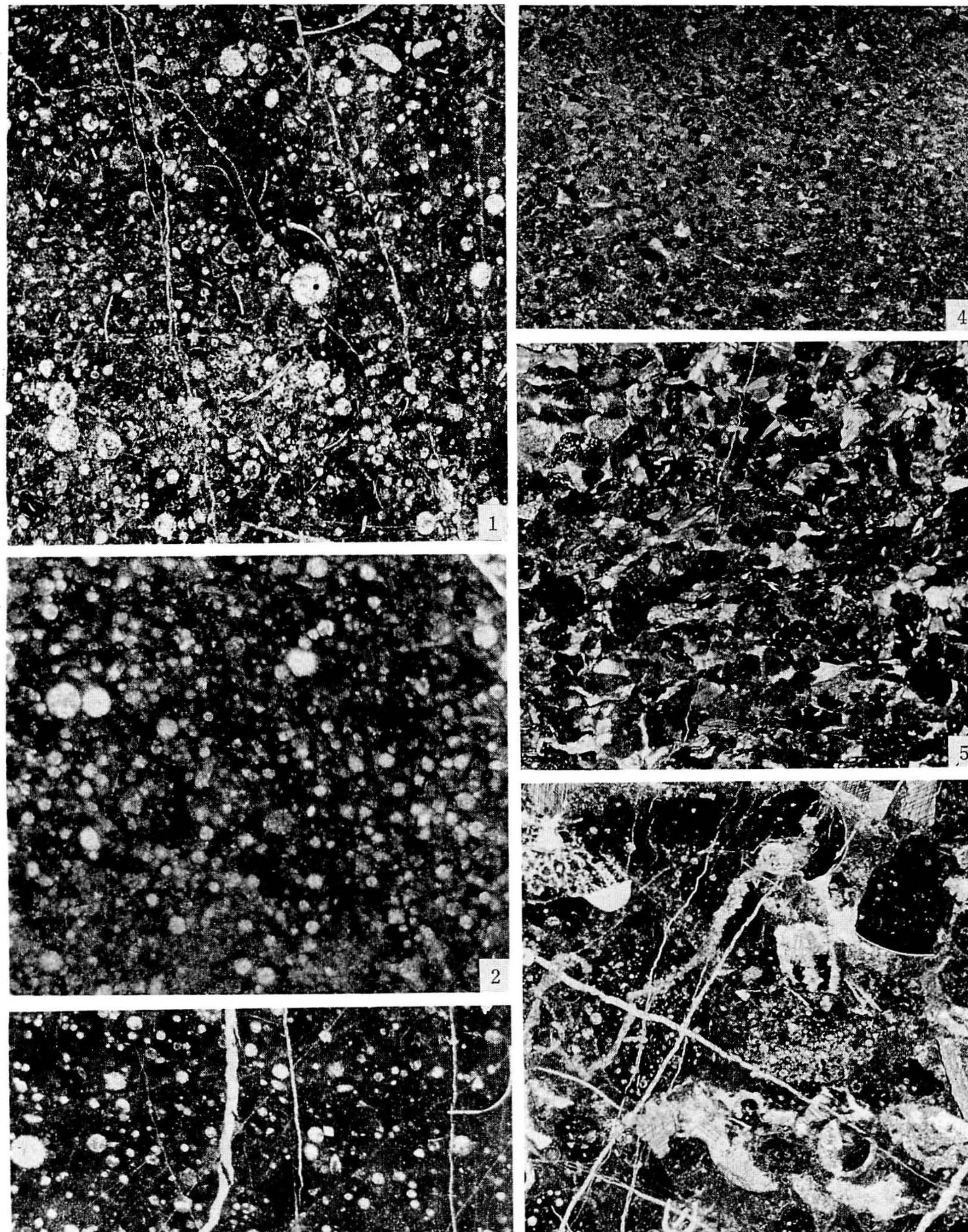
1, containing fairly abundant radiolaria and a few shell fragments, with a micrite matrix. Ko. 79B–2, uppermost part of the Gongenyama Formation. 2, containing abundant radiolaria, Ko. 592–2, Tsugé Formation, T_2 Member. 3, radiolarian micrite, Ko. 59–7a, lower member of the Ohsé Formation.

All $\times 25$. Radiolarian remains are entirely replaced by sparry calcite in early diagnetic processes.

Figs. 4–6. Microbreccia (fine-grained calclithite) .... p. 25

4, fine-grained microbreccia consisting of micrite of sand- and silt-size, with an extremely narrow micritic matrix. Ko. 614, Tsugé Formation (T_1 Member). 5, microbreccia consisting of micrite, radiolarian micrite and volcanic rock fragments (black). Breccias are mostly in stylolytic contact and cemented with secondary sparry calcite produced probably by pressure-solution recrystallization, Ko. 59–1, Ohsé Formation. 6, coarse-grained microbreccia composed of rock fragments of radiolarian biomicrite, shell-radiolaria micrite, crinoid ossicles and some calcisponges, with a radiolarian micrite matrix. Ko. 60–6a, Ohsé Formation (lowest member).

All $\times 10$.

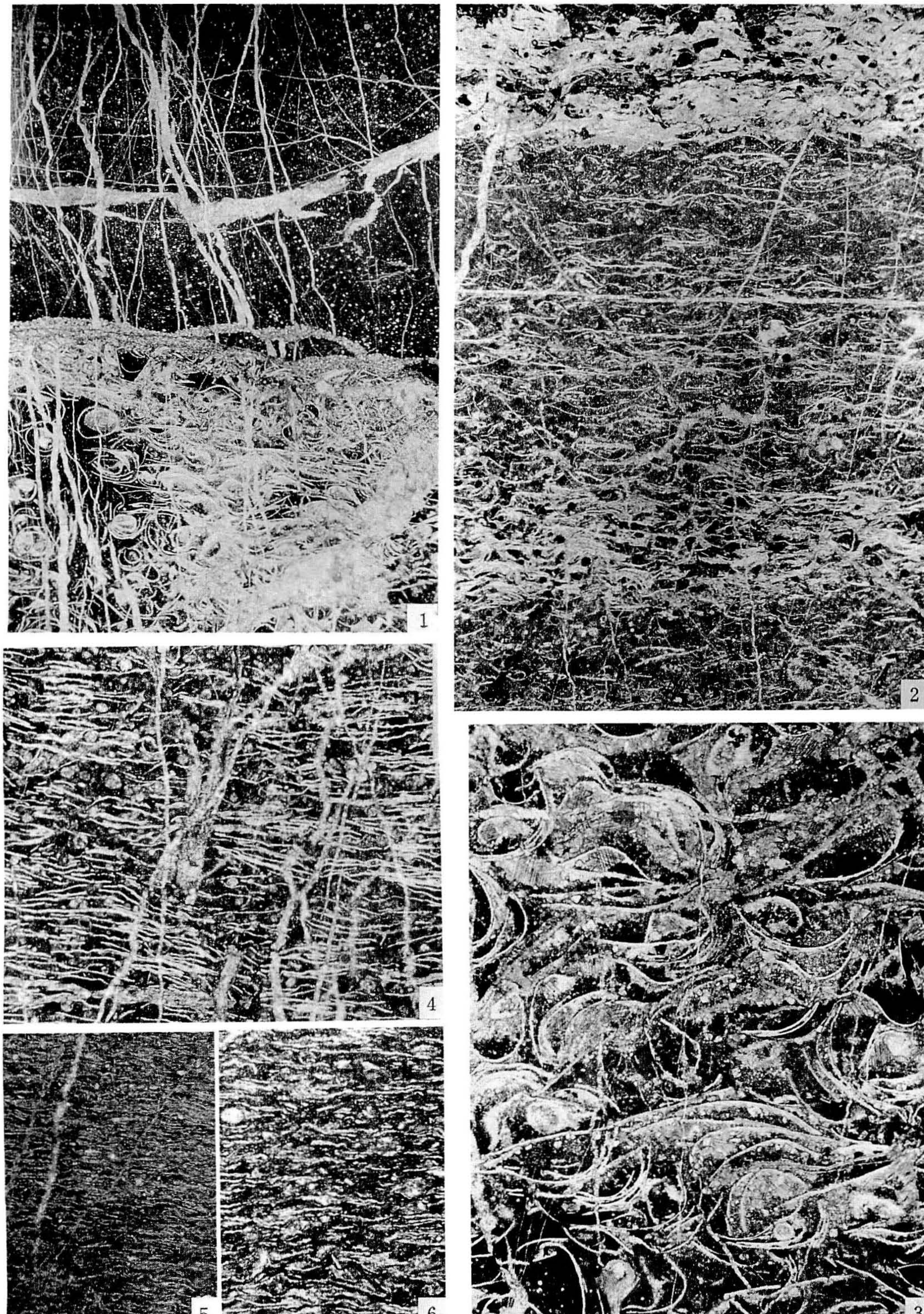


K. KANMERA: Geosynclinal Limestone of the Konosé Group

Explanation of Plate 6

Fig. 1. Radiolarian micrite and shell biomicrite .... p. 20
A part of alternating beds of these two kinds. Note that along the boundary zone of the two layers there occur dolomite bands which cut calcite veinlets. Dolomite crystals are also disseminated in the micrite. ×3, Ko. 59–7a, Ohsé Formation.

Figs. 2–6. Shell biomicrite and micrite .... p. 21
2, shell biomicrite consisting of extremely thin-walled shells and some radiolaria. A rough grading is recognized in the amount of shells. Note small, black, spherical particles of radiolarian remains (mostly casts) filled with dense micrite, which suggest penecontemporaneous allochthonous components. White, small particles are radiolaria replaced by sparry calcite. ×6, Ko. 59–7b, Ohsé Formation. 3, a part of shell biomicrite of Fig. 1, ×10. 4, shell-radiolaria biomicrite; shells are mostly fragmentary, ×10, Ko. 60–C2, Ohsé Formation. 5, shell biomicrite consisting of abundant fragmentary shells, ×10, Ko. 592 B, T_2 Member of the Tsugé Formation. 6, enlarged figure of a part of Fig. 5, ×20, Ko. 592B.



K. KANMERA: Geosynclinal Limestone of the Konosé Group

Explanation of Plate 7

Fig. 1. Algal biosparrudite .... p. 23
Consisting of codiacean algae of rudite- and arenite-size and a coarse sparry calcite matrix. Grain diminution is distinct in the marginal part of coarse debris and the most part of fine debris. Minute white spots are secondary quartz crystals. ×5, Ko. 61, isolated limestone block in the upper part (K_3) of the Kamasé Formation.

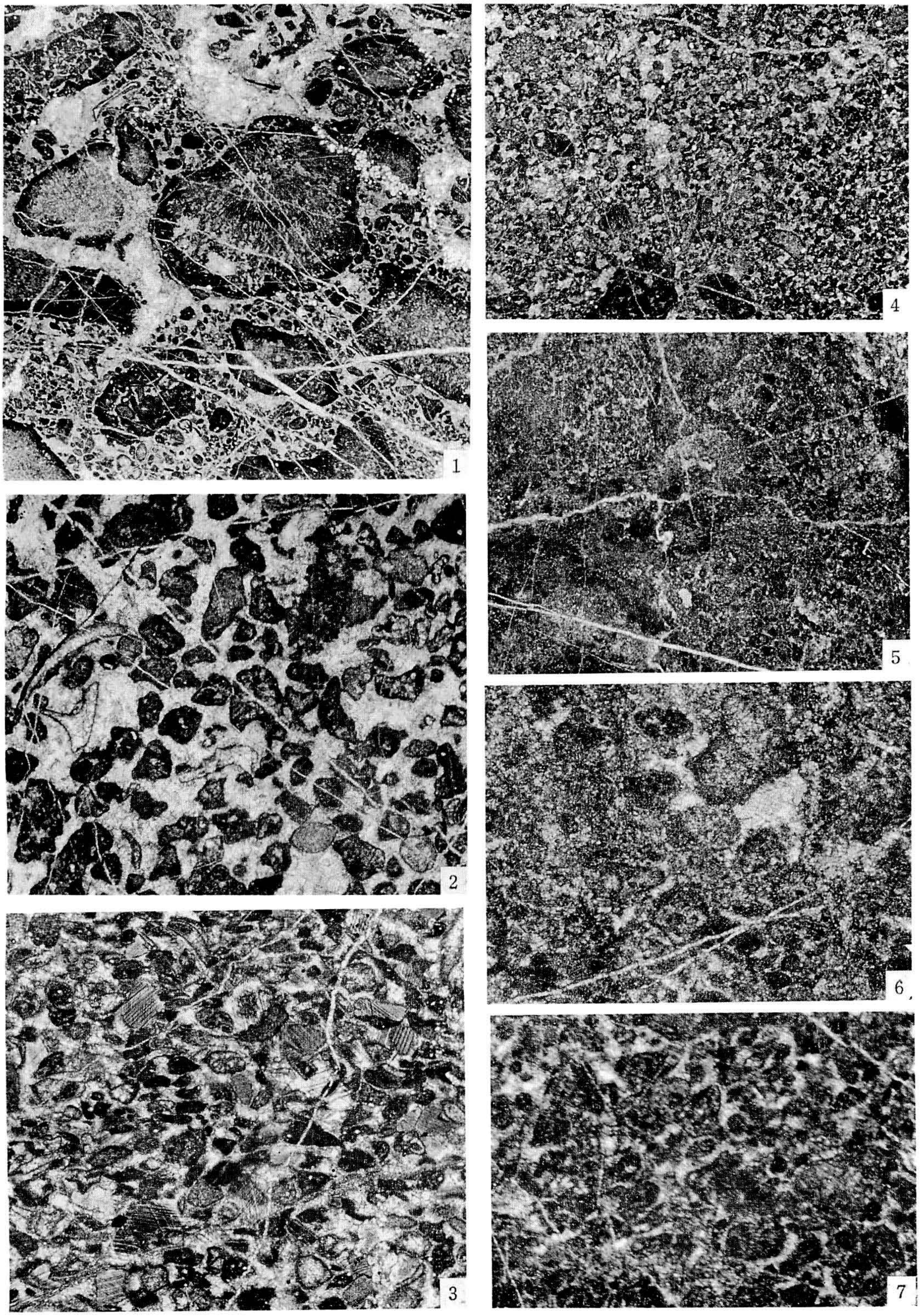
Fig. 2. Algal biosparite .... p. 23
Grains are almost exclusively algal debris. Matrix is wide, consisting of coarse mosaic sparry calcite. ×10, Ko. 80A-11, G_2 Member of the Gongenyama Formation.

Fig. 3. Algae-crinoid biopelsparite .... p. 24
Many algal debris are recrystallized to fine pseudosparite, leaving a micrite rim. Minute white spots are secondary quartz crystals. ×10, Ko. 589-b, lower member (K_1) of the Kamasé Formation.

Fig. 4. Fine-grained algal biosparite .... p. 23
Algal debris are more or less recrystallized to fine-grained pseudosparite, ×10, Ko. 61, isolated limestone block in the upper part (K_3) of the Kamasé Formation.

Figs. 5, 6. Algal biomicrite .... p. 21
5, fine-grained algal biomicrite consisting almost exclusively of algal debris, ×25, Ko. 80A-12. 6, algal biomicrite partly with a sparry calcite matrix. Algal grains are also slightly recrystallized. ×25, Ko. 80A-13. Main limestone of the Gongenyama Formation.

Fig. 7. Algal pseudosparite .... p. 23
Consisting of well-rounded algal debris and a narrow, fine-grained, mosaic sparry calcite matrix. ×20, Ko. 80B-5. Main limestone of the Gongenyama Formation.



K. KANMERA: Geosynclinal Limestone of the Konosé Group

Explanation of Plate 8

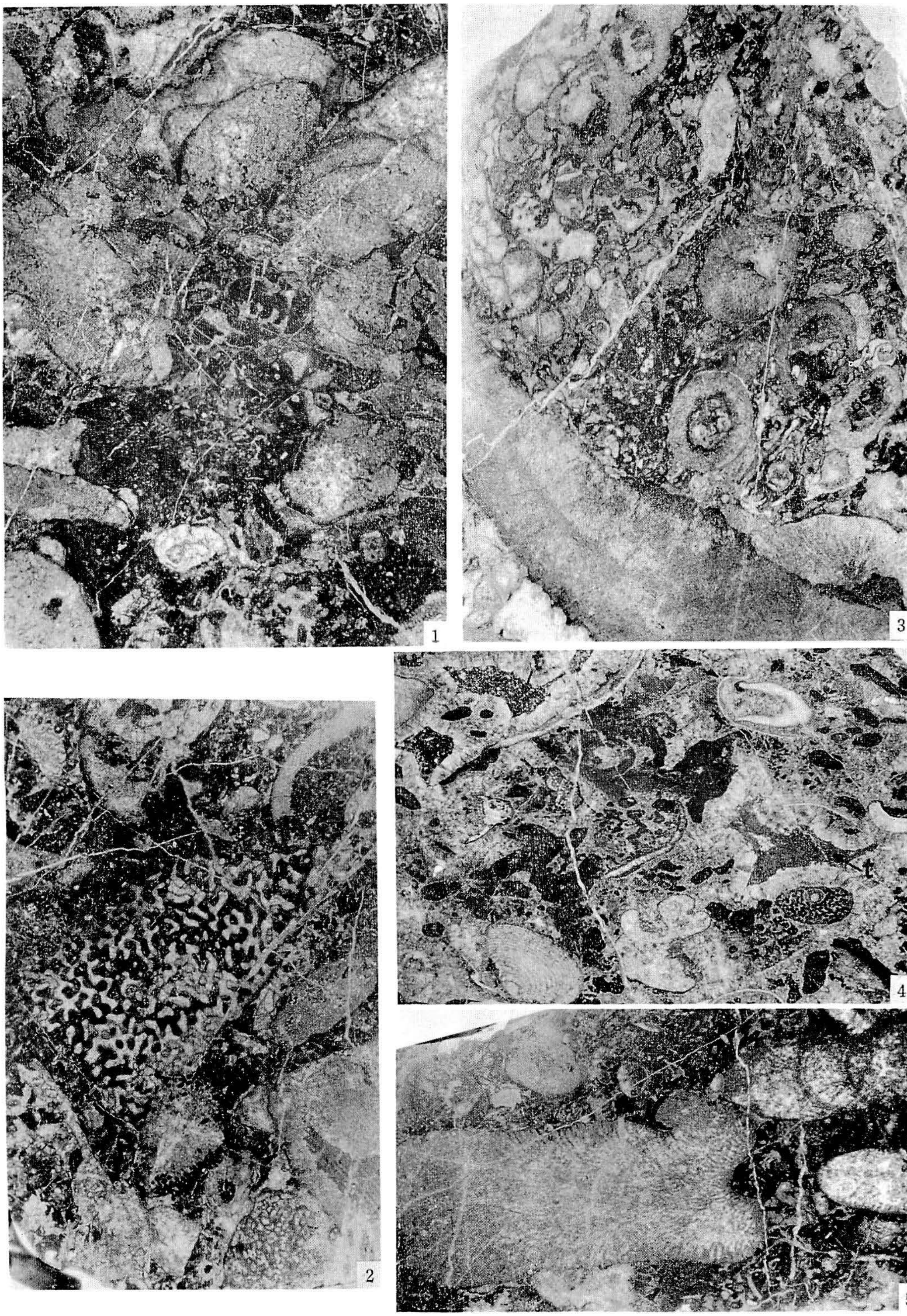
Fig. 1. Porifera biolithite .... p. 24
Calcisponges constitute the main frame-builders, but their internal structures are considerably obliterated by diagnetic recrystallization. Interspace fillings are micrite with some skeletal debris. ×2, Ko. 286, lower member (K_1) of the Kamasé Formation.

Fig. 2. Porifera-spongiomorphid biomicrudite.. p. 22
Consisting of fragmentary frame-builders mainly of calcisponges and spongiomorphids and interspace fillings containing abundant fine-grained algal debris. ×2.2, Ko. 286, lower member (K_1) of the Kamasé Formation.

Fig. 3. Porifera-algae biolithite.. p. 24
Frame-builders are mostly calcisponges and coralline algae, but their internal structures are largely obliterated by recrystallization. Interspace fillings consist of micrite with skeletal debris of various kinds. ×2, Ko. 278, isolated limestone block in the upper part of the Koguchi Formation.

Fig. 4. Biolithite with mixed frame-builders and fibrous calcite interspace fillings...... p. 24
Frame-builders are coralline algae (Solenoporacea), codiacean (?) algae (black), sponges, and some shells. Interspace fillings show two generations, the first consisting of fibrous calcite which was formed perpendicular to the wall of frame-builders and the second is composed of fine-grained volcanic material (shown by t with an arrow mark). ×2.2, Ko. 278, upper part of the Koguchi Formation.

Fig. 5. Algal biolithite.. p. 24
Consisting of codiacean algae showing a digitate developmental pattern and a micritic matrix containing abundant algal debris and some other skeletal fragments. ×2.2, Ko. 278, upper part of the Koguchi Formation.



K. Kanmera: Geosynclinal Limestone of the Konosé Group

PERMIAN LIMESTONES OF WEST CAMBODIA

– Lithofacies and Biofacies –

(Contribution to the Geology and Palaeontology of Cambodia, Part 3)

By

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1. Introduction

Numerous monadnocks made up of limestones are scattered in the wide plain of west Cambodia. These limestones have been noted by the abundant occurrence of well preserved Permian fossils. A number of stratigraphical and palaeontological studies on the Permian of west Cambodia have already been made by DEPRAT (1912, 1913), MANSUY (1913, 1914), GUBLER (1935a, b), DELPEY (1941-42), SKINNER & WILDE (1954), SAURIN (1959), VIEN (1959), Chi-THUÂN (1961), FONTAINE (1961, 1965, 1967), SERRA (1966), ISHII & NOGAMI (1964) and ISHII (1966).

In 1962 Osaka City University sent a scientific expedition to Cambodia, and ISHII and Y. NOGAMI of the University of Kyoto carried out a detailed biostratigraphical investigation on the limestone hills in the Sisophon and Battambang areas of west Cambodia.

In 1965 ISHII, in collaboration with S. HADA of Kochi University, continued further the investigation. In early 1967 ISHII and M. KATO of Hokkaido University again made a field investigation in west Cambodia with special attention to the relationship between lithology and fossil contents of these limestones. K. NAKAMURA of Hokkaido University studied and analyzed the brachiopod fauna from these limestone hills.

We wish to acknowledge with many thanks the constant encouragement and instructive advice of Prof. M. MINATO of Hokkaido University and Prof. K. ICHIKAWA of Osaka City University during the course of our study. Thanks are due to Dr. Y. NOGAMI of the University of Kyoto and Mr. S. HADA of Kochi University for their assistance and collaboration in field and laboratory.

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2. Outline of Geology

West Cambodia is a vast plain which is only occasionally disturbed by the presence of a number of low limestone hills standing as monadnocks in resistance to the monsoon weather. These limestone hills are exclusively Permian in age. Judging from the geologic structure of these limestone hills, it is concluded that they take a part of the gently undulated major structure of dome and basin (Text-fig. 1). An elongated shallow basin of elliptical outline is to be located west of Battambang, stretching roughly NWW-SEE, and an oval shaped half dome is to be conceived to the south of Sisophon.

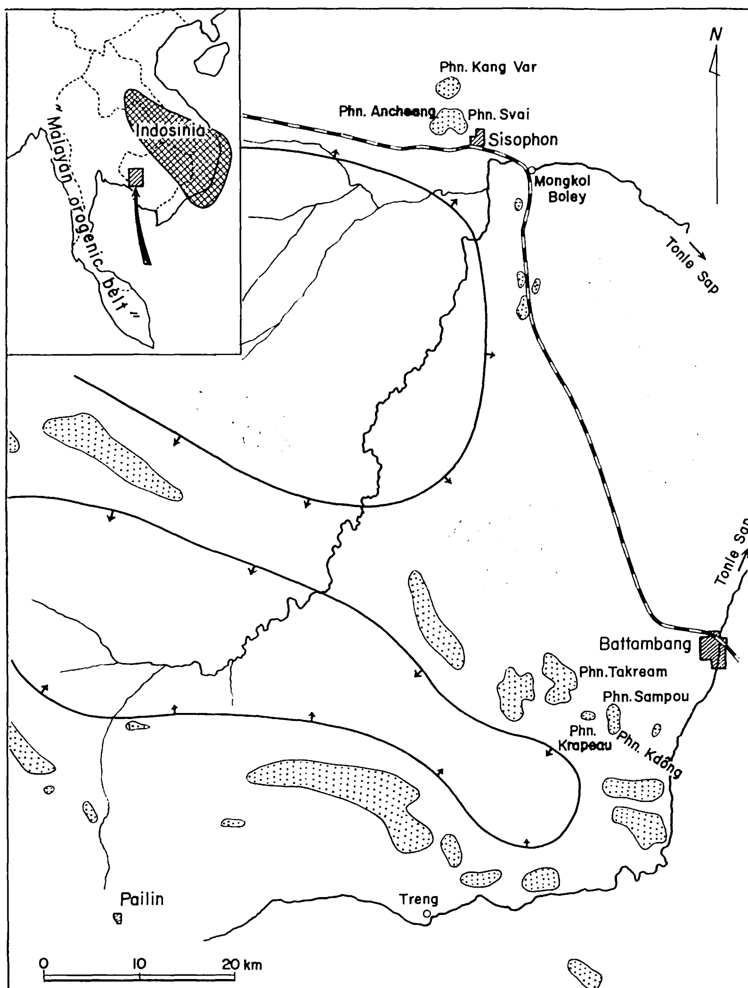

Fig. 1. Index map showing the geographic location of the investigated area.

The area is geotectonically situated to the west of the Indosinian Massif and it must have been under relatively stable shelf condition during the Permian.

Although the basement rocks for these Permian limestones have been seen nowhere in the plain, folded and partially metamorphosed rock series of supposedly

Devono-Carboniferous or possibly much older formations crop out with E–W direction in the Pailin region, near the Thai-Cambodian border. The same kind of the ancient complex may form the basement of the shelf region on which marine Permian formations were deposited.

The gentle structure of the Permian in west Cambodia today is in strong contrast to the strongly folded and faulted Permian formations in Burmese-Malayan mountain chain which was then under geosynclinal condition.

Towards the end of Permian the emplacement of granite of 227 m.y. by the Rb-Sr method (LASSERRE et al., 1968) is known in Cambodia. This disturbance must be responsible for the undulation of the Permian and the delimitation of depositional basin for the Mesozoic. Subsequently the whole area was uplifted and has been eroded down to the present status.

3. Geology of the Sisophon Limestone

The limestone hills west of Sisophon are especially rich in fossils and provide a good, standard geologic section for the Permian of west Cambodia. There the Permian may be lithostratigraphically divisible into four members, A, B, C and D in ascending order (Text-fig. 2). And this division is widely applicable to the limestone of other hills in west Cambodia.

In southern hills of Phn.* Svai and Phn. Ancheang, A and B members are stretching from east to west, dipping northward with low to sometimes moderate angles. A member is especially well exposed on the southern foot of these hills and adjacent parts of the plain.

Between these hills and northern group of hills there lies a saddle like depression where C member is typically developed. Northern hills of the Sisophon limestone are called as Phn. Tup, Phn. Lang k Tom, Phn. Dong Preas and Phn. Bak. D member is exposed on these hills with roughly E–W strike and gentle northerly dip (Pl. 9, Fig. 1).

An isolated hills of Phn. Kang Var, north of Sisophon limestone hills, consists entirely of D member, dipping also gently northward.

4. Lithofacies and biofacies of the limestones in Sisophon and Battambang regions

Member A

Lithofacies.—The thickness of this member is over 5 m; its lower part being concealed underneath the plain. The member underlies carbonate sediments of B member and consists of pale green to reddish brown andesitic tuffs and tuff-breccias. Tuffs laterally shift into more muddy facies which is easily weathered to brown or reddish brown soil (Text-fig. 4). Under the microscope tuffs and tuff breccias have matrix of both glassy and calcareous parts, in the latter of which fossils are embedded. Phenocrysts of plagioclase and pyroxene are observable within glassy groundmass of breccias (Pl. 9, Figs. 4, 5). Small lenses of limestones are often

* Phn. is an abbreviation of Phnom meaning mountain in Cambodia language.

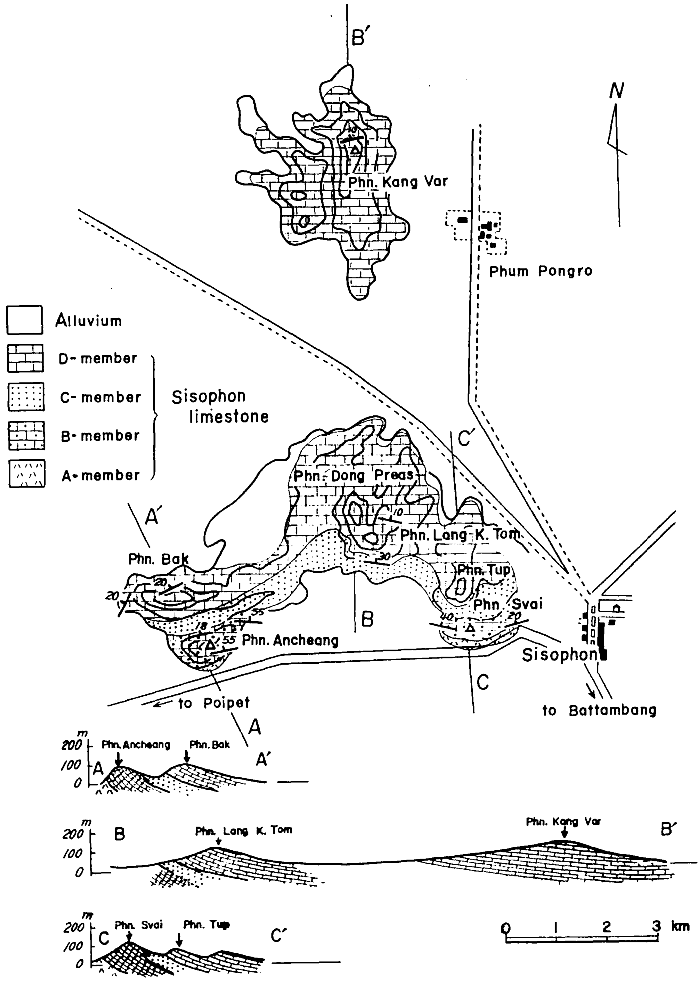

Fig. 2. Geologic map of the Sisophon region, west Cambodia.

intercalated in the upper part of the member.

Member A corresponds to " niveau I° " of FONTAINE (1967) in Phn. Svai in the Sisophon area. In the Battambang area the member is represented by reddish tuffaceous mudstones at the base of Phn. Kdông where we found no fossils.

Biofacies.—In A member of the Sisophon area there occur abundant fusulinids and some brachiopods, corals, crinoids and calcareous algae. But fossils are barren in the same member at the base of Phn. Kdông in Battambang area.

Fusulinids referred to *Pseudodoliolina* are overwhelmingly dominant, being more or less concentrated in tuffs just beneath the limestones of B member. Schwagerinids are less common. In spite of the abundance, fusulinids are few in the number of genera and species. They are not corroded and their external walls are mostly well preserved. Therefore they are thought as denoting an autochthonous community (Pl. 9, Fig. 3).

Corals are scarce both in the number of individuals and species in the A member, and are represented by solitary and comparatively small forms. They resemble in

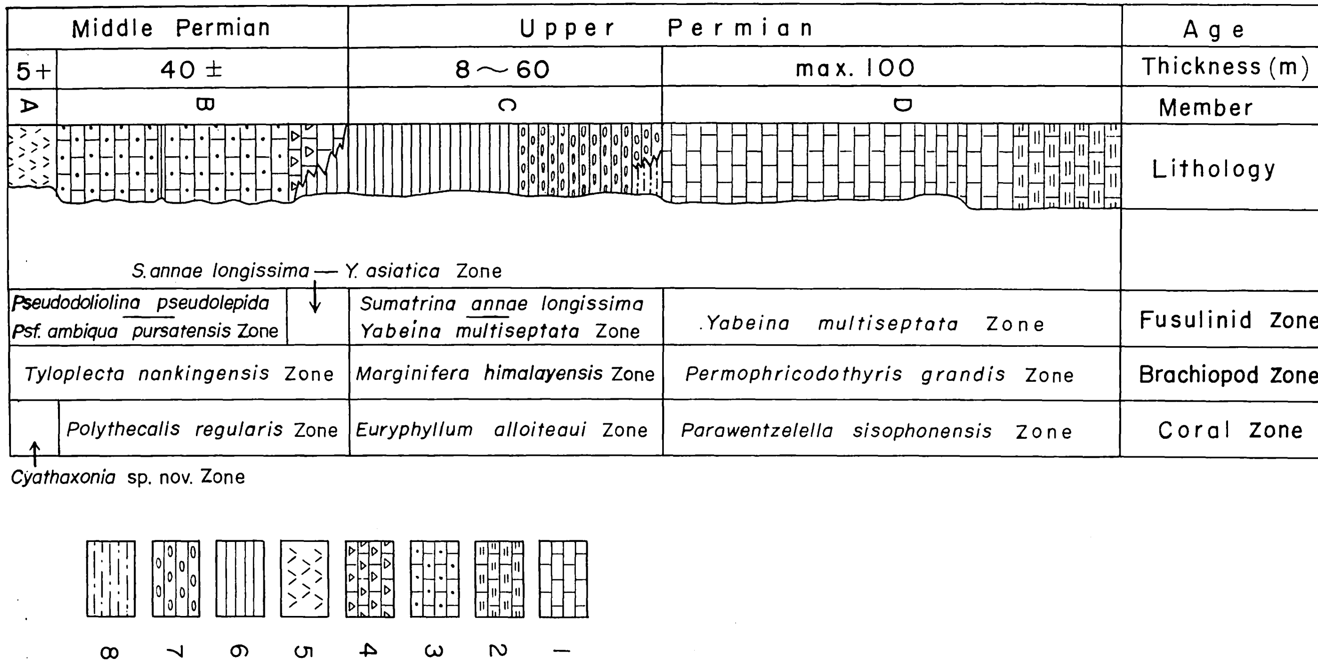

Fig. 3. Generalized columnar section of the Permian of west Cambodia.

1: bedded limestone, 2: muddy limestone or micritic limestone, 3: crinoidal limestone, 4: limestone breccias, 5: tuff breccias or tuff, 6: reddish shale, 7: reddish brownish calcareous mudstone with calcareous nodules, 8: drusy coating skeletal limestone (grainstone).

Table 1. Distribution of fusulinids in the Permian limestones of West Cambodia.

Fusulinids — Specific name	member A	member B	member C	member D
1. *Nankinella inflata* (COLANI)			—	- -
2. *Nankinella quasihunanensis* SHENG		—		
3. *Schubertella* sp.		—		—
4. *Minojapanella* ? sp.		—		
5. *Pseudofusulina padangensis* (LANGE)	—	—	—	—
6. *Pseudofusulina ambigua pursatensis* GUBLER		—		
7. *Pseudofusulina margheritii* (DEPRAT)			—	
8. *Schwagerina crassa* (DEPRAT)		—	- - -	—
9. *Chusenella cambodgiensis* (GUBLER)			—	—
10. *Chusenella globularis* (GUBLER)				—
11. *Chusenella* cfr. *ishanensis* HSÜ		—		
12. *Parafusulina gigantea* (DEPRAT)				- -
13. *Parafusulina* sp. A				- -
14. *Parafusulina* sp. B				- -
15. *Pseudodoliolina pseudolepida* (DEPRAT)	—	—		
16. *Pseudodoliolina dunbari* (GUBLER)	—	- - -		
17. *Pseudodoliolina* sp. nov. A	—			
18. *Pseudodoliolina* sp. nov. B	—			
19. *Pseudodoliolina* sp.	—	—		
20. *Verbeekina verbeeki* (GEINITZ)			- - -	—
21. *Verbeekina* sp.		- -		
22. *Sumatrina annae longissima* DEPRAT		—	—	
23. *Neoschwagerina douvillei* OZAWA		—		
24. *Neoschwagerina* aff. *margaritae* DEPRAT		—		
25. *Neoschwagerina* (*Gifuella*) sp.		- -		
26. *Yabeina asiatica* ISHII		—	—	
27. *Yabeina multiseptata multiseptata* (DEPRAT)			—	—
28. *Yabeina multiseptata gigantea* (GUBLER)				—
29. *Yabeina elongata* (GUBLER)				—
30. *Yabeina minuta* THOMPSON & WHEELER				—
Fusulinid Zone	I	II	III	IV

IV: *Yabeina multiseptata* Zone
III: *S. annae longissima—Y. multiseptata* Zone
II: *S. annae longissima—Y. asiatica* Zone
I: *P. pseudolepida—Psf. ambigua pursatensis* Zone

the mode of occurrence the Carboniferous *Cyathaxonia* fauna, characterized by such non-dissepimented corals as *Lophophyllidium* and *Cyathaxonia.* Columellate forms are relatively common. Corals probably indicate that the depositional area of A member was neither very deep nor very shallow.

Brachiopods are generally less numerous, but such a *semireticulatus* group of Producti as *Tyloplecta nankingensis* and large *Choristites* are characteristically common. Some species persist the overlying B member.

Table 2. Distribution of corals in the Permian limestones of West Cambodia.

Corals Specific name	member A	member B	member C	member D
RUGOSA STREPTELASMATINA				
1. *"Amplexus" pustulosus* HUDDLETON		—		
2. *Lophophyllidium wichmanni* (ROTHPLETZ)		—		
3. *Lophophyllidium* sp.	—	—	—	
4. *Stereostylus* sp.			—	
5. *Lophocarinophyllum* sp. nov.	—	—	—	
6. *Khmerophyllum cambodgense* FONTAINE	—	—	—	
7. *Verbeekiella australis* (BEYRICH)		—		
8. *Wannerophyllum cristatum* (GERTH)		—		
9. *Tachylasma magnum* GRABAU		—	—	
10. *Amplexocarinia cristata* (WAAGEN & WENTZEL)			—	- - -
11. *'Rotiphyllum'* sp.	—			
12. *Cyathaxonia khmeriana* FONTAINE		—	—	
13. *Cyathaxonia* sp.	—	—		
14. *Cyathocarinia* sp. nov.	—			
15. *Euryphyllum alloiteaui* FONTAINE			—	
16. *Euryphyllum minor* FONTAINE			—	
17. *Euryphyllum cainodon* (KOKER)			—	
18. *Euryphyllum* sp.			—	
19. *Allotropiophyllum* sp. nov.	—			
20. *Yatsengia sisophonensis* FONTAINE			- - -	—
21. *Yatsengia* sp.	—			
RUGOSA COLUMNARIINA				
22. *Waagenophyllum kueichouense* HUANG		—		
23. *Huayunophyllum* ? sp.				—
24. *Parawentzelella sisophonensis* FONTAINE				—
25. *Parawentzelella canalifera* (MANSUY)				—
26. *Parawentzelella regularis* FONTAINE				—
27. *Parawentzelella* sp.		—		
28. *Wentzelella regularis* FONTAINE				—
29. *Polythecalis bauryi* FONTAINE		—		
30. *Wentzelloides (Multimurinus) khmerianus* (FONTAINE)		—	- - -	
31. *Wentzelloides (Multimurinus) regularis* (FONTAINE)*		—	- - -	
32. *Lonsdaleiastraea* sp.			—	- -
TABULATA				
33. *'Pseudofavositis'* sp.	—	—	—	
34. *'Michelinia' abnormis* MANSUY			—	—
35. *Michelinia* sp.		—		
36. *Sinopora asiatica* (MANSUY)				—
37. *Aulohelia* sp.			—	
Coral Zone	I	II	III	IV

VI: *Parawentzelella sisophonensis* Zone
III: *Euryphyllum alloiteaui* Zone
II: *Polythecalis regularis* Zone
I: *Cyathaxonia* sp. nov. Zone
* *ex Polythecalis regularis* FONTAINE

Table 3. Distribution of brachiopods in the Permian limestones of West Cambodia.

Brachiopods Specific name	member A	member B	member C	member D
ORTHIDA				
1. *Orthotichia* ? aff. *tani* (HUANG)			—	
2. *Orthotichia* sp.	—			
3. *Rhipidomella corallina* (WAAGEN)			—	
ORTHOTETACEA				
4. *Schuchertella semiplana* (WAAGEN)			—	
5. *Schuchertella* ? *sisophonensis* (THUÂN)			—	
6. *Schuchertella* sp.	—			
7. *Derbyia* sp.			—	
8. *Meekella* ? sp.			—	
PRODUCTIDA				
9. *Chonetinella* ? sp.		—		
10. *Strophalosiina tibetica* (DIENER)			—	
11. *Strophalosia* ? *costulata* THUÂN	—		—	
12. *Edriosteges poyangensis* (KAYSER)			—	
13. *Tschernyschewia typica* STOYANOW			—	
14. *Costiferina* cfr. *indica* (WAAGEN)		—		
15. *Tyloplecta* cfr. *yangtzeensis* (CHAO)			—	
16. *Tyloplecta nankingensis* (FRECH)	—	—		
17. *Reticulatia* cfr. *uralica* (TSCHERNYSCHEW)		—		
18. *Alexenia gratiosa* (WAAGEN)	—	—	—	
19. "*Dictyoclostus*" *margaritatus* (MANSUY)	—	—		
20. *Spinomarginifera kueichowensis* HUANG			—	
21. *Echinauris* ? *khmerianus* (MANSUY)				—
22. *Spinomarginifera* ? *banphotensis* (YANAGIDA)			—	
23. *Monticulifera sinensis* (FRECH)				—
24. *Anidanthus* ? *sinosus* (HUANG)			—	
25. *Cancrinella cancriniformis* (TSCHERNYSCHEW)			—	
26. *Linoproductus* sp.			—	
27. *Marginifera himalayensis* DIENER			—	
28. *Echinoconchus* spp.			—	
29. *Leptodus* cfr. *nobilis* (WAAGEN)		—	—	
30. *Oldhamina* ? sp.				—
SPIRIFERIDA				
31. *Neospirifer fasciger* (KEYSERLING)			—	
32. *Spiriferella* aff. *tibetana* (DIENER)			—	
33. *Brachythyrina* cfr. *rectangula* (KUTORGA)			—	
34. *Choristites* sp.	—	—	—	
35. *Phricodothyris elegantulus* (WAAGEN)				—
36. *Permophricodothyris grandis* (CHAO)				—
37. *Neophricodothyris* ? *rostrata* (KUTORGA)			—	
38. *Martinia semiplana* WAAGEN			—	
39. *Martinia* cfr. *nucula* ROTHOPLETZ			—	
40. *Spiriferellina margaritae* (GEMM.)			—	
41. *Spiriferellina* ? *multiplicata* (SOWERBY)				—
42. *Hustedia grandicosta* (DAVIDSON)			—	
43. "*Athyris*" sp.			—	
RHYNCHONELLIDA—STENOSCISMATACEA				
44. *Stenoscisma purdoni* (DAVIDSON)			—	
45. *Stenoscisma* sp.	—			
46. *Terebratuloidea davidsoni* WAAGEN			—	
47. *Uncinunellina timorensis* BEYRICH			—	
48. "*Rhynchonella*" *devreuxiana* DE KONINCK			—	
49. "*Rhynchonella*" aff. *confinensis* SCHELLWIEN			—	
TEREBRATULIDA				
50. *Dielasma indosinense* MANSUY			—	
Brachiopod Zone	I		II	III

III: *Permophricodothyris grandis* Zone
II: *Marginifera himalayensis* Zone
I: *Tyloplecta nankingensis* Zone

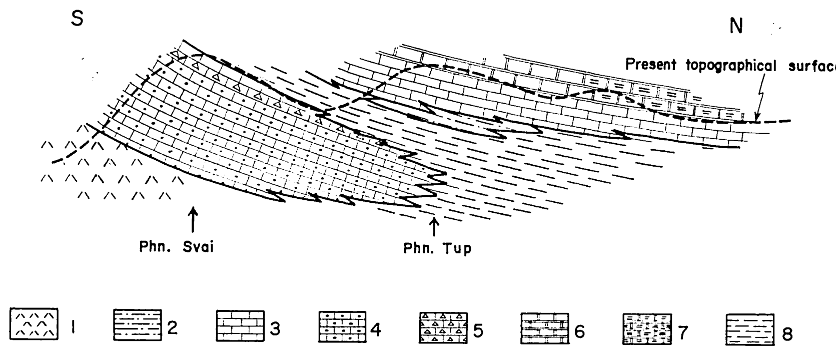

Fig. 4. Diagrammatic profile of the Sisophon region, showing vertical and lateral change of facies.

1: tuff breccias or tuff, 2: drusy coating skeletal limestone (grainstone); 3: bedded limestone, 4: crinoidal limestone, 5: limestone breccias, 6: bedded limestone with cherty bands, 7: muddy limestone with cherty bands, 8: reddish shale.

Member B

Lithofacies.—The thickness of the member is about 40 m. It conformably overlies A member and consists of the alternation of dark gray to milky white, massive limestones and bedded limestones. Lithologically they are skeletal-micrite and skeletal-sparite which are rich in the fragments of crinoids, together with scattered calcareous algae, echinoid spines, fusulinid foraminifers, corals and brachiopods (Pl. 10, Figs. 1-3). The member is well exposed especially in Phn. Svai and Phn. Ancheang in the Sisophon area. Majority of allochems is crinoidal stem joint. Therefore B member may be called the crinoidal limestone. In the bedded part, limestone with large fragments of crinoids grades upward into the aggregates of fine grained fragments of crinoids. The matrix of the limestone also varies from sparite to micrite in texture. In the upper part of B member limestone breccias and stromatolites are formed, and fossils are extremely rare. FONTAINE's "niveaux 2°-4°" correspond to B member.

In Phn. Sampou in Battambang area B member exceeds 30 m in thickness, but its lower limit is unexposed.

The crinoidal limestone of B member is only 10 m at Phn. Kdông. The same member is more than 50 m in thickness in Phn. Takream, though its lower limit is again unexposed there.

Everywhere in the studied area the member reveals the same lithological character as in the Sisophon area. But the uppermost limestone breccias and stromatolites found in the Sisophon area cannot be traced elsewhere.

Biofacies.—The B member is rich in fossil species. In addition to the dominant crinoids there occur calcareous algae, corals, brachiopods, bryozoans and fusulinids. Fossils are often crushed, abraded and fragmental.

Solitary corals are common in the lower part, while colonial ones increase their number from the middle part of the limestones of B member. Frequency of coral occurrence is, however, yet not very large. Colonial forms include both fasciculate as well as massive forms, the latter of which is mostly plocoidal with reduced wall structures. The size of each colony is relatively small.

Brachiopods are, as in A member, not numerous, and some diagnostic species are common to members A and B. Producti of the *semireticulatus* group tends to increase their number of individuals in B member. The occurrence of *Choristites* becomes rather rare.

Fusulinids are of different composition between the Sisophon and Battambang areas. In the Sisophon area *Pseudodoliolina pseudolepida* and *Pseudodoliolina* sp. occur in B member, persisting from A member. *Neoschwagerina* (*Gifuella*) occurs in the upper part of B member in Phn. Svai of the Sisophon area.* In the Battambang area, especially in Phn. Sampou and Phn. Kdông, on the other hand, *Pseudodoliolina* is absent in B member, and individuals of both *Pseudofusulina* aff. *ambigua pursatensis* and *Pseudofusulina* sp. are numerous. In the relatively lower part of the member in Phn. Takream, *Pseudofusulina* sp. occurs together with *Pseudodoliolina.* The bed at the uppermost horizon of B on the same hill contains rich fusulinids such as *Yabeina asiatica, Neoschwagerina douvillei, Neoschwagerina* aff. *margaritae, Sumatrina annae longissima* and *Verbeekina* sp.

In general, however, apart from the rich fauna of *Yabeina-Neoschwagerina* from the uppermost part at Phn. Takream, fusulinids are less common in B member.

Member C

Lithofacies.—C member conformably overlies B member and passes gradually in lithology to the overlying D member. It consists of reddish or brownish mudstones or calcareous mudstones. It varies in thickness from 8 to 60 m. from place to place. It is thick (60 m$\pm$) in the Sisophon area, but is thinning towards south. In Phn. Takream in the Battambang area, for example, the thickness is only 8 m.

In the Sisophon area the C member is exposed in the north of Phn. Svai, on the southwestern foot of Phn. Lang k Tom in the north of Phn. Ancheang and especially between Phn. Svai and Phn. Tup. The member, in the Sisophon area, may correspond to "niveaux 5°-7°" of SAURIN (1959, p. 125) and "niveaux 5° & 6°" of FONTAINE (1967, p. 53).

The lower part of the member between Phn. Svai and Phn. Tup consists of reddish brown mudstone without fossils and may be partially synchronous to but of different facies from the upper part of B member (Text-fig. 4). The reddish, brownish calcareous mudstones in the upper part of the member contains numerous calcareous nodules and many fossils.

A special kind of facies is found in a limited place at the top of C member in the north of Phn. Ancheang. This particular part is packed by such fusulinids as *Yabeina multiseptata, Sumatrina annae longissima, Kahlerina* aff. *sinensis, Pseudofusulina*

* In 1964 ISHII & NOGAMI described collectively two different hills of Phn. Svai and Phn. Tup as "Phn. Svai." The mentioned occurrence of *Yabeina multiseptata* at "Phn. Svai" was actually meant to be that at Phn. Tup (ISHII & NOGAMI, 1964, p. 20). *Yabeina multiseptata* does not seem to occur at Phn. Svai. SAURIN (1959, p. 126) reported the occurrence of '*Lepidolina*' *multiseptata* and '*Wentzelella*' from the southern slope and the summit of Phn. Ancheang. But according to our observation Phn. Ancheang is made up mostly by crinoidal limestones of B member as in Phn. Svai, and we failed to detect the fossils SAURIN recorded.

cfr. *crassa padangensis* etc. Under the microscope peripheral portion of each abraded fusuline foraminifer is coated with needle like calcite or fine crystals of calcite, the pore space among fusulinid grains being cemented by sparry calcite (Pl. 10, Fig. 5). Fusulinids are abraded to almost similar grain size and this type of carbonate rock was called grainstone by DUNHAM (1962). The abraded fusulinids were probably deposited under the strong influence of agitating sea water. Muddy matrix which may have existed between grains must have been washed away by the moving sea water. Then the sea water filled the pore space and may have led the suspended material to crystallize into needle like calcite by evaporation, using the grains of fusulinid as cores. Later, newly penetrated sea water introduced the cement of sparry calcite between the overgrown grains during the course of diagenesis.

In fusulinid rich bed of the same horizon as above, in other areas, hematite (limonite?) and magnetite are formed at the periphery of fusulinid individuals and also in the matrix (Pl. 10, Figs. 4, 6). The skeletal limestone is interpreted to have been diagenetically altered under the condition where the circulation of water is more or less restricted.

C member at Phn. Takream in the Battambang area is made up of red mudstones without fossils. In Phn. Kdông the member consists of red calcareous mudstones (Pl. 11, fig. 6).

Biofacies.—From the upper part of the C member abundant brachiopods, corals, calcareous algae, sponges, bryozoans, fusulinids are to be found.

Fusulinids are less numerous than in D member. *Sumatrina* and *Parafusulina* which do not occur in both B and D members are characteristic of C member in the Sisophon area. *Pseudodoliolina* which is characteristic to A and B members does not occur in C member. Fusulinids are seldom found in the same member in the Battambang area, although a *Nankinella* bed was detected in reddish calcareous mudstone at Phn. Kdông (Pl. 11, Fig. 6).

Brachiopods are especially numerous in the number of species as well as individuals. Productida, Spiriferida, Rhynchonellida and Orthotetacea are all represented. Also the fauna includes Orthida and Terebratulida. Amongst Producti, small forms like *Strophalosia? costulata* and *Marginifera himalayensis* become more common than the *semireticulatus* group. Athyrids, *Neospirifer* and Brachythyrids are rich amongst Spiriferida, and reticulate Spiriferids are represented by *Martinia.*

Corals are also abundant in C member. They are mostly solitary in form, though massive forms are also discernible. Altogether 18 species are identified from the corals of C member. Eight species are common to both B and C members, whereas only 4 species persist to D member.

Member D

Lithofacies.—D member attains to 100 m, in the maximum thickness. It consists of gray to dark gray massive and bedded limestones. It is well exposed in Phn. Tup, Phn. Lang k Tom, Phn. Dong Preas, and Phn. Bak, all in the Sisophon areas, and Phn. Sampou, Phn. Kdông, Phn. Krapeau and Phn. Takream in the Battambang area. Lithologically the limestones of D member have the matrix of micritic or sparitic texture and allochems of fusulinids (Pl. 11, Figs. 1, 2). In the bedded limestones calcilutite and calcarenite are alternated, each forming a unit ranging in thickness from several tens of centimeters to several meters (Pl. 9, Fig. 2). Also the calcarenitic part packed with fusulinids is alternated with the calcilutite in which fusulinids are scarce. Within a single unit layer, larger individuals of *Yabeina multiseptata* are accumulated in the lower part and sorted and graded upwards to the accumulation of smaller individuals.

The upper part of the member becomes muddy and is intercalated with many bands of siliceous nodules in Phn. Lang k Tom and Phn. Dong Preas of the Sisophon area. Fossils are becoming less common.

Biofacies.—Fusulinids and corals are overwhelmingly rich in D member, together with calcareous algae, brachiopods and gastropods. Fusulinids are however less numerous in the number of species, of which *Yabeina multiseptata* group is dominant. Although shells of fusulinids must have been sorted, the degree of damage of their peripheral part is appreciably small. Therefore fusulinids do not seem to have been transported by current action for a long distance, but may have been accumulated by the effect of sorting at the place where they lived.

As to brachiopods not a single common species is found between C and D members. This may be partially due to the chronological difference, but is thought to be largely by the evironmental difference between the two members. Elythidae are relatively common, and the *semireticulatus* group of Producti is replaced by such spinose forms as *Echinauris*? and *Monticulifera* which may be adapted to the substratum with calcareous muds.

D member also contains numerous massive and dendritic corals of large size. They are found in natural growth position with their calicular side pointing upwards.

5. On the Stratigraphical Relationship between the Limestones of Phn. Takream and those of Phn. Popul and Phn. Anseh

About 15 km west of Battambang there is a group of Phn. Takream monadnocks. There the arcuate hills of Phn. Takream are located as if they surround small hills of Phn. Anseh and Phn. Popul (Text-fig. 5). It is interesting to compare this configuration with subsurface structure of a Niagaran reef as revealed by Lowenstam (1950). Although they are of different scale, general similarity between the two is striking.

Limestones of Phn. Takream show the strike encircling the Phn. Anseh and Phn. Popul, and are dipping inward towards two hills, where, in turn, limestone beds show rather variable strike but are less steeply inclined than those of Phn. Takream.

As stated before, limestones cropping out in Phn. Takream are fossil-rich reef like limestones of B and D members, showing pale gray to dark gray in color. The thickness of C member is greatly reduced in Phn. Takream.

In Phn. Popul and Phn. Anseh, on the other hand, limestones are pinkish gray or dark gray in color and are fine grained, muddy, and micritic in texture. Fossils are less numerous and less common, and especially fusulinids are extremely rare in these limestones. The southern slope of Phn. Anseh consists of fine grained bedded limestones intercalated with numerous thin siliceous bands.

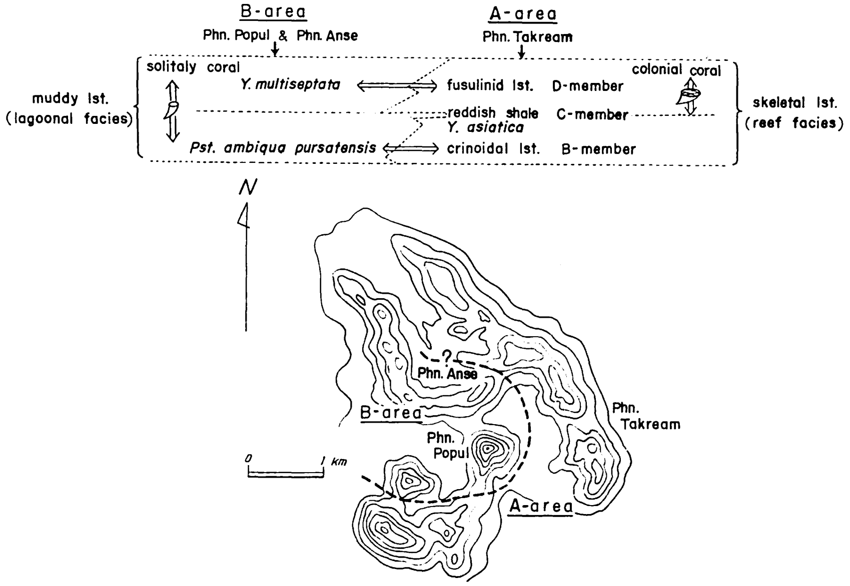

Fig. 5. Diagram showing the change of facies in the Permian limestone, with a sketch map of Phnom Takream limestone hills. A-area; skeletal limestone (calcarenite) showing barrier reef facies. B-area; muddy limestone (calcilutite) showing lagoonal facies.

GUBLER (1935) considered the limestones of Phn. Popul and Phn. Anseh were younger than those of Phn. Takream. However, according to our field investigation, *Yabeina multiseptata* occurs, though rarely, from the upper part of these micritic limestones of Phn. Anseh and Phn. Popul (Pl. 11, Figs. 4, 5). And further in Phn. Popul there occurs from the lower part *Pseudofusulina ambigua pursatensis* which is stratigraphically lower than *Yabeina multiseptata* in the Sisophon and Battambang areas (Pl. 11, Fig. 3).

Corals are common in Phn. Takream and are represented by both solitary and colonial forms, of which colonial corals are remarkably developed in D member. In Phn. Anseh and Phn. Popul, corals are by no means abundant and chiefly represented by small, solitary forms. Through the sequence of limestones there the composition of coral species is less variable as we compared it with the vertical change observed in Phn. Takream.

Brachiopods are also fairly abundant in Phn. Takream but not numerous in both Phn. Popul and Phn. Anseh, where they are almost exclusively represented by small forms.

Therefore, when we view the development of lithofacies, geologic structure, topography, and the difference in biofacies of the limestone hills in the Phn. Takream area, we may conclude that the centrally situated hills of Phn. Popul and Phn. Anseh are constructed with micritic limestones formed under relatively quiet, shallow, internal, lagoonal condition which was introduced by the development of external, atoll like, sometimes crinoidal reef limestones which now constitute Phn. Takream.

6. Conclusion

Numerous monadnocks scattered in the plain of west Cambodia are composed of limestones of Middle to Upper Permian ages (' *Neoschwagerina* ' to *Yabeina* zone) deposited in a stable, epicontinental sea, west of the Indosinian Massif.

The configuration of these limestone monadnocks appears to be tectonically controlled by the undulation of basement complex. Further, we see volcanic and pyroclastic deposits (A member) at the base of the limestone sequence. Therefore the Permian limestones in west Cambodia may have been originated from the limestone deposition on the crest of submarine mounds or banks made of pyroclastic rocks.

After the formation of volcanics environmental condition gradually became favourable for the settlement of some living organisms. Fusulinids flourish towards the top of A member, and are associated with some other benthonic forms. They are followed by the vigorous development of such sessile benthos as crinoids, resulting in the formation of crinoidal limestones of B member, which shows steeper inclination than the overlying members. These bedded crinoidal limestones probably formed a part of reef talus or reef flanks. Rolled massive colonial corals found in B member are the derivatives from a reef body. A part of C member may be a leeward equivalent to B member. Trunks of *Dadoxylon khmerianum* found from the C member were probably derived from a small island on the reef. Reddish coloured C member is probably indicative of interreef and backreef environments. The limited occurrence of grainstone in a particular part at the top of C member is probably of channel origin. These are followed by well bedded, fine grained limestones of the D member. They might be in part lagoonal, but became widely spreading to cover all the previously deposited members. Both dendritic and massive colonies of corals in D member are growing freely towards all directions. This indicates that the environment under which D member was deposited might have been lacking in strong prevailing current. The abundant occurrence of calcareous algae was naturally within the range of euphotic zone. The condition was therefore probably a sheltered shallow shelf sea.

The sea was finally deepened to lead the deposition of thinly bedded, less fossiliferous and siliceous limestones. Late Permian and early Triassic crustal movement and granite emplacement known in this area terminated the development of limestone bodies, and formed undulated geological structures of these limestones as they are seen today.

In general, various biofacies in the Permian limestones of west Cambodia may be largely controlled by the changing environments, which, in turn, resulted in the development of various lithofacies. There is, of course, chronological changes of the faunas as well, on which grounds biostratigraphic zonation is made as is summarized in Fig. 3.

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Plates 9–11

Ken-ichi ISHII, Makoto KATO and Koji NAKAMURA

Permian Limestones of West Cambodia

—Lithofacies and Biofacies—

Explanation of Plate 9

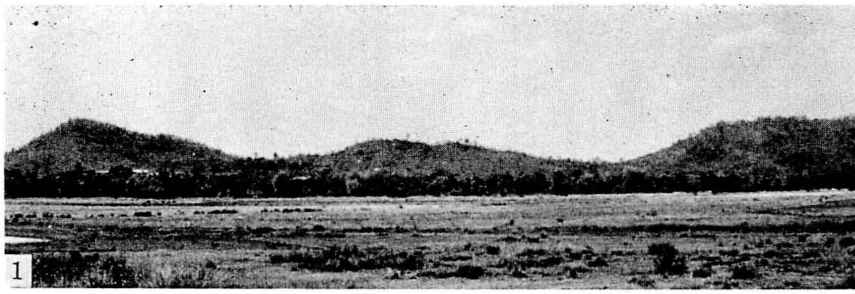
Fig. 1. Sisophon limestone hills. The hill at left side of the photograph is called Phnom Svai consisting of the B member. The central hill is called Phn. Tup consisting of the D member. The hill at right side is called Phn. Long K Tom consisting also of D member. C member is distributed at the valley between Phn. Tup and Phn. Svai, Sisophon region, Cambodia.

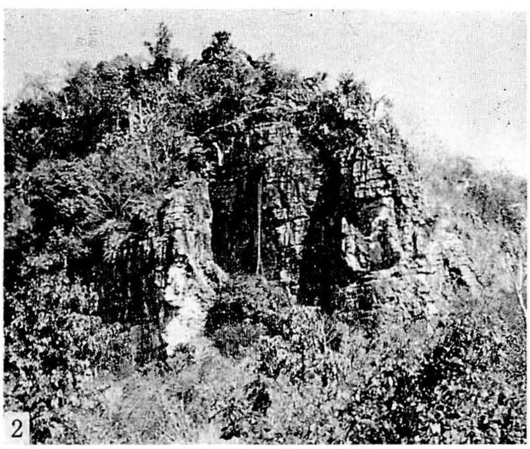
Fig. 2. Bedded limestone of the D member. Zone of *Yabeina m. multiseptata*. Phn. Bak, Sisophon region, Cambodia.

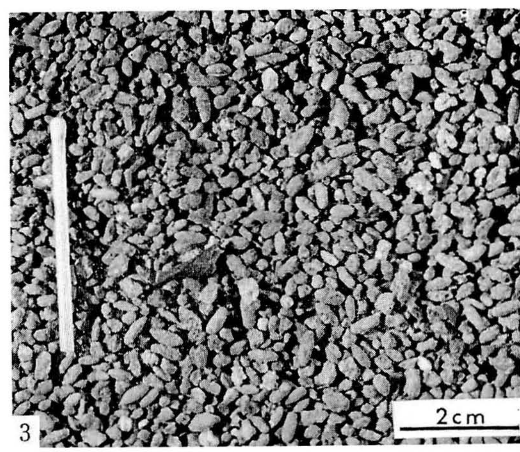
Fig. 3. The fossils observed on the weathered surface of a bedding plane (A member) are mostly composed of *Pseudodoliolina*. Fossils are included in volcanic tuff and are scarcely abraded by wave or current action. A member, the southern foot of Phn. Svai, Sisophon region, Cambodia.

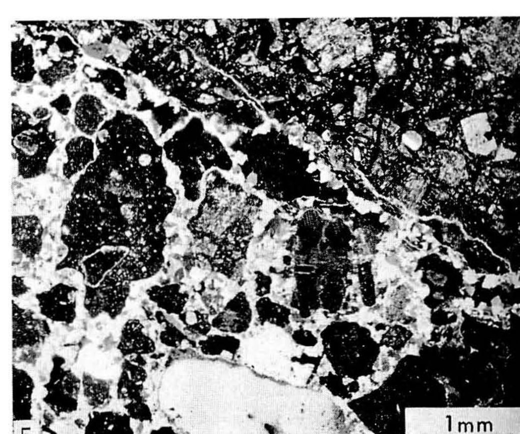
Fig. 4. Tuff breccia of A member. Locality *ditto*.

Fig. 5. Andesitic tuff breccia. Cementing materials consist of the volcanic fragments, calcite and calcareous materials including the crinoid fragments. Locality *ditto*.









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Explanation of Plate 10

Fig. 1. Skeletal-sparite. Rock is composed of broken tests of fusulinids (*Pseudodoliolina* and schwagerinid) and crinoid ossicles, all in sparite. Sisophon limestone, B member, Phn. Svai, Sisophon region, Cambodia.

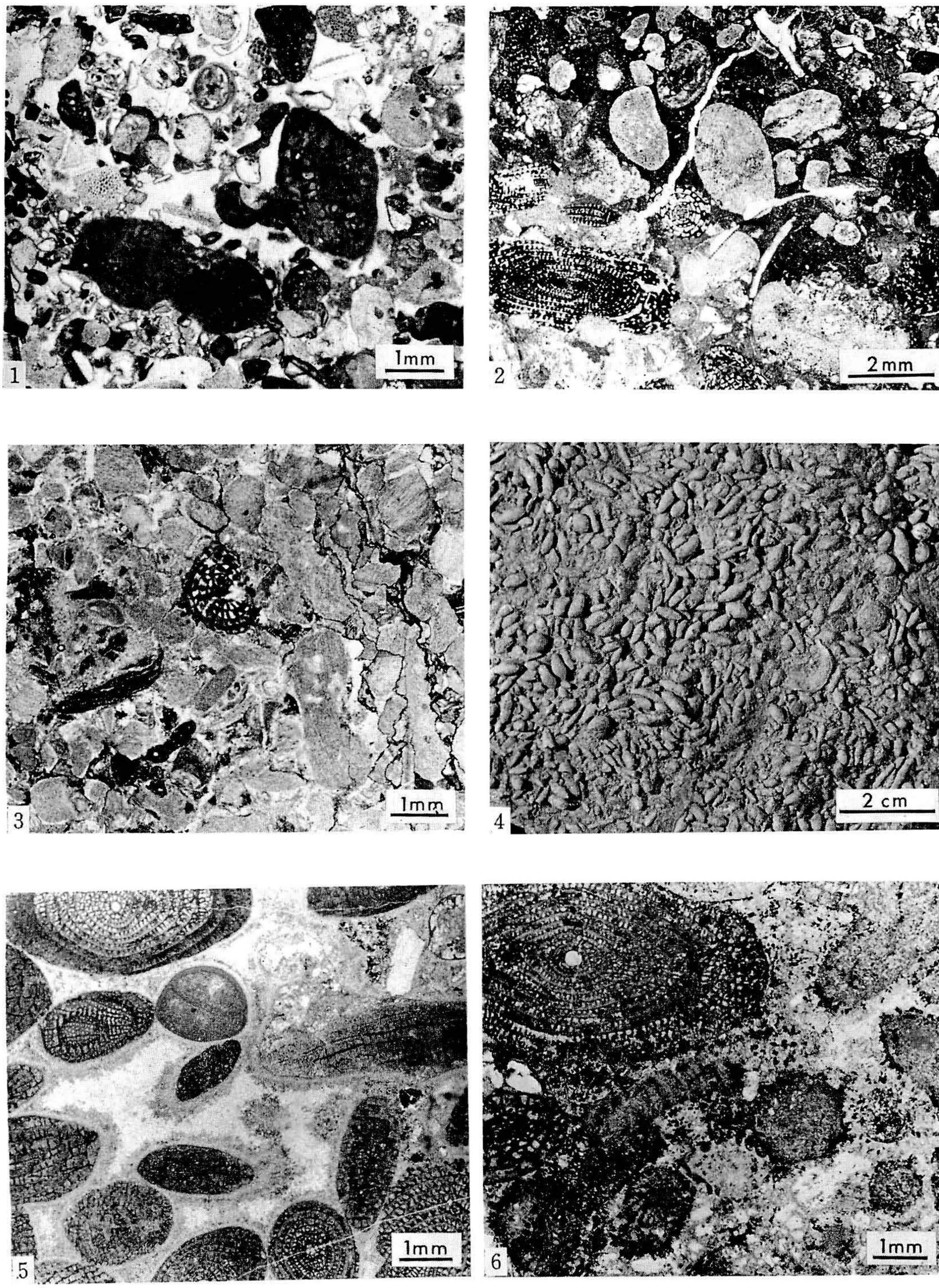
Fig. 2. Skeletal-micrite. Skeletons are composed of brocken tests of fusulinids (*Pseudodoliolina*) and crinoid ossicles embedded in micrite. This rock alternates with skeletal-sparite (pl. 10, fig. 1). B member. Locality *ditto*.

Fig. 3. Calcarenite. Allochems consist of crinoid ossicles and fusulinids fragments. Interstitial space is filled with micrite. Sisophon limestone, B member, Phn. Ancheang, Sisophon region, Cambodia.

Fig. 4. Fusulinid limestone. Fusulinids consist of *Yabeina*, *Schwagerina*, *Verbeekina*, *Sumatrina* and others. The upper part of C member, Phn. Bak, Sisophon region, Cambodia.

Fig. 5. Drusy coating skeletal limestone (grainstone). Fusulinid grains are surrounded by a thin layer composed of needle-like calcite, and fossils are diagenetically altered. The intergranular pore space is filled with medium-crystalline sparite. The upper part of C member. Locality *ditto*.

Fig. 6. Diagenetically altered skeletal limestone. Allochems consist of fusulinids. Interstitial space is filled with sparite. Fossils and matrix are impregnated with magnetite and limonite. The upper part of C member. Locality *ditto*.



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Explanation of Plate 11

Fig. 1. Sparite with skeletal material. Rock consists of abraded tests of fusulinids that are enclosed by medium-crystalline sparite. This rock alternates with skeletal-micrite (pl. 11, fig. 2). Sisophon limestone, D member, Phn. Bak, Sisophon region, Cambodia.

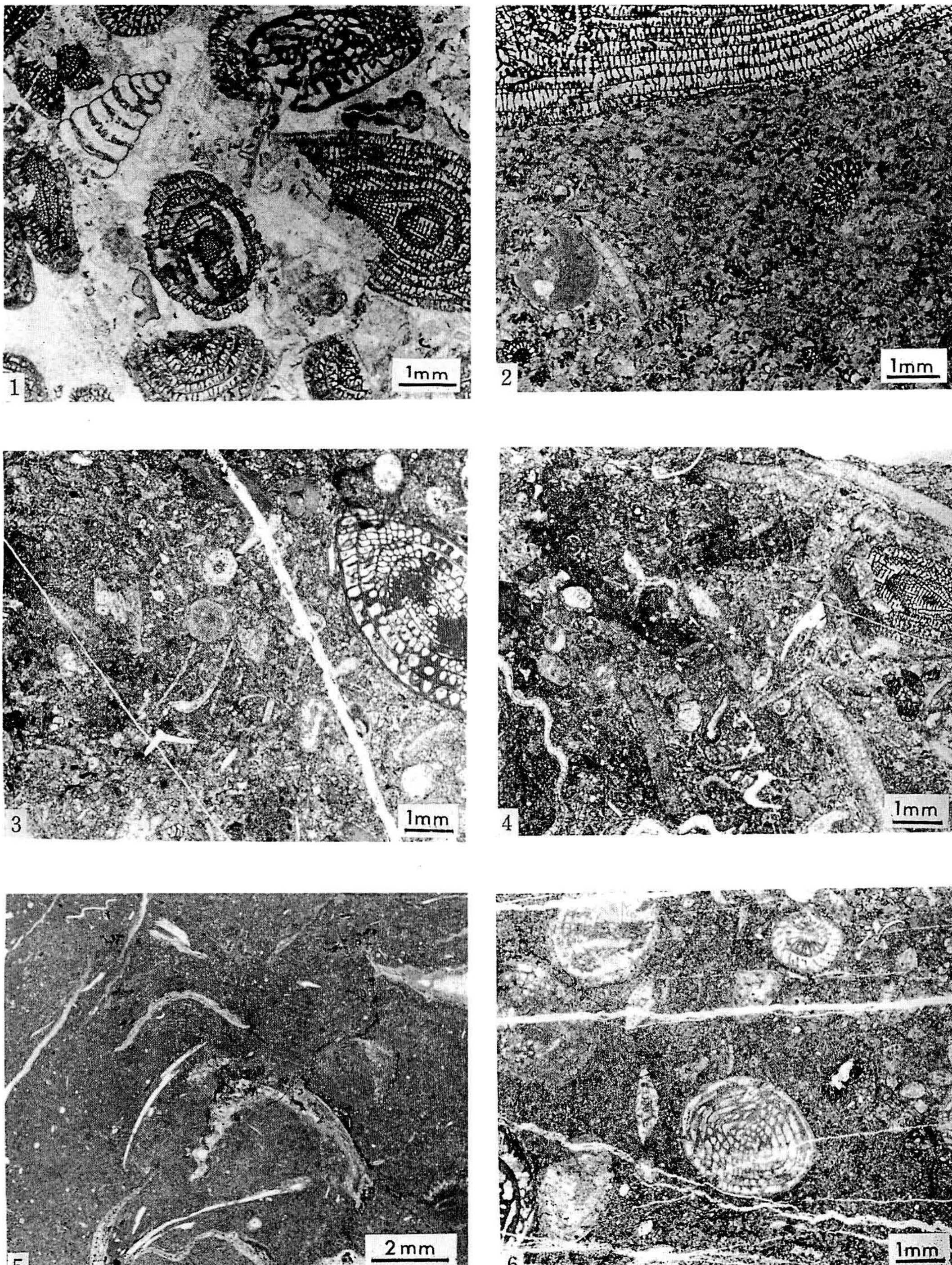
Fig. 2. Skeletal calcisiltite, skeletons are composed of abraded tests of fusulinids and other biogenic materials. Rock includes a lot of unabraded tests of fusulinid. This rock alternates with sparitic rock (pl. 11, fig. 1). Locality *ditto.*

Fig. 3. Skeletal calcisiltite. Skeletons are composed of fusulinid, crinoid and brachiopod shell fragments. This indicates the lagoonal facies. It is stratigraphically correlated with the B member of marginal facies (barrier reef) of Phn. Takream. Lower part of Phn. Popul limestone, Phn. Popul, Battambang region, Cambodia.

Fig. 4. Micrite with skeletal materials. Rock consists of silty-size grains, containing fusulinids (*Yabeina m. multiseptata*) and brachiopod shells. This indicates the lagoonal facies. It is stratigraphically correlated with the D member of the marginal facies (barrier reef) of Phn. Takream. Upper part of Phn. Popul limestone. Locality *ditto.*

Fig. 5. Micrite with skeletal materials. Rock includes brachiopod shell fragments in micrite. This indicates the lagoonal facies. Phn. Anseh, Battambang region, Cambodia.

Fig. 6. Calcareous mudstone with skeletal materials. Rock consists of fusulinids (almost wholly *Nankinella*) and biogenic materials, all in micrite. C member of Phn. Kdông, Battambang region, Cambodia.



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CONODONT-BEARING CARBONATE ROCKS

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1. Introduction

Conodonts have been found from various marine sedimentary rocks. Particularly carbonates are thought to be the most suitable rocks for conodont research. Most of the conodont workers have been devoted to establish the biostratigraphic zonation and systematics of conodonts, but they seem to have ignored the description of detailed lithology. We have observed numerous conodont-bearing carbonate rocks collected from various stratigraphic levels and localities of Japan, Thailand and Malaysia. The attempts have been made to elucidate the relations between various facies of carbonates and abundance of conodont specimens to know the optimums of conodont-bearing animals.

MÜLLER (1956) pointed out that conodonts are frequently associated with cephalopods and fish remains. According to him, however, abundant corals, crinoids, brachiopods and reefs seem to be unfavorable for association of conodonts. Furthermore, he emphasized that "the slower the rate of sediment accumulation, the better the chance for preservation of a good fauna". LINDSTRÖM (1964) showed the general tendency of conodont frequency per unit weight in marine sedimentary sequence of different thickness. He distinguished following five types of accumulation of marine sediments in relation to conodont frequency:

1) trough with thick pile of terrigenous sediments

2) distal trough with reduced rate of terrigenic sedimentation

3) submarine rise with little access to terrigenic sediments, top of rise kept clean of fine sediment by currents, conodonts and other heavy particles left as residue

4) basin with little access to terrigenic material, fine, eventually black, mud as bottom deposit

5) rise with thick carbonate deposits on top, eventually reef and reef debris.

Among these five types of environments, conodonts are most abundant in the third one, and are also fairly rich in the fourth one. The second one has less numerous conodonts than the above two. The first and fifth environments are very poor in number of specimens. His conclusion is similar to MÜLLER's and a great number of conodonts per unit weight are recognized in the sediments formed under slower accumulation. He further stated that "the fact the conodonts may occur in such great number in some deposits is certainly in part due to the circumstance

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that they are among the most resistant sediment particles, and in part to their relative heaviness. In carbonate rock sequences they may have been left after the carbonate was removed by subaerial or submarine dissolution. Thus, they would have been concentrated through chemical processes that destroyed the rest of the rock. On the other hand, their heaviness would prevent them from being carried away by currents that scoured the bottom deposits and removed other small particles thereby leaving the conodonts as a residue."

Recently KOHUT and SWEET (1968) have reported an interesting fact of the distribution of conodonts in the Cincinnati region in North America. *Rhipidognathus symmetrica symmetrica* BRANSON and MEHL seems to have flourished in a near shore, shallow water environment, perhaps on the tidal mud flat that was periodically exposed to the atmosphere. *Panderodus gracilis* (BRANSON and MEHL) is particularly abundant and associated with large compound corals in the Bardstown Reef in the Fredericktown, Kentucky section. On the other hand, *Phragmodus undatus* BRANSON and MEHL and others have been found in deep water sediments.

WINDER (1968) made faunal analysis in the Middle Ordovician of Lakefield, Ontario, Canada. He graphically showed the frequency of conodonts and carbonate petrography. MÜLLER (1962) suggested that the genus *Icriodus* is fairly abundant in a certain facies only (e. g., near-reef) and it may well be considered that these become adapted to a benthonic mode of life, or at least lived near the bottom. Subsequently, however, KLAPPER and ZIEGLER (1967) extensively studied *Icriodus* came from Europe and North America and they called MÜLLER'S opinion in question. They have obtained *Icriodus* faunas from limestones of various kinds of lithology that represent different depositional environments. Their samples include cephalopod limestone, crinoidal limestone, marly limestone and a coral biostrome.

Similar investigations of the paleoecological meaning of conodont distribution seem to be more necessary for each conodont fauna. We describe and discuss herein the relations between conodont frequency and carbonate types.

2. Lithologic Characteristics of Some Conodont-bearing Carbonate Rocks

As has already been mentioned by many workers, conodonts are rich in cephalopod limestone throughout the world. We examined several cephalopod limestones collected from the Carboniferous Omi limestone, Niigata Prefecture; the Triassic Taho limestone, Shikoku; the Lower Triassic limestone, Kelantan, Malaysia; the Lower Permian limestone in North Thailand; the Ordovician and Silurian limestones in northern Malaysia and southern Thailand. The Omi limestone is thick organic limestone, ranging from late Early Carboniferous to Permian. The Carboniferous part of this limestone contains rich conodont fauna (KOIKE and WATANABE, MS). IGO and KOIKE (1964) have already described well-preserved and numerous conodonts from the cephalopod limestone. This limestone (Pl. 12, Fig. 5) is white to pale gray and massive to thick-bedded. This limestone is typical well-sorted biosparite and consists mostly of ammonoids and interlocking clear sparry calcite. Conodonts are preserved within sparry calcite. Fragmentary bryozoans, foraminifers, brachiopods, crinoids and lime mud are minor constituents of this limestone. These organisms were undoubtedly transported from some distant area. However, no distinct abrasion can be observed on the surface of ammonoid shells and even delicate conodonts, such as *Hindeodella, Synprioniodina, Ligonodina* and others, are well-preserved. Therefore, ammonoids and conodonts seem to be autochthonous or paraautochthonous. The environment of deposition of this limestone is thought to be off-shore and rather agitated sea water on a raised sea floor. It is worthy to note that conodonts are rather resistant under such assumed agitated condition.

In the Triassic limestone of Taho, Ehime Prefecture, ammonoid-bearing limestone is thin-bedded, dark gray and yields abundant conodonts in association with pelecypods and fish remains. Under the microscope this limestone is mostly biosparite. Allochems are dolomite euhedra and its fragments, pelecypods, ammonoids, fish dermal spine and teeth, and problematical fossils. They are cemented with rather small crystals of clear calcite and fine lime mud. Conodonts are scattered at random in sparry calcite cement (Pl. 14, Fig. 1). Conodont specimens are very numerous and can be frequently seen even in thin sections although fragmentary. The Lower Triassic ammonoid limestone distributed in the Gua Musang area, Kelantan, Malaysia, contains a great number of conodonts (IGO, KOIKE and YIN, 1965). Under the microscope this limestone is typical biosparite and the interlocking calcite crystals are clear and fairly large (Pl. 12, Fig. 6). Frequency of conodonts in this limestone attains more than 300 in 1 kg. rock sample and can be seen even with the naked eyes.

Ammonoid-bearing Permian limestone distributed near Loei, northern Thailand, is white and thickly bedded or massive. It is very fossiliferous, containing fusulinids, algae, brachiopods and many others, in addition to numerous well-preserved conodonts. Petrographically the limestone is typical biosparite and cemented with large sparry calcite crystals in the space between the above mentioned fossils and also with a small amount of fine lime mud. Fusulinids and other microfossils show some attrition but brachiopods and ammonoids do not show any abrasion and seem to be authochthonous.

Characteristic microfacies of the above mentioned examples of cephalopod limestones are mostly typical biosparite and conodonts are embedded within the sparry calcite. Lime mud and other initial sediments were winnowed away by current or agitating water but conodonts remained as residue and were concentrated. Interstitial pores were later filled by direct precipitation of sparry calcite cement.

Conodonts have been found at many stratigraphic levels of the Ordovician and Silurian thick sequences of limestone distributed in northern Malaya and southern Thailand (IGO and KOIKE, 1967, 1968). This limestone is called the Setul limestone in Malaysia. The Setul limestone is subdivided into the upper and lower parts, with the intercalated detrital member in between, and consists mainly of black to dark gray limestones bedded in various grade of thickness. Dolomitized part or reddish limestone is interbedded at various horizons. JONES (1968) suggested that the Setul is a typical miogeosynclinal sediment. KOBAYASHI (1959), KOBAYASHI and HAMADA (1963) described gastropods, cephalopods, trilobites and others from this limestone. IGO and KOIKE (1967, 1968) discriminated many conodonts from more than ten different stratigraphic levels. Microfacies of this limestone is variable but mostly biomicrite and intercalating biosparite and intrasparite. One of the most prolific conodont beds is situated at the basal part of the upper Setul formation immediately above the graptolite shale. This limestone is gray and well-bedded, containing orthoceratids, trilobites and conularids. Microscopically this limestone is fine micrite (Pl. 12, Fig. 1). Fossil fragments are allined parallel with the bedding plane and are cemented with fine-grained dark lime mud. More than 300 individuals of conodonts are counted per 1 kg. rock sample.

About 40 meters above this bed is a thin-bedded, earthy and dark gray limestone, which again contains numerous well-preserved conodonts. Large orthoceratids are frequently associated with the conodonts. This limestone is micrite in texture (Pl. 12, Fig. 2). Minute brachiopod shells and spherical problematical fossils are cemented with earthy fine material. Limestones at various horizons of the lower Setul formation are also rich in conodonts. They are mostly biomicrite consisting of brachiopod shells, trilobites and gastropods. Intrasparite intercalated in the lower part of the Setul (Pl. 12, Fig. 4) yields a rich conodont fauna. Intraclasts show rhythmic lamination which are cemented with fine sparry calcite. Similar limestones are developed in the southern part of peninsular Thailand. Red, cephalopod limestone exposed near Ban Na, Tung Soung, is particularly rich in conodonts. Under the microscope this limestone is also typical biomicrite and large cephalopods, small brachiopods and bryozoans are cemented with hematitic fine lime material.

The depositional environment of these widespread Ordovician and Silurian limestones was a rather off-shore miogeosynclinal trough as suggested by JONES (1968). No reef type sediments are observed in these limestones. As mentioned above, the Setul and Tung Song limestones yield abundant conodonts from the residue, but cephalopod limestones are particularly rich in conodonts.

Crinoidal limestones are also sometimes rich in conodonts. The Mississippian crinoidal limestones distributed in the Upper Mississippi Valley region of the Mid-continent in North America carry numerous conodonts (COLLINSON *et al.*, 1959; etc.). The Ichinotani limestone developed in the Fukuji area, Gifu Prefecture, central Japan, is well-known Carboniferous fossiliferous limestone and worked out by IGO (1957). Characteristic crinoidal limestones are intercalated at several horizons, and most of them yield numerous conodonts. These crinoid limestones are the so-called skeletal limestone and angular to subangular fragments of crinoids are closely packed and surrounded with sparry calcite cement (Pl. 14, Fig. 3). Lithology of these limestones shows considerable agitation by wave or current.

As will be discussed later, the Atetsu limestone developed in the Atetsu plateau, Okayama Prefecture, southwestern Japan, contains prolific conodont faunas, which were worked out by KOIKE (1967). Most of the conodont-rich beds are composed largely of fragmentary crinoids.

Brachiopod limestones treated by us sometimes contain abundant conodonts. We have found numerous well-preserved conodonts from the lower part of the Akiyoshi limestone (IGO and KOIKE, 1965). This limestone is brachiopod coquinoid limestone composed of heaped brachiopod shells. We also collected Carboniferous conodonts from brachiopod limestone developed in the Sungei Lembing area, Kuantan, Malaysia (IGO and KOIKE, 1968).

As has been pointed out by YOUNGQUIST (1952) and others, conodont association with fish remains (bone, scale, dermal denticles and teeth) is very common. The Triassic Taho limestone, mentioned above, intercalates black to dark gray dolomitic beds containing abundant fish remains. Dermal denticles, teeth and others are very common in these beds associated with numerous conodonts. Microscopically these limestones are biomicritic and allochems are cemented with less amount of fine lime material. As has already been pointed out by MÜLLER (1956) and others, coral and algal limestones contain very few conodonts. His opinion is widely accepted, though with some exceptional cases. We treated numerous coral and algal limestones collected from various localities in Japan. The Fukuji limestone exposed in the Fukuji area, Gifu Prefecture, contains abundant Devonian reef corals, such as *Favosites* (s. l.), *Heliolites* and many others, which are associated with stromatoporoids and brachiopods. So far as we are aware, no conodonts have been found in this fossiliferous limestone.

The Lower Carboniferous Onimaru limestone distributed in the Kitakami massif is highly fossiliferous and contains prolific coral and brachiopod faunas. This well-bedded black to dark gray earthy limestone is also devoid of conodonts. *Halysites*-bearing Silurian limestone developed in Yokokurayama, Kochi Prefecture, Shikoku, is also barren of conodonts, but different types of limestone collected from the same limestone body contain fairly abundant conodonts.

We have dissolved many samples of fusulinid limestones collected from various parts of Japan and southeastern Asia and those from some parts of North America, but conodonts are rare or mostly absent. Some Carboniferous fusulinid limestones collected from the Ichinotani formation, Gifu Prefecture, Omi limestone, Niigata Prefecture, and Atetsu limestone, Okayama Prefecture, contain conodonts. Generally speaking, limestones crowded with fusulinids have uncommonly conodonts.

3. Relations between Frequency of Conodonts and Microfacies observed in the Carboniferous Atetsu Limestone, Southwestern Japan

KOIKE (1967) discriminated numerous conodonts from the Atetsu limestone distributed in northwestern part of Okayama Prefecture, southwestern Japan. The Carboniferous part of this huge limestone mass is subdivided into the Nagoe and Kodani formations in ascending order. He collected conodonts from several almost continuous sequences and calculated the number of specimens per one kilogram rock sample. We have reexamined the relations between microfacies of this limestone sequence and the frequency of conodonts. As a result we have obtained some initimate connections between them.

The Nagoe formation is composed of bedded limestone, with thin intercalates of chert, and tuffaceous limestone. Microfacies of the limestone is mostly biomicrite and biomiclutite. Biomicrudite is also recognized but less common. Generally speaking, conodonts are rich in thin-bedded biomicrite and biomiclutite. Conodonts are less numerous or entirely absent in the tuffaceous limestone. Allochemical composition of conodont-rich limestone is fragments of crinoids, bryozoans, fusulinids and other foraminifers. Crinoid fragments constitute almost 80 to 95 per cent of total allochems throughout. We measured the diameter of allochems in thin slices (average size 4.5 cm×6.0 cm.), although larger fossils and a few other larger allochems are excluded. We treated the allochems with diameters larger than 0.05 mm and smaller than 1.0 mm and obtained the median diameter and TRASK's sorting coefficient of these allochems.

The Kodani formation is mainly composed of thin-bedded biomicrite and biomiclutite with intercalated thin layers of chert. Conodonts are contained in almost entire part of the formation. Crinoid fragments occur abundantly as the allochemical components throughout. The vertical fluctuation of number of conodont specimens, the median diameter and the sorting coefficient of allochems are shown in Text-fig. 1. The diagram has been obtained from the lower to middle part

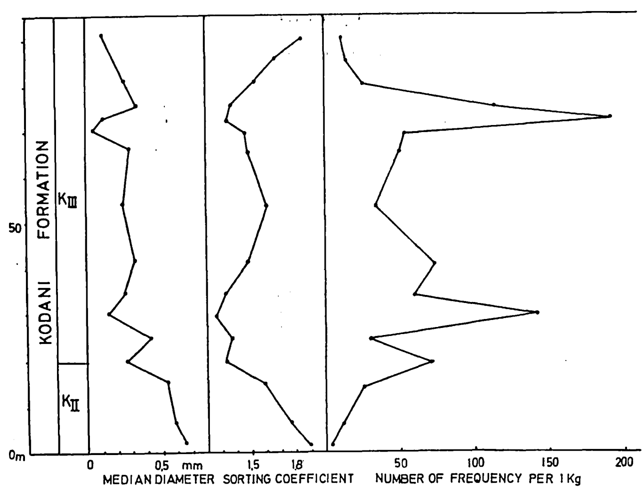

Fig. 1. Vertical fluctuation of the number of conodonts, median diameter and sorting coefficient in KII and KIII of the Kodani formation.

of the Kodani formation (KII and KIII of the Morikuni section) which yields conodonts almost successively. The sorting coefficient of allochems ranges from 1.25 to 1.9 in this section. There are tendency that the limestone with comparatively numerous conodonts (over 100 specimens per 1 kg.) have the sorting coefficient of 1.2 to 1.3. In other words, well-sorted limestone is rich in conodonts. On the other hand, there is no distinct relation between the median diameter of allochems and number of frequency. Some limestone beds consisting of fine allochems are rich in conodonts, but some others consisting of similarly fine allochems have less common conodonts. Generally speaking, however, conodont-rich beds consist of fine and well-sorted allochems. The upper part of the Kodani formation (KIV of the Iwamoto section) also yields conodonts almost successively. Text-fig. 2 shows the vertical fluctuation of the median diameter and the sorting coefficient of allochems related with the number of the specimens per 1 kg of the upper part of KIII and KIV members. The median diameter of allochems is generally larger than those of KII and lower part of KIII. Conodont-rich beds (over 100 specimens per 1 kg.) have about 0.5 mm in the median diameter of allochems. Limestone beds

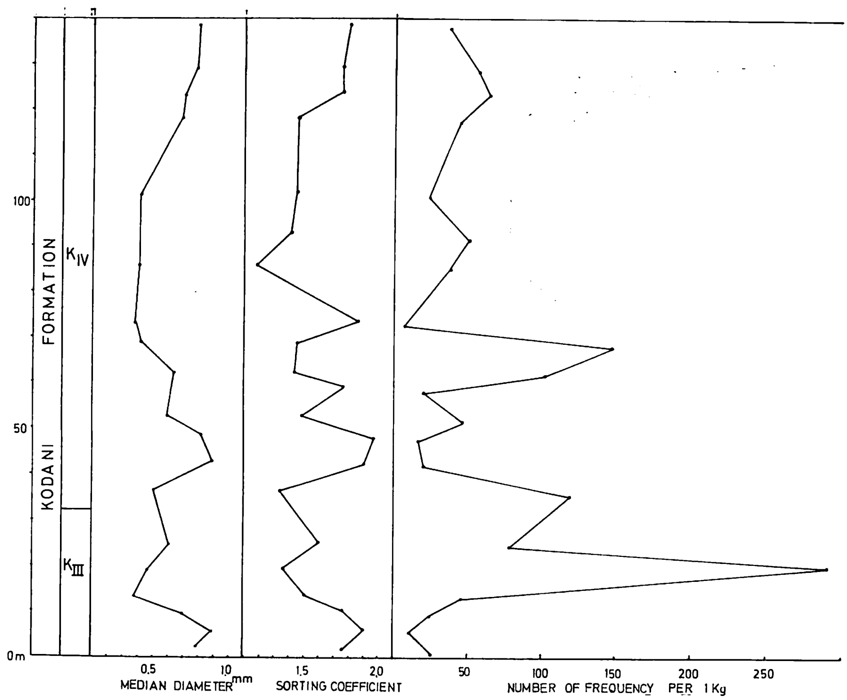

Fig. 2. Vertical fluctuation of the number of conodonts, median diameter and sorting coefficient in KIII and KIV of the Kodani formation.

consisting of coarser allochems do not contain numerous conodonts. There is again an interesting relation between the sorting coefficient and the number of frequency. Limestone beds including prolific conodonts are always well-sorted. The sorting coefficient always becomes lower in conodont-rich bed, with a few exceptions, in this part of the Kodani formation. As demonstrated in Text-fig. 2 the sorting coefficient is in inverse proportion to the number of frequency.

It is worthy to note that the number of conodont specimens per unit weight has an intimate relation with the sorting and the median diameter of allochems. Unfortunately, in the Nagoe formation conodonts do not occur successively. Therefore, the measured thin slices of conodont-bearing limestone are less numerous than those of the Kodani. We plotted the average number of frequency in the axis of ordinate and the median diameter of allochems in the axis of abscissa which were measured from the Nagoe and Kodani formations (Text-fig. 3). This diagram shows bimodal relations between them. Namely the highest peak of the average number of frequency is found at 0.25 mm of the average median diameter of allochems. The other minor peak can be seen at 0.65 mm of the average median diameter. Generally speaking, limestone types consisting of 0.2 to 0.7 mm of the average diameter of allochems almost constantly yield numerous conodonts. Average size (length) of conodonts in the Nagoe and Kodani formations is about 0.5 mm. Therefore, there are some relations between the average size of conodonts and the median diameter of allochems.

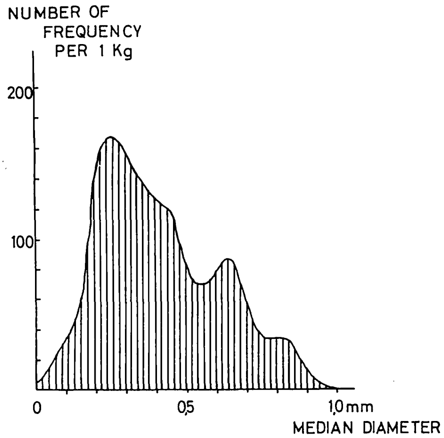

Fig. 3. Relation between the average number of conodonts and the average median diameter of allochems in the Nagoe and Kodani formations.

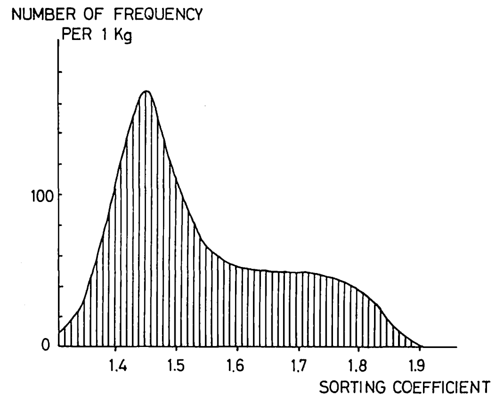

Fig. 4. Relation between the average number of conodonts and the average sorting coefficient of allochems in the Nagoe and Kodani formations.

Text-fig. 4 shows the relation between the average number of conodont specimens per 1 kg rock sample and the average sorting coefficient of allochems obtained from the thin sections of both Nagoe and Kodani formations. The peak of frequency corresponds with the sorting coefficient of 1.45.

In conclusion there is a considerable range in the relation between the average median diameter of allochems and conodont frequency, but well-sorted limestone beds are rich in conodonts. Furthermore, there are some relations among conodont frequency, the median diameter of allochems and the individual size of conodonts. Therefore, conodont frequency in the Nagoe and Kodani formations may be related to the wave or current agitation during the deposition.

4. Concluding Remarks

There are no distinct relations between limestone-building organisms and conodont frequency. However, it is true that the particular organisms such as cephalopods, fish remains and ostracods are associated with prolific conodont faunas. Biostromal and biohermal limestones are generally rare in conodonts, but there have been reported many exceptions. Conodonts often occur independent of facies and conodont-bearing animals are considered to have been nekton rather than benthos. Mostly bilateral symmetry in morphology of conodonts also suggests the nektonic mode of life. Conodont frequency in a unit weight does not directly show the abundance of conodonts. Slower rate of carbonate deposition or more removal of finer materials has the occasion of more numerous conodont accumulation in the unit weight of sediments, and *vice versa*.

Sparite microfacies of cephalopod limestone and crinoid limestone which contain rather prolific conodont faunas may be interpreted by the above mentioned consideration. The sparsity of conodonts in rapid accumulated reef and other type deposits may be also explained for the same reason. Furthermore, we have the following hypothesis about the mode of life of conodont animals. The fact that certain conodonts occur in particular types of organic limestone (e. g., cephalopod limestone) and that certain others are independent of facies suggests that conodont-bearing animals were not wholly free swimmers (nekton) but some of them took other mode of life. In other words, there may have been epiplanktonic conodonts besides the nektonic ones. Conodont-bearing animals may have been widely distributed in attachment with the active swimmers, such as cephalopods and fishes. Also they could be removed for a considerable distance in attachment with some floating algae.

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Plates 12–14

Hisayoshi IGO and Toshio KOIKE

Conodont-bearing Carbonate Rocks

Explanation of Plate 12

Fig. 1. Biomicrite of the basal Upper Setul formation (Lower Silurian), Langkawi Islands, Malaya. Conodonts are particularly rich in this limestone (negative print $\times 15$).

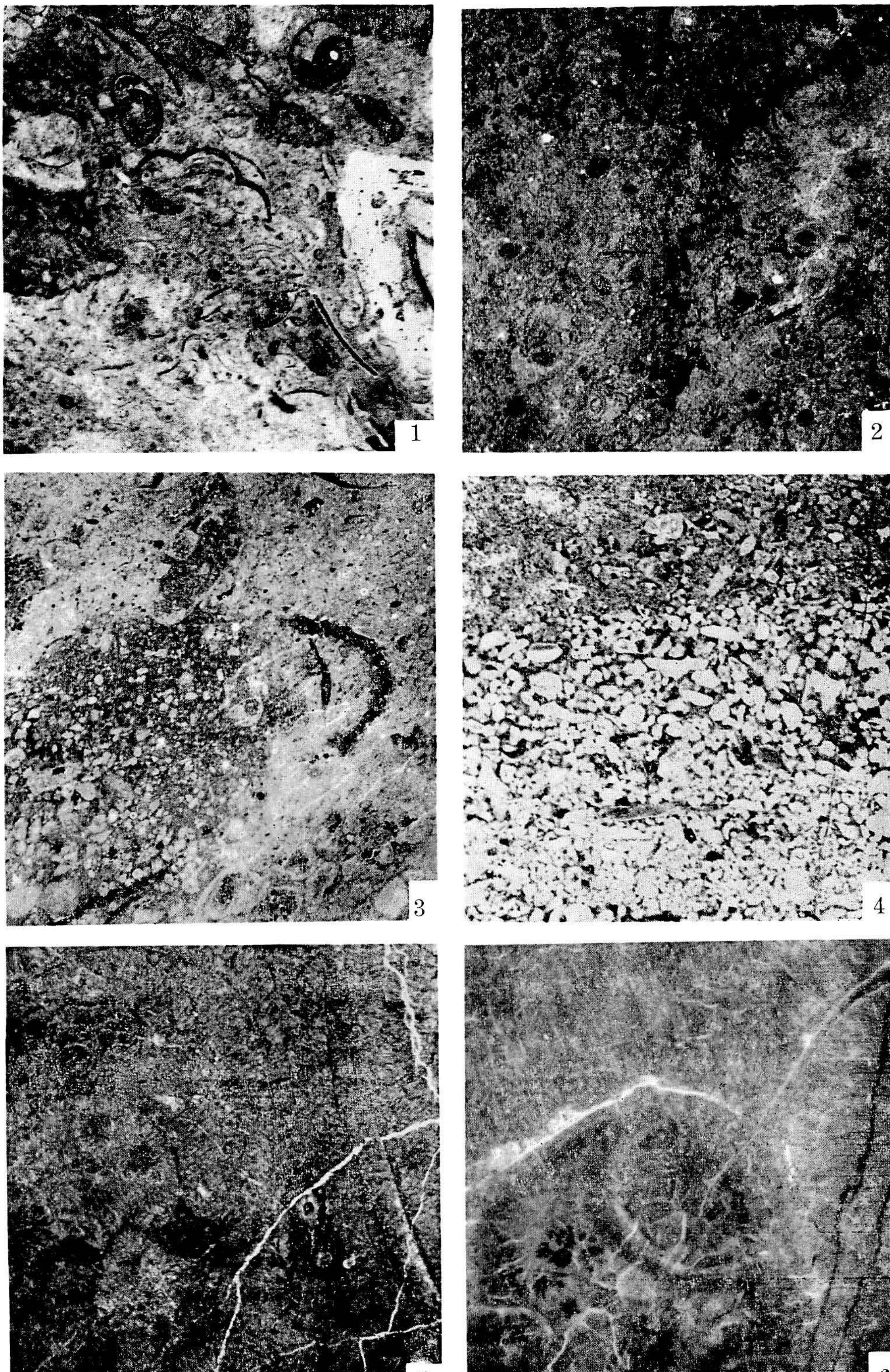
Fig. 2. Biomicrite of the Upper Setul formation (Middle Silurian), loc. ditto. Spherical problematical fossils and orthoceratid are associated with abundant conodonts (negative print $\times 15$).

Fig. 3. Biomicrite of the Lower Setul formation (Middle Ordovician), loc. ditto. (negative print $\times 15$).

Fig. 4. Conodont-rich intrasparite of the Lower Setul formation, loc. ditto. Intraclasts show grading and are cemented with fine sparry calcite (negative print $\times 15$).

Fig. 5. Conodont-rich ammonoid limestone. Omi limestone (Carboniferous), Niigata Prefecture, Japan. Large sparry calcite crystals cement the interstitial cavity (positive print $\times 10$).

Fig. 6. The Lower Triassic conodont-ammonoid limestone, Gua Musang, Kelantan, Malaya. Conodonts are preserved within sparry calcite (negative print $\times 15$).

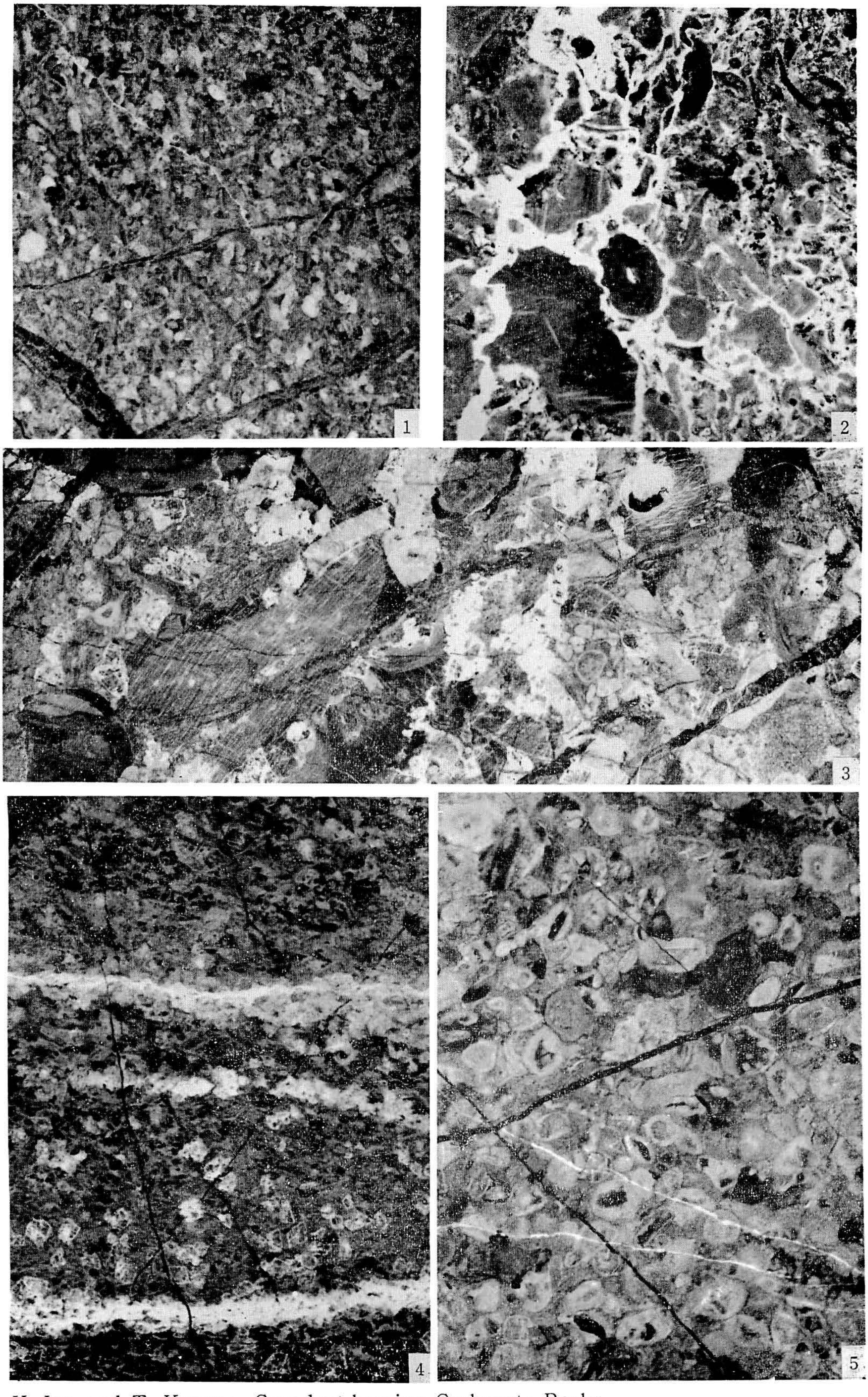


H. IGO and T. KOIKE: Conodont-bearing Carbonate Rocks

Explanation of Plate 13

Figs. 1–5. Conodont-rich Atetsu limestone (Carboniferous), Okayama Prefecture (all negative print $\times 15$).

1. Conodont-rich well-sorted biomicrite of the Kodani formation.
2. Crinoidal biosparite of the Kodani formation. Crinoidal fragments are cemented with clear sparry calcite.
3. Crinoidal biomicrite of the Kodani formation.
4. Thinly laminated dolomitic limestone of the Kodani formation.
5. Well-sorted biomiclutite of the Kodani formation.



H. IGO and T. KOIKE: Conodont-bearing Carbonate Rocks

Explanation of Plate 14

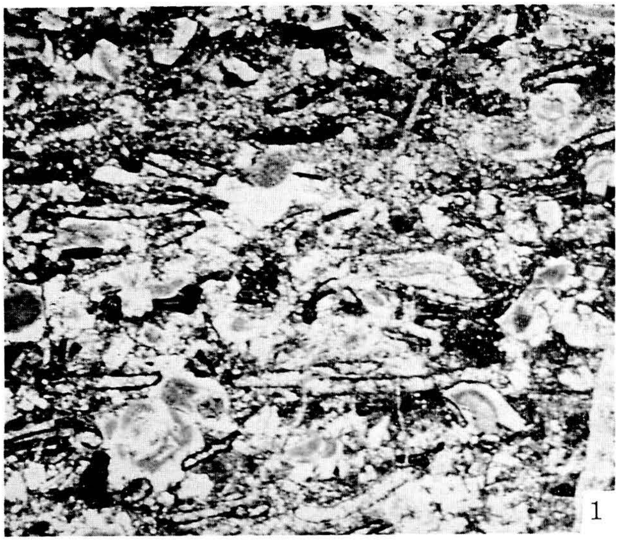
Fig. 1. The Triassic Taho limestone, Ehime Prefecture, Shikoku. Problematical cylindrical fossils, conodonts and dolomite crystals are cemented with finely crystalized sparry calcite (positive print $\times 18$).

Fig. 2. Intrasparite of the conodont-rich Lower Setul formation (Middle Ordovician), Langkawi Islands, Malaya (positive print $\times 18$).

Fig. 3. Crinoidal limestone of the Ichinotani formation (Carboniferous) Fukuji, Gifu Prefecture (positive print $\times 18$).

Fig. 4. Biosparite of the basal Permian limestone, near Loei, north Thailand (positive print $\times 18$).

Fig. 5. Well-sorted biomicrite of the Kodani formation, Atetsu limestone. More than 150 specimens of conodonts are counted per 1 kg of this limestone (negative print $\times 15$).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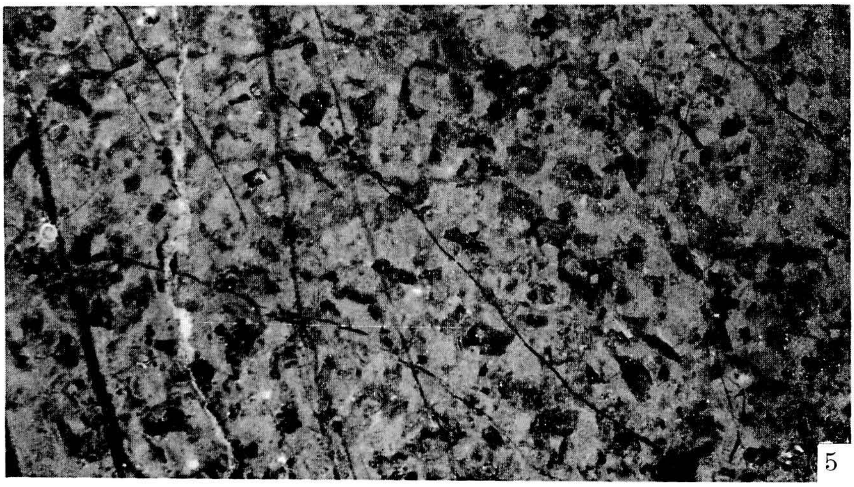
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H. IGO and T. KOIKE: Conodont-bearing Carbonate Rocks

STUDY OF FINE GRAINED CARBONATE MATRIX: SEDIMENTATION AND DIAGENESIS OF "MICRITE"

By

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1. Introduction

Regarding carbonate rocks, a number of attempts at precise classification have been made (e. g. FOLK, 1959, 1962; TODD, 1966) and there are also a large number of studies comparing carbonate rocks and recent calcareous sediments (e. g. ILLING, 1954). Excellent studies have also been made in applied fields such as the development of carbonate oil reservoirs and porosity in carbonate rocks (e. g. HARBAUGH, 1967).

The origin of carbonate rocks has been investigated by extensive field studies as well as by diversified experiments to substantiate various theories (e. g. CLOUD, 1962). In particular, some investigators have emphasized the importance of organisms in forming and modifying carbonate sediments, especially the formation of very fine grained carbonate particles (called *micr*ocrystalline calc*ite* or "micrite" by FOLK, 1959).

Other investigators, however, have put emphasis on the role of inorganic precipitation in forming "micrite". Even accepting inorganic precipitation, it may well be doubted whether or not the origin of most fine grained carbonate rocks can be explained in such a simple manner in view of their complicated and diversified nature.

As described in a later part of this report, the author now envisages a method to determine whether the micrite in a fine grained limestone is of organic or inorganic origin. The prime purposes of the present work are to examine in detail the "micrite" of various fine grained limestones and to clarify the sedimentary mechanisms involved in the light of carbonate petrology utilising electron microscope and geochemical observations.

2. Components of Carbonate Rocks

The major components of carbonate rocks can morphologically be classified into the following categories: (1) Grains, skeletal and nonskeletal, (2) Micrite, (3) Cement, and (4) Pores (or Vugs).

Sedimentary carbonate rocks normally contain a large amount of subsidiary components including terrigenous material and may also include significant amounts

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of clay minerals which are of authigenic origin; in fact, many normally appearing carbonate rocks may contain very large amount of non-carbonate minerals.

Carbonate cements are of authigenic origin and often consist of clear transparent crystals filling intergranular space, and can thus be easily identified. These carbonate cements are equivalent to the silica cement in sandstone. Spar, a type of coarse calcite, is represented in many cases by the large and transparent crystals of wedge shape which fills the intergranular space.

Porosity is an important factor in determining the reservoir properties of carbonate rocks for hydrocarbons, and may occur in various forms but it takes diversified shape.

Grains are equivalent to sand grains in sandstone and are normally represented by particles larger than 30 μ in diameter, that is larger than fine silt size (LEIGHTON and PENDEXTER, 1962). Grains may also include non-skeletal carbonate particles such as, pellets, lumps, öolites and oolith shaped spherical objects. Fossils are of course an integral component of carbonate rocks and such rocks without fossils or their traces are rarely found.

The carbonate matrix formed by particles which are smaller than the grains is called " micrite ". Though has been defined according to its size, the exact size has not been fully discussed. It is generally understood that the micrite is smaller than fine silt but some students as FOLK (1962) limit use of the term to particles of clay size, less than 4 μ; others, such as LEIGHTON and PENDEXTER (1962), consider micrite as particles less than 30 μ in diameter.

Very often it turns out that the term " micrite " is applied to any fine grained carbonate material which cannot be clearly resolved with the optical microscope. It is quite natural then that a great discrepancy arises in the use of this term, depending on the resolution of the microscope used, and depending also on whether or not observation is made on fracture surface, on a polished surface, or in a thin section.

" Micrite " has also been considered either as un-lithified calcareous ooze or as lithified calcareous mud resulting from diagenetic process. Therefore the usage of the term varies depending on the interpretation of the individual workers.

3. Fine Grained Matrix or " Micrite "

Until now micrite has not been precisely defined either morphologically or genetically. Many workers consider any fine grained carbonate matrix that cannot be clearly resolved in thin sections as " micrite ", but thin section studies by optical microscope do not permit detailed examination. Thus there has been a tendency to lump all " micrites " together and no attempt has been done for more precise descriptive or genetic classifications.

However, there is no reason to state that the fine grained matrix of all limestones is of the same origin and at least two different origins are discussed in this paper. The author, therefore, will often use in this report such terms as matrix of limy ooze, matrix of limestone or aphanitic limestone depending on the individual cases. " Micrite " has been defined as calcite particles smaller than silt size, but the author is of opinion that even this numerical definition may not be entirely valid.

The fine grained carbonate matrix is almost ubiquitous in most unmetamorphosed limestones. Aphanitic limestones, composed either entirely of matrix or of matrix and fossils are extensively distributed throughout the geologic column and are one of the most common sedimentary rocks. The matrix of limestone is considered not simply fine grained-product of sedimentary process (as are clays in terrigenous rocks) but rather as an independent element with a unique origin. The author is also of opinion that the formation of matrix takes a fundamental role in the genesis of limestone.

4. Marginal Efficiency of the Optical Microscope and Application of the Electron Microscope

Binocular (stereoscopic) microscopes which have often been used for the study of carbonates, have a maximum magnification of about 200X. With this power, theoretical resolution obtainable will be approximately 15 μ, but in fact the actual value is much lower because of topographical complexities and incoherent illumination. The aperture number of a high power objective lens reaches as high as 1.37, and with this the theoretical limit of resolution reaches 0.4 μ. This, however, does not mean that a grain of 0.4 μ in diameter can easily be resolved when observation is made on a thin section of an aphanitic limestone. Petrographic thin sections are normally ground to a thickness of about 30 μ for convenience in identifying rock forming minerals. Thin section of limestones designed for the identification of fusulinids and other fossils are in many cases even thicker, e. g. 50 μ.

If the fine carbonate grains in a limestone are 5 μ in diameter, a normal thin section would be composed of numerous grains stucked on top of each other. When this thin section is illuminated by coherant light, the crystalline surfaces of the lower layer in the thin section will cause light scattering, and will negate the effects of the condenser in concentrating light on the section. And even though an objective lens with a large aperture is used, its resolving power in the optical system will sharply decrease. Actual resolution of the microscope in a thin section of 30 μ thickness, and containing crystals about 5 μ in diameter, is thus less than 4 μ.

A thin section that is 2 or 3 μ thick will provide better microscopic resolution without the handicaps as mentioned above but such a section has notably inferior contrast, thus making it harder to observe the precise grain shape. For these reasons, it is virtually impossible to conduct thorough studies of "micrite" grains with an optical microscope.

Electron microscopes have extraordinary resolution as compared to optical microscopes; they enable us to observe small object ranging from a several microns to a few angstroms in diameter and their resolution is several thousand times greater than optical microscopes.

Therefore, the application of electron microscopy would be appropriate for clarifying the morphology of the fine grained matrix of limestones (FISCHER, HONJO and GARRISON, 1967). However, an electron beam differs from a beam of light and it has very weak penetrating power. Thus it is almost impossible to make electron microscopic observations directly on the thin section of limestone unless a unique method is adopted, such as ultra high voltage electron microscopy (HONJO, 1969, in press). The author, therefore, has adapted a carbon replica method in which the topography of a rock surface is replicated with a carbon film thin enough for the electron beam to penetrate (e.g. HONJO and FISCHER, 1964). As described later, electron microscopic observation of replicas of ground, polished and etched surfaces (G. P. E. surface) has proved of great value in the study of the fine grained matrix of limestones.

One of the purposes of this paper is to present some of the findings on the fine grained matrix of limestone using the electron microscope.

5. Method of Sample Replication for Electron Microscopy

The preparation of replicas for electron-microscopic observation can be divided generally into the one stage replica method and the two stage replica method. In this report, the author has adopted the latter technique, the precise details of which are described elsewhere (HONJO and FISCHER, 1965; HONJO, 1969).

The two stage replica method is the optimum technique for the study of fine grained limestones. Using this method, one has a choice in the type of surface that is to be replicated: (1) artificial or natural fracture surfaces (SHOJI and FOLK, 1964) or (2) polished and etched surfaces (HONJO and FISCHER, 1964). To date there has been no evaluation of which types of surface yield the best information. Percussion fracture method, hereafter abbreviated as the P. F. method, involves obtaining the first stage replica, using materials such as acrytic resin and styrene resin, from a fresh fracture surface (SHOJI and FOLK, 1964).

On the other hand, the method involving grinding, polishing and etching, hereafter abbreviated as the G. P. E. method, is to produce a thin carbon film of the surface by application of two stage replica technique. The preparation process begins by cutting the specimen with a rock-saw so as to isolate the surface of interest within a small rock cube. The surface will then be lapped and polished to produce a surface as flat and smootn as possible; this is followed by etching with a very weak acid solution (HONJO and FISCHER, 1965).

P. F. surfaces are not treated by any process and remain as natural as possible. Thus, any artifacts acquired during later preparation steps can easily be recognized under the electron microscope. If observation is confined to grains, a replica with projecting grains can easily be observed by the manipulation of the focal depth of an electron microscope which yield a stereoscopic image (FISCHER, HONJO and GARRISON, 1967). It is, however, impossible in many cases to define the boundary of each grain on a replica of a fracture surface. Fractures often run through structural defects within the grains, such as portions with more fluid inclusions or pores. Thus, a fracture which passes through a desired plane cannot always be obtained. It is also almost impossible to observe the internal structure of a grain using this method.

With G. P. E. method as previously mentioned, any desirable cut surface can be obtained. Preparation by the G. P. E. method closely resembles the preparation of thin sections used for the histological or petrographic studies. Since the etched relief on the specimen surface is weakly developed, the image obtained resembles the optical microscopic image of thin section and is therefore easy to understand in detail. Grain boundaries are clearly seen on one hand, and internal features of the grains are easily observable on the other.

Since replication of a G. P. E. surface is made subsequent to processes such as polishing, lapping, etching, etc., there is more possibility of acquiring artifacts in this method as compared to the P. F. method. However, artifacts such as scratches and pits produced during polishing and lapping, or amarphous layers caused by excessive polishing, or contamination can be avoided by very careful sample preparation. Such artifacts can be recognized experienced workers.

Comparative studies using both G. P. E. and P. F. methods as mentioned above assure us that the former is more suitable for the study of the fine grained carbonates (HONJO, 1969, in press).

6. Electron Microscopic Petrography

A variety of fine grained limestones, or fine grained matrices of limestones, or calcareous sediments have been observed under the electron microscope. The geologic age of those samples ranges from Ordovician to the Recent. The materials examined include: Lower Ordovician Marathon limestone from Texas, Lower Permian Akasaka limestone from central Japan, Cretaceous limestone from Hokkaido, Upper Cretaceous Niobrara chalk from midwestern North America, Maestrichtian chalk from Denmark, and Recent deep sea carbonate deposits from various localities. Carbon replicas were prepared from the G. P. E. surface of samples which were etched in 0.1 N HCl or 5% NH_4Cl solution. The two stage replica technique was applied as was described in HONJO and FISCHER (1965). The shadow casting angle was approximately 35°. Hitachi HU-11B and HS-6 transmission electron microscopes and a Hitachi HISCAN-2 scanning electron microscope were used for the present study.

The electron microscopic petrographic description of the Zumaya limestone and the Akasaka limestone is herewith given for examples. The fine grained matrices of those two limestones contrast with each other in terms of the basic character of the grains.

Zumaya Limestone

Zumaya rocks are extensively distributed in northwest Spain and consist of the thick, Paleogene flysch sequences. The total thickness is unknown. These rocks occur in rhythmic interlayers of fine grained greyish marly limestone, limestone-shale, etc., with thin layers of fine grained sandstone. They contain abundant planktonic foraminifers.

The samples examined are from the *Globorotalia subbotinae-G. lensiformis* zone (personal communication from SAITO, T., 1964), Lower Eocene (Ypresian). They were collected in the eastern part of Playa de San Telmo. They are homogeneous fine grained limestones, most of which have matrix material of less than 20 μ in diameter, when viewed with the optical microscope. And in most cases the matrix seems to be an aggregation of cryptocrystalline calcite grains, with a few *Braarudosphaera bigelowi* of pentagonal shape and occasional tests of planktonic foraminifers.

Electron microscopic observation reveals that the greater part of this matrix consists of nannofossil or fragments of nannofossils (although they are rare) including coccolith (Pl. 15), and shows no minute crystals which might be interpreted as primary inorganic precipitates. The placoliths consist mainly of *Coccolithus pelagicus*, as well as lesser number of *Braarudosphaera bigelowi* and a few shells of *Thoracosphaera* sp.

As for the grains larger than 20 μ in size, 5-10% of the field of view is occupied by *Thoracosphaera* sp., including *Thoracosphaera sexea* with an approximate diameter of 25 μ, and such planktonic foraminifer as *Globigerina* sp. The voids in such fossil are generally filled with secondary spar calcite, but may sometimes be occupied by matrix material, probably the resulting of filling of test interiors by nannofossils dues to breakage of the shell walls.

A noteworthy fact is that some of nannofossils are compressed against the microfossils or fragments thereof (Pl. 16, Fig. 1); in such a case, the nannofossils always protrude into walls of the larger fossils such as foraminifers or *Thoracosphaera*. In this case there is no evidence of deformation, and the protrusion seems to be the result of solution processes.

Some specimens contain more than 20 per cent of clay minerals. The relation between the clay minerals and other grains is unknown, although the clay minerals seem to have developed as thin films covering the surfaces of some nannofossils.

Akasaka Limestone

Optical microscopic observation shows many fusulinids and calcareous algae. The matrix is a mosaic of fine grained crystals, and subhedral calcite aggregates of 20–30 μ in diameter.

The electron microscope shows a very uniform mosaic of calcite cryptograins of 2 or 3 μ diameter mixed with relatively larger calcite grains. The grains are in contact with each other along crystal boundaries.

The boundary between the fossils (fusulinid and calcareous algae) and the matrix is not clearly seen under the electron-microscope.

Wide distribution of fluid inclusion is observed in most of the grains, particularity in those subhedral calcite of about 10 μ diameter. The fluid inclusion-like topography presents euhedral crystal shape with its longer axis of about 0.5 μ. Fluid inclusions are also observed in the grains composing fusulinids shell walls, including keriotheca. This suggests that those calcite grains with fluid inclusions may have been recrystallized in water.

Apparently amorphous substances are sometimes distributed in sheet-like masses between grains. These substances conceivably are carbonaceous material which are recovered as a black residue when the limestone samples are dissolved in acid.

7. Discussion

It is almost impossible to distinguish the two types of matrix in the fine grained limestones mentioned above solely on the basis of optical microscopy, regardless of the magnification. This, as mentioned previously, is because the identification of the individual grains composing the fine grained matrix of carbonate rocks is extremely difficult. However, applying the electron microscope and using the two stage replica method on G. P. E. surfaces, grains of the matrix of different fine grained limestones have proved to be conspicuously different in terms of morphology, although some common characteristics are found as well.

For instance, in the case of the Zumaya limestone, most grains are nannofossils and the matrix appears to have no inorganic crystals except in the former void space of microfossils. On the other hand, in the Akasaka limestone, the micro-grained matrix appears to have no grains of organic origin, and a mosaic of crystalline calcite constitutes the entire matrix.

The configuration of adjoining two grains shows a marked contrast between those two different limestones. In the Zumaya limestone, when the two grains of organic origin (nannofossils) adjoin directly, one of them is usually partially dissolved producing *solution welding*. Contrary to this, the Akasaka limestone has crystal of subhedral shape adjoining each other, and its G. P. E. surface looks as if it were paved with subhedral crystals with crystalline mosaic.

Limestone having such a distinctive grain shape and overall texture as ameoboid mosaic were recognized in the Solenhofen limestone (FISCHER, HONJO and GARRISON, 1967). An ameoboid mosaic consists of grains with either curved or irregular boundaries rather than straight ones.

Oberalm limestones of late Jurassic age from the Austrian Alps (GARRISON, 1967) have been studied by means of replicas of G. P. E. surfaces and by thin section study using the ultra high voltage electron microscope. These rocks shows a polygonal mosaic of crystalline grains, and most grains appear to be of inorganic origin. However, light etching process on polished samples reveals the traces of nannofossils in polygonal subhedral calcite crystals (FISCHER, HONJO and GARRISON, 1967, fig. 54).

Well-preserved nannofossils, such as those in the Cretaceous chalks and Tertiary coccolith shells, contain in their component crystals concentrically developed steps with a width of 200Å. The nannofossils which occur in polygonal crystals do not show such ultra structure and the coccoliths retain only a relatively obscure outline of each rhomb plate.

It is not clear how the ultrastructure of nannofossils is preserved in such subhedral crystals as those in the Oberalm limestone. The crystal that shows the "phantom" of a coccolith records recrystallization of a coccolith as a single crystal, yet the morphology of nannofossils still remains partially visible.

In general, fluid inclusions are seemingly common in unmetamorphosed Paleozoic limestones. A great quantity of fluid inclusion is also observed within microcrystal of dolomite and proto-dolomite (FISCHER, HONJO and GARRISON, 1964).

On the other hand, nannofossils and the walls of microfossils do not contain fluid inclusions. It is also interesting to note that fluid inclusions are not detectable in the secondary spar of calcite which often fills the interior spaces of foraminifers, coccospheres, etc.

8. Nannoagorite

The components of compositional grains of the Zumaya limestone (Paleogene) and a part of the Setogawa limestone (Eocene, HONJO and MINOURA, 1968) are same as those of the matrix of the "low energy type" calcareous bottom sediment (HONJO, 1967). Such limestones as a whole are composed of aggregated nannofossils and contain very few carbonate minerals considered to be of inorganic origin. In other words, the Zumaya limestone is interpreted as lithified calcareous ooze of a low energy type which is cemented by a small quantity of authigenic carbonate.

The nannofossils composing the matrix of this type of fine grained limestone have not changed in shape. The grains adjoin each other along the surface where solution welding has taken place and in some cases spar calcite has filled up void space.

The author, therefore, should like to apply the name *nannoagorite* (Gr. *nannos*; dwarf, or nannofossils, Gr. *agora*; assembly) to fine grained limestones or fine grained matrices (1) when the grains of the matrix are dominantly composed of nannofossils, or fragments thereof in amount of approximately 50 per cent or more, and (2) when some of componental grains adjoin each other along surfaces of solution welding, and (3) when the limestones contain relatively small amount of cement.

It should be emphasized that some nannoagorites can only be clearly recognized with use of electron microscope. Using only optical microscopy, the component grains may be misinterpreted as being of terrigenous or inorganic origin. The electron microscope, on the other hand, may reveal the presence of nannofossils in quantities of up to 10^8 individuals per cubic centimeter of limestone, and this instrument therefore becomes a necessary tool for studying such rock.

Supply of Nannoplanktons.—The original material of nannoagorite accumulates at water depths above the compensation depth for calcite and composed largely of the hard tissue of nannoplankton which were supplied from the overlying sea water and deposited at slow rates of sedimentation (BRAMLETTE, 1958; BLACK and BARNS, 1961).

At present, the coccolithophoridae, the supplier of coccoliths, are found almost in all sea areas of the oceans (MCINTYRE and MCINTYRE, 1967). According to OKADA and HONJO (1969, in press), in the Southwestern Pacific Ocean during the winter period of 1968-1969, the most dense distribution of Coccolithophoridae was observed in the water layer surface to a depth of about 50 meters. Coccoliths found at this layer are the largest in weight and occur in abundance of about 10^{-6} gram per liter of sea water in the Southwestern Pacific Ocean during winter period of 1968-69.

In the case of the Zumaya limestone, since at least 0.6 gram per 1 gram of limestone is considered to be coccoliths, it would take about 10^5 liter of euphotic water to produce 1 gram of nannoagorite, assuming that conditions were analogous to the above mentioned environment in the Pacific Ocean.

The sedimentation of nannoagorite may resemble the deposition of present calcareous deep-sea ooze. It, however, is conceivable that the material may have been supplied in a different manner from that in the present oceanic environment, and many points still remain unsolved. We do not precisely know, for instance, how much was the abundance and how was the distribution of the inorganic salts and nitrogen, that could produce a large quantity of phytoplanktons or how was the status of the food chain, such as the ecology of copepods, in the geologic part.

Resistance to diagenesis observed in nannofossils.—The preservation of nannofossils, in particular of coccoliths, is usually quite excellent. Not only the external feature of the coccolith, but also the delicate internal ultrastructures, such concentrically developed steps with a width of 200Å in their component crystals, are preserved in fossil coccoliths from the Eocene (Zumaya limestone) or the Pliocene formation (Chinen sand, Okinawa).

Nannofossils are always more resistant than coexisting microfossils; it is commonly observed that a coccolith or a plate of *Braarudosphaera* is protruding into a foraminifer wall (Pl. 16, Fig. 1 and the middle part of Pl. 15, where a plate of *Braarudosphaera* is caving itself into a foraminifer wall.)

A thin filmy material which coats entire surface of a coccolith has been observed in the Recent Coccolithophoridae (OKADA and HONJO, 1969, fig. 2, or fig. 4). Such organic coating in a coccolith must have played an important role in giving strong resistance to the earlier stages of diagenesis.

The organic materials may still be preserved in nannoagorite. HAMANO and HONJO (in press) have found approximately 0.08% of organic material (mainly polysaccarides and amino acids) in the Eocene Cambridge chalk from New Zealand.

MINOURA and HONJO (1968) have conducted an electron-microscopic study of Niobrara chalk after leaving it in a hydrothermal bomb at 400 atmosphere pressure and 300°C for 72 hours. In a comparative observations on the samples before and after such a treatment, they observed that the sample underwent scarcely any change. Aragonitic sediment can easily be dissolved but calcite nannofossils are virtually insoluble under these experimental conditions and show excellent stability. This can at least partly explain the generally excellent preservation of nannofossils in ancient rocks.

Burial of nannofossil-rich sediment may induce solution welding ultimately when the pH of the seawater filling the pore space between grains is relatively low. The contact points between the grains are sharp and the stress is larger there. The calcite crystals in a coccolith are protected by a stronger organic coating, when the contact points underwent effects of stress and show more stability against other calcite grains which have no or inferior coating.

Dissolved $CaCO_3$ may be transferred in the interstitual water and may later precipitate partly as cement and partly as spar in the void spaces of foraminifers, depending on changes of pH. Because the pressure of overburden is not exceedingly large, when the contact points between grains dissolves and widen into surfaces, such pressure will eventually become ineffective in the development of solution welding along this surface. Furthermore the sediment may become highly consolidated to form a rock by the developed cement.

Chalk as a nannoagorite.—Chalk (HATCH et al., 1938) is calcareous sediments found particularly in parts of Cretaceous and Paleogene sequences in Europe, North America and other areas. Chalk is sparse in the circum-Pacific region, except for rare examples such as the Eocene Cambridge chalk in New Zealand and a few others. The distribution of the chalk encompasses a tremendous area when such as corrective units as the Niobrara, Selma, and Austin chalks of the Upper Cretaceous in North America as well as various areas in Europe are considered. The thickness of Niobrara chalk in western Kansas is as much as 300 f.

These chalk deposits are formed largely by nannofossils, and the chalk can be considered as a special type of semi-consolidated nannoagorite.

Many questions still remain regarding the environment of sedimentation and diagenesis of chalk; for example we can consider chalk as a comparatively open sea sediment judging from the occurrence of planktonic foraminifers. It is, however, impossible to consider chalk as deep sea deposits throughout, since the Niobrara chalk, for instance, yields a large quantity of near shore organisms such as *Inoceramus* and *Mosasaurus*.

9. Orthomicrite

The matrix of the Akasaka limestone, in contrast to nannoagorite, consists of a microcrystalline mosaic with polygonal calcite grains of clay size. Electron microscopic observations on G. P. E. surfaces show that the grains contact with each other along crystalline surfaces. Such micrograined limestones are abundant in Paleozoic sequences, and here termed *orthomicrites*.

The Upper Paleozoic sequence (Kansas type) in the middle western part of the North America is characterized by cyclothems, and contains limestones with abundant fusulinids and brachiopods. The fine grained matrix in these limestones is exclusively orthomicrite. In particular the upper Pennsylvanian Levenworth limestone of Kansas bears close resemblance to the matrix of the Akasaka limestone when observed with the electron microscope.

The Original Material of Orthomicrite.—Grains in orthomicrite might be originally produced either (1) by break-down of organic skeletal material, e. g. from reef organism, or (2) by inorganic precipitation from sea water.

Reef structures having typical wave resistant framework have scarcely been found in the Japanese Paleozoic. Most Paleozoic limestones in Japan have fossils embedded in a predominant matrix, and the fossils are generally well preserved.

The observations suggest that the Akasaka limestone, for example, could not have originated entirely from the skeletal hard parts of organisms. Even though some limestones conceivably are composed largely of calcareous algae such as *Mizzia* (FUJINUKI, 1968), it seems more reasonable to consider most of them are at least partially derived from inorganic sediment.

The Paleozoic limestones in Japan contain abundant fossils such as fusulinids and brachiopods which indicate in many cases shallow water, rather uniform sedimentary environments.

It is not conceivable that fine grained calcite in the subhedral mosaics of these Paleozoic limestones could be formed directly from the sea water. If inorganic sedimentation were to take place, there should have been formation of euhedral and discrete rhombic crystals of calcite. The character of the Akasaka limestone suggests that the sea floor was at one time covered with unconsolidated ooze. Assuming this carbonate ooze was deposited inorganically by sedimentary processes as seen on the Bahama Banks (CLOUD, 1962), this sediment would have been in the form of needle crystals of aragonite mixed with a small amount of rhombic calcite. Calcite, as compared to aragonite, is hardly dissolved in the sea water and will not be dissolved during the early stages of diagenesis. Contrary to this, the needle crystal of aragonite can easily be dissolved in the sea water and could be reprecipitated as calcite crystals.

It seems logical to consider that orthomicrite is a recrystallized product of an original inorganically precipitated aragonite, formed in a bank environment. The recrystallization would produce mosaic calcite even under small static pressure and shallow overburden.

That calcite may crystallize simultaneously with the aragonite needles is suggested by the fact that a few percent of calcite crystals is always found along with the predominant aragonite needles of inorganic origin both in materials produced experimentally and in actual calcareous oozes from the Bahama Banks (CLOUD, 1962). It seems quite possible that such crystals might be retained without dissolution in the mosaic which was formed by recrystallization. Many orthomicrites show a bimodal size distribution of grains; the larger grains may represent these original calcite crystals, while the smaller ones may be recrystallization products of the primary aragonite needle.

Calcareous nannofossils of the coccolith type have not yet been detected in rocks older than Early Jurassic. However in some orthomicrites, particularly in the matrix of the Jurassic Torinosu limestone, grains of nannofossil origin may have coexisted along with aragonite, as may have been the case for the Oberalm limestones. If the coccoliths, even in this pre-Jurassic time, had been composed of calcite, they should have been preserved without showing recrystallization such as develops when aragonite is transformed into calcite during diagenesis. It is conceivable, however that the formation of phantom grains takes place when the coccoliths are placed under severe conditions such as metamorphism.

Since the Japanese Paleozoic sequences often include interbeds of basic lava and pyroclastic of submarine volcanos (MINATO, 1953), HORII (1964) and ETO (1967) have tried to link the sedimentation of limestones by inorganic precipitation from sea water with eruptive submarine volcanic activity. IGO (1960), in his study on the paleoenvironment of the Nibugawa formation, central Japan, interpreted the sedimentation of the limestone in this formation as being formed by the bank-like upheaving subsequent to volcanic activities, and no reference was made toward a direct inorganic reaction with the sea water.

In addition to the limestones in the Paleozoic, the geosynclinal carbonate such as those in the Sorachi formation (Jurassic-Cretaceous), the Setogawa formation, etc. are in many cases accompanied by basic volcanic rocks (MINATO, 1967). It is readily conceivable that there were large scale eruptions of submarine volcanoes following the early stages of orogenic cycles in the Paleozoic to Mesozoic geosynclines of the Tethyan and the circum-Pacific regions.

The author of this paper, however, is of opinion that such explanations postulating chemical reactions due to volcanism leave several points open for question. For many of the Paleozoic limestone such as the Permian Sakamotozawa limestone in Kitakami Mts. (Northeastern Japan), etc., there is no rule that volcanic activity immediately precedes carbonate sedimentation. In addition, all limestones deposited in the Paleozoic Tethys contain abundant fossils such as fusulinids and brachiopods. Therefore a direct supply of material by submarine volcanism is difficult to imagine.

Limestone sequences are thick and lenticular, and if chemical reactions by submarine volcanoes were the cause for their deposition, one might expect them to be more widespread. Accordingly, the eruption of submarine volcanoes may have had only a secondary effect and that physico-chemical factors such as changes in the partial pressure of CO_2 resulting from the upward movement of the sea water around the submarine volcanoes may have played the most important role for this.

10. Comparison of Trace Element Content between Nannoagorite and Orthomicrite

The table 1 is taken from TABUCHI (1968) and shows the comparison of the amounts of Mg, Sr and other elements in the Lower Middle Permian Akasaka limestone (60 samples) and the Upper Cretaceous Niobrara chalk (82 samples).

Table 1. Comparison of trace element concentration (in ppm) from the Akasaka limestone and the Niobrara chalk.

	Mg	Sr	Fe	Mn	Zn	V	Cu	Ni
a. Akasaka limestone	$1\text{–}5\times10^3$	$10^2\text{–}10^3$	10–100	1–10	>10	>10	>1	>1
b. Niobrara chalk	$10^2\text{–}10^3$	10^3	$10^3\text{–}10^5$	$10\text{–}10^3$	$10\text{–}10^2$	$10\text{–}10^2$	1–10	$10\text{–}10^2$
rough value for b/a	>1	1–10	300	>100	10	40	10	30

Analyses of the Akasaka limestone yield results very similar to those of FUJINUKI (1968). The Akasaka limestone is a typical orthomicrite. On the other hand, chalk contains abundant nannofossils and is a typical nannoagorite except for the fact that solution welding is not well developed.

As seen in the comparison of trace elements in these formations enumerated in the table, the Niobrara chalk shows a more marked concentration of trace elements. The Mg content, however, is an exception, since it is more abundant in the Akasaka limestone. These analyses represent the concentration of these elements only in that portion of the rock that can be dissolved by hydrochrolic acid. The trace element content in the net sample including the insoluble residue of the Niobrara chalk may be greater, while the insoluble residue in the Akasaka limestone is almost negligible.

Trace element analysis of cemented nannoagorites, such as the Zumaya limestone or the Setogawa limestone, greatly differ from those of chalks. But, even these well lithified nannoagorites generally contain more metallic trace elements than the Paleozoic limestones. The author considers that such a difference reflects fundamental differences in the mode of sedimentation and diagenesis. Enrichment of heavy metals is due to the fact that nannoagorite is of slow sedimentation and has not been resolved, reprecipitated. Analyses obtained from Recent and Neogene calcareous deep sea oozes shows a conspicuous resemblance to that of the chalk (Table 2).

Contrary to this, the original material of orthomicrite (aragonite ooze) is lost during subsequent diagenetic solution and recrystallization. Moreover, orthomicrites were probably rapidly deposited and the author is of opinion that a relatively high rate of sedimentation of aragonite ooze would result in less concentration of trace

Table 2. Minor or trace elements in deep sea carbonate sediments, in ppm.

	Mg	Sr	Fe	Mn	Zn	Cr	Cu	Ni	I.R.*%
D-1	5450	1170	7420	2570	116.0	2.1	270.0	121.0	25.8
D-2	12100	1500	4870	3010	145.0	6.1	187.0	90.3	60.5
D-3	5020	2880	3450	3050	60.2	2.8	167.2	46.5	48.4
D-4	3620	630	1210	280	8.8	3.7	9.4	6.4	19.6
rough value	10^3	10^2–10^3	10^2	10^2–10^3	10–10^2	1–10	1–10^2	10–10^2	

D-1, Up. Pliocene, 7°19′S, 118°40′W, depth ; 4230 m
D-2, Mid. Miocene, 3°20′N, 165°10′E, depth ; 4225 m
D-3, Low. Miocene, 7°17′N, 148°12′W, depth ; 4925 m
D-4, Low. Oligocene, 14°55′N, 143°00′W, depth ; 4770 m
* Insoluble residue

elements.

Since the crystalline habit of $SrCO_3$ is of the aragonite type, Sr tends to be concentrated in aragonite rather than calcite. However, as is shown in table 1, the concentration of Sr in the orthomicrite is nearly as much as or somewhat less than that in the nannoagorite. This may be caused by that Sr was conceivably dissolved and forfeited at the time when aragonite were developed into the mosaic crystals of calcite.

11. Characteristic, Geohistoric Feature and Geographic Distribution of Nannoagorite and Orthomicrite

The matrix of fine grained limestones shows particular types clearly characterized by geologic ages. The matrix of nannoagorite type is found in formations younger than Early Jurassic. It is often accompanied by the environment of sedimentation of eugeosyncline type throughout the world. The development of chalk is limited largely to the Atlantic area of the northern hemisphere, and is not found in the circum-Pacific area except e.g. in the Cambridge chalk of New Zealand. However, on the floor of the Pacific, extensive distribution of Late Mesozoic and Cenozoic deposits similar to the chalk has recently been detected (SAITO, 1968).

The development of nannoagorite must have direct relation with the geologic history of the nannofossils. Since the first appearance of coccoliths is considered to be in the Early Jurassic, the formation of nannoagorite is not conceivable prior to that time. As some Jurassic limestones contain abundant phantom grains of coccolith which are, in a sense, intermediate between nannoagorite grains and orthomicrite microcrystals.

In contrast to this, most of the fine-grained limestones and the matrix of limestones in the Paleozoic are composed uniformally of orthomicrite. This applies to the limestones of the Paleozoic Tethyan seaway as well as to the limestones occuring in cyclothems in the middle west of North America. Orthomicrite is not abundantly distributed in Mesozoic and Cenozoic rocks, and many of these younger orthomicrite are not typical, e. g. the Solenhofen limestone. In the present oceans, no deposition of potential orthomicrites is taken place on a large areal scale.

It is not clear whether or not the mechanism of sedimentation of orthomicrite can be applied to the interpretation of the Precambrian limestones. Paleozoic limestones are greatly affected by dolomitization which complicates the situation.

The relatively rapid, geologically speaking, transformation of sedimentation of calcium carbonate in the ocean from the orthomicrite type into nannoagorite type after the Middle Mesozoic may be related to fundamental changes such as the characteristics of sea water, the distribution of oceans and continents, the composition of the atmosphere, etc. These will be the subject of interest for further study.

12. Conclusions

The origin of the fine grained matrix in limestones is integrally related to genesis of limestones in general and requires further study. This would also help in developing more rational classifications of limestones. Use of the electron microscope is essential in the up-to-date studies, and one cannot rely solely on optical method. For such studies, the author recommends the application of the two stage replica technique to G. P. E. surfaces.

The fine-grained matrix of limestones can be generally classified into two categories: *orthomicrite* and *nannoagorite*. Orthomicrite is composed of a subhedral crystalline mosaic. The grains of the mosaic adjoin each other along crystalline surfaces. Orthomicrite is abundant in Paleozoic limestones and is distributed universally.

It seems likely that the original material of orthomicrites may have been aragonite ooze inorganically precipitated in sea water on a bank or other shallow water environment, or disaggregated aragonitic hard parts of organisms. It is further suggested that aragonite was recrystallized as mosaic crystals of calcite under small static pressure and perhaps under a shallowly buried condition.

The development of nannoagorites can be explained by sedimentary mechanism of the low energy type. Such sedimentation took place in the Jurassic to early Cretaceous throughout the world and nannoagorites are abundantly distributed in chalks and in Flysch in the Cretaceous to Cenozoic. However, the supply conditions of nannoplankton in the Cretaceous to Paleogene chalk must have been different from those in the present ocean.

Nannoagorites represent concentration of nannofossils in a innumerable number. In some cases solution welding and a small quantity of cement played an important role in lithification. Accordingly, the way of contact between adjoining grains differs greatly between nannoagorite and orthomicrite. The component grains of the sediment in nannoagorites, namely nannofossils, are very resistant to recrystallization.

In some orthomicrites in the Late Mesozoic, the nannofossils are partly recrystallized and form phantom grains.

The sedimentation of orthomicrite probably occurred intermittently at a high rate, whereas the nannoagorite tended to be deposited slowly and continuously.

Certain minor or trace elements are more concentrated in limestones having a fine grained matrix of the nannoagorite type rather than in orthomicrites. This fact is probably attributable mainly to the different history of diagenesis.

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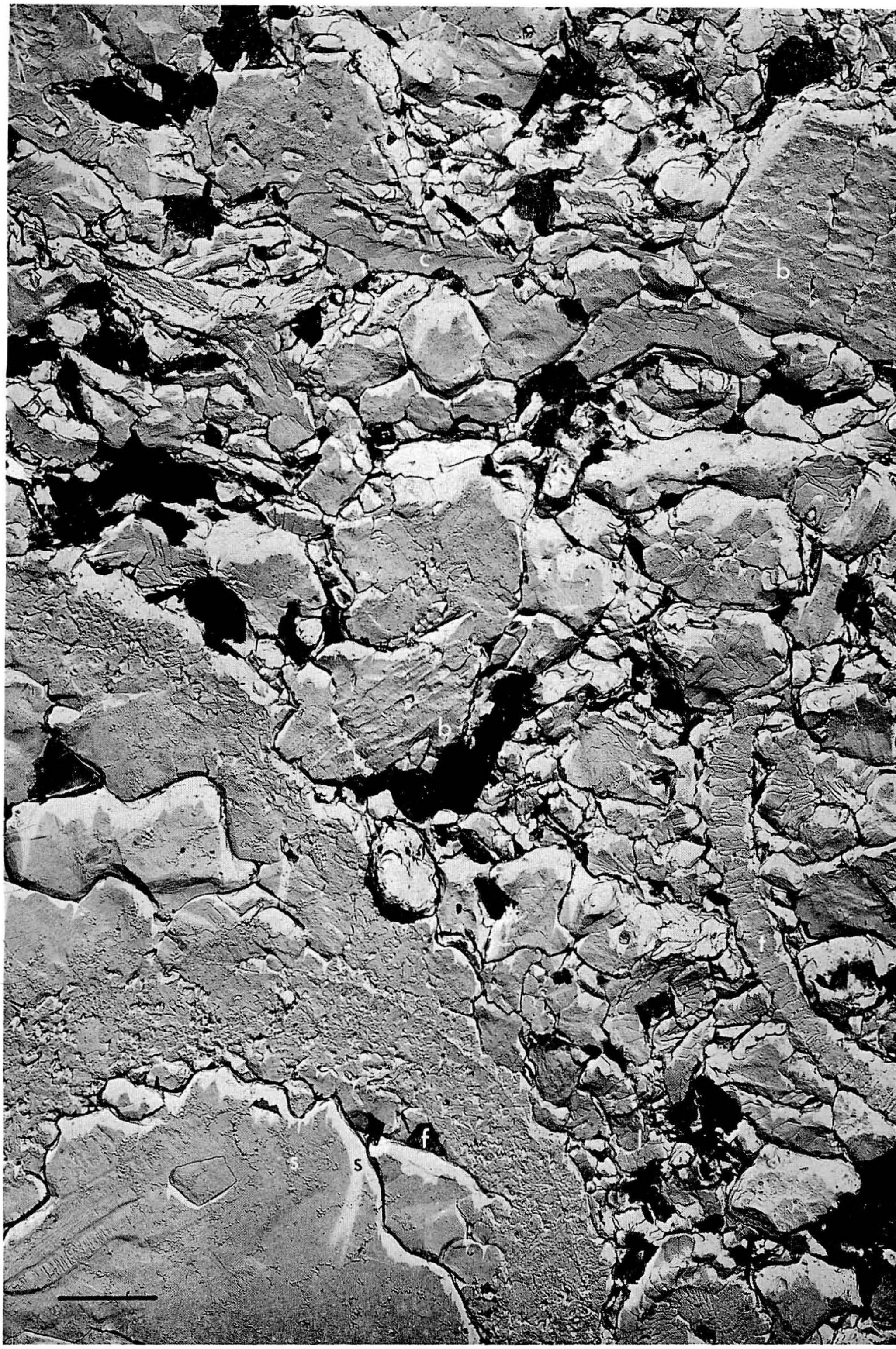
Plates 15 – 19

Susumu HONJO

Study of Fine Grained Carbonate Matrix:
Sedimentation and Diagenesis of "Micrite"

Explanation of Plate 15

An electron micrograph of the Zumaya limestone, G.P.E. surface, Eocene Flysch, Spain. The component grains are all of organic origin except for the spar calcite (s), filling the internal space of planktonic foraminifers (f). A variety of nannofossils appear in the section. b: a plate of *Braarudosphaera*, c: coccoliths, t: wall of *Thoracosphaella*, and x: unknown nannofossils. Scale bar 5 microns.



S. HONJO: Fine Grained Carbonate Matrix

Explanation of Plate 16

Fig. 1. An electron micrograph showing solution welding in Zumaya limestone. A coccolith (C) protrudes into a foraminifer wall (F) without being distored. The same phenomenon is observed around the center of Plate 1, where a plate of *Braarudosphaera* also protrudes into a foraminifer wall. Scale bar 5 microns.

Fig. 2. Oberalm limestone, Upper Jurassic, Austrian Alps (GARRISON, 1967) a phantom of coccolith. The outline of the grain appears as a subhedral crystal of calcite that is surrounded by other subhedral grains. The organic micro-structure of the coccolith is revealed by etching. Scale bar 3 microns.

Fig. 3. A well preserved free specimen of a fossil coccolith. *Coccolithus pelagicus*, from the Lower Pleistocene sequence developed in the Boso area, Central Japan. Scale bar 3 microns.

Fig. 4. The matrix of *Globigerina* ooze, the raw material of nannoagorite, from the Middle Atlantic ocean floor. c: *Coccolithus leptoporus*, d: *Discoaster brouweri*, f: The wall surface of *Globigerina crassaformis*. Scale bar 5 microns. Scanning electron micrograph.

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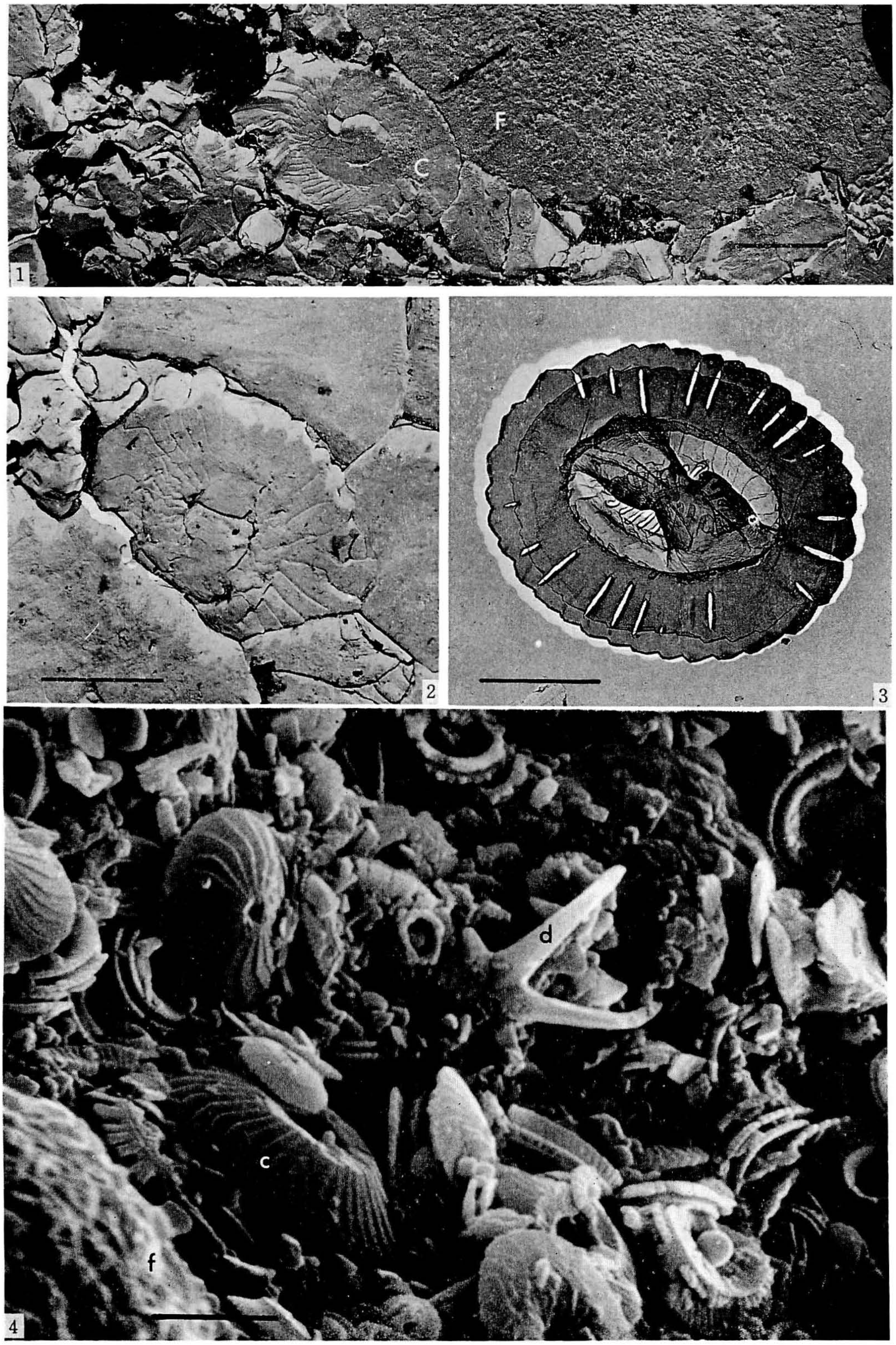

S. HONJO: Fine Grained Carbonate Matrix

Explanation of Plate 17

An electron micrograph of a typical orthomicrite. A mosaic of subhedral calcite microcrystals covers the entire matrix. No sign of organic remains is observed. The rhombic euhedral microcrystals giving the impression of projecting outward from the G.P.E. surface are presumably dolomite. The Middle Paleozoic East Poplar Unit, North America. Scale bar 5 microns.

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S. HONJO: Fine Grained Carbonate Matrix

Explanation of Plate 18

Fig. 1. A bimodal size distribution of calcite grains in the Oberalm limestone, [illegible] Valley, collected by Dr. [illegible] in 1963. The fine grained matrix of the limestone is composed of two types of grains; one approximately 1 or 2 microns in diameter (a) and the other 5 to 7 microns (b). Such textures are commonly observed in orthomicrites.

Fig. 2. Aragonite needle crystals precipitated *in vitro*, as aragonite, or small quantity of calcite crystals are usually precipitated mixedly with the dominant aragonite crystals. An optical photomicrograph. Scale bar 5 microns.

Fig. 3. An artificial orthomicrite (Minoura and Honjo, 1968). The raw material (inorganically precipitated aragonite crystals, such as shown in Fig. 2 in the same plate) was subjected to an uniaxial pressure of few Kg/cm^2, as well as to static pressure of 100 atm. at a temperature of 400°C for 3 days. The grains of the product are all calcite. This electron micrograph of a C.P.R. surface shows that the needle crystals of aragonite are converted into a mosaic of calcite composed of subhedral crystals which adjoin each other along crystalline surfaces (such as where encircled). The porosity is large and occurs as intercrystalline pores such as is observed at (p).

Explanation of Plate 18

Fig. 1. A bimodal size distribution of calcite grains in the Oberalm limestone, Unken Valley, collected by Dr. GARRISON in 1963. The fine grained matrix of the limestone is composed of two types of grains; one approximately 1 or 2 microns in diameter (a) and the other 5 to 7 microns (b). Such textures are commonly observed in orthomicrites.

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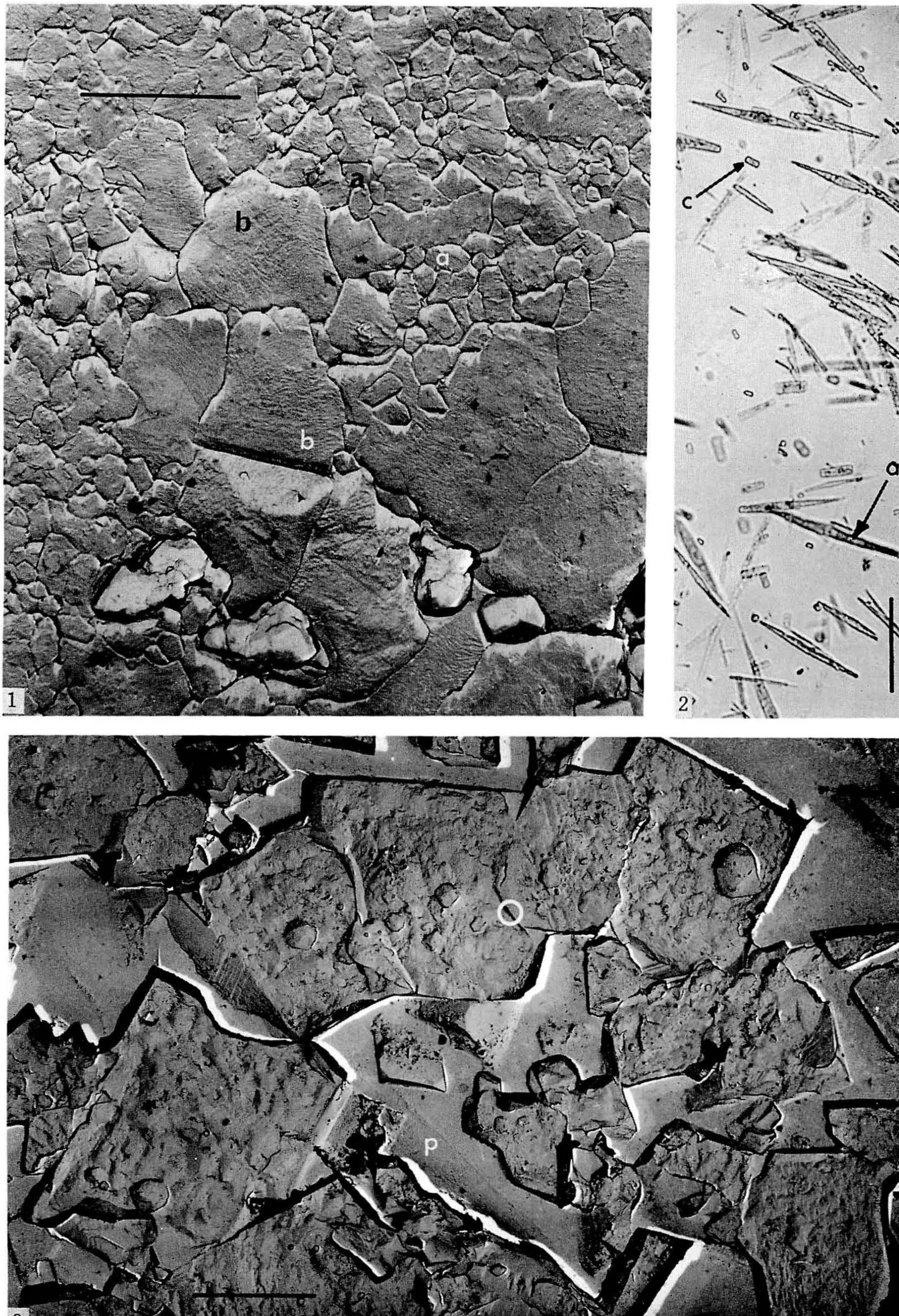

S. Honjo: Fine Grained Carbonate Matrix

Explanation of Plate 19

Fig. 1. An electron micrograph of Setogawa limestone (Eocene, Honjo and Minoura, 1965) from the G.P.E. surface. A typical nannoagorite. The rock consists of grains such as nannofossils (a), carbonate cement (b) amorphous silica (S or white arrow-marks) and non-carbonate grains (c). Scale bar 5 microns.

Fig. 2. The P.P. surface from the same sample of Fig. 1. The origin of grains are hard to identify. Dark spots (p) are the pseudo-replica of carbonate grains. Scale bar 5 microns.

Fig. 3. The G.P.E. surface of Akasaka limestone (Permian, Yabeina zone). Grains suggesting organic origin are not discovered in the compact mosaic of subhedral calcite crystals. Scale bar 5 microns.

Fig. 4. Also the electron micrograph from the G.P.E. surface, Akasaka limestone. The large grains on the right are vein crystals. Scale bar 5 microns.

Explanation of Plate 19

Fig. 1. An electron micrograph of Setogawa limestone (Eocene, HONJO and MINOURA, 1968) from the G.P.E. surface. A typical nannoagorite. The rock consists of grains such as nannofossils (a), carbonate cement (b) amorphous silica (S or white arrow-marks) and non-carbonate grains (c). Scale bar 5 microns.

Fig. 2. The P.F. surface from the same sample of Fig. 2. The origin of grains are hard to identify. Dark spots (p) are the pseudo-replica of carbonate grains. Scale bar 5 microns.

Fig. 3. The G.P.E. surface of Akasaka limestone (Permian, *Yabeina* zone). Grains suggesting organic origin are not discovered in the compact mosaic of subhedral calcite crystals. Scale bar 5 microns.

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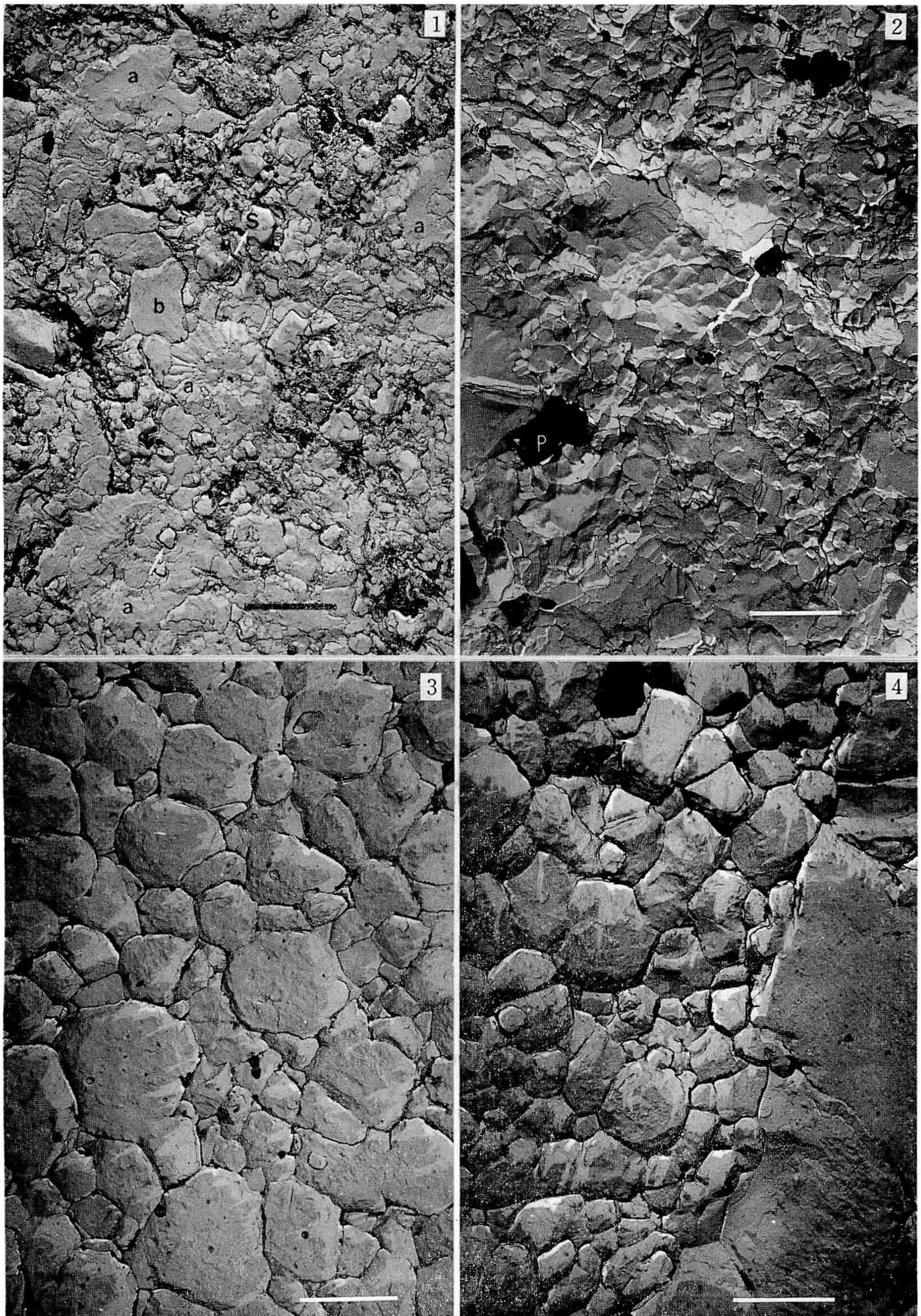

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