TECHNICAL BULLETIN

Vol. 3

ECONOMIC COMMISSION FOR ASIA AND THE FAR EAST
COMMITTEE FOR CO-ORDINATION OF JOINT PROSPECTING FOR MINERAL RESOURCES IN ASIAN OFFSHORE AREAS

May, 1970

The authors of the papers alone are responsible for the statements and opinions contained in their respective papers. All communications relating to this Bulletin should be addressed to the Editor-in-Chief, Technical Bulletin of CCOP. c/o Geological Survey of Japan.

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ECONOMIC COMMISSION FOR ASIA AND THE FAR EAST

COMMITTEE FOR CO-ORDINATION OF JOINT PROSPECTING FOR MINERAL RESOURCES IN ASIAN OFFSHORE AREAS (C.C.O.P.)

TECHNICAL BULLETIN Vol. 3

This third issue of C.C.O.P.'s technical bulletins was printed by the Geological Survey of Japan, as a contribution to the work of the Committee.

PREFACE

The Committee for Co-ordination of Joint Prospecting for Mineral Resources in Asian Offshore Areas (referred to briefly as the Co-ordinating Committee for Offshore Prospecting, and abbreviated to CCOP) is an intergovernmental body established under the sponsorship of the United Nations Economic Commission for Asia and the Far East (ECAFE). The steps leading to its establishment are outlined in the reports of its first session (paragraphs 1–5) and second session (paragraphs 1, 2); its terms of reference are contained in appendix 11 of the report of its first session.

At the eighteenth session of the ECAFE Committee on Industry and Natural Resources, held at Bangkok in February 1966, the Governments of the Republic of China, Japan, the Republic of Korea and the Philippines affirmed their readiness to join in the establishment of the Co-ordinating Committee. At the invitation of the Government of the Philippines, the first session of CCOP, attended by representatives of the Governments of those countries, and professional staff of the ECAFE secretariat, was held at the University of the Philippines, Quezon City, from 27 May to 2 June 1966.

Since that time, five more sessions of CCOP have been held (second session at Tokyo, 29 October to 7 November 1966; third at Seoul, 24 June to 4 July 1967; fourth at Taipei, 6–16 November 1967; fifth at Tokyo, 10–19 June 1968; and sixth at Bangkok, 13–27 May 1969), together with meetings of its Technical Advisory Group at each of these sessions; the seventh session of CCOP is planned to be held at Saigon, Republic of Viet-Nam, from 12 to 26 May 1970. At its fourth session, the Governments of the Republic of Viet-Nam and Thailand were welcomed as full members and Malaysia was represented by an observer. At the fifth session, both Indonesia and Malaysia were represented by observers. At the sixth session, Cambodia and Malaysia were welcomed as full members and Indonesia was represented by a group of observers; it was announced that the Government of Indonesia was actively considering becoming a full member.

During the course of these meetings the Committee decided that technical studies relating to marine geology and offshore prospecting for mineral resources, particularly in the offshore areas of the member countries of CCOP, together with preliminary accounts and detailed reports of the results of offshore surveys conducted through the medium of CCOP, should be published in a series of Technical Bulletins, separately from the reports of the Committee's sessions. The Committee was pleased to accept the offer of the Government of Japan to print one volume of the Technical Bulletin annually; this third volume of the series, also printed by the Geological Survey of Japan, contains articles and documents that were recommended to be included in Technical Bulletin, volume 3, at the sixth session of CCOP, together with others subsequently submitted.

The Technical Bulletins and the printed reports of the sessions of CCOP, including technical documentation, are distributed to the appropriate organizations and authorities concerned in the member countries of CCOP. Enquiries as to their availability to institutions and organizations in other countries may be directed to: The Technical Secretariat of CCOP, United Nations ECAFE, Sala Santitham, Bangkok-2, Thailand. The contents of volumes 1 and 2 of the Technical Bulletin series are listed on pages v and vi.

FOREWARD

The activities of CCOP have increasingly become great stimulus to the development of offshore mineral resources of the ECAFE region, through the promotion of prospecting, exchange of information, training of technical personnel and other related matters. Under these circumstances, it is very significant that the Technical Bulletin is published periodically as one of the undertakings of CCOP.

Dr. Masami Hayakawa is responsible for the editing of this bulletin, but I would like to note here that Dr. Shun-ichi Sano has kindly taken great pains in the actual editorial work.

In this third volume, reports concerning the CCOP projects and related papers are included. It is a great pleasure for me to see this volume published. And I would like to express my sincere gratitude to the authors of the report, staff of the ECAFE Secretariat, and various personnel who have contributed to the completion of this volume.

Konosuke Sato
Director,
Geological Survey of Japan

NOTE BY EDITOR

It gives me a great pleasure to be able to present Vol. 3 of the Technical Bulletin to the Committee for Co-ordination of Joint Prospecting for Mineral Resources in Asian Offshore Areas (CCOP), as well as to all who are concerned about development of mineral resources including petroleum underlying the marine shelves in eastern Asia or researches of marine geology and geophysics in the western Pacific area.

Since Vol. 1 of the Bulletin was published in June 1968, nearly two years has already passed and a number of the co-ordinated survey projects were brought into operation. Remarkable progress in the activities of CCOP is shown here by the fact that most articles contained in this issue are reports of the projects included in the Work Programme of CCOP, which occupy the first half of this issue, or results of the investigations closely related to them. It was recognized in course of editing of this volume that several reports had been in preparation, but left for the publication in future volumes.

Considering such circumstances, the editor felt that the dead-line date for submission of the manuscripts for Vol. 4 could be advanced, for example, to the end of October 1970 so that sufficient time would be available for the editing and the printing. The dead-line date, however, should be decided at the seventh session of CCOP, which is expected to be held in middle of May 1970.

The editor felt also that the editorial standards should be discussed and established at the coming session of CCOP and should be adviced the contributors beforehand. The editor should note that minor amendments of the manuscripts of this volume were made for standardization purpose without permission of the authors.

In addition, discussions on technical contents of the articles appeared in this series of the Technical Bulletin are highly desirable for advancement and promotion of marine geologic and geophysical studies in this region. If readers wish to make comment or ask question to the contributors the editor will willingly act as intermediary, although the contributors alone are responsible for the statements and opinions contained in their respective articles.

I would like to express my gratitude to Dr. Shun-ichi Sano for taking over practical editorial work of this volume and also to extend my sincere thanks to Mr. Leo W. Stach of ECAFE, acting as Co-ordinator of CCOP, for his kind co-operation and suggestion on technical editing.

Finally, on behalf of the co-editor, I would like to convey our gratitudes for the kindness of the Geological Survey of Japan in the printing, as well as for the co-operation made by many personnel of the Survey in completing this volume.

February 1970
Masami Hayakawa
Editor-in-chief

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I. AEROMAGNETIC SURVEY OF OFFSHORE TAIWAN

By

W. Bosum[1], G. D. Burton[2], S. H. Hsieh[3], E. G. Kind[1], A. Schreiber[1], and C. H. Tang[3]

(with figures I-1 to I-19)

ABSTRACT

A reconnaissance aeromagnetic survey was conducted in the offshore areas of western and southern Taiwan in the spring of 1968 by the U.S. Naval Oceanographic Office Project Magnet to help the Republic of China searching for oil. A metastable helium magnetometer was used to measure the total magnetic intensity and a fluxgate magnetometer served as a backup unit at an altitude of 180 m above sea level. The direction of flight traverses over the survey areas was northwest-southeast in the northern part and east-west in the southern part. Track spacing never exceeded 6～7 km. Approximately 25,000 km of magnetic data were collected over an area of about 85,000 sq km.

The residual magnetic intensity map was prepared by removing the International Geomagnetic Reference Field (IGFR). The observed magnetic data were quantitatively interpreted to give depth and shape for the isolated magnetic body and the magnetic basement by mathematical analyses, using modern computer techniques based on the methods of least squares and Fourier analysis.

Because no magnetization data of basement samples are available, the magnetization contrast was assumed to be 250 gammas for calculations of magnetic basement in the Penghu Lieh-tao and the northwest offshore area and 180 gammas in the southwest and the southern part of offshore Taiwan.

The configuration of the magnetic basement of offshore Taiwan reveals a good coincidence with the geologic basic figures recognized in the onshore area of Taiwan, such as the Kuanyin Shelf, the Hsinchu Basin, the Miaoli Swell, the Taichung Basin, the Peikang Shelf (or Peikang Massif), and the South Taiwan Basin.

The central Penghu Lieh-tao region and the southeast offshore of Taiwan are characterized by narrow, high amplitude, high frequency anomalies possibly caused by shallow basaltic extrusives similar to the basaltic rocks cropping out in the Penghu Lieh-tao and the Lanyu islet. The magnetic trends observed in the contour chart around the Penghu Lieh-tao region indicate various structural elements either lineaments or fault zones that were partly filled by volcanics. There probably exists two magnetic storeys, one represented by the near-surface anomalies, the other by the deeper situated magnetic basement. Although some scattered smaller anomalies with an extent of only a few Kilometers can be seen over the whole area, the smooth, large area anomalies of low amplitude are the prominent features recognized in the areas of the northwest and the southwest offshore of Taiwan. These larger anomalies are

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2) U.S. Naval Oceanographic Office, Washington, D.C. 20390.
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interpreted to originate from deep basement rocks ranging from 8,000 m to 10,000 m below sea level. The sequences of strata above the magnetic basement are assumed to consist of non-magnetic metamorphosed Mesozoic, indurated or metamorphosed Paleogene and unaltered Neogene-Quaternary rocks.

These Neogene sediments consisting mainly of sandstone and shale series of marine origin have been proved productive of hydrocarbons in the coastal plain of western Taiwan. It is inferred that the reservoir rocks may extend westward into the Taiwan Strait, where future petroleum exploration is considered favorable as far as the structural and stratigraphic conditions are concerned.

The magnetic basement does not necessarily agree with the Mesozoic basement (geological basement in the west coastal plain area of Taiwan) which was discovered by drillings in the Peikang Massif and the Penghu Lieh-tao. The Peikang Mesozoic basement may extend from the Peikang Massif across the Penghu Channel to the Penghu Lieh-tao and continue westward to the Fukien province of Chinese mainland.

INTRODUCTION

In 1966, the United Nations Economic Commission for Asia and the Far East (ECAFE) established a Committee for the Coordination of Joint Prospecting for Mineral Resources in Asian Offshore Areas (CCOP) to aid member nations in the exploration for mineral resources. As part of the United States contribution to this effort, the U.S. Naval Oceanographic Office conducted a reconnaissance aeromagnetic survey of the offshore areas of western and southern Taiwan. The area surveyed and the regional bathymetry are shown in Figure 1. The primary purpose of this survey was petroleum exploration for the Republic of China, with scientists of the Chinese Petroleum Corporation (CPC) participating in all phases of the project. A magnetic survey would provide valuable information about the geological structure of the continental shelf off Taiwan as well as provide estimates for the thickness of sediments in the area by determining the depth to the magnetic basement.

Taiwan lies on the edge of the continental shelf with the Philippine Sea to the east and the shallow Taiwan Strait separating it from the Chinese mainland to the west. Taiwan is also in the unique geological position of being at the apparent terminus of the Ryukyu Arc curving southwestward from Japan (Fig. 1). In addition, a bathymetric ridge extends almost continuously from Taiwan to the Philippines, broken only by the Bashi Channel, a deep canyon joining the waters of the South China Sea with the Philippine Sea. The major bathymetric and structural features of the Western Pacific have been discussed previously by Hess (1948), Dietz (1954), and Menard (1964).

SURVEY OPERATIONS AND DATA REDUCTION

Survey operations in Taiwan were carried out in the spring of 1968 by a U.S. Naval Oceanographic Office Project Magnet aircraft. Measurements of total magnetic intensity were obtained from a metastable helium magnetometer. Flight altitude was 180 m with the magnetometer sensor towed about 30 m below the aircraft. A fluxgate magnetometer mounted internally within the aircraft served as a backup unit. In the northern part of the survey area, tracks were flown in a general northwest-southeast direction changing to an east-west direction for the southern part of the survey. Track spacing never exceeded 6 ~ 7 km. Approximately 25,000 km of track data were collected over an area of about 85,000 sq km. Loran-A navigation was used south of the island, but navigation for the remainder of the survey was by

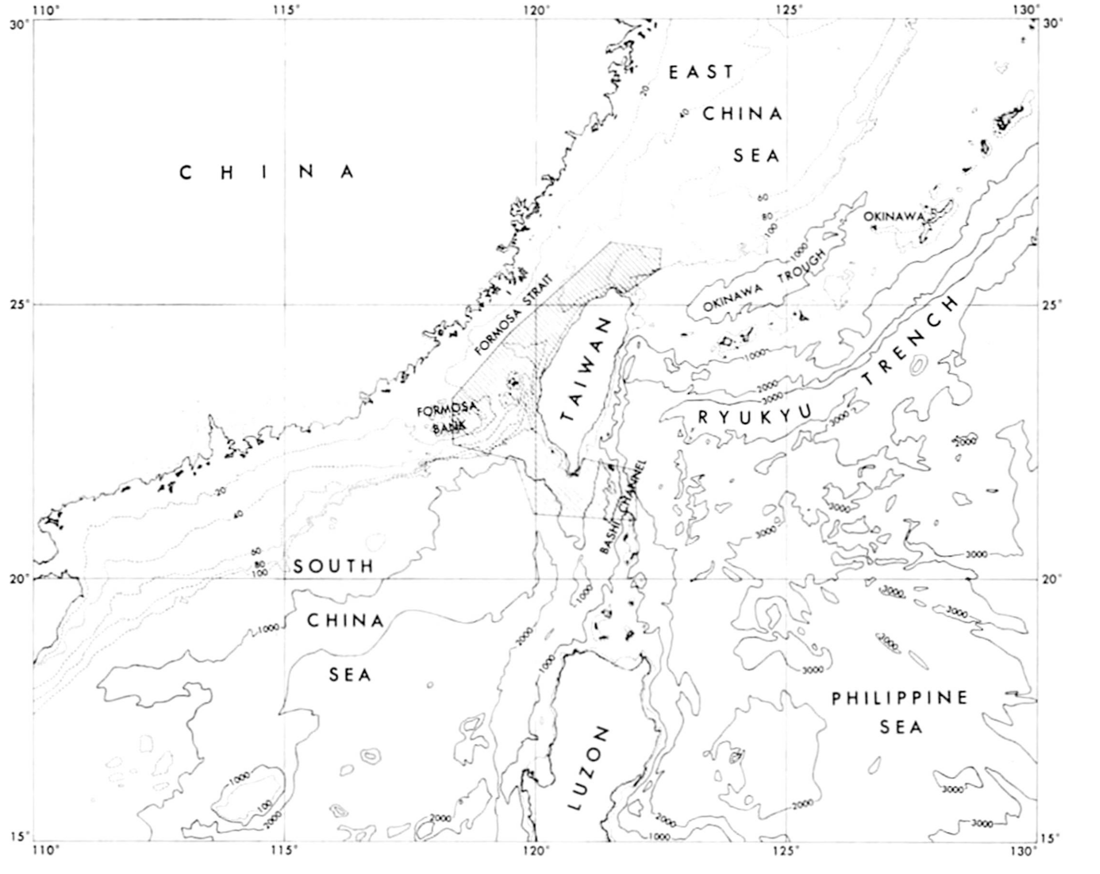

Figure I- 1. Regional bathymetric chart showing location of survey area. Contour interval is 1000 fathoms with 20 fathom contours dashed to the 100 fathom depth. Bathymetric contours taken from H. O. Pub. 1301, U.S. Naval Oceanographic Office.

means of visual fixes, TACAN, and dead reckoning. Uncertainty in final aircraft positioning is generally estimated to be within 2 km, but may be as great as 4 km along the western limits of the survey area.

A cesium station magnetometer was set up at Lumping Observatory about 50 km southwest of Taipei. It was operated on a continuous basis during the survey period to monitor temporal variations in magnetic total intensity.

First order corrections for temporal variation were made to the total intensity data by assuming that there was a one-for-one correlation in fluctuations of the magnetic field at the ground station and throughout the survey area. A mean value of the magnetic field was established for the ground station and deviations from this mean were removed from each survey track to reduce all survey data to a common datum level. Diurnal variations were observed to have a range of about 60 gammas. No severe magnetic disturbances occurred during times of survey.

Total magnetic intensity contour charts were prepared at both 20 gamma and 50 gamma contour intervals. Copies of these charts are available upon request from the U.S. Naval Oceanographic Office. Figure 2 shows the total magnetic intensity with 100 gamma contour intervals for the original chart was condensed. A residual magnetic intensity contour chart (Fig. 3) was then prepared by graphically removing the International Geomagnetic Reference Field (IGRF) (Fabiano and Peddie, 1969).

The residual magnetic contours (Fig. 3) show a regional magnetic high over the southern half of the survey area, with only minor areas having negative values. The areal distribution between positive and negative values in a contour chart is partially a function of the reference field removed in the construction of the residual chart. Bullard (1967) aptly discusses the problems encountered in deciding upon a main reference field. For this particular survey a change of 40 gammas in the level of the IGRF would provide a visually more appealing chart in the area southwest of Taiwan, but such as shift in level would be disproportionate for the entire northern part of the survey. If the shape of the IGFR is correct for this area, the presence of a regional magnetic high south and southwest of Taiwan may be of significance in the regional interpretation of the Asian continental margin.

MATHEMATICAL ANALYSIS OF MAGNETIC DATA

Interpretation Methods

The German Geological Survey (Bundesanstaldt für Bodenforschung) of Hannover conducted a mathematical analysis of the survey data using modern computer techniques.

Isolated magnetic anomalies, chiefly those whose source is near the surface, can be interpreted by two-dimensional and three-dimensional model bodies. The two dimensional analysis assumes the source body to be infinitely extended along the direction of strike and magnetized in the direction of the present field. Appropriate two-dimensional model bodies (such as cylinder, infinite and finite thin plates, broad dike and steps) are initially presumed and their anomalies are compared with the measured magnetic profile to determine the type of model body best approximating the actual magnetic anomaly. By a repeated process of comparing the theoretical and observed profiles, the form of the model body can be varied until a best fit is obtained between the calculated and the measured anomaly profiles.

The iteration method just described has been programmed for computers according to the method of least squares (Bosum, 1968). The computer program generally determines depth, form and magnetization (or equivalent quantities, respectively, as for instance the product thickness times magnetization for a thin plate, etc.) of the body. If further analysis

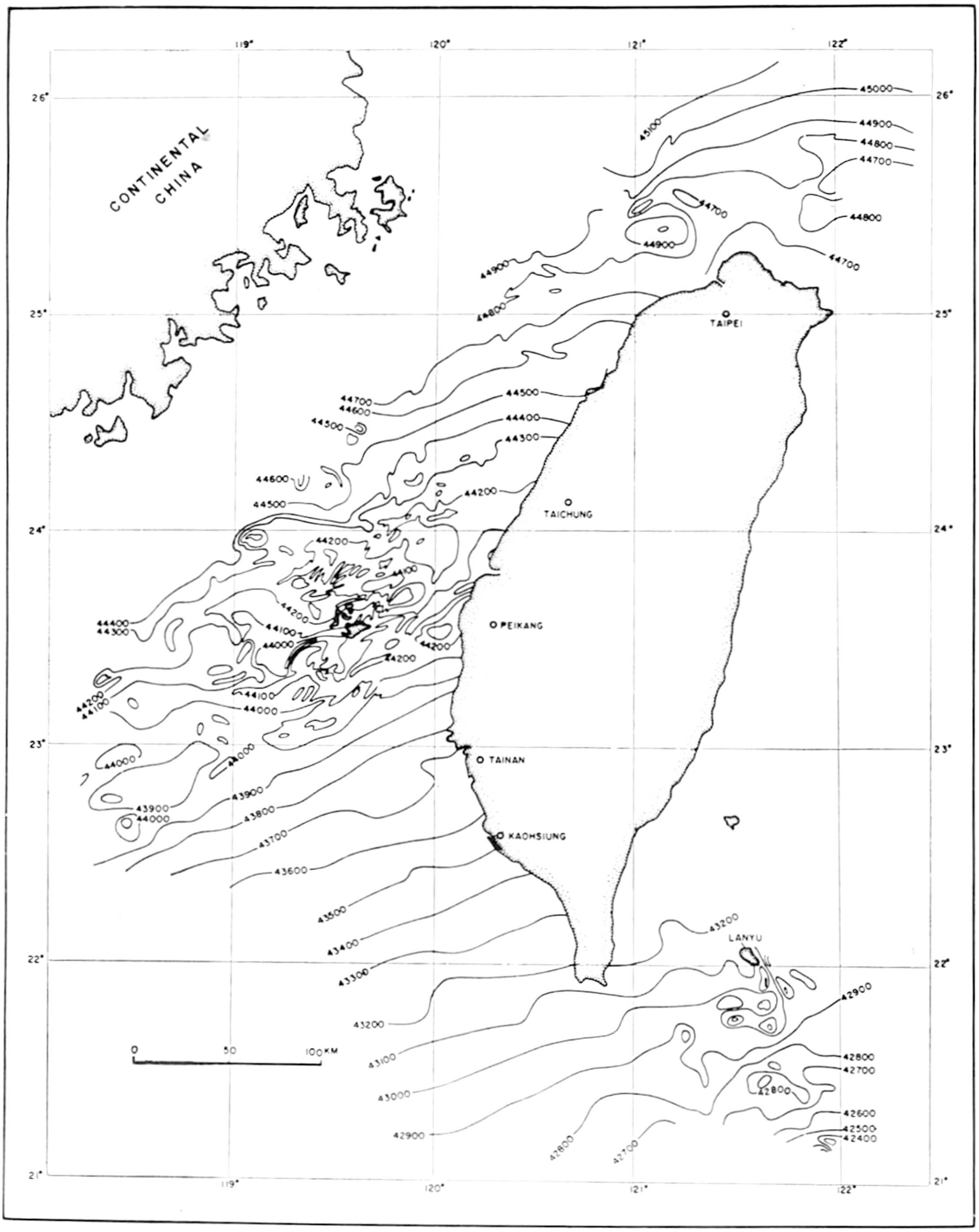

Figure I– 2. Total magnetic intensity chart of offshore Taiwan. Contour interval is 100 gammas.

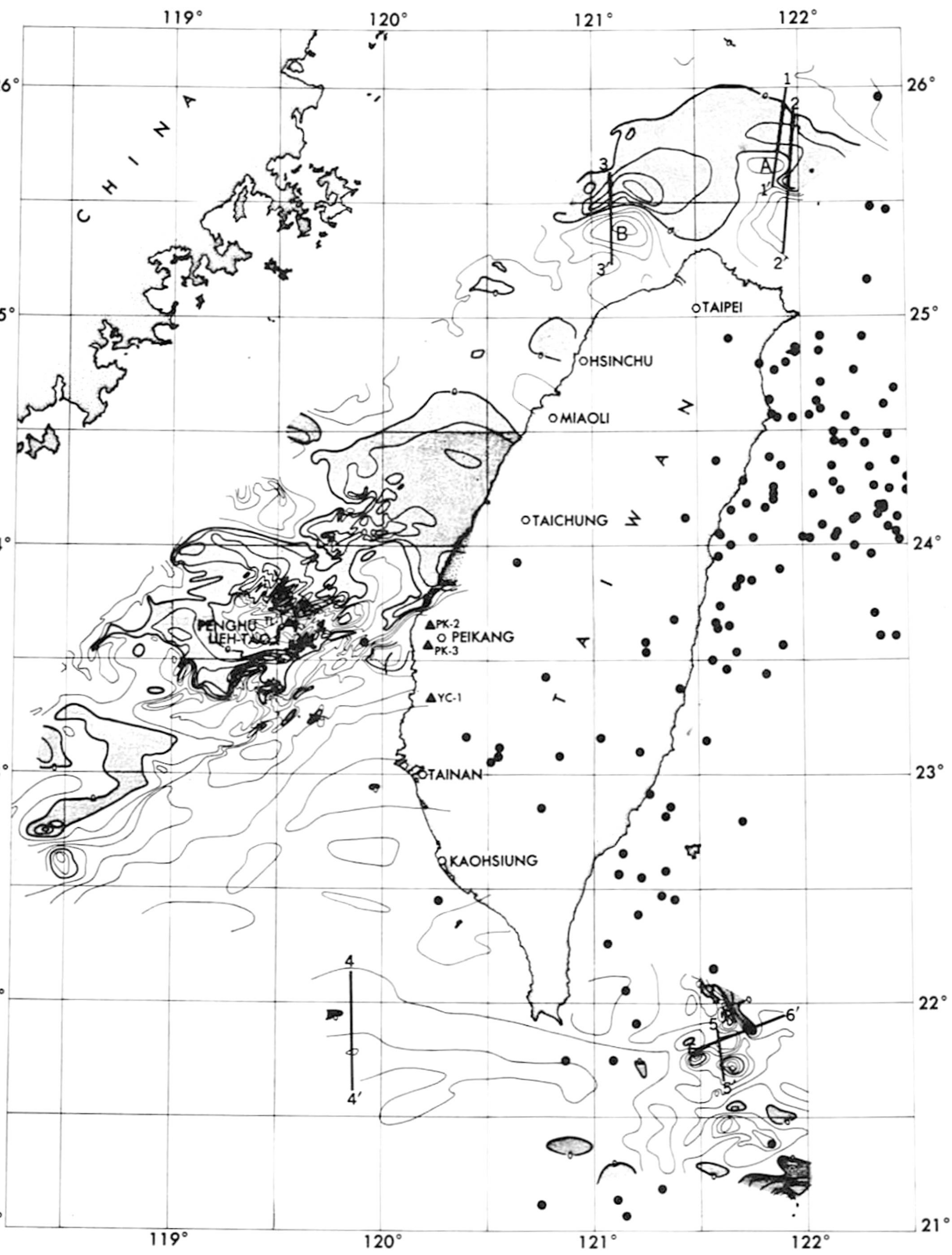

Figure I– 3. Residual magnetic contour chart based on IGRF. Contour interval is 50 gammas. Negative residuals are shaded. Dots indicate earthguake epicenters (Katsumata and Sykes, 1969). Triangles indicate wells drilled by CPC. Profile lines 1–6 indicate location of model studies.

is required or if the shape of the magnetic anomaly indicates that a two-dimensional body would not provide a satisfactory interpretation, one constructs, after a preceding two-dimensional approximation, a three-dimensional body, computes its field and approximates it to the measured anomaly. This is done with a computer program written for a body of arbitrary magnetization bordered by planes. The program produces, in connection with an automatic plotting machine, the contours of the anomalies. The results are then plotted on interpretation maps in the customary way by indicating the strike, dip, and depth of the bodies.

Rather than being an isolated magnetic body, the source of many magnetic anomalies is often surface relief along a magnetized layer. In order to calculate the surface relief, a computer program was developed in which the computation proceeds directly from the measured field to the relief of the magnetic basement (Hahn, 1965). In this process of calculation the magnetic field is represented by a two-dimensional finite Fourier's series. The partial waves are continued separately down to the projected interpretation depth and used for the construction of the relief. The only variables required by the computer program are the mean depth to the basement and the contrast of magnetization at the relief plane, which in general is equal to the magnetization of the basement. The resulting computed relief represents a model which duplicates the measured field completely. With this method of analysis, the amplitude of relief varies inversely with the magnetization contrast. If, e.g., with a magnetization contrast of 200 gammas a relief amplitude of 3 km is calculated, a magnetization contrast of 100 gammas would involve a relief amplitude of 6 km.

Results of Analyses

The computer techniques described above were applied to the data of the Taiwan survey to determine the depth and relief of the magnetic basement and to suggest various model bodies as the sources for some of the isolated magnetic anomalies. The track spacing of the reconnaissance survey presents certain limitations for detailed analyses, especially for that of anamalies with source bodies near the surface (depth less than 3,000 m below flight level).

For an analysis of magnetic anomalies it is appropriate to have in view the form of the anomalies above different model bodies to reach a first qualitative interpretation. Therefore, several theoretical curves for various two dimensional model bodies have been represented in Figure 4. A homogeneous magnetization is assumed parallel to the earth's magnetic field (inclination $I = 32°$ for Taiwan). The upper portion of Figure 4 shows the theoretical anomalies caused by thin dikes of varying dip (0°, 45°N, 90°, 45°S). The model for a dip of 0° means, in practice, a step of a magnetic sheet which in one case is located south of the body and in the other case is north of it. As can be seen, the relation of the maximum to the minimum of the magnetic anomaly is altered with the changing angle of dip of the dike. Positive anomalies indicate a northward dipping dike or an upstep to the north. Negative anomalies are to be found in the case of an upstep to the south or for southward or steeply dipping bodies. The lower part of Figure 4 shows the theoretical anomaly above a circular cylinder. Geologically this mathematical model represents a body whose dimensions are small compared to its depth. Thus, it may be a dike-like body of small extensions, as indicated by the hachures in Figure 4.

An analysis of the magnetic contour charts for the Taiwan survey suggests the subdivision of the survey area into four distinct regions:

(1) the northwest offshore of Taiwan
(2) the central Penghu Lieh-tao (Pescadores) region
(3) the southwest and south offshore of Taiwan
(4) the Taiwan-Philippine ridge southeast of Taiwan

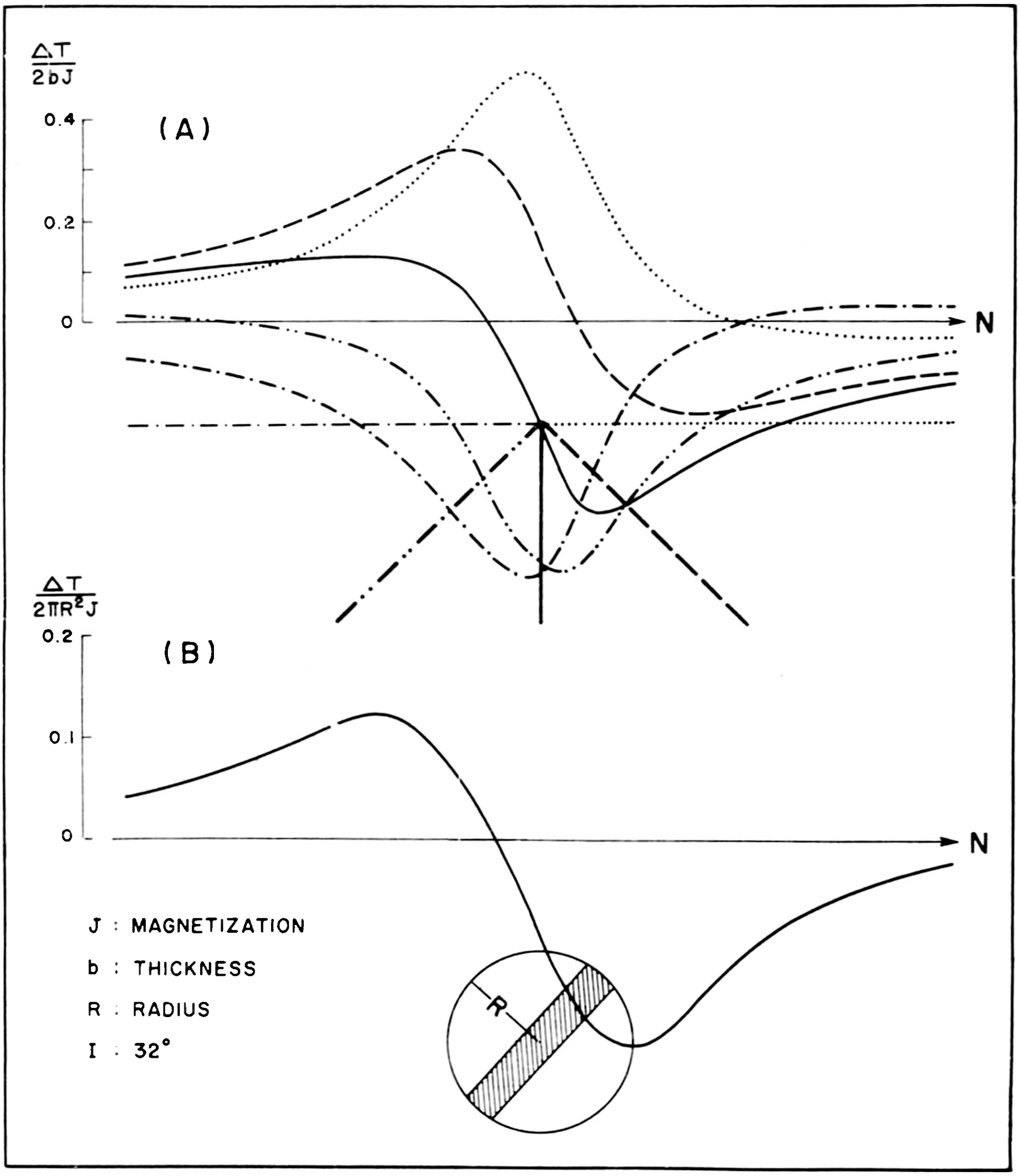

Figure I– 4. Theoretical profile for ΔT–anomalies above two-dimensional thin dike-like bodies of different dip (A) and a circular cylinder (B).

Region (1)—The Northwest Offshore of Taiwan

This area extends from the northernmost extent of the survey to an approximate line extending from 24°30′N, 120°30′E. It is characterized by large area anomalies (Fig. 3), notably a minimum west of Taichung, a maximum northwest of Miaoli and north of Hsinchu, and a maximum and minimum north of Taipei. In addition there are two strong magnetic anomalies of minor area extent, one about 80 km north-northeast of Taipei (designated A in Fig. 3) and the other about 50 km northwest of Taipei (designated B). Both anomalies consist of a maximum with an associated minimum to the north, the amplitude of A being about 160 gammas and B about 300 gammas. Finally, many smaller anomalies having an extent of only a few kilometers can be seen scattered over the whole area. They possess small amplitudes and often cause only slight deviations of the magnetic contours.

It can be assumed that the large area anomalies initially referred to arise from the magnetic basement. The two strong anomalies, A and B, may be caused by magnetic intrusions, but it cannot be determined from the available magnetic data whether the intrusions are located in the basement or in the overlying sediments. The small amplitude local anomalies are probably caused by shallow basaltic rocks. Because of the track spacing these anomalies are not mapped in detail, and indeed many similar anomalies were probably undetected by the survey.

A quantitative interpreatation by Fourier analysis to determine basement relief has been done for the whole area except the northeastern part, where the anomalies are not completely measured. It should be kept in mind that the limits of the survey did not necessarily permit complete coverage of some anomalies, so that the results of interpretation may change slightly if additional survey data are obtained. Anomalies A and B have been interpreted both by Fourier analysis and by model studies based on profiles.

Figure 5 shows the relief of the magnetic basement for the northwest offshore area of Taiwan. The magnetization contrast is 250 gammas. By experience it is known that the "Basement" generally consists of magnetic and non-magnetic parts. It shall be stressed that by a magnetic survey, of course, only the magnetic basement or magnetic parts of the basement can be detected. The question of the magnetic properties of the "Basement" and of the relation between the magnetic basement and the geological basement can be answered only by rock magnetic investigations and geological studies. In the southwestern part of the area, a basin of about 11,000 m is present. Northeast of the basin is a narrow ridge at a depth of 7,000 m striking northwest-southeast. Beyond is a local depression of 10,000 m which rises to the northeast in a high swell of 3,000 m depth. This swell also strikes northwest-southeast, but shows near its center a protrusion to the southwest. A profile of these main features is shown in Figure 6.

The result of the two-dimensional interpretation of a profile (3–3′ of Fig. 3) across anomaly B is shown in Figure 7. The model body has the form of a thick dike dipping 70° to the north. The depth to the top of the dike, amounting to 3,000 m, is in good agreement with the basement relief shown in Figure 5. The dike-like form indicates the possibility of an intrusive body as the magnetic source. The northsouth striking is anomals north of Taiwan in connection with the local anomaly B suggests a magnetic structural element, which is the line I in Figure 9.

Two profiles (1–1′, and 2–2′, Fig. 3) across anomaly A are shown in Figure 8. Profile 2–2′ indicates that the model body may be either a dike or a horst. The observed and calculated anomalies agree well for both profiles. In this case the model may represent intrusive bodies lying at depths of 2,000 m and 3,000 m, respectively, below mean sea level.

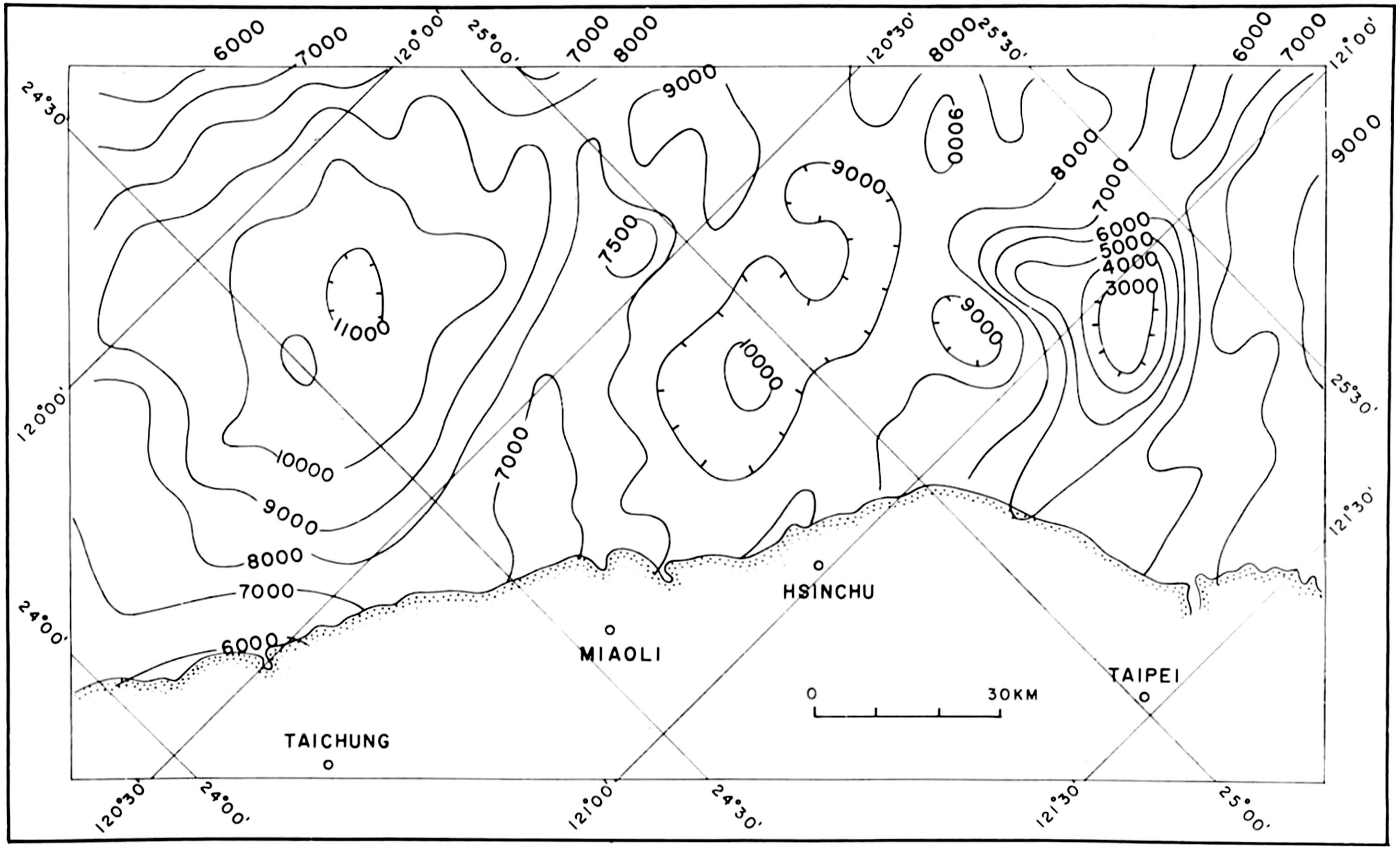

Figure I– 5. Relief of the magnetic basement of the northwest offshore of Taiwan, depth in meter below sea level.

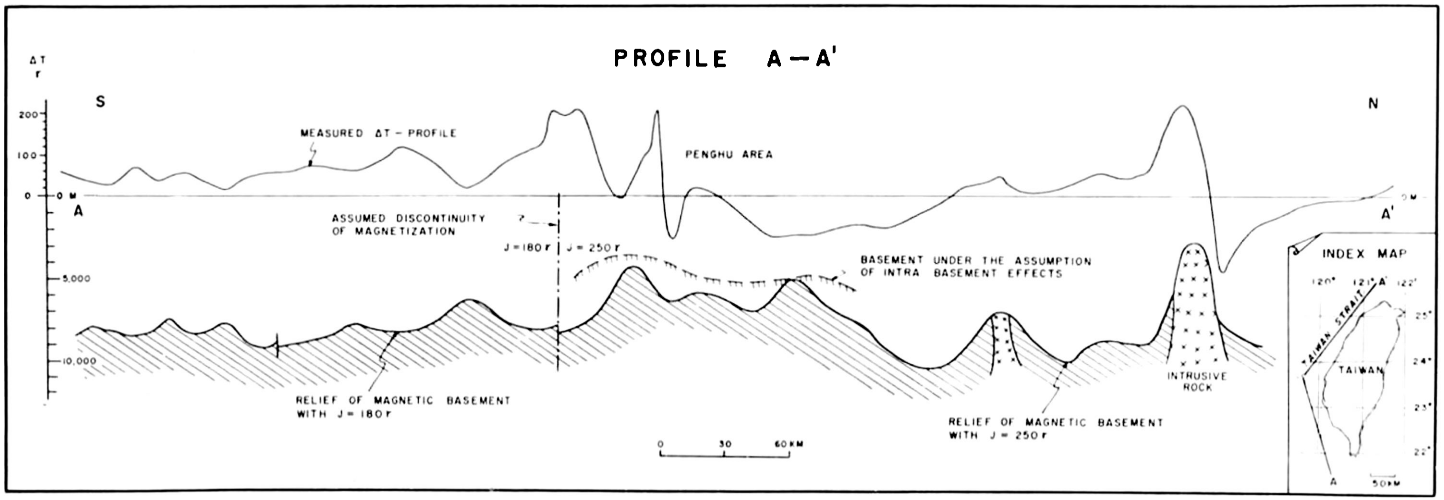

Figure I- 6. North-south profile A–A′, showing the measured magnetic ΔT–profile and the relief of the magnetic basement of the Taiwan Strait.

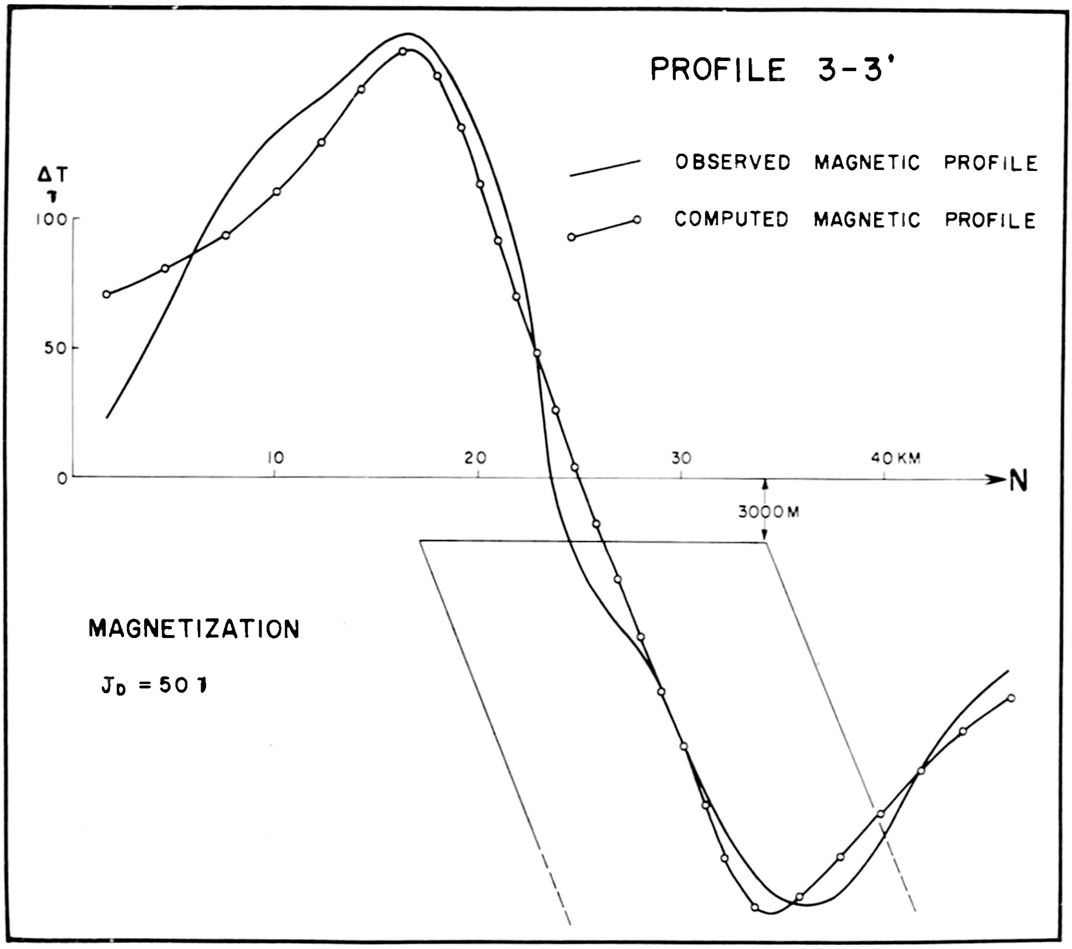

Figure I- 7. Profile 3-3', showing the two-dimensional model study of anomaly B in the northwest offshore of Taiwan.

Region (2)—The Central Penghu Lieh-tao Region

This region, extending southwest of region (1) to a line from about 22°30′N, 118°30′E, to 23°30′N, 120°30′E, is characterized by a strongly disturbed magnetic field. The narrow magnetic anomalies indicate that the source bodies are situated at shallow depths. They are probably basaltic extrusives similar to the basaltic layers cropping out in the Penghu Lieh-tao.

Besides these local anomalies, other large scale anomalies of minor amplitude can be seen qualitatively from the magnetic contour charts. There are several large-area magnetic minima, accompanied by smaller more detailed magnetic maxima. Especially it shall be pointed to the extended SW–NE striking maximum at the SE boundary of the "Penghu interpretation area."

The magnetic trends observed in the contour charts indicate various structural elements, the principal ones of which are plotted in the summarizing interpretation map (Fig. 9). It can be assumed that lines 2 and 5 indicate lineaments. They form the boundaries of regions of distinct magnetic character enclosing the Penghu interpretation area. Line 4 may indicate a lineament, but numerous anomalies lying along this line and with a similar strike of WSW–ENE indicate the existence of a main fault zone partly filled by volcanics. The lines 3, 6 and 7 may indicate either fault zones or lineaments with a WNW–ESE trend. Lines 8a, 8b and 8c striking N–S indicate possible faults of smaller extent.

For a quantitative interpretation of the large scale anomalies a Fourier analysis from the isanomalic map has been done, which proved the existence of two magnetic storeys, one represented by the near-surface anomalies, the other by the deeper situated magnetic basement. To calculate the relief of the most interesting latter one, a separation of both anomaly-parts was carried out by a filtering process based on the Fourier analysis. It should be kept in mind that such a separation theoretically is not possible strictly. The received result therefore will be affected by appropriate uncertainties. The result is shown in Figure 10. As in the northwest interpretation area the magnetization contrast was assumed to be 250 gammas. The relief is dominated by a large scale swell, striking SW–NE throughout the whole area. The depth values amount to about 4,000 m. These values are valid under the assumption of a magnetization of 250 gammas, but will change by changing the magnetization, as is mentioned above. Because the magnetization of the basement is not known, the depth values are affected by a corresponding error. If for instance we would take a magnetization of 180 gammas, as is done in the southwest and south interpretation area, the tops will amount to less than 3,000 m.

This large scale swell region shows several SE–NW striking spurs. The swell is accompanied in the NW by a similar formed depression zone of more than 10,000 m depth, which joines in the NE with the Taichung-Basin. If one compares the magnetic structural elements of Fig. 9 with the magnetic basement relief of this area, one finds that the elements No. 2, 3, 5 and 8a are followed—at least partially—also by the magnetic basement relief, thus pointing to lineaments, whereas the other elements are not indicated by magnetic basement relief, thus pointing to near-surface effects, for instance faults.

The magnetic basement relief in Figure 10 shows the behaviour of the boundary-surface between magnetic and non-magnetic material. If now we assume that the magnetic anomalies in the Penghu area originate from single magnetic source bodies, intercalating the basement, (so called Intra Basement effects)—an assumtion, which is suggested by the form of several isolated maxima and minima of the magnetic relief—a corresponding map of the basement can be derived from Figure 10 by only using the top-depths. This is done in Figure 11. The Penghu swell now shows a more uniform shape. In this case the islands are lying in the central part of the swell, whereas in the first case they are lying at the flank of the swell. But it shall

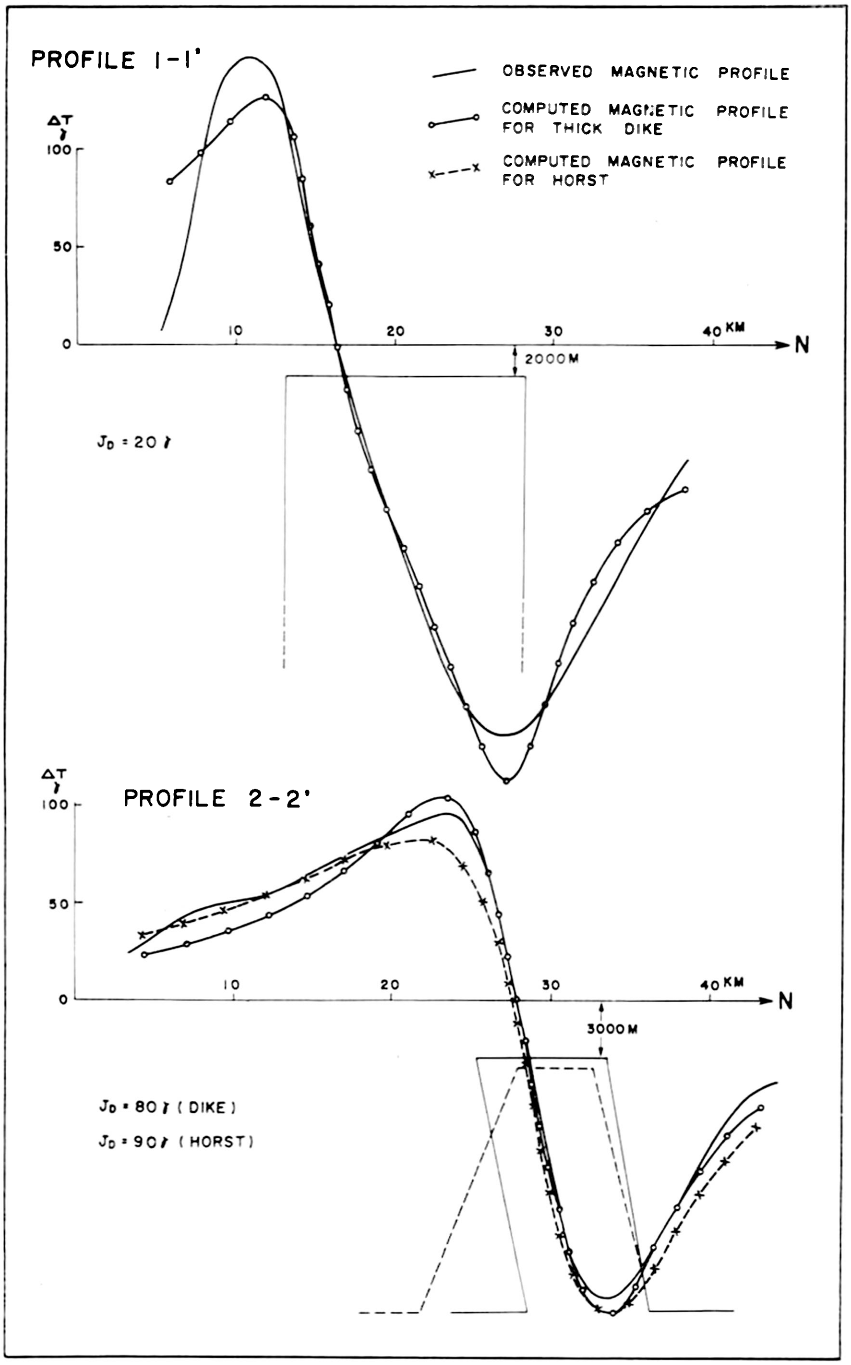

Figure I– 8. Profiles 1–1′ and 2–2′, showing the two-dimensional model study of anomaly A in the northern offshore of Taiwan.

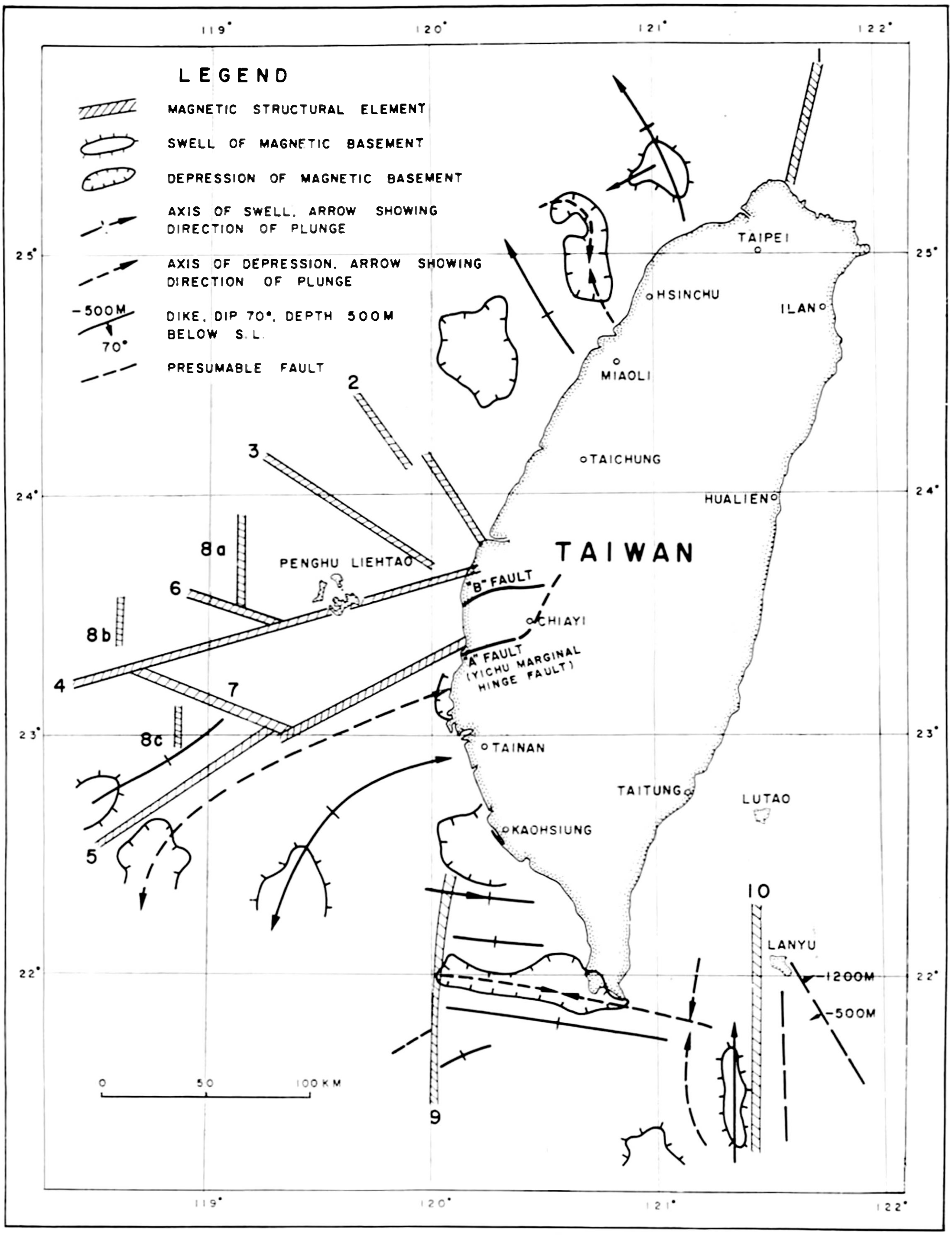

Figure I– 9. Summarizing interpretation map of the aeromagnetic survey of offshore Taiwan.

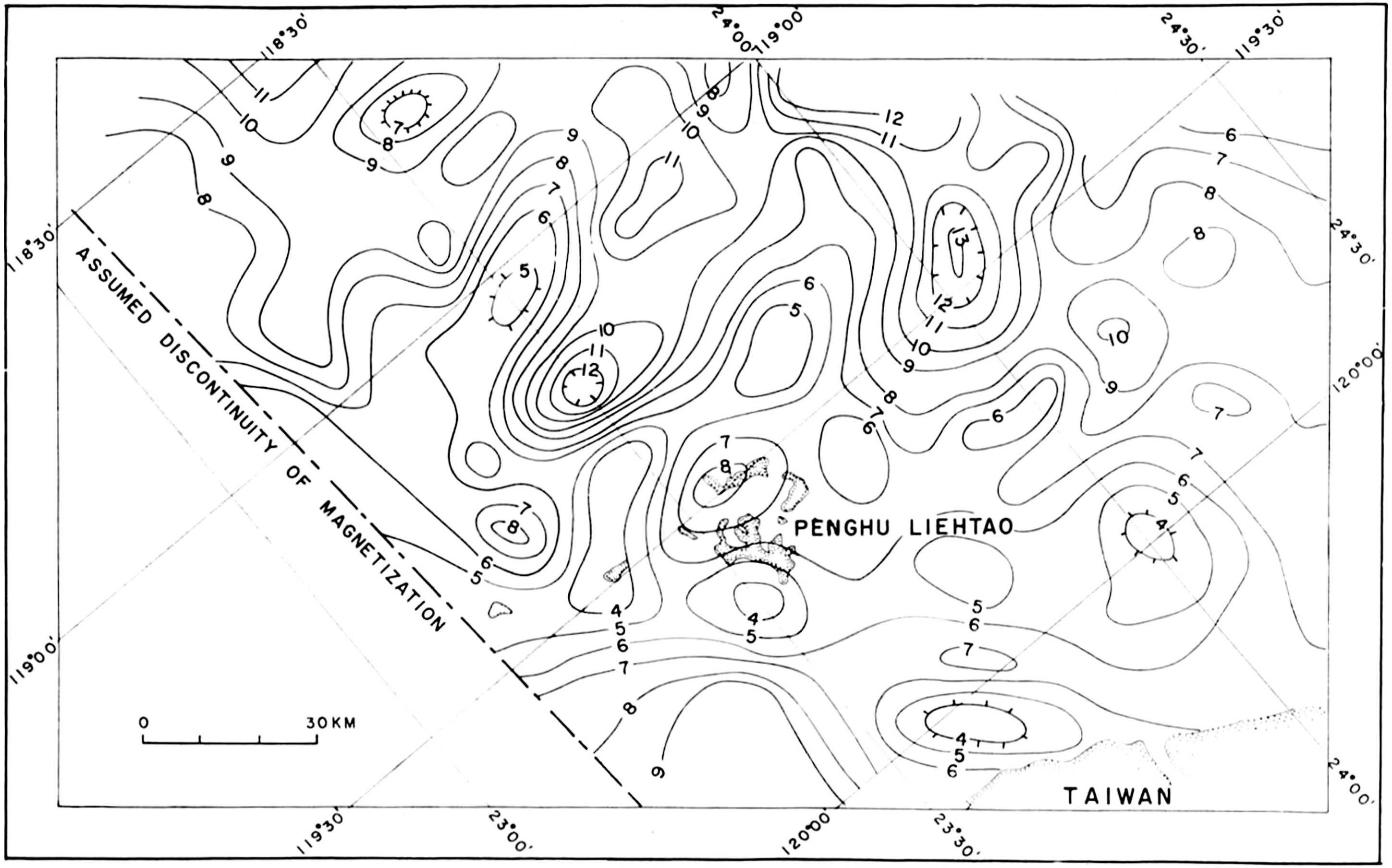

Figure 1–10. Relief of the magnetic basement of the Penghu Lieh-tao area, depth in 1,000 m below sea level.

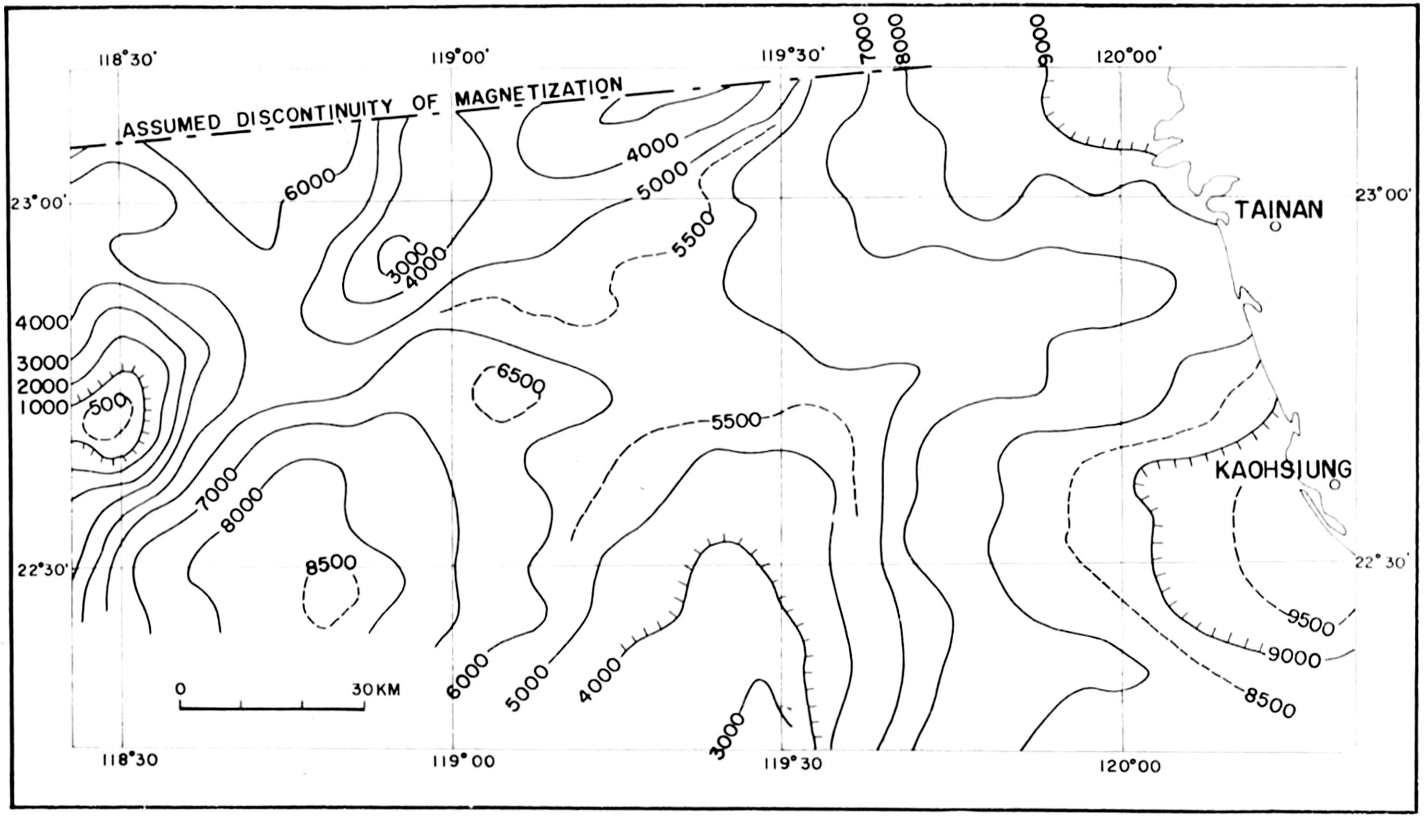

Figure I-11. The basement relief of the Penghu Lieh-tao area, constructed from the magnetic basement relief of Figure 10 under the assumption of intra basement effects. Depth in meter below sea level.

be stressed that this result is based upon a certain geological model, by magnetics and from the isanomalic map. It can not be decided neither for the one nor for the other model.

Region (3)—The Southwest and South Offshore of Taiwan

This region lies south of the Penghu region. The northern boundary is maked by the broad magnetic high, striking NE–SW, described in the preceding paragraph (line 5 in Fig. 9). The eastern boundary of this area is along the 121°30′E meridian.

The strike of the anomalies in this area is predominately east-west (Fig. 3) with the magnetic field showing smooth, large-area anomalies of low amplitude. The northern anomaly with its minimum west of Tainan and its maximum west of Kaohsiung has an amplitude of about 100 gammas. Another remarkable anomaly, the maximum of which lies at the southern tip of Taiwan, runs east-west to about the 120°E meridian, where it is apparently offset about 30 km in a north-south direction.

Another east-west striking anomaly of about 60 gammas lies south of the one discussed above. It consists of an elongated minimum with several maxima. Remarkably in this case also, two maxima end at 120°E, so that a north-south magnetic structural element may be present along the 120° meridian (line 9 of Fig. 9).

The relief of the magnetic basement has been calculated for this area southwest and south of Taiwan (Figs. 12, 13 & 17). The calculation of the relief is based on an assumed magnetization of 180 gammas. Because of the lower magnetization, the relief contour lines do not continue into the Penghu Lieh-tao area. As can be seen in Figure 12, the basement relief varies between 10,000 m and 3,000 m depth off the southwestern coast of Taiwan. A basement swell with depth values of about 3,000 m follows along the southeastern boundary of the Penghu region and can be seen in the northwest corner of Figure 12. Southeast of this swell is a depression varying in depth from 6,000 m to 10,000 m that plunges in both a northeasterly and a southwesterly direction.

Farther to the southeast is a parallel striking swell with its highest point in the southwest at 3,000 m and with the axis plunging gradually northeastward. Obvious embayment is shown beneath Kaohsiung. To the south, characteristic east-west striking parallel ridges and depressions are found (Fig. 13). The most remarkable depression and swell lies slightly south of 22°N latitude, with the depths to the magnetic basement amounting to 10,000 m and 8,000 m, respectively. The anomaly associated with this feature has been interpreted by two-dimensional models, using both a broad horst and a thin dike as models (Fig. 14). The horst model yields a depth of only 3,000 m, whereas the thin dike yields 9,500 m. The depth to the magnetic basement as calculated by the method of Fourier analysis (using a magnetization contrast of 180 gammas) agrees quite well with that calculated for a thin dike, whereas the horst model shows a much lesser depth. However, it should be kept in mind that the horst model yields minimum depth values, and a lower magnetization used in the method of Fourier analysis would result also in lower depth values of the magnetic basement. But possibly the discrepancy will originate from the too large spacing.

Figures 6 and 16 show profiles A–A′ and B–B′ across Region (3). The eastern part of Figure 13 shows the magnetic basement becoming more shallow (also shown in Profile B–B′). These lesser depth values may not indicate the true magnetic basement because the magnetic field in the eastern part of this area is influenced by local anomalies caused by near-surface bodies. Therefore, this zone may belong to the area discussed below.

Region (4)—The Taiwan-Philippine Ridge Southeast of Taiwan

This region includes the southeastern part of the survey. It is characterized by narrow,

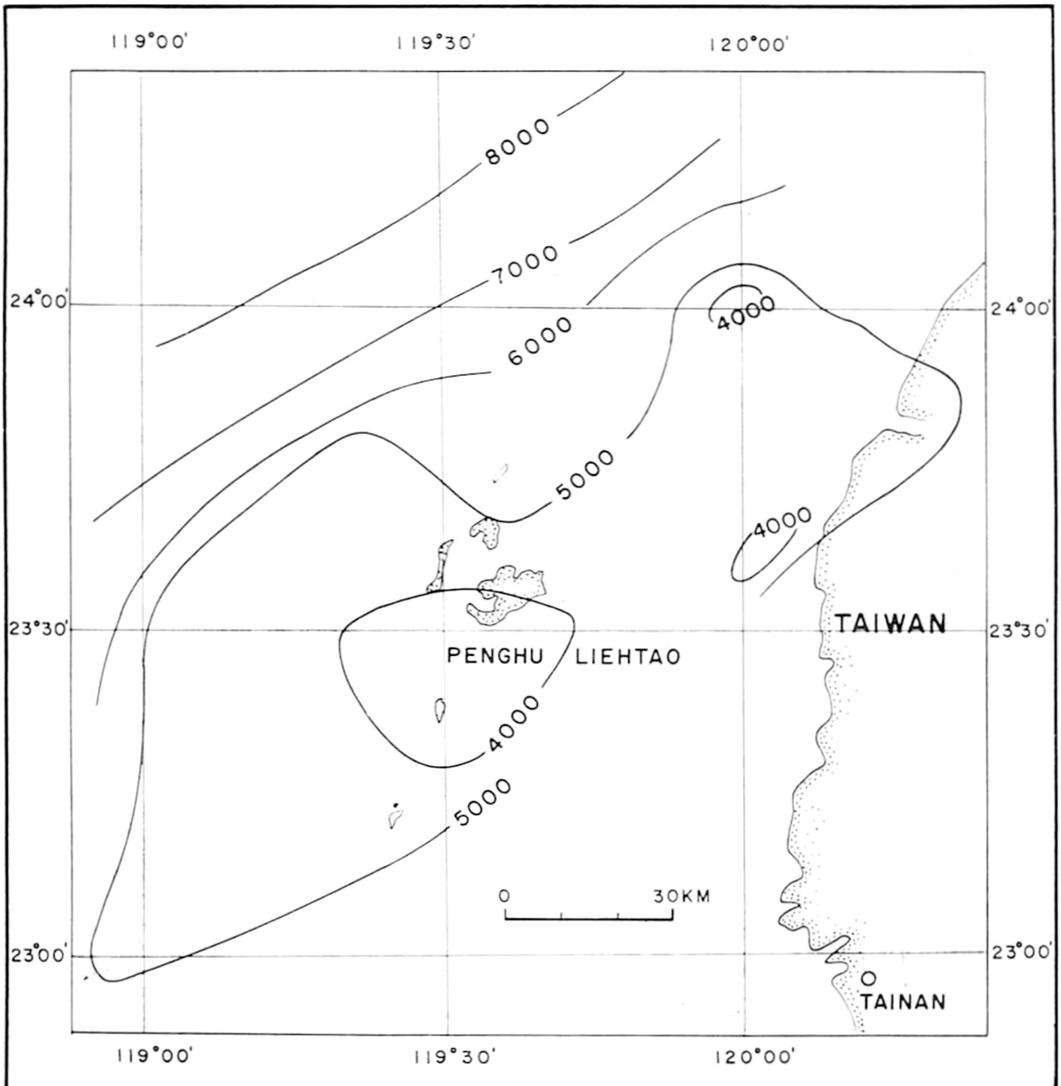

Figure 1-12. Relief of the magnetic basement of the southwest offshore of Taiwan, depth in meter below sea level.

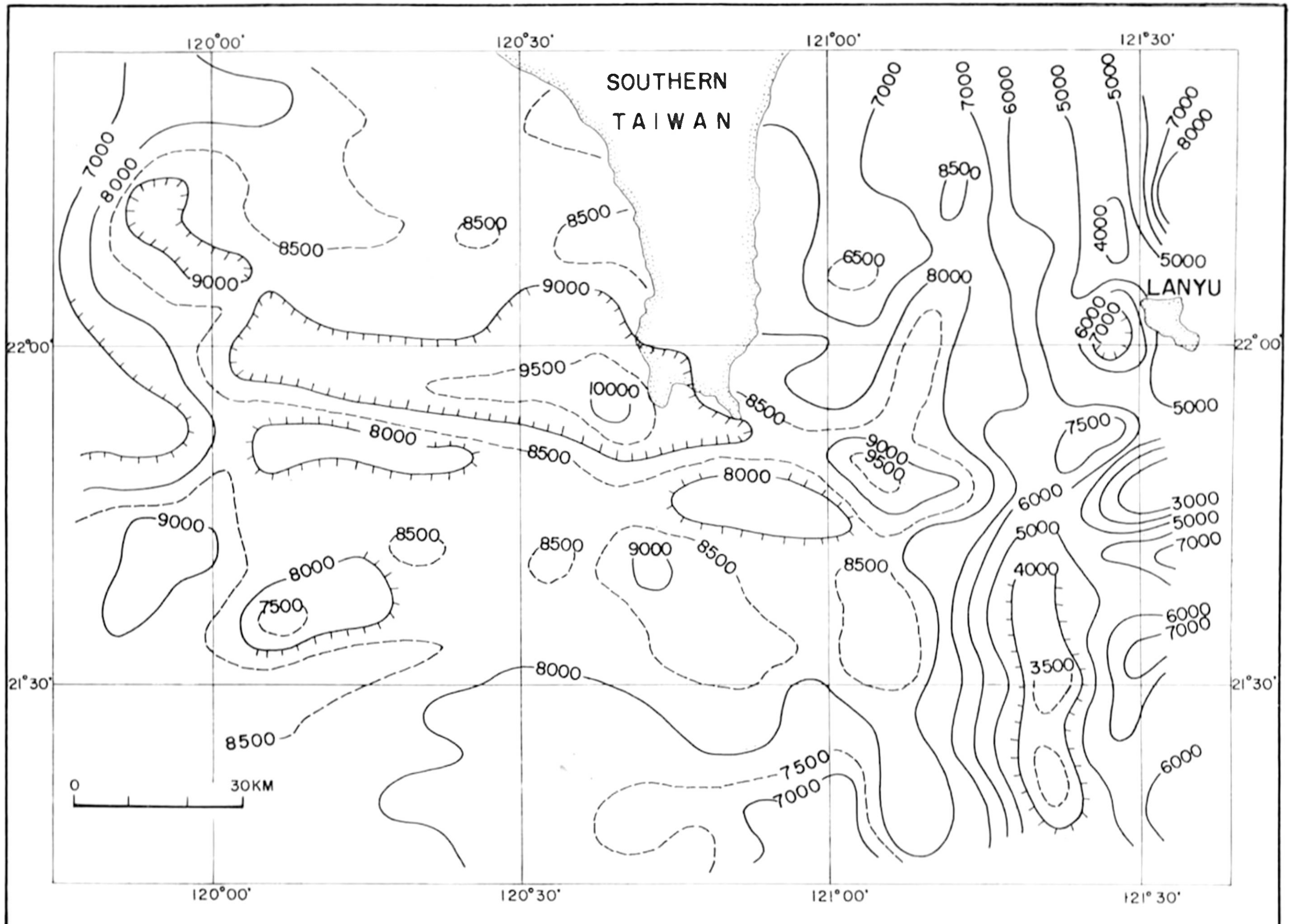

Figure I-13. Relief of the magnetic basement of the southern offshore of Taiwan, depth in meter below sea levvel

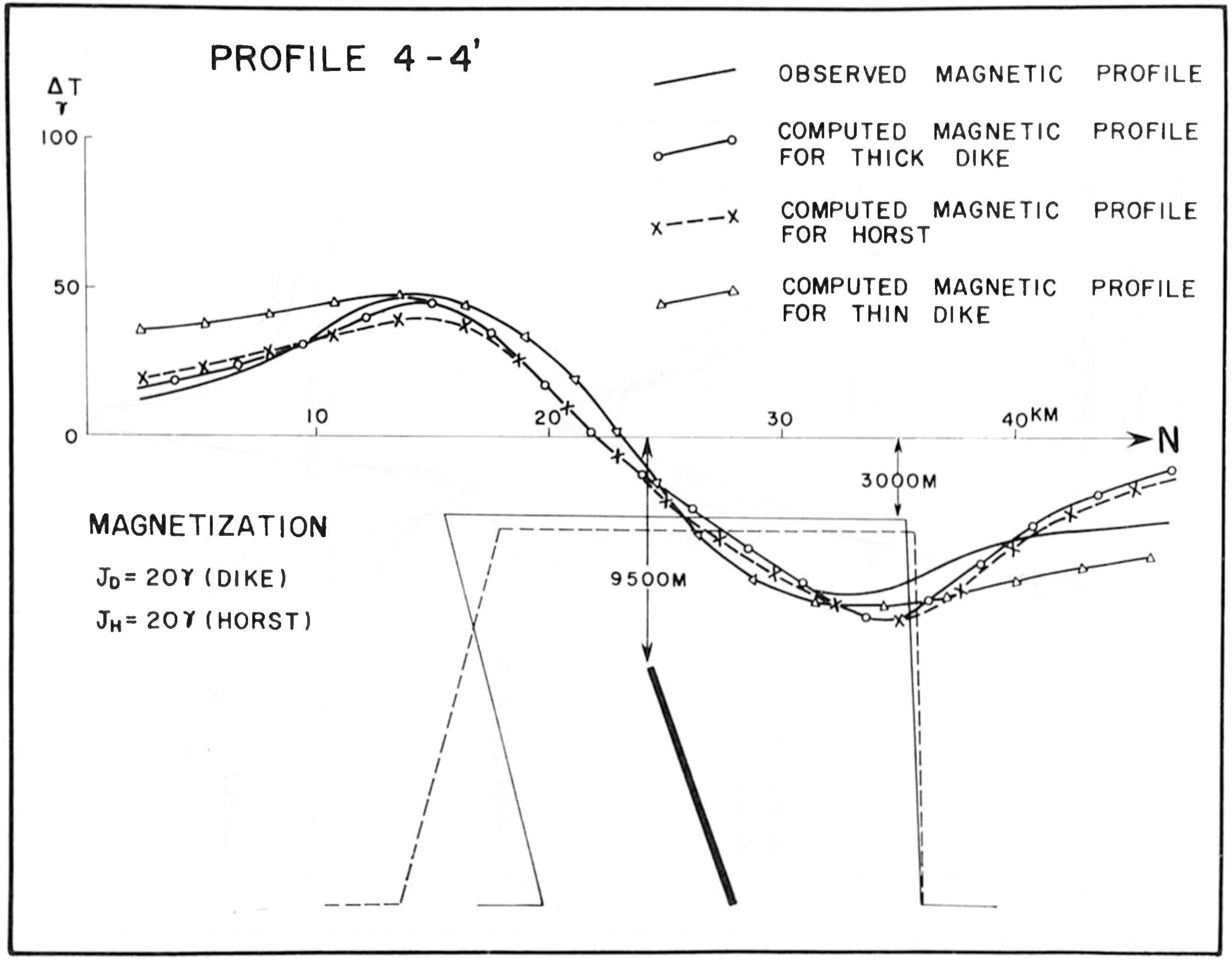

Figure I-14. Profile 4-4′, showing the two-dimensional model study of anomaly in the southern offshore of Taiwan.

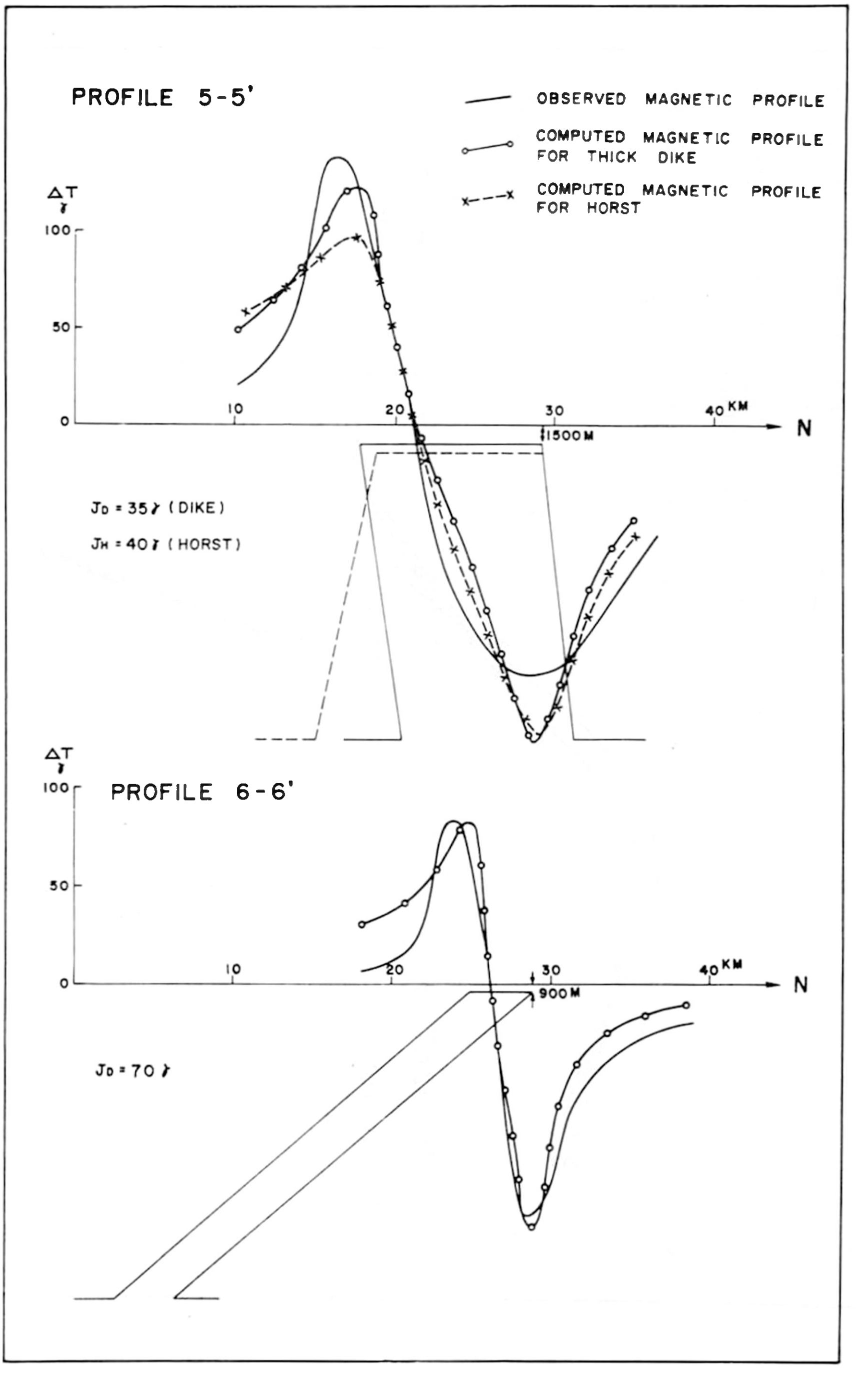

Figure I–15. Profiles 5–5′ and 6–6′, showing the two-dimensional model study of anomaly in the Lanyu area, southeast offshore of Taiwan.

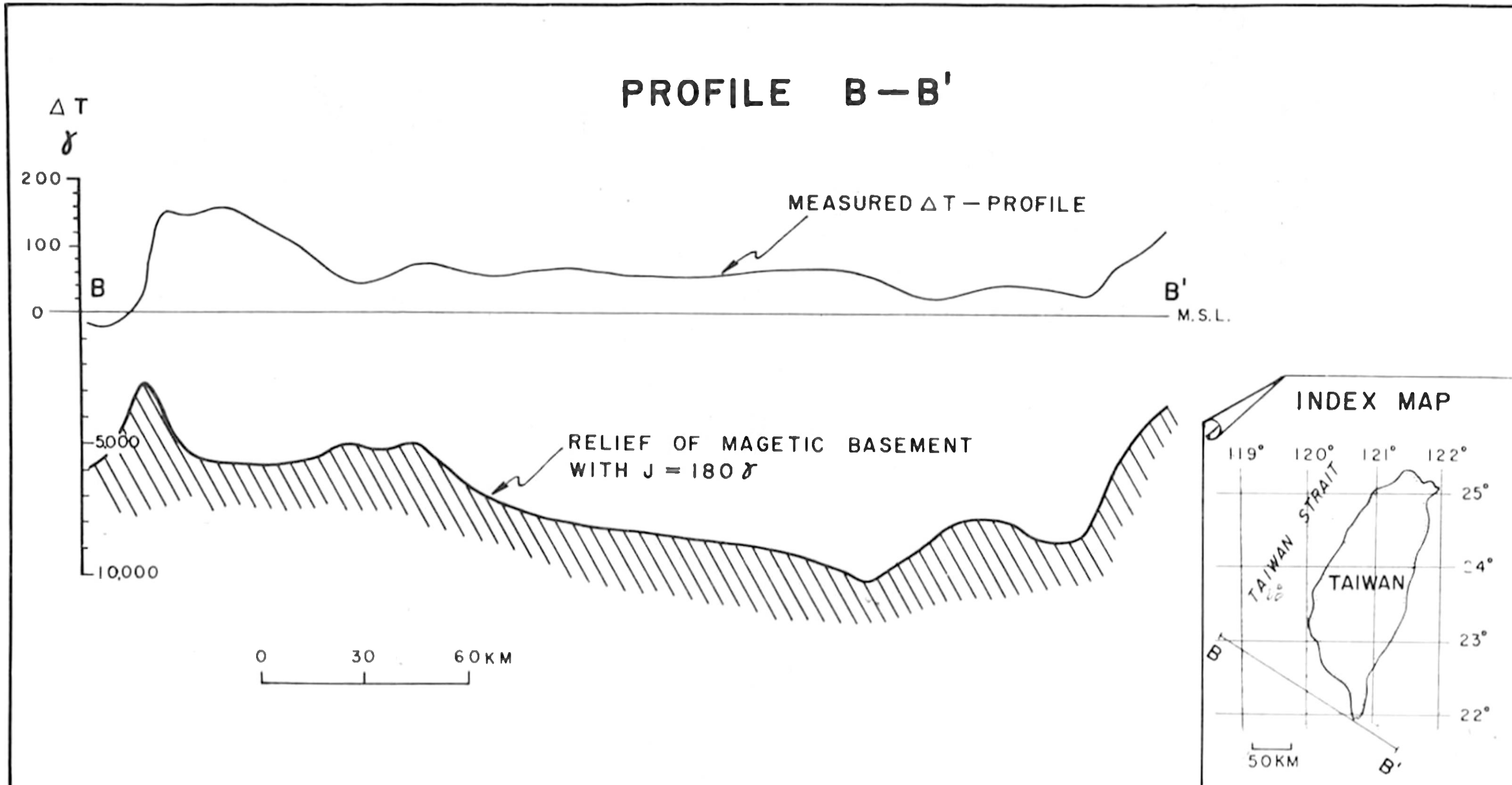

Figure I–16. Profile B'B', showing the measured ΔT–profile and the relief of the magnetic basement of the southwest and the south offshore of Taiwan.

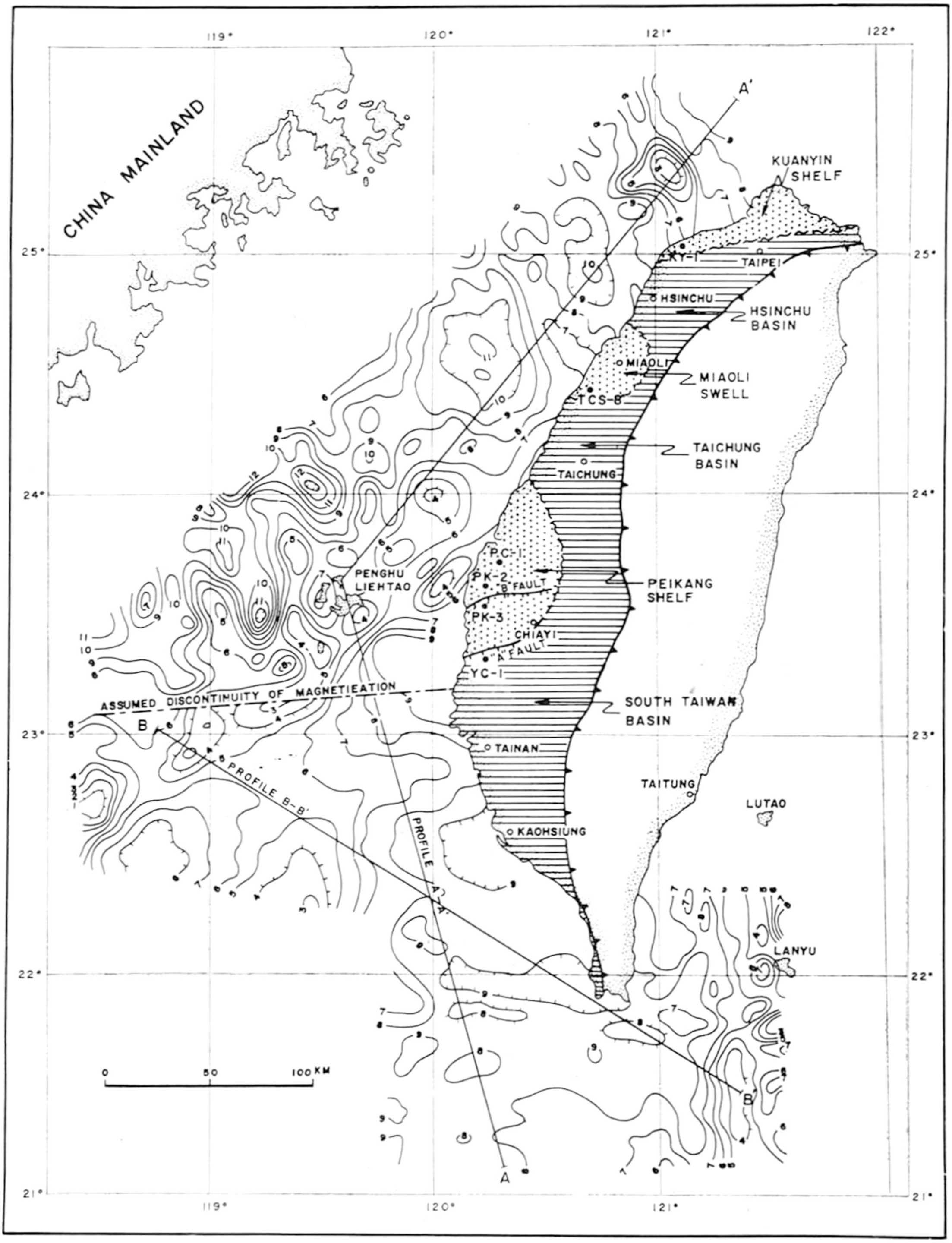

Figure I–17. The relief of the magnetic basement of offshore Taiwan, depth in 1,000 m below sea level.

strong anomalies with a N–S striking zone possibly caused by shallow igneous rocks. The line 10 of Figure 9 probably indicates a structural element either fault or lineament. Because of the disturbed magnetic field, a relief of the magnetic basement could not be calculated. An interpretation by two-dimensional bodies has been undertaken along profiles 5–5′ and 6–6′ (Fig. 3), with the results shown in Figure 15. In both cases shallow intrusions are indicated, with depths to the tops of the bodies being 1,500 m and 900 m, respectively.

GEOLOGICAL GENERAL VIEW

The island of Taiwan is about 370 km in length and 130 km at its maximum width. It is situated in the intersection of the Ryukyu Arc and the Taiwan Philippine Arc which fringe the eastern margin of the Asia continent. The topography of the island is dominated by a generally north-south trending mountain range, the Central Range, with the main axis lying east of the central part of the island. Elevations as high as 4,000 m make this the highest landmass within 1,300 km. Along the east coast of Taiwan is the lesser Coastal Range, separated from the Central Range by a major tectonic break, the East Taiwan Rift. This remarkable feature, also referred to as the Longitudinal Valley, will be discussed in more detail later in this report. The continental shelf follows closely along the eastern coast of Taiwan, with numerous seamounts and a few islands being located to the east in the Philippine Sea.

The western half of Taiwan consists of the foothills of the Central Range and broad alluvial coastal plains. The Penghu Lieh-tao (Pescadores) are separated from Taiwan by the Penghu Channel, which extends from the shallow Formosa Strait into the deeper waters of the South China Sea (Fig. 1).

An extensive literature has been published on the geology of Taiwan, a good part of it due to the efforts of scientists of the Chinese Petroleum Corporation and the Geological Survey of China. Only a brief summary of the geology of Taiwan can be included in this report. More complete accounts are given by Juan (1953), Kobayaski (1954), Juan (1956), Meng (1962), Ho and Lee (1963), and Ho (1967a, 1967b).

Figure 18 shows a general geologic map of Taiwan. Four main tectonic provinces can be recognized. On the east is the Coastal Range, generally regarded as eugeosynclinal sediments of Neogene age, possibly overlying directly the pre-Tertiary basement. All the sediments in this eugeosynclinal basin are marine and consist of a mighty sequence of Miocene to Pliocene pyroclastic and Clastic rocks. The abundance of allochthonous deposits are recognized. Further to the west, the eastern part of the Central Range is a metamorphic belt of Pre-Tertiary age (Late Paleozoic to Mesozoic). It is the oldest tectonic element of Taiwan. The belt is made up mostly of schists and crystalline limestone with subordinate amounts of gneisses, migmatites, and basic intrusions. The western part of the Central Range is a eugeosynclinal province of Paleogene sediments which are dominantly dark gray shaly rocks and siltstones and have been greatly deformed and indurated. Late Cretaceous rocks may also be included in this sequence. A Mid-Tertiary Orogeny was followed by the miogeosynclinal deposition of sediments in the fourth province, the western foothills and coastal plains of Taiwan. These sediments of Neogene age are mostly non-metamorphosed, while all the earlier sediments generally show some degree of metamorphism. Folding and thrust faulting of Neogene sequence occurred in early Pleistocene, with the intensity of deformation decreasing toward the west. The western miogeosynclinal basin was deeping from the north toward the south. The maximum thickness of the Neogene sediment which consist mainly of sandstone and shale series of marine origin may reach over 8,000 m. There is a marked thinning of all the Neogene sediments toward the western foreland, forming a typical clastic wedge tapering

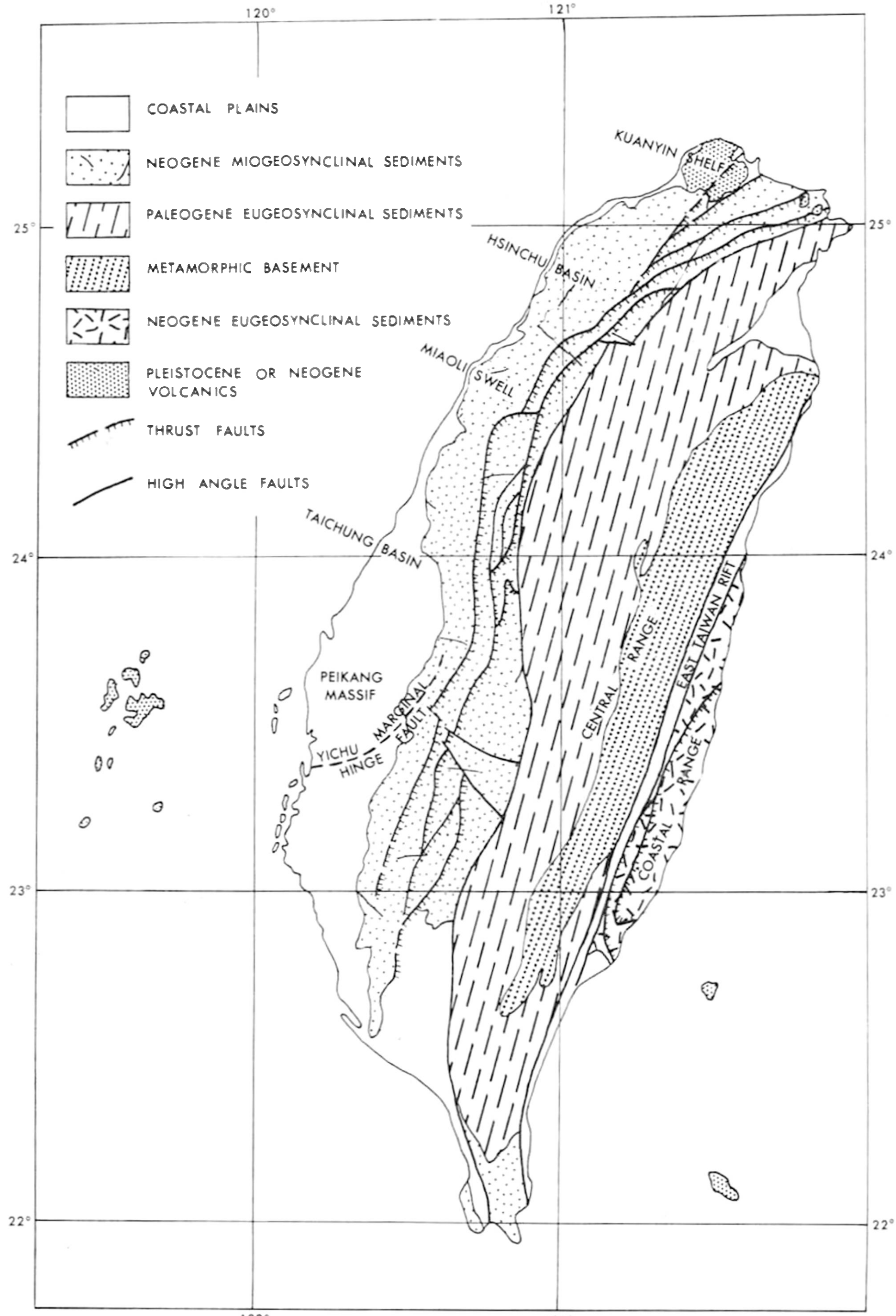

Figure I-18. Generalized tectonic chart of Taiwan after Ho (1967).

off toward the western coastal plains and the Taiwan Strait.

At the end of the main orogeny in the western miogeosynclinal province, great quantities of andesite and dacite lavas poured out from a number of volcanic cones distributed in the northern-most part of the province and in some northeastern offshore islands. Plateau basalts were extruded as fissure eruption, both under water and on lands, in the present Taiwan Strait which tectonically lies on the shallow shelf zone of the western geosynclinal basin. They were erupted over the surface of the Neogene rocks and are now exposed on the Penghu Lieh-tao.

GEOLOGICAL INTERPRETATION

The quantitative interpretation of the aeromagnetic survey of offshore Taiwan demonstrates a good coincidence with and useful completion of the geological basic features recognized in the onshore area of Taiwan. The pertinent structural elements shall be discussed on the basis of the subdivision given of the magnetic survey area.

Region (1)—The Northwest Offshore of Taiwan

Schreiber (1965) gives a comprehensive summary of the Neogene stratigraphy of the northern half of western Taiwan. Paleogene sediments are present only in the central part of the island and are not known to exist below the Neogene sediments along the western coast. Throughout this area, lower Miocene sediments (Wuchihshan Formation) are presumed to rest unconformably on Mesozoic basement. On the basis of stratigraphy Schreiber (1965) recognizes a series of basins and shelfs underlying the Neogene sediments of northwestern Taiwan. From north to south these are termed the Kuanyin Shelf, the Hsinchu Basin, the Miaoli Swell, the Taichung Basin, and the Peikang Shelf or Peikang Massif (Fig. 17). The locations and descriptions of these basins and shelfs agree well with the basement relief calculated from the magnetic data (Fig. 17). The magnetic basement contours serve to delineate the westward extensions of these features beneath the Taiwan Strait across approximate 60 km, at least until the northwestern boundary of the survey area. It is inferred that a part of these basins or swells may extend further into the area of the East China Sea.

The measured or estimated total thickness of the Neogene and Quaternary in the coastal onshore belt (Schreiber, 1956; Chang, 1968; Chou, 1965) in the Kuanyin Shelf amounts to approximate 4,300 m; in the Hsinchu Basin, 7,000 ~ 9,000 m; in the Miaoli Swell, 6,500 ~ 8,000 m; in the Taichung Basin, 7,500 ~ 10,000 m; and in the Peikang Shelf, 1,500 ~ 2,100 m. Recent seismic data (Meng, et al., 1969) indicate that the Mesozoic basement slopes down from the Peikang Shelf into the Taichung Basin, with the overlying Neogene sediments becoming thicker from south to north (Fig. 19).

The Taichung Basin in its northwestern seaward extension is a similar important transversal epeirogenic element as it could be inferred in the onshore regions of Central Taiwan where it was named (Schreiber 1965; Hsiao 1968). The onshore and offshore depressions of the basin seem to lie at depths of 11,000 m in the order of magnitude. The main proportion of these sequences above the Mesozoic basement might exist of comparatively thick Neogene and thick Quaternary sediments.

The Miaoli Swell is indicated, as in the onshore area, by a swell ridge less pronounced than the other two comparable positive elements, the Kuanyin Shelf and the Peikang Shelf. It appears to fade in the NW seaward direction. The swell sediments above the Mesozoic basement might be composed of Paleogene formations but prevailingly of late Cenozoic sequences.

The Hsinchu Basin, with its latitudinal extension of a width of approx. 50 km, strikes offshore NW–SE and is bordered by the prolongation of the Kuanyin Shelf on its NE side and the prolongation of the Miaoli Swell on its SW side. It is characterized by several individual depressions of maximum depths of 9,000 ~ 10,000 m. The bulk of the sediments above metamorphosed Mesozoic strata might be formed of questionable Paleogene but mainly of Neogene-Quaternary sediments.

The Kuanyin Shelf, north of the Hsinchu Basin is the Kuanyin Shelf, with which may be associated intrusive bodies as mentioned earlier in the two-dimensional analyses of anomalies A and B (Figs. 7 and 8). Pleistocene volcanism is known to have occurred in northern Taiwan resulting in large scale andesitic eruptions such as the Tatunshan volcanic group north of Taipei (Ho, 1967a). The magnetic anomalies observed off the coast of northern Taiwan may have a similar andesitic origin.

The magnetic interpretation indicates that the shelf reaches a depth around 3,000 ~ 7,000 m. It strikes in a more NW direction into the sea than it was assumed previously. The sequences of strata above the magnetic basement are assumed to be composed of nonmagnetic metamorphosed Mesozoic, indurated or metamorphosed Paleogene and unalted Neogene-Quaternary rocks.

Region (2)—The Central Penghu Lieh-tao Region

Geophysical surveys and drilling by the Chinese Petroleum Corporation in west central Taiwan near the city of Peikang resulted in the discovery of the Peikang Massif underlying the coastal Neogene sediments. Two of the wells drilled (PK–2, PK–3) penetrated basement at 1,463 m and 1,962 m, respectively. This basement was determined to be indurated metamorphics of Cretaceous age (Matsumoto, et al., 1965). This is overlain unconformably by mid-Miocene sediments (Huang, 1963) with a continuous sequence then present through the Pleistocene (Chang, 1963, 1964, 1965). Lower Miocene and Paleogene sediments are completely absent in this area, although farther to the north, in the Hsinchu Basin, lower Miocene is present (Fig. 19).

This Mesozoic basement, the Peikang Massif, beneath the western coast of Taiwan is apparently bounded to the east and south by the Yichu Marginal Hinge Fault (Meng, 1967) as shown in Figures 17 and 18. Along its southern portion this fault has also been referred to as "Fault A" by others (i.e. Pan, 1968). North of this fault seismic and well data indicate that both the Mesozoic basement and the overlying Neogene sediments through the Pliocene are cut by a series of east-west faults which are not present at the surface (Chang, 1964, 1965; Meng, 1967; Pan, 1968). South of the Yichu Marginal Hinge Fault the Mesozoic basement is either absent or greatly down-faulted, as evidenced by one CPC well (YC–1) which, at a depth of 2,600 m, was still in Pliocene sediments (Sun, 1965; Meng, 1967). East of the Peikang Massif the Neogene sediments are observed to thicken rapidly from about 1,500 meters near Peikang to more than 6,000 m only 30 km further east (Chang, 1965). The Peikang Massif, therefore, is seen to extend only a short distance eastward beneath west central Taiwan where it is apparently terminated or truncated.

Another well (TL–1) drilled in the Penghu Lieh-tao off the western coast of Taiwan revealed a similar occurrence of mid-Miocene sediments unconformably overlying a Mesozoic basement (Huang, 1967; Chou, 1969). The basement was reached at only 500 m, about 1,000 m shallower than the Peikang Massif beneath the Taiwan coastal plains. The Pliocene and Pleistocene rocks of well TL–1 are partly tuffaceous rocks and basalt similar to the surface basalts observed in the Penghu Lieh-tao (Chou, 1969).

With the above information as background, a more meaningful interpretation can be made of the magnetic data. It is inferred that parts of Penghu Lieh-tao region are to be con-

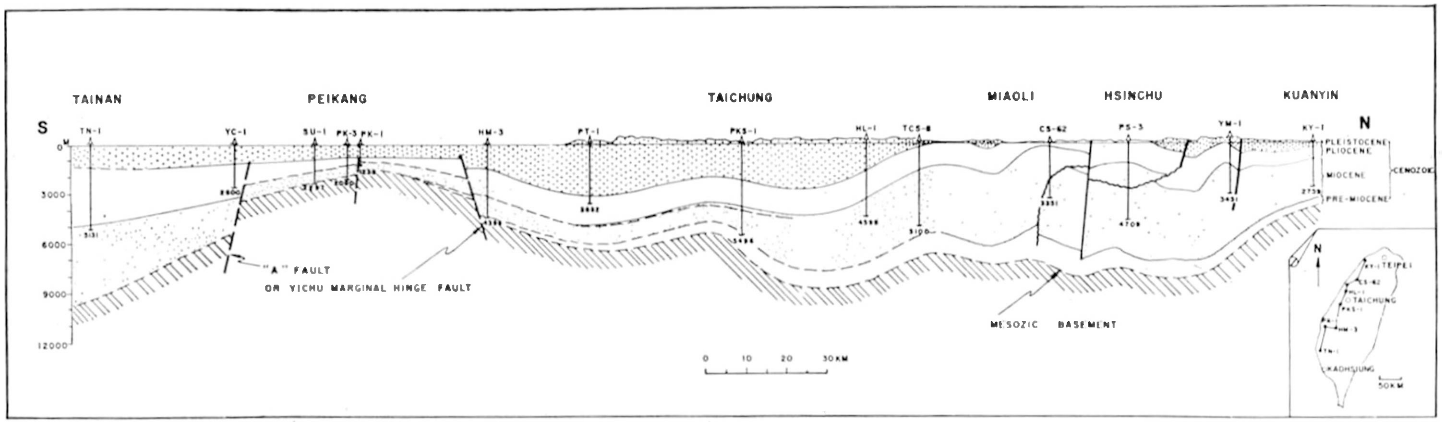

Figure 1-19. North-south stratigraphic cross section of the Cenozoic basin in the coastal plain region of western Taiwan.

ceived as the offshore extension of the Peikang Massif. If the minimum depth data of the magnetic basement in Figure 10 calculated to amount roughly to 4,000 m or even less are taken into consideration, the basement at all probability might be correlated to ancient Mesozoic or Paleozoic dependent on the degree of metamorphism and on the ratio of magnetic rocks. The intersection of the major northeast-southwest magnetic trend in Figure 3 (Line 5 of Fig. 9) with the coast of Taiwan agrees well with the Yichu Marginal Hing Fault and, therefore, may be assumed to delineate the southern boundary of the Mesozoic basement. The high amplitude high frequency magnetic anomalies observed off the coast of central Taiwan are a direct expression of the surface and near-surface Pleistocene basalt flows of the Penghu Lieh-tao area. Several trends in the magnetic data (Lines 3, 4, 6, and 7 of Fig. 9) also indicate that the Mesozoic basement complex is probably broken by east-west faults similar to those mentioned earlier for the Peikang Massif of western Taiwan. The basalt flows seem to be confined generally to a block bounded by two of the east-west faults (Lines 3 and 7 of Fig. 9). It is assumed that the Mesozoic basement continues westward to the Fukien province of the Chinese mainland.

Region (3)—The Southwest and South Offshore of Taiwan

The prominent northeast-southwest magnetic trend discussed in the previous section separates zones of distinct magnetic character and represents a major structural break between the northern and southern parts of the survey area. To the north is the shallow continental shelf while to the south the water deepens into the south China Sea, and the magnetic contours show the gentle gradients and general smoothness indicative of a deep magnetic basement. It has already been mentioned that along the west coast of Taiwan CPC drilled into Cretaceous basement at a depth of about 1,500 m, while a short distance south of the Yichu Marginal Hinge Fault a well (YC–1) was still in Pliocene sediments at a depth of 2,600 m.

The sediments of southwestern Taiwan are Neogene in age and vary from Pleistocene coral cropping out at the extreme southern tip of the island to a Pliocene mudstone formation in the vicinity of Tainan and Kaohsiung which is over 4,000 m in thickness (Meng, 1967). In contrast to the area around the Penghu Lieh-tao, there seems to be no recent igneous activity in southwestern Taiwan. There are numerous mud volcanoes in the area east of Tainan (Shih, 1967), but these are unrelated to any igneous activity.

Directly south of the southern tip of Taiwan, the magnetic contours show a general east-west trending anomaly having an amplitude of any $30 \sim 40$ gammas. This remarkable feature is one of the most intriguing magnetic anomalies in the survey area. Because the feature lies parallel to the flight lines and is of such low amplitude, its very existence can be questioned as being artificially created by the presence of uncorrected magnetic time variations or by possible navigational errors. However, careful evaluation of the data indicates that it is indeed real. Survey cross-tracks at the western side of the area show that the feature extends eastward at least as far as 120°30′ East, and additional Project Magnet tracks flown in May 1969 indicate its presence south of Taiwan. Considering the depth to the magnetic basement (Fig. 13), the small amplitude of the feature would be expected. The two-dimensional model study of this feature (Fig. 14) indicates it may be caused by intrusion of a thin dike, probably along an east-west fault at great depth. If any lateral displacement has occurred along this fault south of Taiwan, it is not evident from any present surface data. The Tertiary structural trends of southern Taiwan are generally north-south (Fig. 18). Also the present bathymetric ridge extending southward from Taiwan (Fig. 1), which the magnetic data indicate to be of sedimentary origin, gives no indication of recent east-west displacement but probably is a southward extension of the Tertiary trends of Taiwan. It seems reasonable to assume that the more recent north-south trends may be superimposed over deeper east-west trends of Mesozoic (?) age.

Region (4)—The Taiwan-Philippine Ridge Southeast of Taiwan

The southeastern part of the survey area is a magnetically anomalous region, separated from the smoother zone to the west by a north-south structural trend (Line 10 of Fig. 9). The bathymetric contours (Fig. 1) also show that this region is part of a submarine ridge which stretches intermittently from Taiwan to the Philippines. Unlike the sedimentary ridge extending directly south from Taiwan, there are numerous magnetic anomalies associated with the Taiwan-Philippine ridge system. Some of the largest anomalies are associated with the islands in the area, which are composed of upper Pliocene and Pleistocene andesites. Andesites are exposed on most of the islands along a general linear trend from Luzon to the eastern coast of Taiwan. Here the andesites crop out along the northern half of the Coastal Range and along the East Taiwan Rift, which separates the Coastal Range from the Central Range. Andesitic pyroclastics of early Miocene or older age form the backbone of the Coastal Range, with basic and ultrabasic plutonic rocks cropping out in the southernmost part (Yen, 1967). Yen points out that the northward plunge of the major fold axis of the andesite formation of the Coastal Range and the decrease in elevation toward the northeast of the Pleistocene-Recent erosional terraces are indicative of the whole Coastal Range block being tilted toward the north and east.

To the west of the Coastal Range of separating it from the Central Range is the East Taiwan Rift. This valley, 150 km long and 5 to 7 km wide, is remarkable for its extreme linearity. The valley floor, bordered by faults, is only about 200 m above sea level, while the Coastal Range and Central Range have elevations of 1,600 m and 3,000 m, respectively. The East Taiwan Rift represents a major tectonic break separating two distinct geologic provinces, each having its own stratigraphic record and independent geologic history. Hsu (1956), Biq (1965), and Ho (1967a, 1967b) recognize the southern portion of the Coastal Range as being of allochthonous origin. This conclusion is based primarily on the presence of the Miocene Lichi Formation, which consists of a muddy to clayey matrix containing numerous exotic blocks of varying sizes, shapes, and rock types. The Lichi Formation is of undetermined thickness, but exceeds 1,000 m as evidenced by a test well drilled in 1965 by CPC (Meng and Chiang, 1965).

Many of the exotic blocks observed in this formation are completely foreign to the rest of Taiwan, and their presence can only be the result of large scale horizontal displacement.

Allen (1962) regards the East Taiwan Rift to be dominantly controlled by transcurrent faulting with sinistral displacements. He regards the faults bounding the valley as essentially vertical fractures. Biq (1965) shows that the East Taiwan Rift is still active with left-lateral displacement being at least 25 km since late Pleistocene time. This would correspond to the eastern Coastal Range moving northward with respect to the Central Range of Taiwan at an average rate of 2.5 cm/yr or greater. The northward continuation of the faults bounding the East Taiwan Rift is uncertain, although they must extend somewhat north of 24° latitude and truncate or terminate the westward extension of the Ryukyu Trench.

In their recent work involving the redetermination of earthquake hypocenters, Katsumata and Sykes (1969) show the seismic pattern undergoing an abrupt change where the Ryukyu Arc meets Taiwan. Here there is a grouping of intense activity, with a steeply dipping seismic zone, generally less than 100 km deep, then continuing along the east coast of Taiwan to the Philippines (Fig. 3). The magnetic data also reflect the continuation of this fracture zone southward from Taiwan through the southeastern part of the survey area. The crustal plates on either side of this fracture zone should be regarded as independent structural and tectonic units. The structures expressed in the main Central Range of Taiwan do not continue southward to the Philippines, but are separated by the fracture zone. The Coastal Range, however, which is allochthonous to Taiwan, may be related to the Philippine block and may be a northward continuation of the structures of Luzon.

The evidence of fault displacement in eastern Taiwan indicates a possible northward movement of the Philippine Sea at a rate of 2 ~ 3 cm/yr. In light of the recent developments in the concepts of sea-floor spreading and plate tectonics (Morgan, 1968; LePichon, 1968; Isacks, et al., 1968), the previous discussion would support the view of the East Taiwan Rift being regarded as part of a fracture zone separating two adjacent crustal plates, with the Philippine Sea plate moving northward and being thrust under and destroyed beneath the Ryukyu Arc.

CONCLUSIONS

The aeromagnetic survey would provide valuable information about the geological structure of the continental shelf off Taiwan as well as provide estimates for the thickness of sediments in the area by determining the depth to the magnetic basement. In general, the basement is composed of magnetic and non-magnetic parts so that only the magnetic basement or the magnetic parts of the basement can be detected by the magnetic survey.

The Mesozoic basement which was encountered by drillings at depth of 1,500 m in west central Taiwan near the town of Peikang and 500 m in the Penghu Lieh-tao is quite different in depth from the magnetic basement off the coast of Peikang. If the minimum depth data of about 4,000 m of the magnetic basement in the Penghu Lieh-tao area are taken into consideration, the magnetic basement is very probably correlated to strongly indurated and metamorphosed ancient Mesozoic or Paleozoic rocks. The magnetic basement ranging from 8,000 to 10,000 m deep in the northwest and southwest areas of offshore Taiwan agrees probably with the Mesozoic basement which is also considered of the strongly indurated and metamorphosed or crystalline rocks below the Cenozoic rocks in the north and south coastal plains of west Taiwan.

As the wide track spacing of the survey presents certain limitations for detailed analyses, the anomalies with source bodies near surface, especially the depth less than 3,000 m below flight level were probably undetected by the survey, and the results of interpretation may change slightly if additional survey data are obtained.

The magnetic data of the Taiwan survey were analyzed to determine the shape and the relief of the magnetic body or magnetic basement. The large area anomalies in the northwest and southwest offshore of Taiwan are assumed to be initially referred to arise from the magnetic basement and the small amplitude local anomalies in the Penghu Lieh-tao and the Lanyu islet are probably caused by shallow basaltic rocks. Some strong amplitude of local anomalies such as anomalies A and B scattered over the area of smooth and large area anomalies of low amplitude may be caused by magnetic intrusions located in the basement or in the overlying sediments.

In the northwest offshore of Taiwan, two magnetic basins and two magnetic ridges are present. From south to north, there are the basin of about 11,000 m, the narrow ridge at a depth of 7,000 m, the local depression of 10,000 m, and the high swell of 3,000 m deep. These deep magnetic basins under a thick sedimentary pile of marine facies are considered to have more petroleum possibility and thus favorable for future petroleum exploration.

In the south of the Penghu Lieh-tao, the prominent northeast-southwest magnetic trend which separates zones of distinct magnetic character and represents a major structural break between the northern and southern parts of the survey area well agrees the Yichu Marginal Hinge Fault in the onshore area and it is assumed to delineate the southern boundary of the Mesozoic basement.

The Tertiary structural trends of southern Taiwan are generally north-south whereas the deeper magnetic trends are east-west, therefore, it is assumed that the more recent north-south trends might have superimposed over deeper east-west trends of Mesozoic age.

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II. NOTE ON SEA BOTTOM SAMPLING IN THE OFFSHORE AREA OF TAIWAN, CHINA

(Project CCOP-1/ROC. 3)

Prepared by the Chinese Petroleum Corporation

(with table II-1 and figure II-1)

After the discussions at the third session of the Committee for Co-ordination of Joint Prospecting for Mineral Resources in Asian Offshore Areas (CCOP), at Seoul, Korea, in June-July 1967, the Chinese Petroleum Corporation (CPC) decided to undertake a sea bottom sampling project off the shores of Taiwan (Document I&NR/R. 58, Report of the 4th session of CCOP, p. 73-75).

The main purposes of this project were: (a) to make various physical oceanographic measurements; (b) sampling of bottom sediments and bedrock by piston-core and gravity-core equipment, and by dredging; and (c) laboratory work comprising paleontologic study of organic remains in the sediments at the Paleontology Laboratory of CPC and sediment analysis at the Sedimentation Laboratory of CPC.

The research vessel HAIHSIEN, with full displacement of 91 tons and all the necessary facilities, was loaned by the Taiwan Fisheries Research Institute to CPC for use in this bottom sampling project. Part of the field work was carried out from 12 to 28 September 1968 but it was suspended due to trouble with the ship's engines. Samples of sea bottom sediments were taken only by using the dredging method, and physical oceanographic measurements could be made only at a few points during this voyage. The details of the operations are summarized in table II-1; figure II-1 shows the locations of the 38 samples of sea bottom sediments. The specimens and data are kept in the laboratory of the Geology Department, Taiwan Petroleum Exploration Division, CPC. More samples of bottom sediments will be taken by using dredging or gravity-core equipment during the next cruise.

Some other samples collected in the vicinity of Taiwan in 1965 to 1967 by the research vessel YANG MING, using a snapper-type bottom sampler or a gravity corer, had been sent by the Chinese National Committee on Oceanic Research (CNCOR) to CPC. All the sea bottom samples collected by the two research vessels are being studied paleontologically and sedimentologically; they will also be chemically analysed if possible. The results of a preliminary micropaleontologic study are summarized as follows:

Microscopically, the variation of the foraminiferal number is generally the same as elsewhere, increasing farther from the shore. Many of the planktonic foraminifers in the bottom sediments are derived from elsewhere and are not *in situ*. *Globigerina bulloides* is the highest in percentage and the species of the temperate zone increase in amount towards the central part of Taiwan Strait. The tropical species are found in certain areas and their distribution indicates how the warm high-salinity Kuroshio current flows with respect to the current along the shore.

The tests of the benthonic foraminifers in the near shore area are all re-worked from older sediments; they consist of different material such as chitinous matter, sand particles

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and calcareous material. There is a greater percentage of tests of arenaceous foraminifers in the shallow part of Taiwan Strait. There is no large north-south variation in facies of the foraminifers and the east-west variation is the same as elsewhere, the fauna increasing gradually from the shore to the central part of Taiwan Strait, both in the number of species and in the number of genera. Re-worked tests from older sediments are abundant west of the Penghu Islands; these may have come from the Penghu Islands and those to the north may have come from formations exposed in western Taiwan.

As well as foraminifers, many other fossils, such as Ostracoda, Bryozoa, Alcyonaria and Otoliths, are also present. Their distribution is influenced by the waves and ocean currents passing through Taiwan Strait.

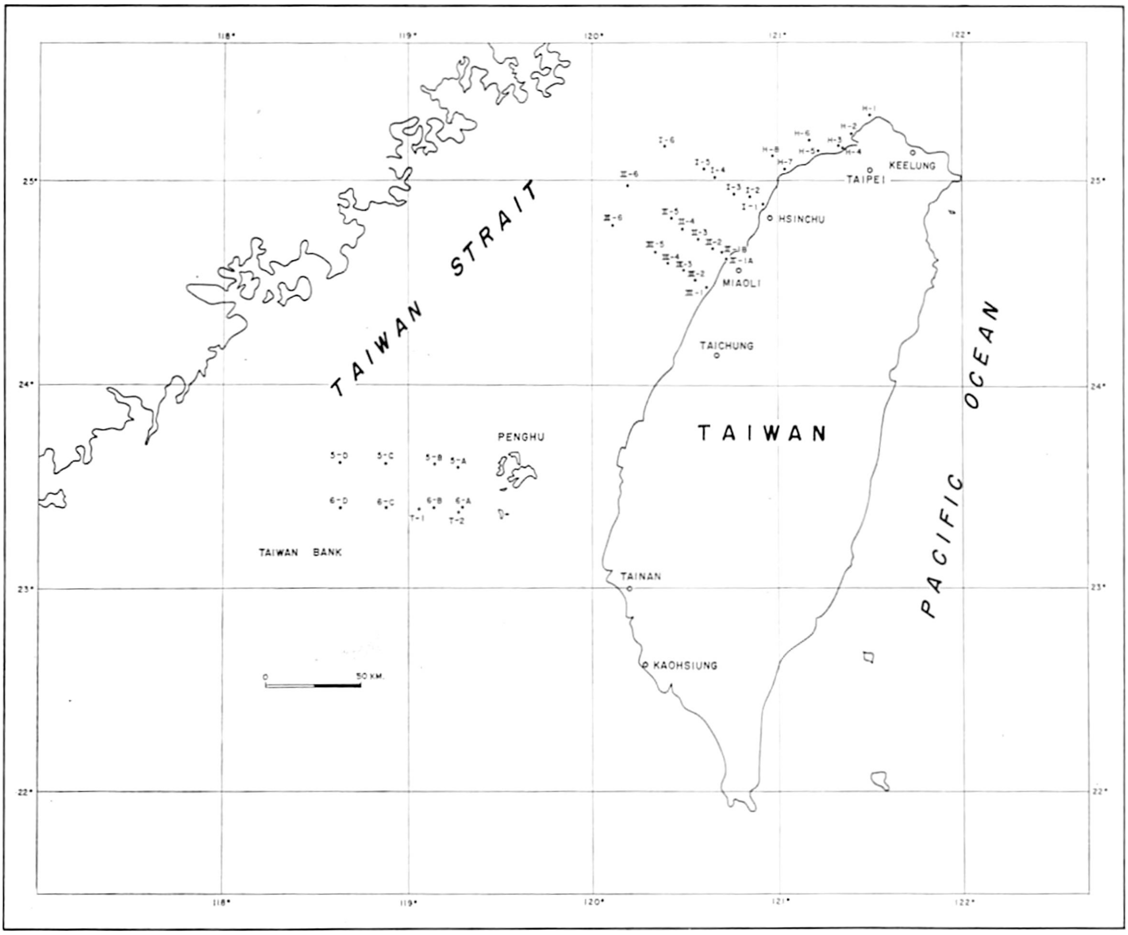

Figure II-1. Map showing locations of bottom samples collected in Taiwan Strait.

Table II–1. Data on bottom sediments from Taiwan Strait.

Serial Number	Date (1968)	Long	Lat	Depth	Temp. (°C)	Field Description
H. Loc. 1	9/12	121°29.5′	25°17.5′	30m		Coaly material, mollusks and bryozoa
H. Loc. 2	9/12	121°4.2′	25°13.2′	20m	27°10	Sand with mollusca
H. Loc. 3	9/12	121°20′	25°10′	17 m	26°90	ibid
H. Loc. 4	9/12	121°21′	25°09.6′	5 f		Fine-grained sand
H. Loc. 5	9/13	121°13′	25°8′	4		ibid
H. Loc. 6	9/13	121°10′	25°12′	34	27°15	Mud
H. Loc. 7	9/13	121°02′	25°03′	10.5		ibid
H. Loc. 8	9/13	120°58.2′	25°07′	45	27°00	Sand with molluscan fragments
I–1	9/13	120°55′	25°52′	9	28°76	Mud
I–2	9/13	120°51′	24°55′	34		Muddy sand with mollusca
I–3	9/13	120°46′	24°56′	38	28°60	Sand
I–4	9/13	120°40′	25°1′	46		Muddy sand, sea weeds
I–5	9/13	120°36′	25°3′	43	28°48	Muddy sand, mollusca, sea weeds
I–6	9/13	120°23′	25°10′	34	28°20	Mud
II–6	9/14	120°11′	24°58′	32	27°16	ibid
II–5	9/14	120°25′	24°49′	37	27°40	ibid
II–4	9/14	120°29′	24°46′	33		ibid
II–3	9/14	120°34′	24°43′	30.2	27°08	ibid
II–2	9/14	120°39′	24°40′	27.8		Sand, sea weeds
II–1a	9/14	120°42′	24°39′	3		Muddy sand
II–1b	9/14	120°37′	24°39′	18	29°05	Mud
III–1	9/14	120°33′	24°31′	9	29°40	Muddy sand
III–2	9/14	120°29′	24°34′	27		Muddy sand, sea weeds mollusca
III–3	9/14			31	28°05	ibid
III–4	9/14	120°24′	24°36′			Mud
III–5	9/14	120°20′	24°39′	36	27°80	ibid
III–6	9/14	120°06′	24°47′	31	27°70	ibid
5–A	9/15					
5–B	9/15	119°08′	23°37′	33.5		Medium grained sand with mollusca
5–C	9/15	118°53′	83°73′	30		ibid
5–D	9/15	118°38′	28°37′	28.5		Muddy sand
6–D	9/15	118°38′	23°24′	21.8		Coarse grained quargz sand
6–C	9/15	118°53′	23°24′	25.5		Coarse grained quartz sand, Mollusca
5–A1	9/17	119°16′	23°36′	34	28°10	Sand contain molluscan fragments coarse grained quartz sand
6–A	9/17	119°17′	23°24′	25.2		Coarse grained quartz sand
6–B	9/17	119°08′	23°24′	25		Protoquartzite

III. SEISMIC INVESTIGATION IN THE REGION OF POULO PANJANG, OFFSHORE FROM SOUTHWESTERN VIET-NAM

(Projects CCOP-/ROV. 2 and ROV. 5)

By

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(with figures 1–11 and tables 1–4)

ABSTRACT

Refraction and continuous seismic measurements were made around the island of Poulo Panjang lying in the Gulf of Siam approximately 150 km offshore of south western Viet-Nam. The area under investigation was between latitudes 102°4′ E and 104°50′ E and longitudes 9°15′ N and 9°40′ N.

The marine geology in this region is not clearly defined. Extrapolation of geological data acquired on land and on the number of offshore islands provide the only basis for establishing a working knowledge of geology in this area. The main purpose of the seismic investigation was to carry out a reconnaissance survey with the object of ascertaining the existence and the thickness of a possible sedimentary formation and to establish their relationship with onshore geology.

A total of four refraction lines was shot in the directions of north, south, east and west of Poulo Panjang. The average length of the first three profiles was about 50 km. The western profile was extended up to 137 km. in an attempt to obtain refracted arrivals from the Upper Mantle. These arrivals were, however not obtained, suggesting an estimated depth to the Mohorovicic discontinuity to be over 25 km. From the computed velocities and the depths of various layers it was possible to postulate the geological structure of the area.

The refraction data correlated with the geology of the neighbouring islands suggest the sea-bed formation to be of Mesozoic type resting on Paleozoic rocks and basement of possible Granitic basis. The average thickness of the Mesozoic layer was estimated to be between 3.0 to 3.5 km. The Paleozoic layer was found to be between 3.2 to 4.5 km. thick. A significant fault was also located at some 60 km. south-west of Poulo Panjang. The alignment of the fault corresponds to an earlier and similar finding from an aeromagnetic measurement and perhaps it also draws the eastern boundary of the Gulf of Siam Tertiary basin. The most significant finding was the complete absence of Tertiary sediments in the area. The attitude of the basement in the north and east correlates well with the known geology on land.

A total of 370 line-km. of reflection seismic profiling was carried out using sparker as the acoustic source in the area to the east and south-east of Poulo Panjang.

From the reflection data it was possible to identify three well defined layers within the Mesozoic sediment. Individually, the three could be correlated to the Jurassic, Triassic and the Red Beds corresponding to the Phu Kadung Formation in Thailand and to the Permian limestone. On the other hand, since the second and third reflectors are quite close to each other, the latter might also be a part of Triassic, with Permian Limestone lying at a greater depth.

The attitude of the first layer, which is exposed at sea bottom, suggests a post-deformation strata except in certain areas where it is truncated by faults originating at greater depths. The second layer, shows numerous major and minor structures. Of particular interest are the salt dome-like diapiric structures and an anticline. This layer is also truncated by faults. It was difficult to follow the last layer on any large area. It is assumed that this layer is also generally affected by the deformation of the second layer.

On the basis of the results obtained the existence of an extensive sedimentary basin about 3-4 km. thick is suggested. Whether this constitutes a part of a larger basin extending to the south and south-east is a matter of further investigation.

INTRODUCTION

Refraction and continuous seismic profiling were carried out around the island of Poulo Panjang in the Gulf of Thailand between latitudes 102°40′ E and 104°50′ E, and longitudes 9°15′ and 9°40′ N. The investigation was sponsored by the Ministry of Overseas Development of the British Government and the Bureau of Natural Resources of the Republic of Viet-Nam with the United Nations' Economic Commission for Asia and Far East (ECAFE) acting as coordinators. Scientists and equipment were provided by the Imperial College of Science and Technology of the University of London. The Government of the Republic of Viet-Nam made available two ships and explosives together with a team of geologists. This paper supersedes the preliminary report published in the report of the sixth session of the Committee for Co-ordination of Joint Prospecting for Mineral Resources in Asian Off-shore Areas (CCOP), held at Bangkok in May 1969 (Dash, 1969). The main object of this project was to carry out a reconnaissance survey in the area with the object of ascertaining the existence and the thickness of sedimentary formations and their relationship with those on the adjoining land area.

The marine geology of this region is not well known. Extrapolation of geologic data acquired on land, particularly on the number of islands scattered along the west coast of southern Viet-Nam (Fig. III-1) provides the only basis for obtaining a general idea of the structure and geologic formations of the area between the west coast and Poulo Panjang. Far to the north at the head of the Gulf of Thailand, and extending about 400 km northward, is the basin of the Chao Phraya River which contains predominantly Quaternary marine and continental sediments, with some scattered Paleozoic limestone and granitic hills which rise above the flat plain. To the northeast, along the shores of Cambodia, continental sandstone and conglomerates of Triassic to Jurassic age and the younger Korat Group ranging up to Cretaceous in age, together with some granites, gneiss and schists, are exposed (Emery and Niino, 1963). The islands of Poulo Dama and other small islands east of Poulo Panjang consist predominantly of Paleozoic sandstone. The islands of Phu Quoc and An Thoi consist of Mesozoic formations. The area to the north of Poulo Panjang may be an extension of the Cardomomes Mesozoic basin, with a Mesozoic section resting on rocks of the "Indo-

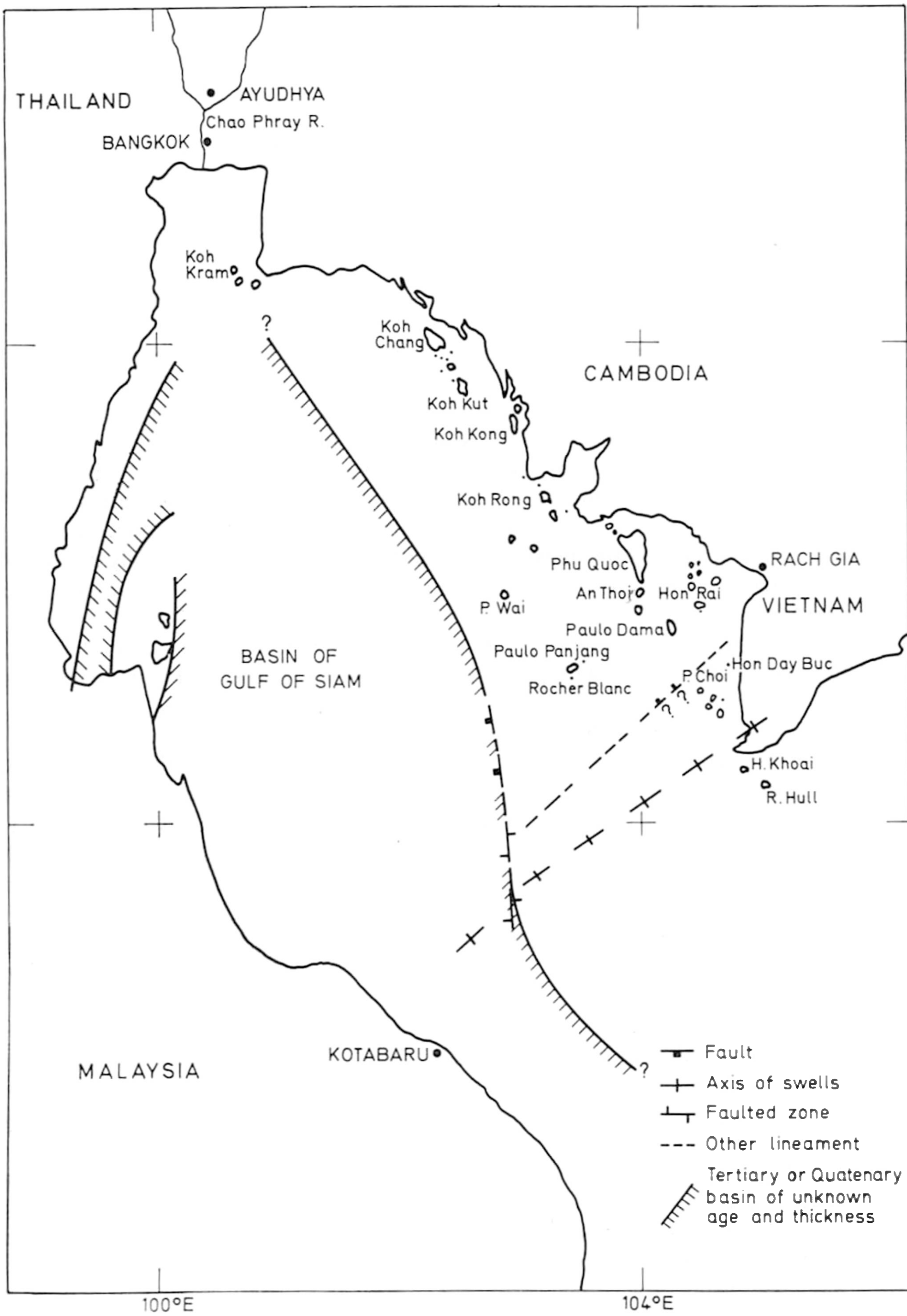

Figure III– 1. Map of Gulf of Thailand and adjacent continental shelf. Part of geologic data after Mainguy (1968).

sinides," which may consist mainly of Permian limestone (Mainguy, 1968). Poulo Panjang itself and the adjacent small island of Rocher Blanc are Upper Sandstone (Mesozoic) corresponding to the Phu-Phan Formation of Thailand. From the geologic map (Fromaget and Saurin, 1952) it can be seen that the Upper Sandstone covers a large area; this formation is underlain successively by red-beds corresponding to the Phu Kadung Formation of Thailand, followed by Permian limestones and, below them, shales and sandstones of Devonian to Carboniferous age may possibly be present.

FIELD OPERATIONS

Refraction Profiles (Project CCOP-1/ROV. 2)

Taking the islands of Poulo Panjang and Rocher Blanc as the base station, four refraction lines were shot in the directions approximately east, west, north and south (Fig. III-2). The Hospital Ship HAT GIANG and Patrol Craft PGM 406 were used for the refraction work; the former acted as the stationary recording boat and the latter as the shooting boat. Navigation was by radar on board HAT GIANG which directed the shooting boat on its course. Visual fixes were also taken by the recording boat for every shot point. Beyond the range of radar, which was limited to about 10 nautical miles, the distances between successive shots were estimated from the ship's speed and dead reckoning. This procedure introduced considerable error. Fortunately the distance between the two ships was accurately determined by the direct water-wave arrivals from each explosion by a hydrophone slung overboard from HAT GIANG.

The detector stations, consisting of 4.5 Hz geophones connected to a seismic telemetering device (Gurney, 1964), were installed on the island close to the shore. Figure III-3 shows a diagram of this system. The signals from the geophone were amplified and frequency modulated with a sub-carrier with frequency of 3375 Hz. The transmitter, operating at 27 MHz, was in turn amplitude-modulated with the sub-carrier and it established the radio link with the recording boat. The radio receiver on board produced an amplitude-limited output at sub-carrier frequency which was recorded on magnetic tape. Variations in the carrier's frequency, proportional to the geophone signal, were reconstituted in the final demodulator stage and were recorded directly on an oscillographic recorder. Filters of band width 0-120 Hz and 0-23 Hz were used for magnetic tape and monitor recording, respectively.

To detect the direct arrivals, a highly sensitive hydrophone was put overboard to a depth of about 15-20 metres. The signals were amplified by a conventional amplifier and were recorded over the seismogram.

Explosive charges ranging from 10 to 130 kg were detonated electrically at about every nautical mile and the shot instant was transmitted over radiotelephone to the recording boat for direct registration on the seismogram. Nearly all the shots were fired at a depth of 20-30 metres, which was very close to the sea-bottom. The transfer of energy was excellent and a number of arrivals were recorded.

Line 1E: The length of this line was about 54 km, running northeastward from the island of Rocher Blanc (Fig. III-2) and a total of 16 shots were fired along it. The geophones were located on the island, on solid rock, at an elevation of about 10 m above sea level. These were connected to the recording instruments on the boat, anchored about 100 m away from the island, by means of a buoyant cable. Unfortunately, towards the end of running this profile, the weather became very bad and the cable was broken repeatedly; strong wind and rising sea forced the abandonment of this station.

Line 2W: For this line both the detector station and the recording boat were shifted

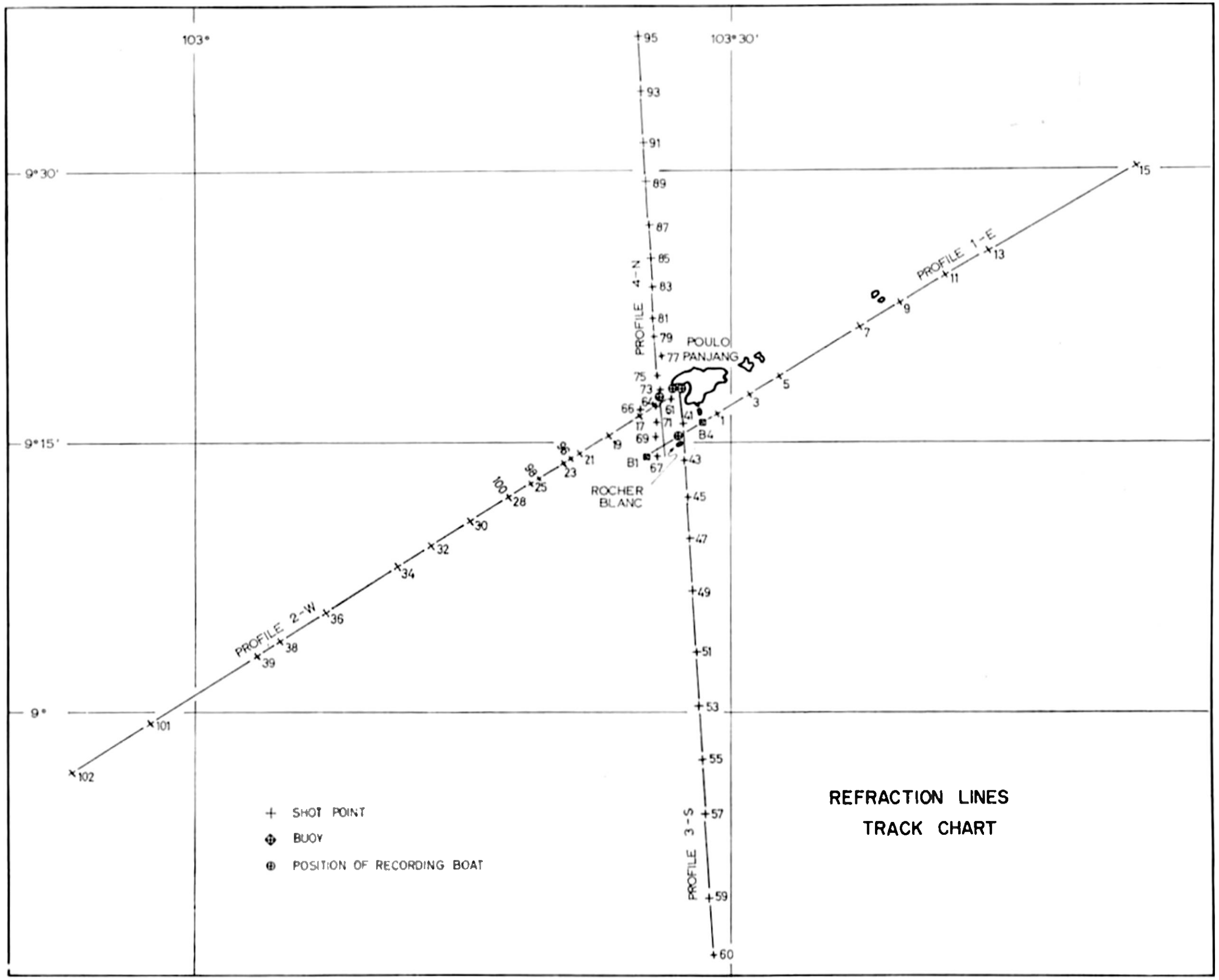

Figure III– 2. Refraction lines showing positions of detector stations and shot-points.

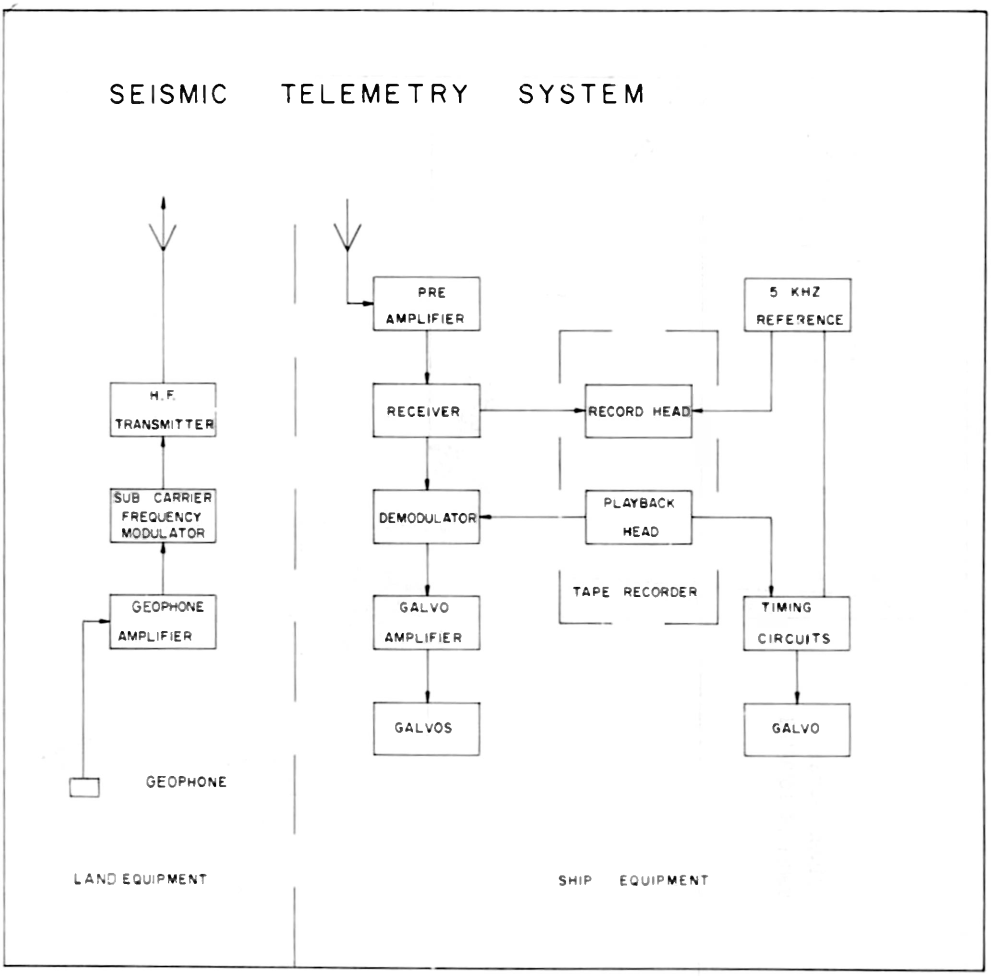

Figure III– 3. Block diagram of seismic telemetering system.

to a sheltered area off Poulo Panjang, about 5 km due north of Rocher Blanc. Geophones were planted close to the shore at an altitude of 3–4 metres above sea level and the recording boat was anchored at about half a mile from the shore. A total of 48 shots were fired on this line. This profile was extended up to 137 km in a southwesterly direction from Poulo Panjang in an attempt to obtain refracted arrivals from the Upper Mantle; it can be seen in Table III–2 that the Moho velocity was never obtained. Taking into account the length of the profile and the velocity configurations, it was estimated that the depth to the Mohorovicic discontinuity is more than 25 km. The profiles 1E and 2W taken together constituted a split spread reversed profile. Figure III–4 shows the time distance plot together with the sea bottom topography along the lines.

Line 3S: This line was run for about 57 km southward from Poulo Panjang. A total of 23 shots were fired along this profile and the geophone locations were the same as for Line 2W.

Line 4N: This profile extended 57 km northward from Poulo Panjang. A total of 29 shots were fired and the detector stations were the same as those for the previous line. Profiles 3S and 4N, taken together, constituted a split spread reversed profile. Figure III–5 shows the time distance plot with sea bottom topography along the line.

Continuous Reflection Profiles (Project CCOP–1/ROV. 5)

Seven continuous reflection profiles (Fig. III–6) were obtained using sparker equipment. The sonic source was a sparker device with capacity of 8,000 joules, fired at intervals of 4 seconds and towed about 30 metres behind HAT GIANG at a depth of about 5 metres. The receiver was a hydrophone streamer cable with an active section of 20 m incorporating built-in preamplifiers. The active section was towed 35 metres behind the ship at a depth of about 7 metres (Dash, 1969). The signals were recorded on a seismic recorder with an overall band pass frequency of 80–200 Hz.

Navigation was by radar supplemented by visual fixes when the ship was beyond radar range of land. The weather during this period of operation was bad with Beaufort wind force of 6 to 7 which caused the ship to roll and pitch heavily at the ship's speed of 5-6 knots. This affected the data collection to the extent that the seismic records were very noisy.

The record was in the form of a strip chart about 27 cm wide, moving at the rate of 70 cm/hr, and the sweep time was 500 milliseconds. This sweep-time corresponds to 750 metres if the sound velocity is assumed to be 3,000 m/sec. The ship's speed during the operation was 5 to 6 knots and consequently the vertical exaggeration on the strip chart is about 6 times.

The records were further reduced for presentation (Figs. III–7, 8, 9, and 10) by digitising each reflected event on a vertical time scale at 5 minutes sampling intervals and replotting them. To show the configuration of major and minor structures the vertical scale has been exaggerated to about 20 times.

INTERPRETATION OF RESULTS

Data processing of refraction results

For data processing, the seismograms were digitised at 10 ms sampling intervals and were recorded on punched cards for detailed analysis with a digital computer. For suitable interpretation the field data were subjected to corrections; the details of two of these are briefly outlined below. The usual corrections for varying sea bottom topography and for surface of reference at sea level are described in detail by Officer *et al.* (1959). This can be

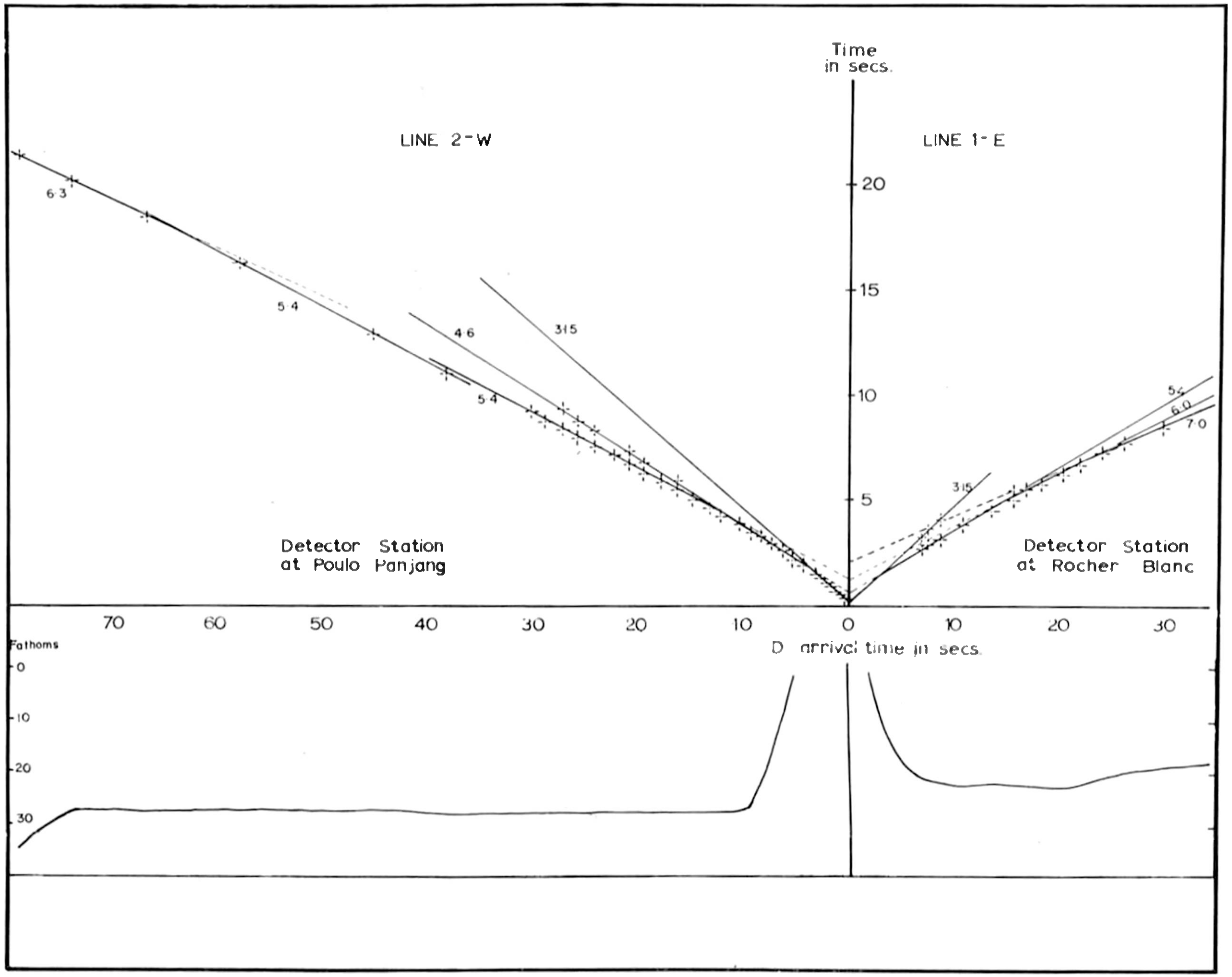

Figure III– 4. Time-distance plots of Lines 1–E and 2–W. The diagram underneath shows sea bottom topography.

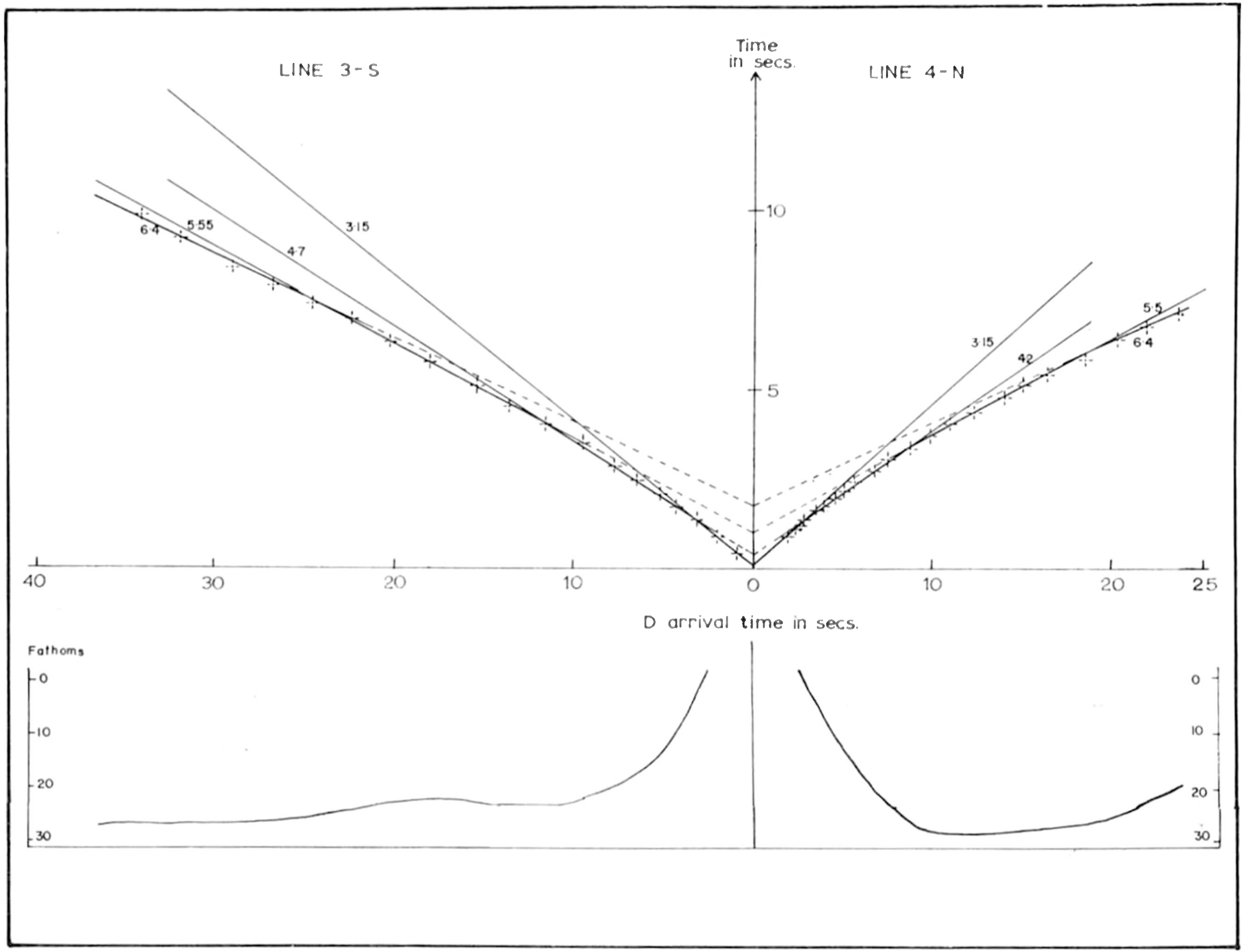

Figure III- 5. Time-distance plot of Lines 3-S and 4-N. The diagram underneath shows sea bottom topography.

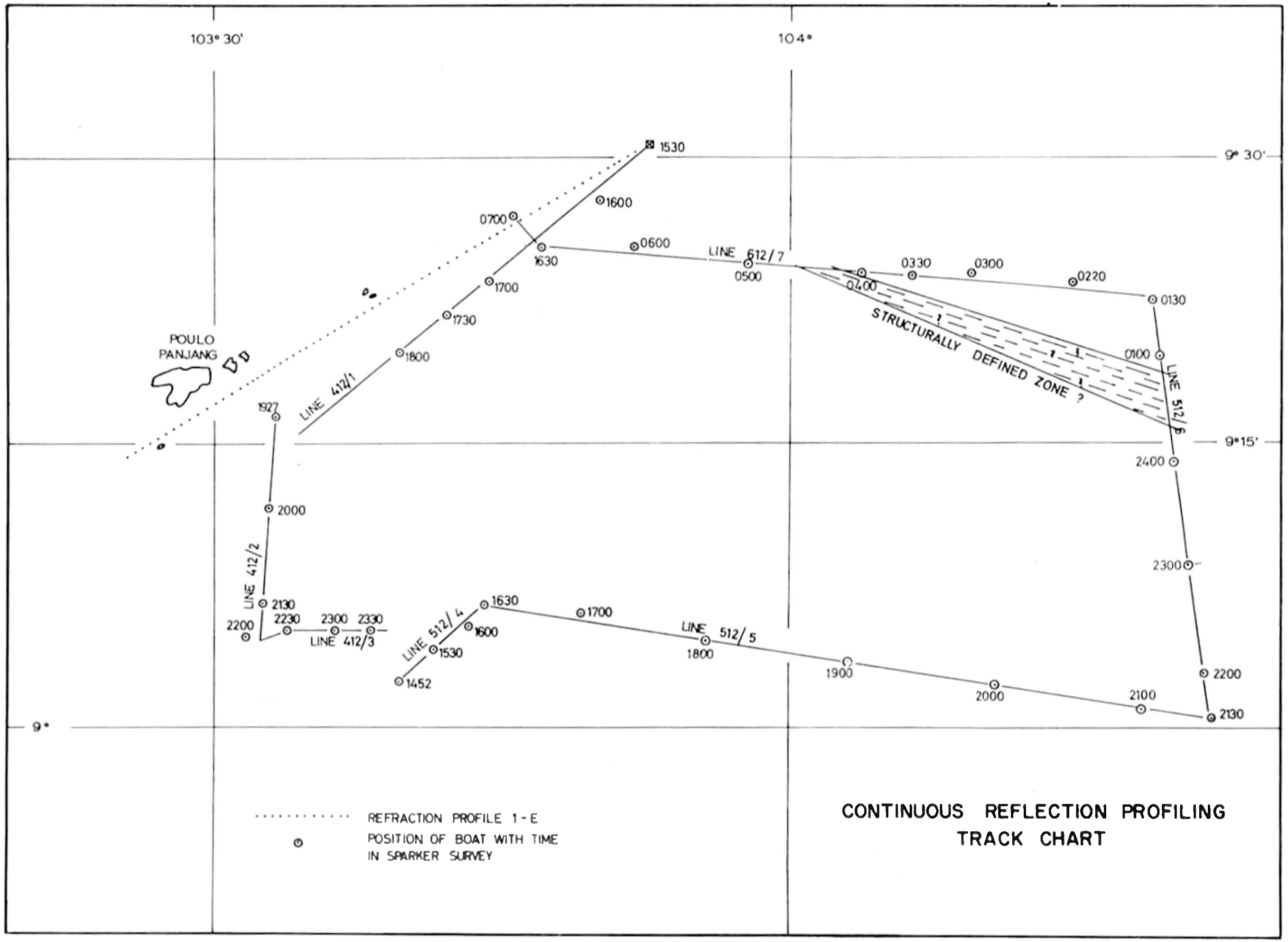

Figure III– 6. Ship's track chart showing continuous seismic reflection profiles and the structurally defined zone.

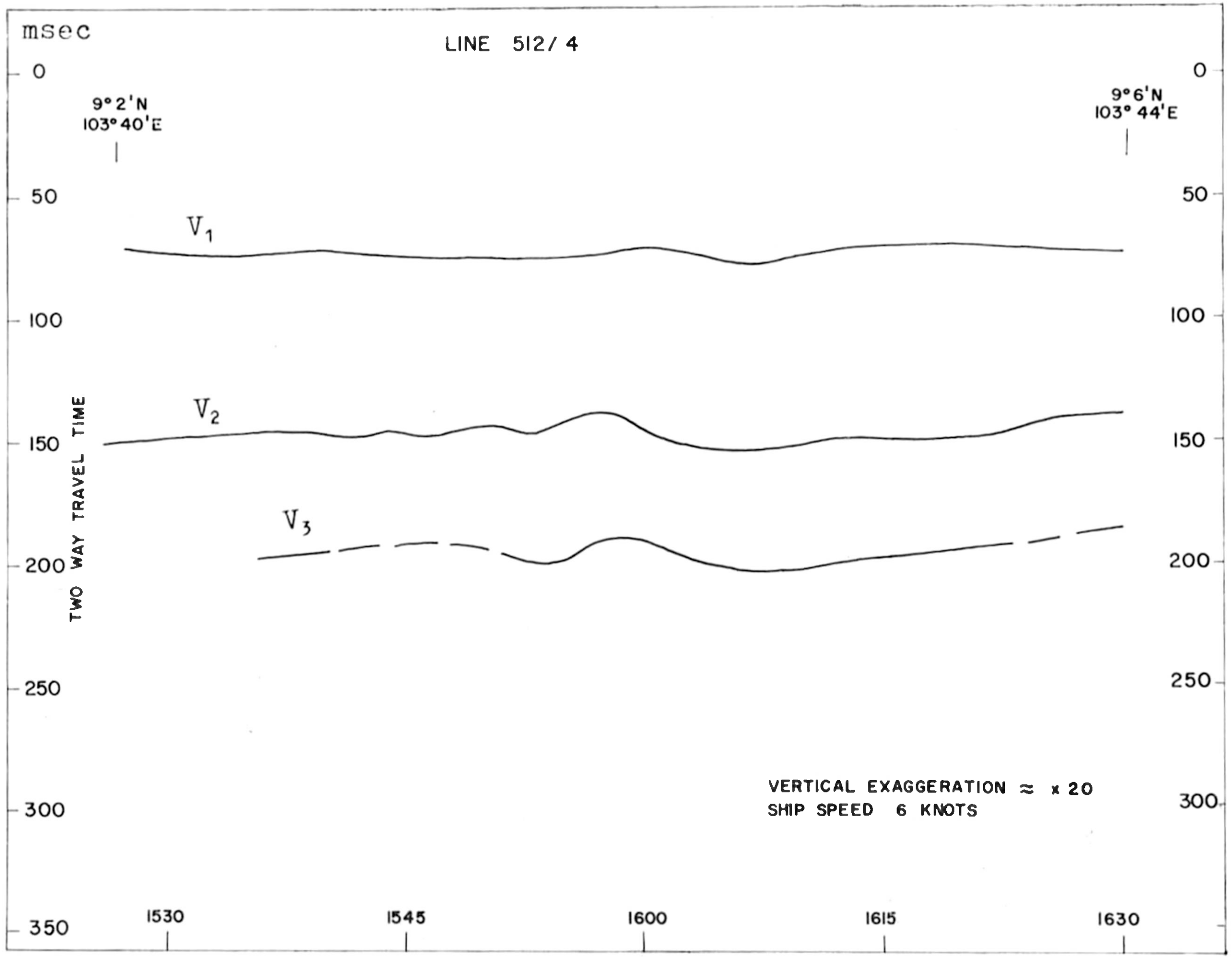

Figure III– 7. Continuous reflection seismic section of Profile 512/4.

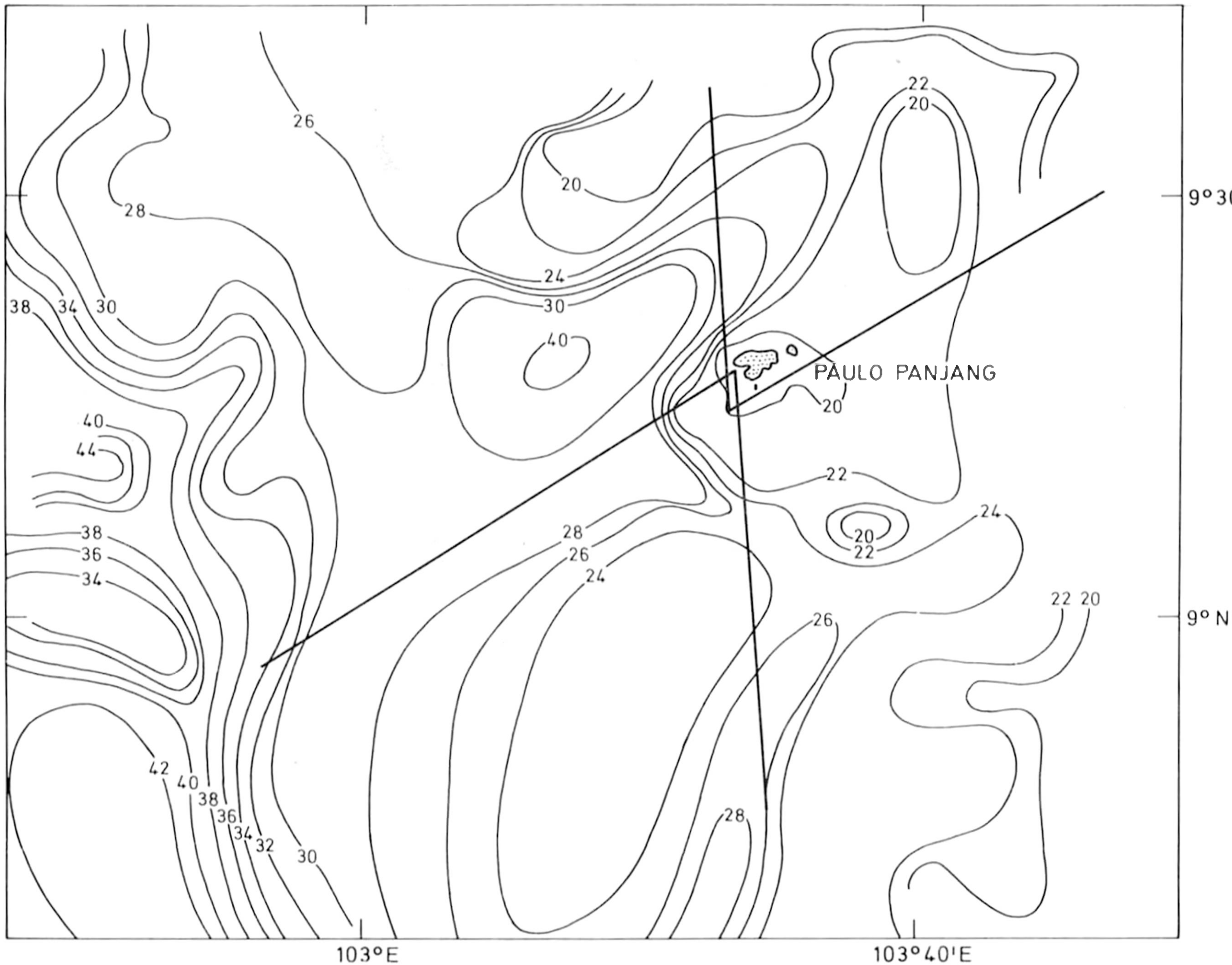

Figure III–11. Topography of the area around the island Poulo Panjang. Contours at 2 m interval drawn from the so undings on British Admiralty Charts 3385 and 2101.

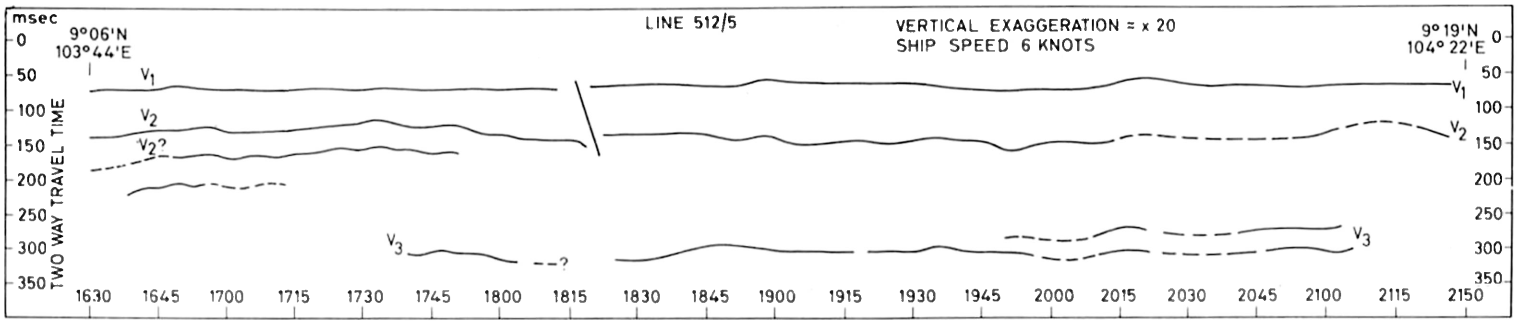

Figure III-8. Continuous reflection seismic section of profile 512/5 showing the definition of a fault.

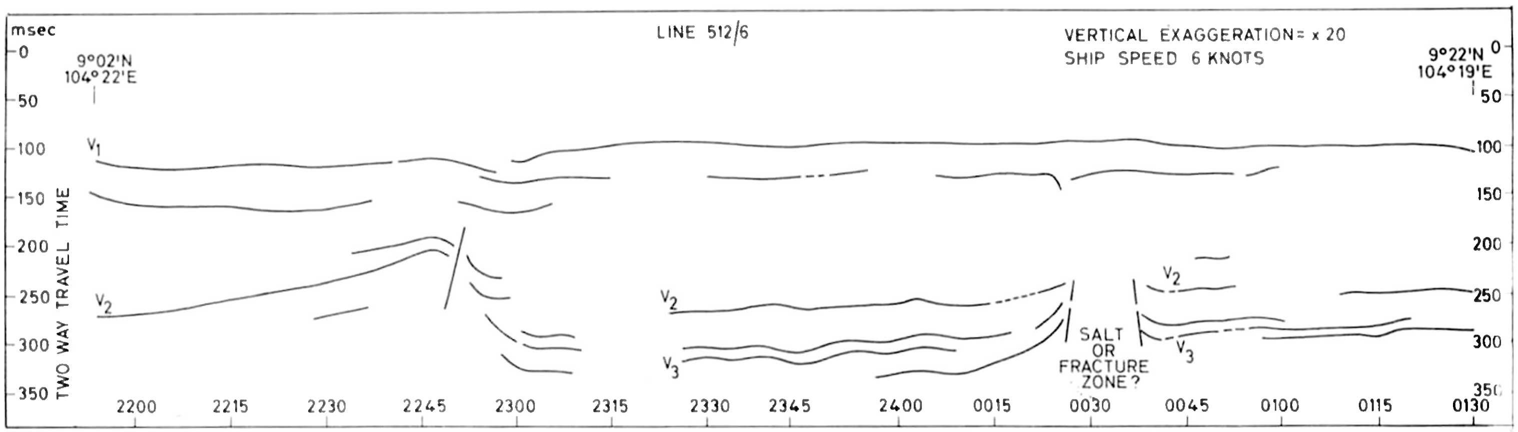

Figure III- 9. Continuous reflection seismic section of profile 512/6 showing definitions of fault and salt or fractured zone.

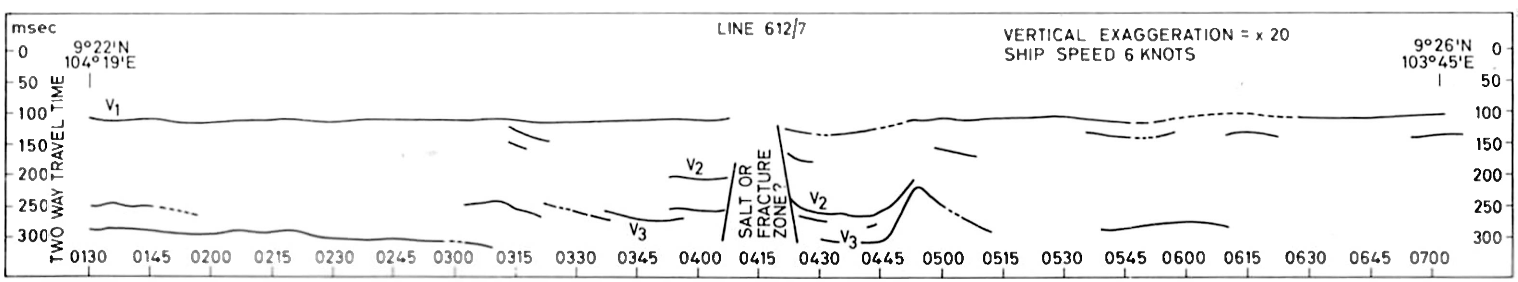

Figure III-10. Continuous reflection seismic section of profile 612/7 showing definitions of salt or fractured zone and anticline.

written in the form:

$$T = T_{SR} + T_{BT}$$

where T = total correction; T_{SR} = surface reference correction; and T_{BT} = bottom topography correction.

The major correction, however, involved the island location of geophones when shots were fired in the sea. No standard interpretation technique could be applied to the refraction data thus obtained. A method was therefore devised which took into account this configuration by comparing observed travel times with theoretical ones, computed for various structural models based on the geologic data of the neighbouring islands. In order to avoid many theoretical travel time plots being produced until one matched the observed travel times, a least squares method was devised. It automatically computed the thickness of various layers after all other parameters influencing travel times, such as the slope of the island, the velocity of the refractors, dip of interface and shot detector distances, had been eliminated. Consequently, the difference between calculated and observed travel times was assumed to be caused only by variations in the thicknesses of the refractors. In order to find the best fitting set of thicknesses z_i, these differences had to be minimised, as follows:

$$E_2 = \sum_{r=1}^{n} [T_r^c - T_r^0]^2,$$

where T_r^c and $T_r{}^{\circ}$ are calculated travel time for a n-layer model and observed travel time respectively for a shot point. To reduce the error E^2, the sum of equation (1) for all the shot points along a line under consideration is partially differentiated with respect to z_i and is equated to zero:

$$= 0 \text{ for } i = 1, 2 \ldots n \qquad (2)$$

Calculation of z_i is hence reduced to the problem of solving a set of simultaneous linear equations of the type (2).

Let the travel times of P-waves for a five layer case be

$$\begin{aligned} T_1^c &= a_1 z_1 + b_1 \\ T_2^c &= a_2 z_1 + b_2 z_2 + c_2 \\ T_3^c &= a_3 z_1 + b_3 z_2 + c_3 z_3 + d_2 \\ T_4^c &= a_4 z_1 + b_4 z_2 + c_4 z_3 + d_4 z_4 + f_1 \end{aligned} \qquad (3)$$

Substituting Eqn (3) in equation (1) yields

$$\begin{aligned} E^2 = {} & [a_1 z_1 + b_1 - T_1{}^{\circ}]^2 \\ & + [a_2 z_1 + b_2 z_2 + c_2 - T_2{}^{\circ}]^2 \\ & + [a_3 z_1 + b_3 z_2 + c_3 z_3 + d_2 - T_3{}^{\circ}]^2 \\ & + [a_4 z_1 + d_4 z_2 + c_4 z_3 + d_4 z_4 + f_1 - T_4{}^{\circ}]^2 \end{aligned} \qquad (4)$$

Equation 4 was differentiated according to (2) and the following expressions were obtained

$$= \alpha_1 z_1 + \beta_1 z_2 + \gamma_1 z_3 + \delta_1 z_4 + \varepsilon_1 = 0$$

and similar expressions for

$$\frac{\delta E}{\delta z_2}, \frac{\delta E}{\delta z_3} \text{ and } \frac{\delta E}{\delta z_4}$$

The coefficients α_i, β_i, γ_i and δ_i are functions of a_i, b_i, c_i, d_i and f_i. The coefficients of eqn (5) are calculated for all the shot points of one profile and added together. In a matrix form, this can be expressed as:

$$\begin{vmatrix} \sum\alpha_1 & \sum\beta_1 & \sum\gamma_1 & \sum\delta_1 \\ \sum\beta_1 & \sum\beta_2 & \sum\gamma_2 & \sum\delta_2 \\ \sum\gamma_1 & \sum\gamma_2 & \sum\gamma_3 & \sum\delta_3 \\ \sum\delta_1 & \sum\delta_2 & \sum\delta_3 & \sum\delta_4 \end{vmatrix} \times \begin{vmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \end{vmatrix} = \begin{vmatrix} \sum-\varepsilon_1 \\ \sum-\varepsilon_2 \\ \sum-\varepsilon_3 \\ \sum-\varepsilon_4 \end{vmatrix}$$

$$A \times z = E$$

An inversion of matrix A enables the z_i to be determined:

or $\quad z = A^{-1} \times E$

$$z_i = \sum_{r=1}^{n} A_{ir}^{-1} \times E_r$$

The coefficients of matrices A and E were determined for various models and the best model giving the compatible time-distance relationship with the observed values was selected. A detailed account of the procedure involved is given by Bosshard (1969) and Dash & Bosshard (1969). This least squares procedure has the following advantages over the conventional intercept time methods: (a) Authentic observed travel times are used in the computations instead of extrapolated theoretical ones; (b) all the thicknesses are fitted simultaneously to the travel times so that the overall error is diminished to a minimum; (c) No error computed from the shallower refractors is transferred to the deeper ones, thus giving more accurate thicknesses and depths of individual refractors; and (d) The results obtained from least squares fit are final thus obviating the necessity for a master curve.

Results from refraction lines

Since the refraction lines were shot in such a way that the lines 1E and 2W and lines 3S and 4N constituted a split spread profile (Figs. III–4 and III–5), the velocities obtained from each section were taken as apparent velocities and standard calculation techniques were applied to obtain the real velocities. The velocity and depth estimate of each line are given in the following tables:

Table III–1: Line 1E

Velocity in km	**Thickness in km**	**Depth to top in km**
1.5	0.04 ± 0.02	
3.1 ± 0.04	1.4 ± 0.33	0.04 ± 0.02
4.8 ± 0.07	2.1 ± 0.49	1.44 ± 0.34
5.7 ± 0.23	4.3 ± 0.6	3.54 ± 0.37
6.7 ± 0.29		8.0 ± 0.82

Table III–2: Line 2W

Velocity in km	**Thickness in km**	**Depth to top in km**
1.5	0.04 ± 0.01	
3.1 ± 0.04	0.84 ± 0.23	0.04 ± 0.01
4.8 ± 0.07	2.4 ± 0.36	0.88 ± 0.24
5.7 ± 0.23	8.8 ?	3.3 ± 0.34
6.7 ± 0.29		12.0 ?

Note: From the time distance plot (Fig. III–4) a discontinuity indicating a fault can be noticed at about 40 sec. on x axis. Around this point, to the left and the right, the velocities are identical, although displaced in time scale. A fault in the bed rock gives rise to this pattern. Since it was difficult to ascertain the existence of a fault by a reverse shooting, the depth calculation was carried out on travel times of the section to the left of the discontinuity. This gives rise to high values of depth estimation which is therefore indicated by a question mark. A detailed interpretation of this zone is given in the following section.

Table III–3: Line 3S

Velocity in km	Thickness in km	Depth to top in km
1.5	0.04 ± 0.01	
3.1 ± 0.02	1.1 ± 0.07	0.04 ± 0.01
4.5 ± 0.06	1.9 ± 0.14	1.14 ± 0.08
5.5 ± 0.09	4.5 ± 0.62	3.04 ± 0.43
6.2 ± 0.08		7.54 ± 0.70

Table III–4: Line 4N

Velocity in km	Thickness in km	Depth to top in km
1.5	0.04 ± 0.01	
3.1 ± 0.02	0.78 ± 0.03	0.04 ± 0.01
4.5 ± 0.06	2.3 ± 0.05	0.82 ± 0.04
5.5 ± 0.09	3.25 ± 0.42	3.12 ± 0.06
6.2 ± 0.08		6.37 ± 0.63

Interpretation of refraction results

The velocities shown in the preceding tables are classified into three sections. The lower velocities of 3.1 to 4.6 km/sec could be attributed to the Mesozoic layer, velocities of 5.2 to 5.7 km/sec to intrusive and other dense rocks of unknown age (possibly Paleozoic and/or Mesozoic intrusives, or Permian limestone) and the higher velocities of 6.2 to 6.7 km/sec to that of the basement, possibly of granitic rocks. The low velocity layers correspond to the Mesozoic sandstone cropping out on the islands of Rocher Blanc and Poulo Panjang. To the east of Poulo Panjang, on the islands of Poulo Dama and other small islands around it, Paleozoic rocks are exposed and it is therefore reasonable to assume that around the area of Poulo Panjang, the Mesozoic formations are underlain by Paleozoic rocks. Farther to the east, sporadic granitic exposures are present on the island of Hon Rai and on the mainland north of Rach Gia. The high velocity basement rocks might be attributed to these.

Inspection of the calculated depths on different profiles shows that it is possible to estimate the extent and attitude of the various layers. The Mesozoic layer, about 3 km thick at Poulo Panjang, dips gently down towards the west coast of southern Viet-Nam and attains a thickness of about 3.5 km at a distance of 23 km east of Poulo Panjang. This layer also dips down to the west and reaches a depth of 3.3 km at a distance of about 18 km from Poulo Panjang. This would indicate that somewhere between these two extreme limits, the Mesozoic layer swells upwards but, as no detailed work was carried out in this area, it is difficult to support this statement. However, the data from continuous reflection profiling certainly indicate a series of tectonic changes in the Mesozoic layer which would partially confirm the above hypothesis. To the north and south of Poulo Panjang, at distances of 15 km and 18 km respectively, the thickness of this layer remains practically the same at 3 km.

The Paleozoic layer, with velocity of 5.5 to 5.7 km/sec, is about 4–4.5 km thick and is uniform towards the east and south of Poulo Panjang. In the north, however, it becomes slightly thinner and attains a thickness of 3.2 ± 0.42 km at a distance of about 35 km. A significant fault in this layer is observed at a distance of 60 km south-west of Poulo Panjang. Since only one refraction line was shot in this area, it is difficult to ascertain the throw of the fault. However, calculations from the travel time indicate a downthrow of about 2 km to the west. On the west side of the fault, the velocity of the Paleozoic layer was found to be the same as on the east side. To the east of the fault the thickness of the layer was 8.8 km, but it was not possible to calculate the thickness on the west side. Mainguy (1968) in his geologic map of the area of the Gulf of Thailand indicates a "faulted zone, of unknown throw and complex faulted zone" at about 8°N and 103°E. This zone, if extended northwards, nearly coincides with the fault observed in Line 2W. Although a layer of velocity 5.7 km/sec was also observed on the downthrown side of the fault, it was difficult to find out if any low-velocity sediments existed above the Paleozoic layer. However, referring to the geologic map of Mainguy (1968) it could be postulated that the above fault marks the edge of the Tertiary or Quaternary basin of the Gulf of Thailand.

The basement velocity of 6.2 to 6.7 km/sec was observed at a depth of about 6.4 to 8 km. The general trend of the basement was found to rise towards the northeast and the granitic exposures at the island of Hon Rai and on the west coast might be associated with the basement. Aeromagnetic surveys in the area of Ayuthaya (65 km north of Bangkok) indicate that the depth of the basement increases from about 1.8 km near Ayuthaya to 3.3 km at the mouth of the Chao Phraya River (Emery and Niino, 1963). This trend of the basement fits in well with the attitude of the basement obtained from the present investigation.

Interpretation of continuous seismic profiling results

Of the seven reflection profiles made in the area east of Poulo Panjang only four (Lines 512/4, 512/5, 512/6, and 612/7) contain some useful information. Due to bad sea conditions the noise level on the other three was so high that no interpretation could be carried out on them.

The records (Figs. 7, 8, 9, and 10) show a number of reflections. Of these only three could be followed across all of the profiles. Other reflected events which occur sporadically may indicate some layering within the sediments, possibly due to differential compaction. The total width of the section represents about 350 milliseconds; if the average acoustic velocity is assumed to be 3.5 km/sec, this would be equivalent to a thickness of about 600–800 metres. No reflections were observed below 400 milliseconds. It is quite possible that since the top layer had a comparatively high acoustic velocity (about 3 km/sec), the energy of the sparker could not penetrate deeper than this limit. Evidently, reflections from the basement were never obtained even when the sweep time of the record was increased to 2 seconds to record all the reflected events.

The three consistent reflectors are:

V_1 sea bottom, perhaps containing a very thin layer of surface soft sediment (mud or sand)

V_2 sedimentary interface underlying V_1 unconformably

V_3 layers with irregular surfaces which give rise to hyperbolic patterns and multiples.

All these layers may be within the Mesozoic sedimentary section. However, individually, V_1 might be correlated to the Jurassic, V_2 to Triassic, V_3 to the Red Beds corresponding to the Phu Kadung Formation in Thailand and to the Permian limestone. As V_2 and V_3 are so close to each other, V_3 might also be part of the Triassic, with Permian limestone lying at greater depth from which no reflections were obtained.

The attitude of V_1, which suggests a post-deformation layer, conforms with the sea floor topography. It is nearly horizontal except in certain places, as in Line 512/5 (Fig. III–8) and Line 512/6 (Fig. III–9) where it is truncated by faults. These faults are characterized by sharp and hyperbolic diffraction patterns. Locally, as in the northern part of Line 512/6 (Fig. III–9) and the central part of Line 612/7 (Fig. III–10), this layer is also disturbed by the structures in layer V_2.

V_2, however, shows numerous major and minor structures. Of particular interest are the kind on lines 512/6 and 612/7 (Figs. III–9 and III–10). These have the character of diapiric structures, perhaps salt domes, but on the other hand, the features shown may be due to folding and fracturing. Attention should also be drawn to the anticline located to the west of the disturbed zone in Line 612/7 (Fig. III–10).

It is more difficult to follow the reflector V_3 over any large area. In places, particularly around the structures, it assumes the same attitude as the overlying layer V_2 and it can be postulated that this is also generally affected by the deformation of the latter.

Discussion

The detailed geology of the area under investigation is not known, but the data obtained from the present project can be used to draw a number of conclusions based on present knowledge of the geology on land and tectonic events that have taken place.

The geologic history of the Gulf of Thailand (Brown et al., 1951; Kobayashi, 1960; Klompe, 1962) began with the accumulation of thick Paleozoic sediments in a geosyncline. During late Paleozoic time the easternmost part of the geosyncline became intensely folded. During late Triassic and late Jurassic times the western part of the geosyncline from the Thai-Burma border to the tip of Malaya was compressed into a series of almost north-south trending folds which were intruded by granite. In the eastern part of the area (Korat Plateau and part of Cambodia) these folds are buried under continental strata of the Korat Group. During late Tertiary times the region of the Korat Plateau was uplifted, while at the same time the belt along the Chao Phraya River was depressed. At that time the seas extended for several hundred km to the north of Bangkok. Subsequently marine and continental sediments filled the depression, up to the present head of the Gulf of Thailand.

The broad depression of the Gulf is not such as would be expected in an epicontinental sea. The continental shelf off the west coast of southern Viet-Nam extending to the region of Poulo Panjang is shallow (Fig. III–11), the maximum depths being about 60 m. The sea bottom is mostly rocky and only thinly overlain by sediments such as mud or sand. The numerous islands and partially submerged rocks which are exposed at low-tide provide evidence of the sea bottom geology. Ultrasonic velocity measurements carried out on rock samples collected from these showed the velocity of 3 to 3.5 km/sec, which was the same as the velocity of the layer nearest to the sea floor.

As shown by Emery and Niino (1963) the area to the west of Poulo Panjang is more likely to be deeply underlain by folded Paleozoic strata. Alexander (1958) and Kobayashi (1960) also show that several anticlines and synclines in the Paleozoic strata of West Malaysia apparently continue beneath the Gulf of Thailand. These strata are buried under Mesozoic sediments in this area. The large fault found to the west of Poulo Panjang affects the Paleozoic section.

On the basis of what is now known, the Mesozoic strata in the area of Poulo Panjang are apparently part of a large basin. The western boundary of this basin terminates at the fault which could have developed late in Paleozoic time. In the west, the Paleozoic section rises steeply, abbuts against the Mesozoic layer, and is exposed on the island of Poulo Dama. The attitude of the basement in the west is not known; in the east, however, it follows the steeply rising Paleozoic layer and granitic exposures are found on the offshore islands of Hon Choi, Hon Day Buc (geologic map prepared by the Directorate of Natural Resources, Republic of Viet-Nam). The limitation of the investigation precludes the definition of the basin along its north and south flanks. However, from the geologic data an land to the north it can be assumed to extend as far as the west coast of Cambodia, including the offshore islands of Ko Kut and Ko Chang where Triassic rhyolite is found.

CONCLUSIONS

According to the data presently available, it can be established that a sedimentary layer about 3 to 4 km thick exists in the area off the west coast of southern Viet-Nam. Whether this layer constitutes a part of a larger basin extending to the south and southeast could not be defined during the period of the present investigation. From the reflection data and with the velocity information it was possible to show the existence of well defined structures in the Mesozoic sediments. Since the reflection lines were widely separated, it was not possible to define the exact size or nature of the structures. However, the results do indicate a region of structurally defined zones (Fig. III–6). A further detailed investigation in this area would be helpful to delineate these structures.

ACKNOWLEDGMENTS

The authors wish to express their thanks to the late Professor J. McG. Bruckshaw for his helpful comments during the initial phase of interpretation. They are also grateful to Dr. O. Kappelmeyer, Regional Adviser in Offshore Prospecting (Geophysics), ECAFE and Technical Secretariat of CCOP, Mr. Ho Manh Trung, Director of the Bureau of Natural Resources, Republic of Viet-Nam, and his colleagues who participated in the field work. The expedition could not have been successfully completed without the assistance of the Captains, officers and crews of HATGIANG, and PGM 406 and we are thankful for their joint co-operation. The loan of the sparker equipment by the Natural Environment Research Council of Great Britain is also gratefully acknowledged. Lastly, we are thankful to Miss C. M. Shepstone for the preparation of the figures accompanying the report.

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IV. NOTES ON THE GEOLOGY OF THE TAMBELAN, ANNAMBAS AND BUNGURAN (NATUNA) ISLANDS, SUNDA SHELF, INDONESIA, INCLUDING RADIOMETRIC AGE DETERMINATIONS

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(with figures IV-1 to IV-6, tables IV-1 to IV-3 and plates to IV-10)

ABSTRACT

The islands described lie on the Sunda Shelf between Borneo and Malaya-Sumatra, and are important for their bearing both on the geology of the Sunda Shelf, and on the relationship of the geology to Borneo to Southeast Asia as a whole.

The Tambelan Islands, on the Sunda Shelf off west Borneo, are composed of basic and intermediate intrusive igneous rocks and tuffs, including gabbro, diorite, dolerite, andesite and keratophyre, which show evidence of alteration and thermal metamorphism, and have been intruded by granite, dated at 84 ± 2 million years (Late Cretaceous) by the potassium/argon method. The granite is itself intruded by basaltic and andesitic dykes of very late Cretaceous or (more probably) of Cainozoic age.

The Anambas Islands, further north, are known from previous work to be composed of granite, and supposedly pre-granite gabbro, andesite, diabase, and metamorphosed clastic sedimentary rocks. The granite is cut by veins of aplite, and intermediate dyke rocks also occur on the islands.

The Bunguran (or Natuna) Islands are composed of strongly folded chert and metasediments of the Bunguran beds, of probable Mesozoic (Jurassic-Cretaceous?) age, which are associated with intermediate to ultrabasic igneous rocks, including diorite, gabbro, serpentinite, and tuff, with amphibolite which is probably metamorphosed basic igneous rock. The Bunguran beds on Bunguran Island are unconformably overlain by the Natuna sandstone, probably Tertiary, which is composed of flat-lying sandstone and conglomerate. The sandstone near the base is an unusual "chert-clast" sandstone, but further up in the sequence feldspathic litharenite and lithic subarkose is found. Granite occurs as three intrusions on Bunguran Island, of which the largest forms Gunong Ranai. The granite intrudes the Bunguran beds, but appears to be older than the Natuna sandstone. Specimens from the Ranai granite are two-mica adamellite. One specimen was dated at 73 ± 2 million years (Late Cretaceous) by the K/Ar method.

A sea-level slightly higher than present by at least 0.3–0.4 m at about 5460 and 5270 years B.P. is proved at Tambelan Islands by radiocarbon dating of giant clam shells; whereas at Bunguran Island peat below low-tide level, dated at 6260 years B.P., indicates a sea

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level relatively lower by at least 0.7 m at that time.

Sulphide mineralization has been recorded from all three groups of islands: traces of chalcopyrite with pyrite in dolerite from Tambelan: pyrite and arsenopyrite from the Anambas: and stibnite from the Bunguran Islands. Small amounts of cassiterite have been recorded from the Anambas and Bunguran Islands, and mercury has been reported from Bunguran. A geological and geochemical reconnaissance of the three island groups is merited.

ICHTISAR

Geologi daripada pulau-pulau Tambelan, Anambas serta Natuna, Paparan Sunda dibahas kembali. Batu-batan adalah terdiri dari berusia Zaman Tengah Atas (Tambelan dan Natuna) jaitu endapan jang telah diterobos oleh granit. K/Ar pengukuran terhadap granit di Tambelan memberi umur 84 $\pm$ 2 djuta tahun (Kapur Tinggi). Granit ini diterobos pula oleh dika-dika berisian basal dan andesit.

Keadaan di Natuna disangka agak-agak sama dengan apa jang dituturkan buat Tambelan. Dari Bukit Ranai di-ambil adamelit bermikadua jang menundjuk usia 73 $\pm$ 2 djuta tahun (K/Ar).

Umur-karbon daripada Tridacna diatas Tambelan memberi angka 5460 dan 5270 tahun B.P. serta mewakil rata-laut jang paling kurang ber-tinggi 0.3–0.4 m. Arang-alam di Natuna dari bawah tanda surut menundjuk umur 6260 tahun B.P. untuk rata-laut kala itu jang ada sedikitnja 0.7 m lebih bawah.

Kalkopirit dengan pirit dikenal dari dolerit Tambelan; pirit dan arsenopirit dari Anambas, dan stibnit dari Natuna. Kasiterit sedikitdikit didjumpai pada Anambas dan Natuna, serta air-berat (Hg) dari Natuna.

INTRODUCTION

The Tambelan, Anambas and Bunguran Islands are situated on the Sunda Shelf between West Malaysia (the Malay Peninsula) and Borneo (see fig. IV–1). The geology of the Anambas and Natuna Islands is known in outline, but no geochronology has hitherto been established there, whereas the geology of Tambelan Islands, before the reconnaissance described here, was completely unknown. Knowledge of the geology of these islands is important for two reasons: firstly, because of their situation on the very extensive and geologically little-known Sunda Shelf between West Malaysia and Borneo; and secondly because of their bearing on the connexion between the geology of mainland Asia and that of Borneo. The large area of plutonic, volcanic and metamorphic rocks in west Kalimantan (west Indonesian Borneo) is little known; it is believed to be largely Palaeozoic and Mesozoic, but no single radiometric or reliable palaeontological age determination is known from West Kalimantan. This area of older rocks in west Kalimantan has been referred to variously by Bemmelen (1949) and other Dutch geologists as the continental core or continental triangle of Borneo, as the Sunda Shield, and as Sundaic Borneo, but the writer has proposed the term West Borneo Basement as more appropriate (Haile, in preparation). Since it is the largest pre-Tertiary igneous-metamorphic complex in the Indonesian archipelago, it is of regional importance, and the present ignorance of the geochronology is a hindrance to understanding the geology not only of Borneo, but of Southeast Asia in general. The Tambelan Islands would appear to belong to the West Borneo Basement.

I was able to visit the Tambelan and Natuna Islands for a total of five days while directing a UNESCO/ECAFE Shipboard Training course in Marine Geology and geophysics in

FIGURE I

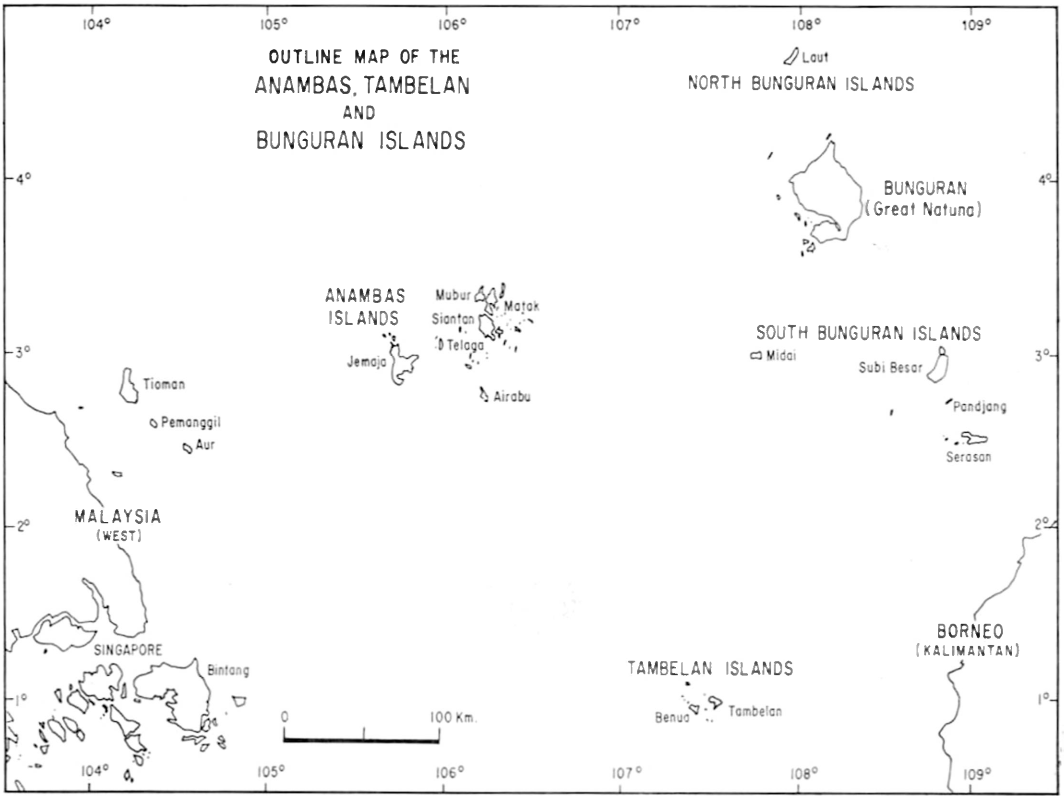

Figure IV–1. Map showing location of the Tambelan, Anambas, and Bunguran Islands.

April 1969, on board the research vessel R/I JALANIDHI (Commander Ch. Melontige) operated by the Hydrographic Branch of the Indonesian Navy. Shore traverses were made on several of the islands to gain some idea of the general geology, to be used in interpreting the marine surveys made, and specifically to obtain material for radiometric age determinations, which were made by Mr J. D. Bignell as part of his research project on geochronology of West Malaysia and adjacent areas, at the Universities of Malaya and Oxford. The Anambas Islands were not visited, but a brief account of their geology is included here based on previous work.

Specimens collected have been housed in the museum collection of the Department of Geology, University of Malaya, and are referred to here by the reference number preceeded by UM e.g. UM1234; they are listed in table IV-3. Colours of rocks described are given according to the names and notation of the Rock Colour Chart produced by the Geological Society of America. In general, the modern Indonesian orthography is used in spelling of place names, although complete consistency may not have been achieved.

I thank the Indonesian Government for permission to visit the islands and for making available, through UNESCO, the excellent research vessel JALANIDHI, Esso Exploration Malaysia for copies and translation of early papers, and Continental Oil for providing geophysical data. I also express my thanks to the geologists from several countries in Southeast Asia who participated in the course, and who contributed useful ideas and discussions in the field. Mr J. D. Bignell of the University of Oxford made the two K/Ar age determinations.

PREVIOUS WORK

Previous geological knowledge of the Anambas and Bunguran (or Natuna) Islands derives mainly from papers by A.C.D. Bothé (1925) 1928 *a* and *b*), which are based on a search for economic minerals, in particular cassiterite, made by R. J. Boers, J. de Kroes and J. E. Loth from 1916–17; it appears that Bothé did not himself visit the islands. Bothé mentions an account of rocks from the Anambas and Natuna Islands written by two former residents, A. C. van Hasselt and H.J.E.F. Schwarz (1898). R. W. van Bemmelen (1949, p. 225, 303; fig. 109, pl. 9) gives an account with maps, based entirely on Bothé's former papers. Because the original papers by Bothé are not generally available, fairly full translated extracts from them are included in this account. No published references to the geology of the Tambelan Islands are known, although geographic descriptions of the Tambelan and Bunguran Islands are given in the China Sea Pilot (Langdon, 1912; Anonymous, 1958–64). An account of the geology of the northern part of the Sunda Shelf has been published by ECAFE (anonymous, 1968).

TAMBELAN ISLANDS

The Tambelan Islands form two groups about 6.5 km apart, each extending northwest to southeast for about 20 km (see Admiralty Chart 361, and figs IV–1 and IV–2). The islands are small, the largest, Tambelan (in the northeast group) and Benua (in the southwest group), being about 7 and 6.5 km long respectively. The islands are rocky and hilly, with hills of several hundred metres not uncommon. The highest point is Bini on Tambelan Island, which is 1300 feet (396 metres) high. Several other peaks occur on Tambelan Island including the steep Bukit Kotit (290 m; see pl. IV–1). The larger islands are sparsely inhabited and there is a small village and administrative office on Tambelan at Batu Lepu. The main activity is coconut growing.

FIGURE 2

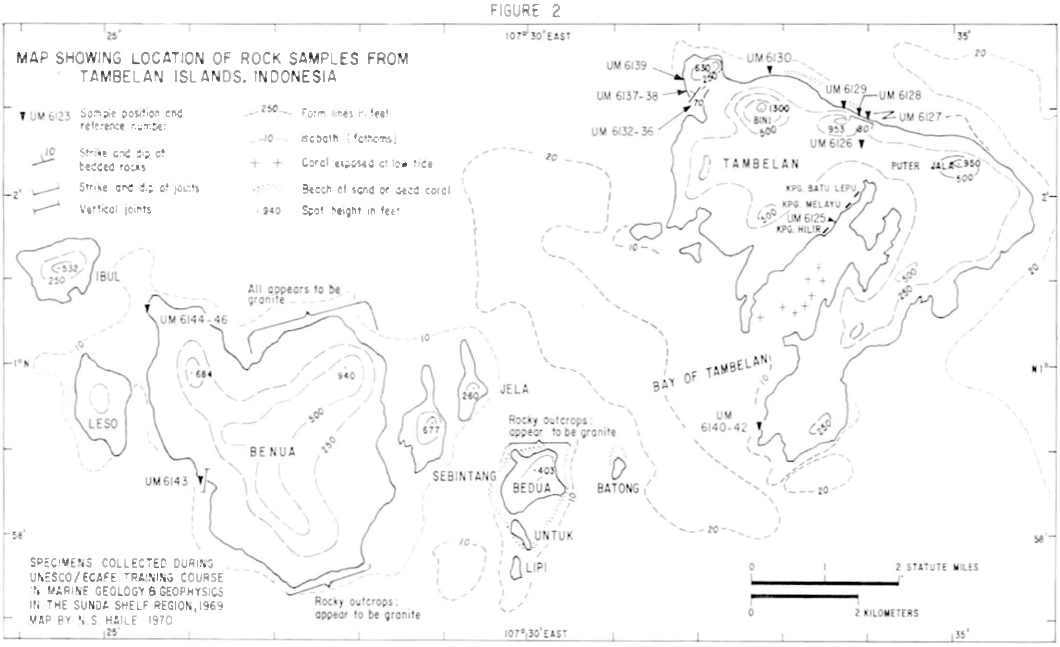

Figure IV–2. Map showing location of specimens collected on the Tambelan Islands.

Traverses were made across Tambelan Island north from the Bay of Tambelan, and westwards along the north coast, and specimens were also collected from the southern tip of the island. Benua Island was circumnavigated by small boat and landings made at two places. Those of the Tambelan Islands that were examined are composed of granitic rocks, which intrude basic and intermediate intrusive igneous rocks and tuffs, and are themselves intruded by basaltic and andesitic dykes. One specimen of granite (UM6143) was dated at 84 $\pm$ 2 million years (Late Cretaceous) by the potassium-argon method (J. D. Bignell, personal communication).

PRE-GRANITE BASIC IGNEOUS ROCKS

The pre-granite basic igneous rocks are exposed along the north coast of Tambelan Island. They are varied in texture and composition and include gabbro, diorite, dolerite, andesite and keratophyre, showing evidence of alteration and thermal metamorphism: one specimen shows slight mineralization.

The location of the specimens is shown on figure IV–2, and brief petrographic descriptions follow:

UM6128. Altered gabbro. A black phaneritic rock with irregular light-grey patches about 1 mm across. The thin section shows sub-ophitic texture. Plagioclase makes up about 60 percent of the rock, as subhedral crystals, up to 1 mm long, mostly brown and turbid and completely altered to sericite and kaolinite, but some showing twinning and determined as andesine-labradorite, An50. Clinopyroxene occurs as a few green crystals, mostly altered. Patches of chlorite, biotite, and ilmenite are probably replacements of pyroxene. The biotite occurs as very small flakes and was probably formed during thermal metamorphism of the rock.

UM6129. Mineralized dolerite. Several specimens from two blocks about 2 m across, presumably derived from the steep hillside behind the beach. The specimens are dark rocks containing small crystals of pyrite and chalcopyrite. In thin section UM6129B is seen to be composed of a mosaic of anhedral plagioclase, mostly untwinned, probably oligoclase, about 0.5 mm across, with many small crystals of actinolitic hornblende, which occur interstitially and in aggregates. Green biotite occurs in patches of minute flakes. Sphene is common in anhedral granular aggregates and as one sub-hedral crystal. Pyrite, chalcopyrite and black ore are common.

UM6129C is similar to JN9/5B but contains a few crystals of anhedral pyroxene, and more abundant biotite.

UM6129D contains quartz and haematite, in addition to oligoclase, abundant green biotite, actinolite and accessory apatite.

UM6131, metamorphosed dolerite (see pl. IV–9a) in contrast to the previous three specimens which all show signs of regional metamorphism, is much less altered. It is composed of phenocrysts, about 2 mm long, of fresh labradorite, showing oscillatory zoning, and of augite, altered around the edges to biotite and actinolite, in a groundmass of labradorite, augite, actinolite, and brown biotite. Accessory minerals include abundant ilmenite, and some rutile.

UM6130, metamorphosed diorite, is a mottled black and light yellowish-grey rock, cut by dark veinlets. Average grain size is about 1.5 mm, maximum 3 mm.

Composition (estimated from thin section) is:

	Percent
Oligoclase	45
Orthoclase	20
Quartz	8
Green hornblende	20
Brown biotite	5
Ilmenite, apatite, Calcite, zoisite	2

The biotite is in small flakes and is probably secondary (metamorphic).

On the foreshore at Telok Birah, on the north cape of Pulau Tambelan are informative exposures of volcanic rocks, apparently intruded by granitic rock which is itself cut by basic dykes (see figure IV–3, and plate IV–3a).

In contact with the granite (which may be a sill) is a thick bed of siliceous vitreous lava or tuff 3 m thick (UM6134; see pls. VI–9 c and d). The rock is brownish grey (5YR 4/1) and cherty looking, with a few whitish spots 2 to 3 mm across and two lighter-coloured coarser layers, 2 to 3 mm thick, visible in hand specimen.

The thin-section shows a few phenocrysts of oligoclase, 2 to 3 mm across, and one of small crystals of green biotite replacing a ferromagnesium phenocryst which may have been biotite, in a matrix of devitrified glass. Numerous minute relict crystallites and microlites can be seen in the matrix, which is composed of quartz and chalcedony with a little chlorite and haematite, and fine black ore dust. Rare isotropic crystals (0.15 mm diameter) are probably garnet.

FIGURE 3

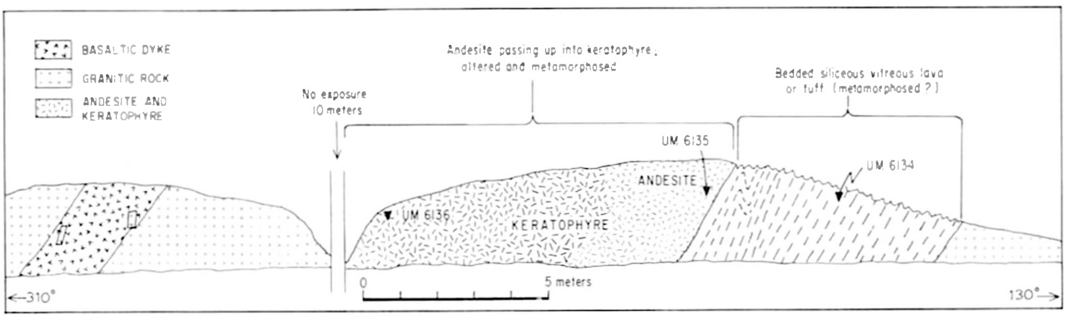

Figure IV–3. Sketch of rock outcrops on the beach at Telok Birah, Tambelan Island.

A dark-grey bed, of which 4 m thickness is exposed, overlies the vitreous rock along a fairly sharp contact. The base of this bed is fine-grained andesite (UM6135; pl. IV–9b), composed of laths of oligoclase up to 0.5 mm long, with smaller crystals of pyroxene much altered to epidote and chlorite, and smaller crystals of green amphibole. Abundant fine grains of ilmenite are present. The section is cut by cataclastic zones a fraction of a millimetre thick.

The andesite passes upward gradually into a porphyritic keratophyre or albitized andesite (UM6136; pl. IV–9c), an olive-grey rock with many dark and light crystals 1 to 3 mm across. In thin section the phenocrysts are seen to be albite, up to 3 mm long, containing much epidote. Patches of minute flakes of green biotite, up to 2 mm across, probably represent altered phenocrysts of amphibole or pyroxene. Abundant ilmenite and a little apatite are present. The groundmass is composed of the same minerals but is much finer grained.

The volcanic rocks at Telok Birah are slightly metamorphosed, and are probably older than, and intruded by, the granite. Metamorphism of the volcanic rocks is indicated by abundant small flakes of green biotite in the groundmass and replacing phenocrysts of mafic minerals, by intense epidotization, and by the presence of garnet. The other possibility is that the volcanic rocks are actually a dyke cutting the granite and the vitreous siliceous rock is a glassy dyke rock or the chilled edge of a thick dyke. This possibility cannot be entirely excluded, particularly as about 10 m to the west, granitic rock (granite porphyry, UM6137) is undoubtedly cut by a dyke trending in the same direction as the volcanic rocks (see below plate IV–3a and fig. IV–3). However, it seems less likely, because:

i) the vitreous rock seems too thick (3 m) to be a chilled margin;
ii) the volcanic rocks show definite evidence of thermal metamorphism;
iii) none of the other dyke rocks found are so vitreous—most are holocrystalline.

I conclude, therefore, that the evidence favours the idea that these volcanic rocks are older than the intruded by, the granite.

GRANITIC ROCKS

Granitic rocks form much of those islands of the Tambelan group which were examined. Normal fine to coarse biotite granite occurs at the south end of Pulau Tambelan, and on Benua Island. Other varieties of granitic rock found on Tambelan Island are alkali leucogranite, alkali microgrnite, granophyric granite porphyry, and metamorphosed microgranite. The mediumgrained biotite granite on Tambelan Island is probably the same age (Late Cretaceous) as that dated from Benua; the fine-grained varieties could also be Late Cretaceous, but might be Tertiary. Specimens of granitic rocks from Tambelan are briefly described below:

Medium to coarse biotite granite (UM6141; pl. 8c and d) crops out at Tanjong Bertumpah on the south end of Pulau Tambelan. It is a coarse-grained rock, mottled pale yellowish-brown and very pale orange. The thin section shows predominant microperthite, with quartz, oligoclase (showing oscillatory zoning), a little biotite (partly altered to epidote and chlorite), and magnetite.

In Kampong Melayu, at the head of Tambelan Bay, alkali leucogranite is exposed (UM6125; pl. IV–8a and b). This is fine to medium-grained, light brownish-grey (5YR6/1), with lighter-coloured feldspars and some dark minerals apparent in hand specimen. The thin section shows hypidiomorphic-granular texture. Predominant microperthite occurs as turbid anhedral crystals. Quartz is abundant; oligoclase as clear crystals showing strong oscillatory zoning is less common. Brownish-green biotite makes up less than 5 percent of the rock. Accessory minerals are magnetite and/or ilmenite, zircon, and epidote.

Alkali microgranite (UM6138) crops out on the coast at Telok Birah. It is composed of deeply embayed crystals of quartz, 1 to 2 m across, enclosing feldspar, and set in an irregular turbid mosaic of potash feldspar and albite. Small aggregates of biotite flakes are mostly altered to chlorite. Aggregates and veinlets of epidote occur, and ilmenite is a common accessory mineral.

A granophyric granite porphyry (UM6137; pl. IV–8e and f) crops out on the foreshore at Telok Birah, about 10 metres west of the keratophyre UM6136 and presumably intrusive into it. This rock shows an unusual textural combination of a granophyric (micropegmatite) groundmass in which are set phenocrysts of quartz, microperthite, sodic oligoclase, and aggregates of dolerite, probably after biotite. The quartz phenocrysts are subhedral and show prism and pyramid faces.

A light-grey fine-grained rock collected from the southeast flanks of Bukit Kotit, Tambelan, appears to be a metamorphosed microgranite (UM6126). The thin section shows abundant quartz, showing undulose extinction, in places intergrown with potash feldspar which is also abundant, and some oligoclase-andesine in a fine grained mosaic of quartz and feldspar. Epidote is common as aggregates and in veinlets with secondary biotite and magnetite.

Benua and Bedua Islands appear to be composed largely of granite. Specimens from Benua (UM6143; UM6144, pl. IV–8g) are normal fine-grained biotite granite. The first of these is the one dated by the potassium argon method as Late Cretaceous (see above).

POST-GRANITE ANDESITE AND BASALT DYKES

Dark dykes cut both the granite and the pre-granite igneous rocks. The dykes seen range in thickness from less than 1 mm (the thinnest dyke the writer has seen anywhere) to about 1 m. The dykes seen strike in various directions: some are vertical, others dip regularly, and two were seen to have a sinuous arching form (see pl. IV–2a). Cutting pre-granite igneous rock on the north coast of Tambelan just east of Tanjong Antu are two vertical dykes, about 10 cm and 20 to 50 cm thick, and 1 m apart, striking northeast (040°), which are crossed and offset by another vertical dyke, 50 to 100 cm thick, striking southeast (130°). This is clear evidence for two successive intrusions of dykes at that place, the southeasttrending dyke being younger.

The dykes show symmetrical variations in composition across their thickness, brought out by differential weathering, which indicate a probable composite origin (see pl. IV–4a). The banding resulting from this compositional variation follows the sinous trends of the dykes closely, and, together with the very thin feather-edged dykes described below, indicates a very fluid magma which was probably intruded at a high level in the crust. It seems probable that at least some of the dykes were intruded in Late Cainozoic, possibly Quaternary time.

Most of the dyke rocks are black in colour and basaltic in composition. A specimen (UM 6127) from a dyke 10 to 20 cm wide cutting granite, on the north coast of Pulau Tambelan, is a black aphanitic rock. The thin section shows microporphyritic texture. Anhedral microphenocrysts of clinopyroxene up to 2 mm long but mostly smaller, occur in a partly glassy, variolitic, mainly turbid groundmass, in which minute laths of plagioclase and anhedral crystals of pyroxene can be seen. The whole section is very turbid and the crystal outlines are indistinct. Veinlets and vesicles contain clear crystals of plagioclase, green hornblende, brown biotite, and ?prehnite; apatie was seen in one vesicle.

At Tanjong Antu, at the northwest end of Pulau Tambelan, a basalt dyke 1 m thick and striking 010° cuts a granite exposure. A small granite boulder found on the beach there contains black dykes only 2 cm thick, thinning out to nothing along a feather edge (see pl. IV–3b). The thin section (UM6139; pl. IV–9g and h), cut across the "dyke" where it is only 4 mm thick, shows that, although so thin, it is composite. A central part is composed of subhedral microphenocrysts about 0.2 mm long of clear labradorite (twinned on the albite law) and pale-green hornblende, in a cryptocrystalline, partly glassy, brownish matrix with a fairly high refractive index. Most of the microphenocrysts are orientated with long axes parallel to the sides of the dyke. Small euhedral crystals of magnetite are abundant. The outer 0.4 mm or so on either side is similar in texture, but lighter in colour. The feldspar in these outer zones is largely altered, and the groundmass more devitrified; magnetite grains are fewer and smaller. Between the dyke and the host granite are thin discontinnuous veinlets of quartz, epidote, and chlorite.

At Telok Birah, about 10 m west of the exposures of pre-granite volcanic rock (UM6134, 6135) cut by granite and described above, the granite is exposed and is itself cut by black dykes up to 1.5 m thick, striking 035; small pieces of the granite have been rafted into the dyke (see plate IV–3a).

On the west side of Pulau Benua, the granite exposed on the rocky coast can be seen to be cut by a number of dykes mostly less than 1 m thick. Two of these dykes, in Telok Manyengat, at the northwest tip of Benua, were seen to be vertical, and to strike about 020. They are of holocrystalline andesitic rock.

UM6145 is a dark-grey rock composed of microphenocrysts of zoned plagioclase, probably andesine, somewhat altered to epidote, sericite and carbonate, in a groundmass of basic plagioclase, much green hornblende, some brown biotite, abundant magnetite, patches of carbonate, and a little haematite and apatite. Albite occurs in a veinlet. UM6146 (pl. IV–9f) is lighter coloured, being greyish green, non-porphyritic and more acid, and can be classified as andesite. It is composed mainly of laths of altered and turbid andesine, containing numerous minute pale-green needles of ?actinolite, with ragged patches of chlorite and a little quartz. Ilmenite, partly altered to leucoxene, is abundant.

QUATERNARY DEPOSITS

The Tambelan Islands are rocky and there is little alluvium. Quaternary deposits are mostly confined to the shore lines. Some sandy shores are backed by flat sandy terraces a few tens of metres wide, 1 or 2 metres above present high-tide level, which were probably formed when the relative sea level was slightly higher than at present.

Clear evidence of Holocene emergence is seen along the north shores of Tambelan Islands and Benua where the intertidal range is formed of a flat platform of dead coral which is clearly a former reef, eroded by wave action. On the north coast of Tambelan dead coral is found attached to rocks on the foreshore at or just above present high-tide level. At Telok Birah giant clam shells (?*Tridacna* sp.) are found embedded in dead coral just below high-tide level. Two of these shells were dated by the radiocarbon method with results shown in table IV–1. The mean tidal range at Tambelan is small, probably about 0.5 m, and so the results prove only that the sea level at Tambelan was relatively higher by at least 0.3 to 0.4 m at about 5460 and 5270 years B.P. (see Haile, in press).

Coral rock also protrudes above the water in Tambelan Bay, on either side of the entrance channel, but this is probably part of a former man-made breakwater built to protect the village of Batu Lepu "from the attacks of pirates, who formerly visited these islands, and carried into slavery any of the natives they could capture." (Langdon 1917, p. 53).

ANAMBAS ISLANDS

The Anambas Islands (see fig. IV–4) consist of two principal groups, the southwestern and the northeastern, and numerous detached islets. They are mainly rocky and hilly, with peaks as high as 564 m.

Published knowledge of the geology of these islands is confined to the compilation by Bothé (1928, *a* and *b*). He described the islands as rocky, and formed largely of eruptive rocks. A few occurrences of clastic rocks and metamorphic rocks found there he considered to be remnants of a previous (i.e. pre-igneous) sedimentary cover. They include siliceous and argillaceous shales, ferruginous clay-shale, contact-metamorphic rocks, and polymict clastic rocks. Pebbles of purplish siliceous rock were found on Pulau Matak (Siantan group of islands), and sericite-actinolite schist and plagioclase amphibolite were found on the Djemadja (Jemaja) group of islands.

Igneous rocks found comprise granite, gabbro, andesite, gabbroporphyry, diabase, and dyke-rocks such as aplite and malchite. (Malchite a little-used name originally given by Osann, quoted by Johannsen (1932, vol. II) to fine-grained dark holocrystalline dyke rocks, usually porphyritic with small and rather rare phenocrysts of hornblende and labradorite, and occasionally biotite, in a holocrystalline groundmass of hornblende, andesine, and a little quartz).

Granite forms the whole of the island of Jemaja (Djemadja) where a light and a dark variety were found (Bothé, 1928*b*, p. 146–147):

> "Sometimes streaks of the coarse-grained lighter type have penetrated through the finer darker granite, as, for example near Tanjong Batoe Kapas Tjamboel. Near Kampong Bangkaran, pink-colored somewhat coarser types of granite occur together with the darker granite. In the river Ayer Rajah (Djemadja), greisen and quartz are found everywhere together with pyrite, arsenopyrite, and haematite. The greisen is coarse to extremely fine-grained, with a strikingly high mica content. Tourmaline and tin ore are absent (from the greisen.)
>
> "Granite and aplite were encountered near the Kampong Pelajar on the island of Matak, and more to the east a porphyritic rock that appeared to be andesite. Bukit Nioelwan appears to be formed of the same rock. How the granite and andesite threre are related to each other here is not clear. Near Piabang, biotite-granite with long green crystals was seen cut by almost vertical veins of aplite 6 to 20 cm wide striking 210°. Light-colored veins of aplite also penetrate the

FIGURE 4

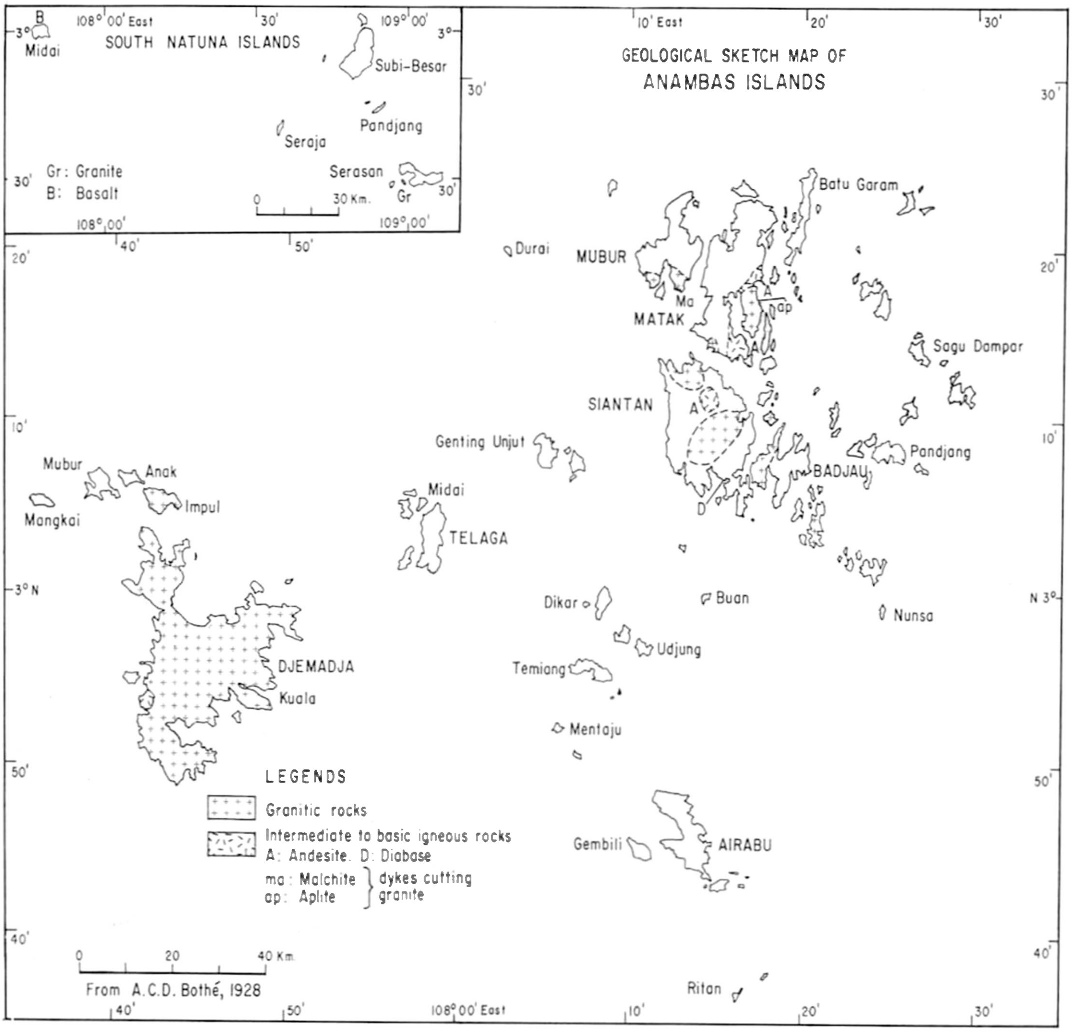

Figure IV–4. Geological sketch map of the Anambas Island.

granite near Sungai Mirak.

"The surroundings of Terempah, the main village on the island of Siantan, consist entirely of granite, but elsewhere in the interior of this island granite and a more porphyritic rock (andesite?) were found alternately. Veins of aplite occasionally occur in the granite.

"At Ajer Temoeroen, a vein of green aplite cuts granite with yellow and red felspars. Large inclusions of quartz are sometimes present in the granite. The porphyritic rock mentioned above can also be found at Tanjong Troeng.

"Gray porphyritic granite with large phenocrysts of feldspar was found on Pulau Moendjan at Tanjong Ampa, and pink granite was seen near Tanjong Njamoek.

"At Pulau Moendjang gray granite predominates. On Gunong Dedap, blocks of magnetite were found on various sides of the hill. Remains of sulphides can still be seen in this magnetite. According to De Kross, judging from the amount of blocks seen, the ore body cannot be large, and the outcrop could not be found.

"The island of Mas Abang consists of granite.

"It is thus mainly granites that form these islands. However, there are also basic rocks, although these are subordinate. Which of the two plutonic rocks was first intruded, can perhaps be deduced from the very interesting rock 741. According to the determination of Dr Gisolf, this is an enclave in a granite magma, i.e. a piece of country rock that was being assimilated, having been metamorphosed to a fine-grained mixture of pyroxene and ore with biotite. Presumably, therefore, olivine or serpentine was the original mineral of the country rock. No serpentine is present among the rocks found on the Anambas Islands, which do, however, include gabbro and gabbro-porphyrite. It is therefore not impossible that the olivine has arisen from this rock and that the gabbro rocks are older than the granites."

MINERALIZATION

In his compilation report, Bothé (1925, p. 38–39) recorded greisen and quartz with pyrite, arsenopyrite, and haematite, in Ayer (River) Rajah, near Kampong Bangkaran, and on Jemaja Island. Near Bukit Kleipan on the south of the island extensive quartz with sulphides was recorded by him; rivers there were seen to contain much pyrite which on analysis showed traces of gold, silver, and tin. "Traces to small amounts" of tin ore were found at several places on Jemaja Island.

On Siantan Island, washed samples were found to contain considerable amounts of pyrite, magnetite, and ilmenite, and traces of cassiterite were found at Terempah, where sulphide-containing greisen was found on the hill.

BUNGURAN (NATUNA) ISLANDS

The Bunguran Islands are divided into two groups: the Kepulauan Bunguran Utara (North Bunguran Islands) and the Kepulauan Bunguran Selatan (South Bunguran Islands). These islands are also referred to in the literature and on some charts as the Natuna Islands; they are as shown on Admiralty Chart 1348.

The Bunguran Islands are far larger in area than the Anambas or Tambelan Islands. The Kupulauan Bunguran Utara (Northern Natuna Islands) includes the large island of Bunguran (Great Natuna) which is about 56 km. (35 miles) long and 40 km (25 miles) broad, and has an area several times that of Singapore (see figs. IV–1, IV–5). The highest mountain on Bunguran is Gunong Ranai, about 1000 m (see pl. IV–6a). The other islands in the northern group are Pulau Laut and a few smaller islets (see fig. IV–6). The Kepulauan Bunguran Selatan (Southern Natuna Islands) include Subi, Serasan and a number of small islands (see fig. IV–4, inset).

PULAU BUNGURAN AND ADJACENT ISLANDS

The geology of Pulau Bunguran is shown on figures 5 and 6. From Bothé's compilation (1928*b*, p. 147–152) it is known that the southern part of Pulau Bunguran (Great Natuna Islands) is composed of sedimentary and metasedimentary rocks named by Bothé the "Bunguran Formation," here referred to as the Bunguran beds. The "Bunguran Formation" contains intermediate, basic, and ultrabasic intrusive igneous rocks, and is also intruded by granite stocks, it is overlain unconformably to the north by thick flat-lying sandstones, called by Bothé "Plateau Sandstone Formation."

Since there is no type section designated, and the description is sketchy, the "Bunguran Formation" cannot be regarded as a valid formal rock-stratigraphic unit in accordance with modern usage of stratigraphic names. It is therefore proposed to refer to the strata by the informal term Bunguran beds. The sandstone strata of Bunguran resemble in some respects the Plateau Sandstone of west Sarawak and west Kalimantan, but they show several lithologi-

FIGURE 5

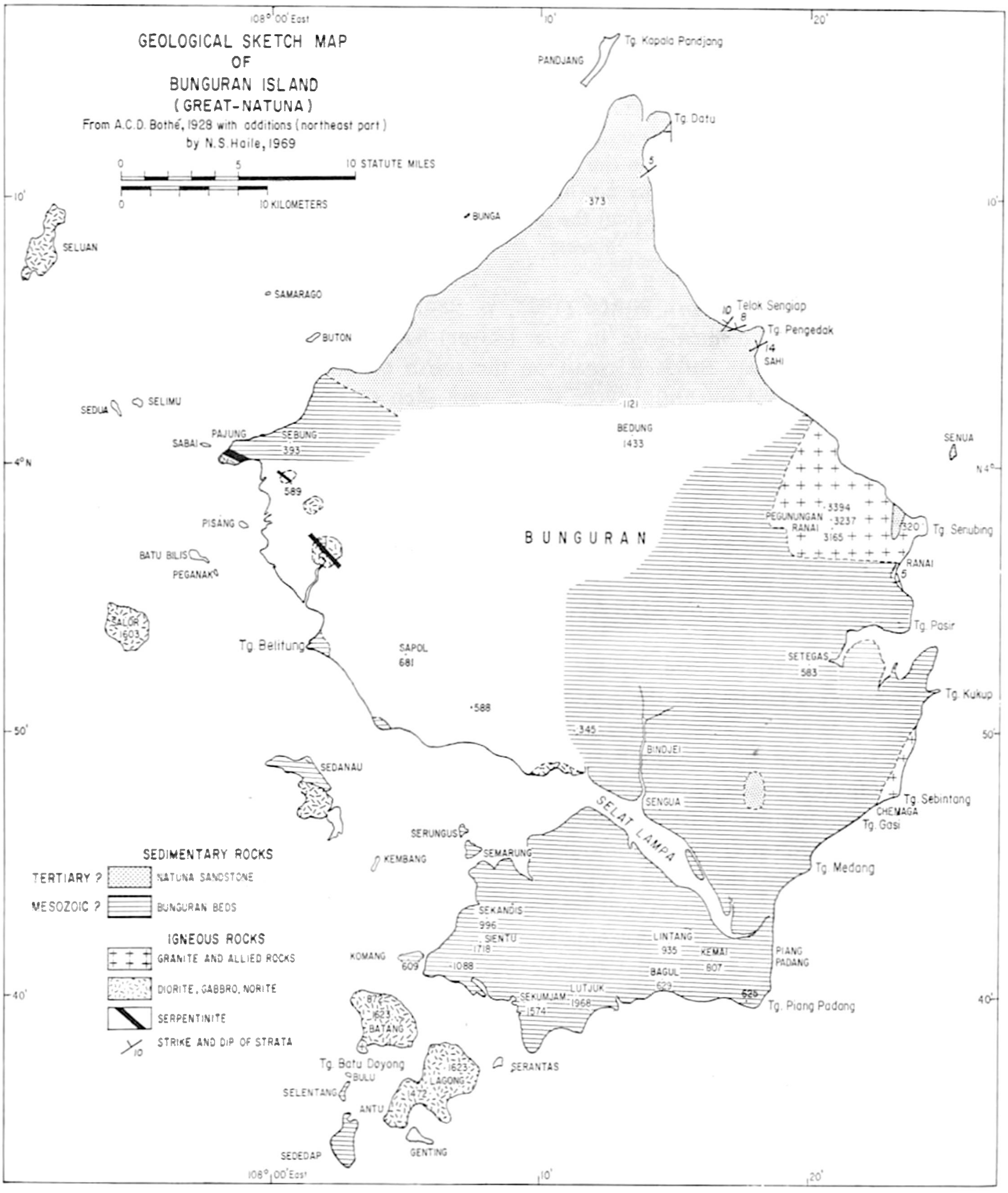

Figure IV-5. Geological sketch map of Bunguran Island.

cal differences, and there is no evidence that they form a rock-stratigraphic unit with the Plateau Sandstone, the nearest occurrence of which is about 275 km away. It is therefore proposed to refer to these strata by the informal name Natuna sandstone, after the old name of Bunguran. Further work may enable two units to be defined formally and be raised to formation status.

BUNGURAN BEDS

Bothé (1928*b*, p. 147 ff.) describes the southern part of Pulau Bunguran as being formed of siliceous shales and clayshales, striking south-southeast to east-southeast. The clayshales form low terrain with the appearance of a peneplane, except where siliceous shales form slightly higher land, such as south of Sungei Penarik, where they form a steep hilly area, bounded by cliffs facing Selat Lampa (Strait of Laplace). At Piang Padang on the south coast radiolarian hornstones were recorded (see below).

Bothé records a bed of schistose conglomerate which extends from Tanjong Gasi behind the pasanggrahan (quest-house) at Chemaga (Tjemaga) and can be followed north for several kilometers. The conglomerate which appears to have been strongly affected by the nearby Chemaga granite, contains fragments of argillite, plagioclase, picotite and epidote amphibolite.

During the present investigation the Bunguran beds were seen on the east coast south of Ranai village, and north of Gunong Ranai. About 400 m south of Ranai, massive brownish meta-arkose is exposed on the beach. It is weathered into a fluted form and cut by major joints dipping 070/60, 120/45 and 290/05. The last direction appears to be the bedding of the meta-arkose.

The meta-arkose (UM6154; pl. IV–10c) is composed of framework grains, maximum size 0.8 mm, average about 0.4 mm, of quartz (some polycrystalline grains) and potash-feldspar, with some oligoclase, albite, and rare chert. The matrix is a mosaic of quartz, feldspar, and abundant small crystals of metamorphic red-brown biotite. The rock is a thermally metamorphosed muddy arkose, presumably metamorphosed during the emplacement of the Ranai granite.

Within the brown meta-arkose are ovoid lighter coloured cherty-looking inclusions, up to 70 cm across, of metamorphosed calcareous muddy arkose. This rock (UM6153) is composed of framework grains of quartz, plagioclase and orthoclase, in a matrix of small grains of quartz and feldspar with abundant metamorphic clinopyroxene and some calcite. The rock was probably originally an arkose with a calcareous muddy matrix, representing calcareous patches or concretions within the parent arkose.

Pulau Senua, off Tanjong Senubing, is a small rocky island. No landing was made there, but it was seen through binoculars to be composed of rock similar in appearance to the meta-arenite south of Ranai.

Chert forms a rocky islet, Pulau Sahi, near the coast between Tanjong Senubang and Tanjong Pengedak to the north (see pl. IV–4b). The chert is bedded, the beds being 1 to 10 cm thick, flexured and folded with a general dip steeply to the northwest. The chert is in places laminated in grey and light grey colour. In thin section the chert (UM6157) is seen to be composed of microcrystalline quartz and some chalcedony. Some brecciated chert (UM6158) occurs in zones along the axes of small folds.

Chert of the Bunguran beds crops out along the west side of Pulau Laut, the most northerly of the North Bunguran Islands (see fig. IV–6, inset). The chert (UM6147) is reddish brown, laminated, and microfaulted, and contains poorly preserved Radiolaria. Near the northwest tip of Pulau Laut, reddish-brown chert and black radiolarian chert (UM6148) are interbedded with vitreous rocks which contain well-preserved Radiolaria and which are probably altered glassy radiolarian tuffs (UM6148; UM6150; pl. IV–10b).

Batu Imung, a rocky islet in the sea south of Pulau Laut, is composed of chert with brecciated zones up to 4 m wide (see pl. 5a and b). The breccia is composed of clasts, mainly 2 to 10 cm across, with a maximum size of 70 cm. A specimen of the breccia (UM6152; pl. IV–10 a and b) shows fragments mostly of chert, but a few of polycrystalline quartz, and of a nearly isotropic material, with microlites, which is probably volcanic glass. The fragments are cemented by haematite-rich interstitial material. The breccia is probably tectonic.

No identification has yet been made of the Radiolaria from Pulau Laut. Bothé records that van der Vlerk examined radiolarian rocks from Piang Padang on the south coast of Bunguran and identified:

Cenosphaera sp.
Stichocapsa rotunda Hinde
Sethocapsa sp.
Dictyomitra sp.

Bothé (1928*b*, p. 148) states that "The rock agrees completely with rocks described by Hinde from the 'Danau' formation of West Borneo and with radiolarian rocks collected by Brouwer from the Upper Jurassic of the eastern part of the Archipelago."

In view of the uncertain value of Radiolaria as age-indications, however, it would be safer to regard these merely as indicating a Mesozoic age.

NATUNA SANDSTONE

Sandstone and conglomerate covering the northern part of Bunguran Island, called by Bothé "Plateau Sandstone" is here referred to by the informal name Natuna sandstone for reasons already explained.

The Natuna sandstone is unconformable on the Bunguran beds and along the northeast coast dips at a few degrees towards northwest. The boundary with the underlying Bunguran beds is not exposed on the coast but can be defined within 1 km, since it must lie between Pulak Sahi, where chert is exposed, and the exposure of conglomerate on the southern side of Tanjong Pengedak, which is the lowest exposure of the Natuna sandstone (see pl. IV–6b). This conglomerate, which is presumably the basal conglomerate of the Natuna sandstone, is reddish brown and is composed of cobbles and pebbles of chert in a sandy matrix, and contains lenses of sandstone. Specimens of the conglomerate are described below:

UM6159, grayish-red (10R4/2) chert-clast sandy conglomerate, (see pl. IV–1 10a and f) contains pebbles and granules, mainly of chert, some clear, some reddish-brown, turbid, and full of Radiolaria. Other clasts that are isotropic, some of which contain Radiolaria, are probably glassy tuff. A few clasts are of metaquartzite, and quartz, mostly polycrystalline. Sand-sized areas of decussate aggregates of small squarish clear crystals (each crystal about 0.02 mm across) may be kaolinite formed by breakdown of original feldspar clasts.

UM6160, chert-clast sandy clonglomerate (see pl. IV–10d) from the north side of Tanjong Pengedak, is yellowish-grey (5Y7/2), but is of the same composition as UM6159, with chert being predominant in all grain sizes (pebbles, granules, and sand)

The sandstone immediately above the basal conglomerate (UM6161) is unusual in showing a high degree of textural immaturity with high compositional maturity: that is, it is poorly sorted, but composed mostly of resistates, namely chert and quartz.

The chert-clear sandstone (UM6161) is yellowish grey (5Y7/2), and contains a few small pebbles of chert. The thin section shows clasts mainly 0.4 to 1 mm size, a few as large as 3 mm, mainly chert, with subordinate polycrystalline quartz. There are a few grains of nearly isotropic brown glassy material with microlites, which are glassy lava or tuff. Aggregates of kaolinite, similar to those found in UM6160 and UM6161, occur.

Specimens of sandstone from the Natuna sandstone, further north, and thus stratigraphically higher, show much more compositional immaturity, containing grains of feldspar and a higher proportion of grains volcanic rock. The sandstone shows conspicuous cross-bedding (see pl. IV–7a).

UM6163, feldspathic litharenite (see pl. IV–10g and h) is a light olive-gray (5Y5/2) rather crumbly sandstone. The thin section shows a fairly well-sorted texture, with subangular grains about 0.5 mm diameter, composed of:

Quartz: mostly monocrystalline grains with undulose extinction, some with straight extinction

Volcanic rocks: brownish and greenish turbid grains, glassy, some microporphyritic, one containing Radiolaria

Alkali feldspar: albite, microperthite, orthoclase, micropegmatite

Brown and green biotite: a little magnetic, muscovite, calcite tourmaline, and garnet.

UM6164, lithic subarkose, from Tanjong Datu, is olive-gray (5Y4/2) and rather friable. The thin section shows fair sorting Grains are mostly 0.2 to 1.2 mm across and are composed of:

Quartz: some with wavy, some with straight, extinction, a few polycrystalline grains.

Potash feldspar: estimated 10～20 percent. Turbid pale-brown nearly isotropic grains, probably volcanic glass

Metaquartzite: a few grains

Microgranite: One grain

Rhyolite: a few grains

Schist: one grain

Mica: bleached biotite. A few fibrous aggregates of greenish biotite

Argillaceous beds within the Natuna sandstone were seen only at Tanjong Data, where a lens of light greenish-grey shale, UM6165, 6 cm thick was observed. It was found to be barren of microfossils. Since the exposures along the coast occur only at infrequent intervals, it is possible that some of the intervals where no rocks are exposed represent argillaceous sequences within the Natuna sandstone.

A probable outlier of Natuna sandstone was shown by Bothé west of Chemaga, and the writer has mapped another outlier west of Tanjong Senubing (see fig. 5, 6). At the second mentioned place, the evidence is hills formed of sand which is much finer than the granite sand forming Gunong Ranai, and higher than any of the beach terraces.

There is no palaeontological evidence of the age of the Natuna sandstone. The generally gentle dips and unmetamorphosed character, however, indicate that the sandstone is very likely younger than the Ranai granite. The clasts in the Natuna Sandstone, (mainly chert, radiolarian tuff, quartz, and feldspar) are consistent with a derivation from a terrain that consisted initially mainly of Bunguran beds, but later provided detritus from granite and possibly from contemporary volcanoes. This confirms the view that the Natuna sandstone is younger than the Ranai granite, which is Late Cretaceous. The Natuna sandstone thus cannot be older than latest Cretaceous, and is probably Tertiary.

The Natuna sandstone is exposed along the northeast coast of Bunguran Island for 18 km, with a gentle dip in general to north or northwest. In view of the gentle and undulating dip, and the sparse exposures separated by long stretches where no outcrops are seen, it is not possible to estimate the thickness of the sandstone sequence with any certainty. Taking to account the available information and the fact that flattopped hill ranges 500–1000 m high seen inland are most probably of Natuna sandstone, it seems likely that the thickness on Bunguran is at least one and probably several thousand metres.

The Natuna sandstone probably continues off-shore, and would be expected to thicken and change into a marine facies. Geophysical evidence collected on the JALANIDHI cruise was studied by the participants, and by B. P. Dash and S. Sano, who identified layers in the

FIGURE 6

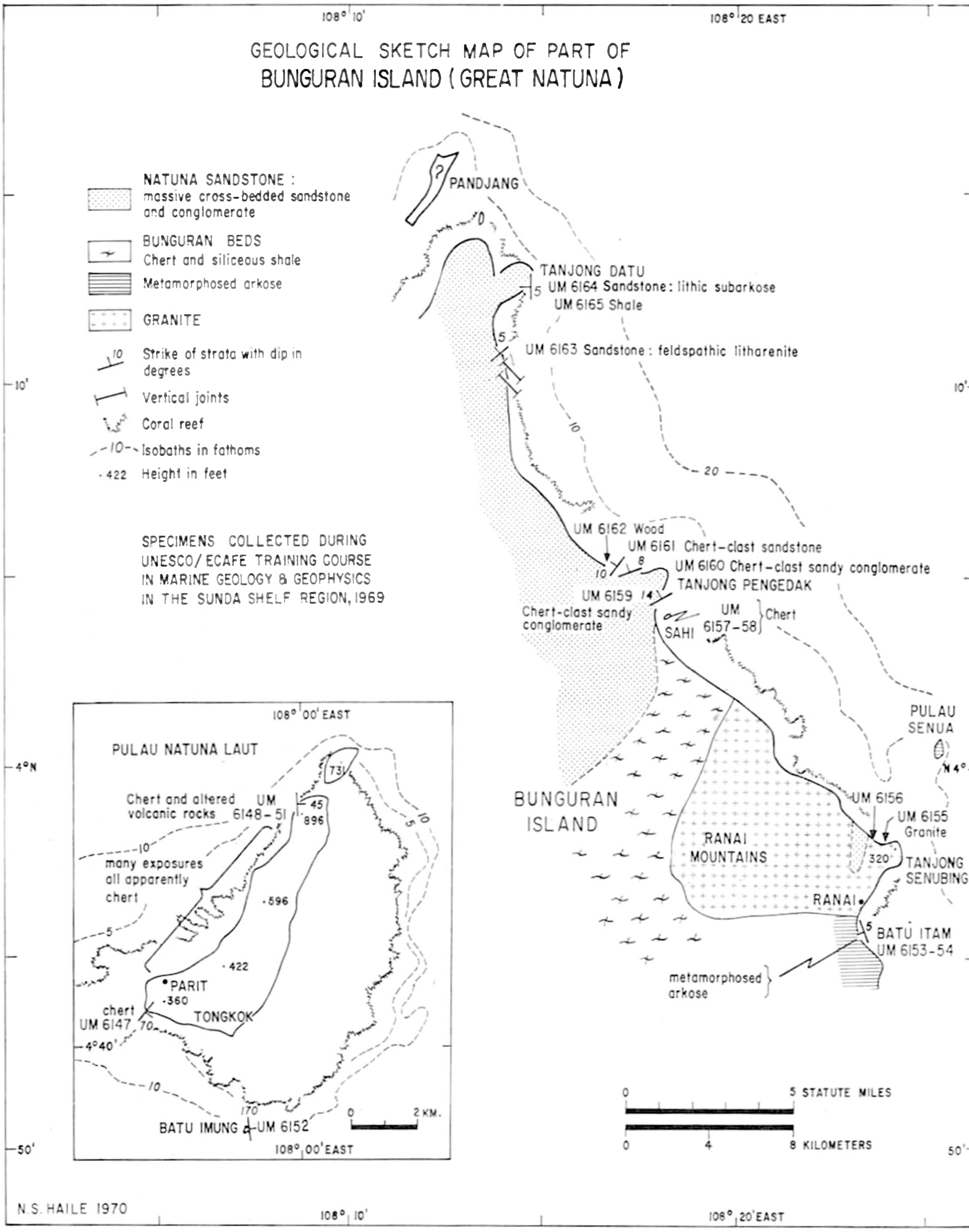

Figure IV-6. Geological sketch map of Pulau Natuna Laut and part of Bunguran Island.

marine subsurface correlable with the Natuna sandstone (see Dash and Sano, 1970). The Continental Oil Company, with the agreement of their Indonesian partner Pertamina, kindly released an seismic section line off Bunguran starting about 21 km east of Tanjong Sebintang, and continuing east, which shows a series of layers identified as Miocene-Pleistocene, probably Natuna sandstone or a time equivalent of it, which has a low-frequency, high-amplitude seismic layer at its base, dipping gently eastward; another east-west seismic profile located near the northeast corner of Bunguran shows the basal layer dipping from 580 m to 3100 m over a distance of about 11 km, an angle of dip of approximately 13°. Thus it seems likely that the Natuna sandstone, or its equivalent, is widespread in the offshore areas, and, should suitable source rocks be present, would form an important reservoir rock for oil.

IGNEOUS ROCKS

Basic and ultrabasic rocks

In addition to glassy tuffs found interbedded with the chert of the Bunguran beds, various basic and ultrabasic plutonic and effusive rocks were recorded by Bothé from Bunguran Island. Many of these show evidence of dynamic metamorphism. These rocks, which include serpentinite, diabase tuff, gabbro, diorite, and norite (and metamorphic equivalents) may represent, at least in part, an ophiolite suite associated with the Bunguran beds.

On the west coast of Bunguran, Bothé (op. cit, p 148) records serpentinite and basic intrusive rocks, near Sungei Semalar, Sungei Sekeran, and Telok Ujong (Ayer Mali). A serpentinite dyke was found in Telok Ujong, near steeply dipping siliceous schists that showed no sign of contact metamorphism. North of Kampong Ayer Mali, diabase tuff was found at Tanjong Kelenteng, which was considered to be related to the siliceous shale of the Bunguran beds there because its strike is the same. Inland from this exposure Tanjong Pajong rises steeply and is formed of dense fine-grained gabbro.

Basic eruptive rocks, dynamically metamorphosed, were recorded from many other places on Bunguran and the small islands adjacent to it. These included saussuritized basic rock with an original porphyritic texture, from Pulau Seluan; serpentinite, diorite, and norite from Sungei Sekeram; gabbro and serpentinite from Sungei Semalar; and saussuritized gabbro, diabase, and fine-grained epidote amphibolite, probably formed from an original diabase-tuff, from Pulau Sedanau, where they are associated with siliceous shale. From the southwest coast of Bunguran, Bothé recorded epidote schist at Tanjong Belitung, epidote phyllite at Tanjong Sedarat, and pyroxene gabbro near Kampong Binjel. In the eastern and central parts of the island, uralite diabase (amphibolite) was found at Sungei Saloi (north of Pian Padang), uralite amphibolite at the foot of Bukit Setegas, with diabase tuff not far away in Sungai Lemang, and epidote amphibolite west of Bukit Setegas in Ayer Peng.

Granite

Granite occurs in three areas; The Ranai Mountains; Chemaga (Tjemaga) and Pulau Batang (Batu Doyang).

The Ranai granite is by far the largest intrusion, being about 1000 m high, and covering about 50 sq. km. According to Bothé it is a generally normal biotite and biotite-amphibole granite. Specimens collected during the present investigation (UM6155, pl. IV–8h, and UM6156, both from Tanjong Senubing) are both fresh coarse two-mica adamellite, composed of andesine or oligoclase-andesine with strong oscillatory zoning, orthoclase, quartz, red-brown biotite, and muscovite. The muscovite occurs in aggregates with a pale-brown almost isotropic substance which could be halloysite. Accessory minerals include magnetite, apatite, monazite, and zircon.

Specimen UM6156 was dated at 73 ± 2 million years (Late Cretaceous, probably Maestrichtian) by the K/Ar method (J. D. Bignell, personal communication).

HOLOCENE DEPOSITS

Well-defined and extensive sandy terraces, about 2 m above high-tide level, occur along the west coast of Bunguran Island. Although these terraces could have been formed when the sea level was relatively slightly higher than present, they do not prove such a relative change, and no conclusive indications of Quaternary higher sea levels, such as raised coral reefs, have been recorded from the Bunguran Islands.

At Telok Sengiap, on the northwest coast of Bunguran, I found a peat layer, containing small tree-boles a few centimeters in diameter, apparently in position of growth, in the sea just below high tide level. Wood from one of these small boles was dated at 6260 $\pm$ 120 years B. P., and indicates that the sea level there was relatively lower by at least 6.7 m at that time (see table IV-1, and Haile, in press).

MIDAI AND BUNGURAN SELATAN (SOUTH NATUNA) ISLANDS

The island of Midai, between the north and south Bunguran islands, is described by Bothé (1928, p. 151–152) as about 50 to 60 m high with a flat top containing a small depression. A piece of basalt was collected from the island, and Bothé considered it possible that the island is an extinct volcano. Bemmelen (1949, p. 303) states that Midai is definitely an extinct basaltic cone quoting Bothé (loc. cit.) as his authority; it appears however that Bemmelen did not have any additional evidence about this and Bothé's original cautious suggestion is more appropriate.

The only information of the geology of the Bunguran Selatan (or South Natuna) Islands, comes from a few rocks collected by de Kroes in 1920, and recorded by Bothe (1928, p152) as granites and contact-metamorphosed rocks from Pulau Serasan, and uralite gabbro with prehnite from Pulau Subi Kechil.

MINERALIZATION

Tin: The Ranai granite contains veins of very clear quartz and tourmaline (seen especially on the road north from Ranai to Tanjong Senubing) but no mineralization has been seen in situ. Bothé (1925, p. 41–42) recorded traces of tin ore (presumably cassiterite) from several places on Bunguran Island. At Ayer Rajer, a tributary of Sungei Ulu on the south side of Gunong Ranai, some bores were made in a "very poor deposit," of which the richest showed "less than 0.19 picul." It is not clear what is meant by this, since the volume yielding 0.19 picul (= 25 pounds or 11.3 kg) is not stated. Later on Bothé quotes results in picul/300m^3, and so he may be using the same measure here. He records that grains of light-yellow fine tin ore were found everywhere in the terraces behind the sea in the Ayer Bulu area, Chemaga. At Kampong Munung (2 km south of Chemaga), much fine tin ore mixed with iron ore was found on the lowest shore terrace, about 60 ~ 80 m from the shore and a drill hole showed 3.6 picul (479 lbs or 217 kg) per 300 m^3. The deposit appeared to be only of small extent.

Traces of tin ore with pyrite were found by drilling in the valley of the Semitan.

Mercury and Stibnite: Bothé (1925) records that mercury was washed out of the sand at Gunong Ranai, and a piece of stibnite was found at Panjong on the east coast, and that "relatively large pieces" of stibnite were taken from Serasan Island. Since stibnite was exported in small boats from west Sarawak to Singapore in the 19th century, however, and many of these boats may have called in at the Bunguran Islands, it would be desireable to have proof that the stibnite from Bunguran, recorded by Bothé, actually originated from there, and was not from loose pieces on the beach, or collected from residents on the Islands, since such pieces could have been brought from Sarawak.

RELATIONSHIP TO REGIONAL GEOLOGY

Although the geology of the islands is only sketchily known, it can be said that the Bunguran Islands differ geologically quite markedly from the Tambelan and Anambas Islands. Neither the thick, distinctive, probably Mesozoic radiolarian chert of the Bunguran beds, nor the flatlying, cross-bedded, probably late Cretaceous or Tertiary Natuna sandstone, from the Bunguran Islands are recorded from the Tambelan and Anambas Islands. The granite of Bunguran Island is coarser and more basic than the mainly alkali granite of Tambelan, and post-granite dykes, common in the Tambelan and Anambas Islands, are not seen in the Bunguran Islands.

The Bunguran Islands show a fairly close resemblance in geology to extreme West Sarawak, particularly the Tanjong Datu area of the Lundu District (see Wolfenden and Haile, 1963). The radiolarian chert of the Bunguran beds finds its counterpart in similar chert in the Serabang Formation of West Sarawak, although the Serabang chert is only a minor component of a predominantly clastic, flysch, sequence. Both the Bunguran beds and the Serabang Formation contain interbedded volcanic rocks, and metamorphosed basic and ultrabasic igneous rocks. The Serabang Formation is pre-Campanian, probably Jurassic and/or Cretaceous.

Table IV-1. Radiometric age determinations (C^{14}) on specimens from Tambelan and Bunguran Islands Indonesia

Ref. No.	Material	Co-ordinates	$-\delta C^{14}$	Estimated position relative to present tide level	Age in years B.P.	Date	Estimated relative sea level implied
UM6162	Wood from peat layer	4°05.3'N 108°16.7'E	541±7	About low tide level	6260±120	4310 B.C.	−0.7 m or lower
UM6132	*Tridacna* Shell	1°01.10'N 107° 31.92'E	493±7	0.2 m below high tide level	5460±110	3510 B.C.	+0.3 m or higher
UM6133	*Tridacna*	1°01.10'N 107° 31.92'E	481±7	0.1 m below high tide level	5270±110	3320 B.C.	+0.4 m or higher

Note: UM6162 from Teluk Sengiap, northwest coast of Pulau Bunguran (or Great Natuna Island); UM6132 and UM6133 from Teluk Birah, northwest end of Tambelan Island. Determinations by Isotopes Inc., Westwood Laboratories, New Jersey, USA

Bemmelen (1949, p. 225, 303) correlates the Bunguran beds with the Danau Formation of Borneo, which was supposed by him to be of Carbo-Permian age; however, the attribution of a Carbo-Permian age to the Danau Formation was later discredited, and the formation shown to be at least in part Cretaceous (see Haile, 1957). There is thus no justification for attributing a Carbo-Permian age to the Bunguran beds; the most that can be said, on the evidence of the identified Radiolaria, and on regional grounds, is that they are probably Mesozoic, possibly Jurassic or Early Cretaceous.

The granite (adamellite) forming Gunong Ranai at Bunguran resembles rather closely that intruded into the Serabang Formation in West Sarawak at Tanjong Datu, Gunong Pueh, and Gunong Gading. The Ranai adamellite and the adamellite of West Sarawak are of the same (Late Cretaceous) age, having been dated at 73 ± 2 and 70–80 million years respectively (see Wolfenden and Haile, 1963, p. 80–85). However, cassiterite, recorded on Bunguran, has never been found in Sarawak. The Natuna sandstone, in its general aspect of a sequence of coarse, thick-bedded, cross-bedded, gently to moderately folded, probably continental, sandstone with basal conglomerate, resembles sandstones in west Sarawak assigned to the Plateau Group, of Late Cretaceous to Early Tertiary age.

The Anambas and Tambelan Islands were placed by Bemmelen in his Anambas Zone of the Anambas Mountain System extending in an arc from north of the Anambas, southeast through Tambelan and east into his Schwaner Subzone of the Basement Complex or Zone C of west Borneo (Bemmelen, 1949, figs. 126, 130). In view of the fact that nothing at all was then known of the geology of the Tambelan Islands, and little of the geology of the Anambas or the Basement Complex of West Borneo—and to this day there is not a single fossil or radiometric age determination from either the Anambas Islands, or the West Borneo Basement Complex—this zonation must be regarded as speculative. Although the geology of the Tambelan Islands does show some resemblance to what is known of the geology of the Anambas and the West Borneo Basement, in view of the scanty evidence and lack of any geochronological control, correlation and zonation of this part of the Sunda Shelf seems premature. More field work on the islands, geochronological determinations, and seismic surveys of the marine areas of the shelf are needed before structural or orogenic zones can be established in this region. The determination of the Late Cretaceous age (84 million years) of the granite from Benua Island in the Tambelan Group is the first from this region (i. e. Anambas and Tambelan Islands and West Borneo Basement). It seem's possible that when the geochronology of the West Borneo Basement is investigated, much of the granitic rock supposed by Zeijlmans van Emmichoven (1939) and Bemmelen (1949, p. 335) to be older than Upper Triassic will be found to be, in fact, late Mesozoic.

CONCLUSIONS

Present knowledge of the geology of the three island groups is summarized in table 2.

Table IV-2. Summary of the geology of the Tanbelan Anambas, and Bunguran Islands

Tambelan Islands	Anambas Islands	Natuna Islands
Basaltic and andesitic dykes (Cainozoic)	Intermediate dyke rocks (Cainozoic?)	*Natuna Sandstone* (Tertiary) Immature, sandstone and conglomerate; gently dipping. Probably continental. Thickness > 1000 m
Granite (Late Cretaceous; 84 m.y.)	Aplite dykes Granite (Cretaceous?)	*Ranai granite* (Late Cretaceous; 73 m.y.)
(No pre-granite sedimentary rocks known)	Meta-sedimentary rocks (Mesozoic?)	*Bunguran beds* (Mesozoic; probably Jurassic to Early
Gabbro, diorite, dolerite, andesite, keratophyre: mostly metamorphosed (Mesozoic or older)	Gabbro, andesite, diabase (Mesozoic or older)	Cretaceous): chert, tuff, metasediments; intensely folded
		Serpentinite, gabbro and dolerite; may be an ophiolitic suite associated with the Bunguran beds

TableIV-3. List of specimens collected from the Tambelan and Natuna Islands, on the Jalanidhi expedition in the Sund a shelf region, April 1969

Museum No. (UM)	Field No.	Locality	Lat. N	Long. E	Name	Remarks
UM6125	JN9/1	Kampong Melayu, Tambelan Bay, Pulau Tambelan	0°59.8′	107°34.65′	Alkali leucogranite	
UM6126	JN9/2	Southeast side of Bukit Kotit, Pulau Tambelan	1°00.55′	107°33.95′	Metamorphosed microgranite?	Composition and texture suggest that the rock is a metamorphosed rhyolite or microgranite
UM6127	JN9/3	North coast of Pulau Tambelan	1°00.90′	107°34.0′	Basaltic dyke rock	The turbid and somewhat altered nature of the rock prevents a more positive identification.
UM6128	JN9/4	North coast of Pulau Tambelan	1°00.90′	107°33.90′	Altered gabbro	
UM6129	JN9/5B–D	North coast of Pulau Tambelan	1°01.00′	107°33.70′	Mineralized dolerite	From blocks 2 m across
UM6130	JN9/6	North coast of Pulau Tambelan	1°01.40′	107°32.80′	Metamorphosed diorite	
UM6131	JN9/5A					
UM6132	JN9/8	Telok Birah, northwest end of Pulau Tambelan	1°01.10′	107°31.92′	Giant clam shell (*Tridacna*)	From dead shell embedded in coral about 0.5 m below present high tide level. For C^{14} dating.
UM6133	JN9/15	Telok Birah, northwest end of Pulau Tambelan	1°01.10′	107°31.92′	Giant clam (*Tridacna* sp.)	From dead shell embedded in coral about 0.25 m below high tide level. For C^{14} determination.
UM6134	JN9/9	Telok Birah, northwest end of Pulau Tambelan	1°01.10′	107°31.92′	Siliceous vitreous lava or tuff	
UM6135	JN9/10	—do—	1°01.10′	107°31.92′	Andesite	
UM6136	JN9/11	—do—	1°01.10′	107°31.92′	Keratophyre	Altered
UM6137	JN9/12	—do—	1°01.10′	107°31.92′	Granophyric granite porphyry	
UM6138	JN9/13	—do—	1°01.28′	107°31.88′	Alkali microgranite	
UM6139	JN9/14	—do—	1°01.30′	107°31.88′	Granite cut by basalt dykes	
UM6140	JN9/16	Tanjong Bertumpah, south end of Pulau Tambelan	0°57.20′	107°32.73′	Porphyritic andesite	From large blocks (3 m across) on shore.
UM6141	JN9/17	—do—	0°57.20′	107°32.73′	Granite	Outcrop on shore
UM6142	JN9/18	—do—	0°57.20′	107°32.73′	Granite	Outcrop on shore
UM6143	JN9/19	West side of Pulau Benua, Tambelan Islands	0°56.60′	107°26.18′	Fine-grained granite	Outcrop on shore
UM6144	JN9/20	—do—	0°58.53′	107°25.05′	Fine-grained granite	
UM6145	JN9/21	—do—	0°58.53′	107°25.50′	Andesitic dyke rock	From a dyke cutting granite
UM6146	JN9/22	—do—	0°58.53′	107°25.50′	Andesitic dyke rock	From a dyke cutting granite
UM6147	JN14/1	Southwest tip of Pulau Laut, Natuna Islands	4°40.7′	107°56.3′	Laminated brown chert	Laminated and microfaulted
UM6148	JN14/2A	Northwest tip of Pulau Laut, Natuna Islands	4°46.0′	107°59.7′	Prehnitized lava, with chert	
UM6149	JN14/2B	Northwest tip of Pulau Laut, Natuna Islands	4°46.0′	107°59.7′	Altered glassy tuff?	
UM6150	JN14/2C	—do—	4°46.0′	107°59.7′	Radiolarian glassy tuff	Well preserved Radiolaria
UM6151	JN14/2D	—do—	4°46.0′	107°59.7′		
UM6152	JN14/3	Batu Imung, rocky islet south of Pulau Laut, Natuna Islands	4°37.8′	107°58.6′	Brecciated chert	
UM6153	JN15/1	Coast 0.8 km south of Ranai, Bunguran, Natuna Islands	3°56.0′	108°23.2′	Metamorphosed calcareous muddy arkose	From light coloured ovoid bodies c. 70 cm across in exposure of JN15/2. Contains much metamorphic clinopyroxene. Abundant metamorphic biotite
UM6154	JN15/2	Coast 0.8 km south of Ranai, Bunguran, Natuna Islands.	3°56.0′	108°23.2′	Metamorphosed arkose	
UM6155	JN15/3	North side of Tanjong Senubig, Bunguran, Natuna Islands.	3°58.2′	108°23.8′	Two-mica adamellite	
UM6156	JN15/4	—do—	3°58.2′	108°23.8′	Two-mica adamellite	
UM6157	JN15/5	Pulau Sahi, islet off west coast of Bunguran, Natuna Islands.	4°03.8′ 4°03.8′	108°18.2′ 108°18.2′	Chert	
UM6158	JN15/6	—do—			Brecciated chert	
UM6159	JN15/7	Northwest coast of Bunguran, Natuna Islands	4°04.5′	108°17.9′	Chert-clast sandy conglomerate	From sandy sharpstone cobble conglomerate, at or near base of Natuna Sandstone:
UM6160	JN15/8	—do—	4°05.1′	108°17.3′	Chert-clast sandy conglomerate	
UM6161	JN15/9	—do—	4°05.2′	108°15.1′	Chert-clast sandstone	
UM6162	JN15/13	Telok Sengiap northwest coast of Bunguran	4°05.3′	108°16.7′	Wood	From peat layer about 5 cm below low water level
UM6163	JN15/10	Telok Muara, southwest coast of Bunguran, Natuna Islands.	4°10.9′	108°13.8′	Sandstone; feldspathic litharenite	
UM6164	JN15/11	Tanjong Datu, north cape of Bunguran, Natuna Islands	4°12.5′	108°14.6′	Sandstone: lithic arkose or lithic subarkose	
UM6165	JN15/12	—do—	4°12.5′	108°14.6′	Light-greenish grey shale	From lens 6 cm thick in massive sandstone

The ages suggested for the rocks of the Anambas Island are speculative, as there is no geochronological control there, and are based on a possible correlation on lithology with the other two island groups.

Although the islands are mainly pre-Tertiary, it does not necessarily follow, as is implied by van Bemmelen's zonation, that the intervening parts of the Sunda Shelf are built of pre-Tertiary rock. The islands may represent areas where the Mesozoic basement is topographically high, and Tertiary sedimentary basins may occur under the intervening marine areas, a view supported by the thickening of the Natuna sandstone (or equivalent) eastwards from Bunguran Island, as shown by seismic studies. Thus this part of the Sunda Shelf, far from being a very stable extension of the Mesozoic basement from Asia across to Malaysia, as is shown on most regional compilations, may have had a complicated history in the Tertiary and have been the site of a considerable amount of tectonic subsidence and sedimentation then.

This conclusion has an important bearing on the hopes of discovering oil deposits on the shelf, since these depend on finding sufficiently thick sequences of post-basement sedimentary rocks. The Natuna sandstone is a potential oil reservoir rock, particularly if, as seems probably, it thickens off-shore and grades into marine sedimentary rocks. The pre-Tertiary rocks on the islands seem worth investigating to see whether any of the traces of mineralization recorded from all three groups are related to economic deposits. A geological and geochemical reconnaissance could be done relatively cheaply, and would produce useful, and possibly economically significant results.

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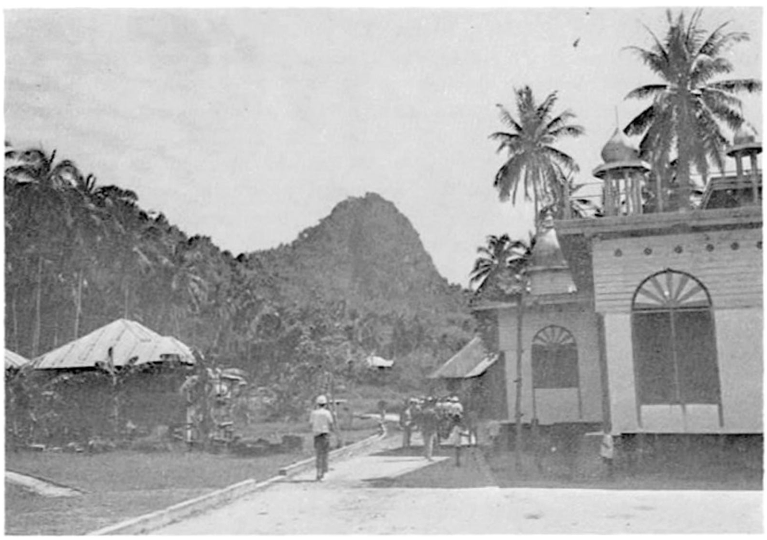
Plate IV-1

1a Tambelan Bay, Tambelan Island, with Bukit Kotit in the distance



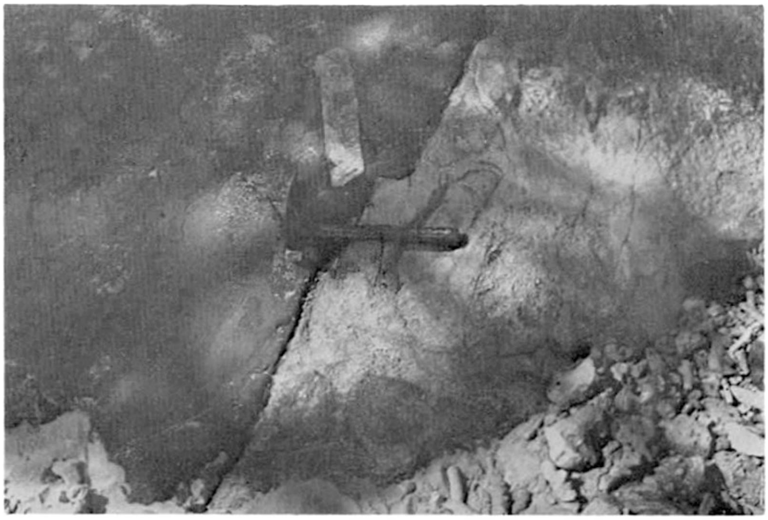
1b Bukit Kotit, probably an igneous stock, from Kampong, Tambelan Island.

Plate IV-2

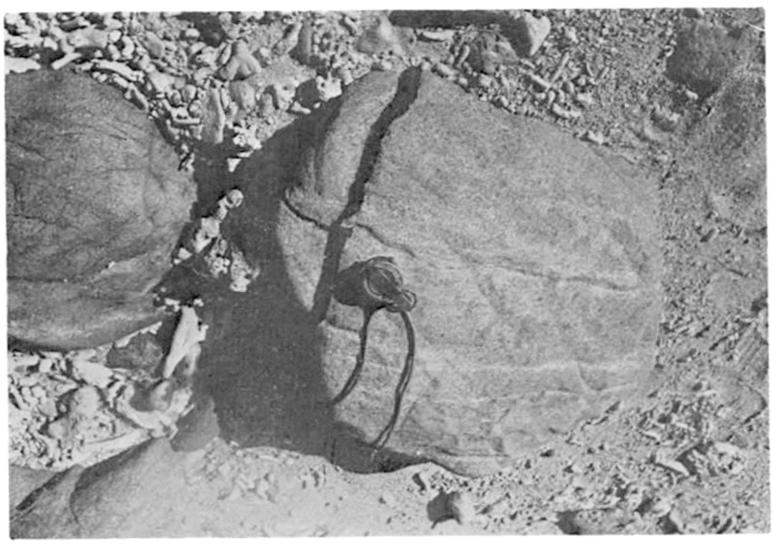
2a Irregular, sinuous basaltic dyke, cutting granitic rock which contains numerous xenoliths, north coast of Tambelan Island.

2b Shell of giant clam (*Tridacna*) in position of growth, on foreshore near high-tide level at Telok Birah, Tambelan Island. The shell was dated at 5460 years B. P. proving a relatively higher sea level at that time.

Plate IV-3



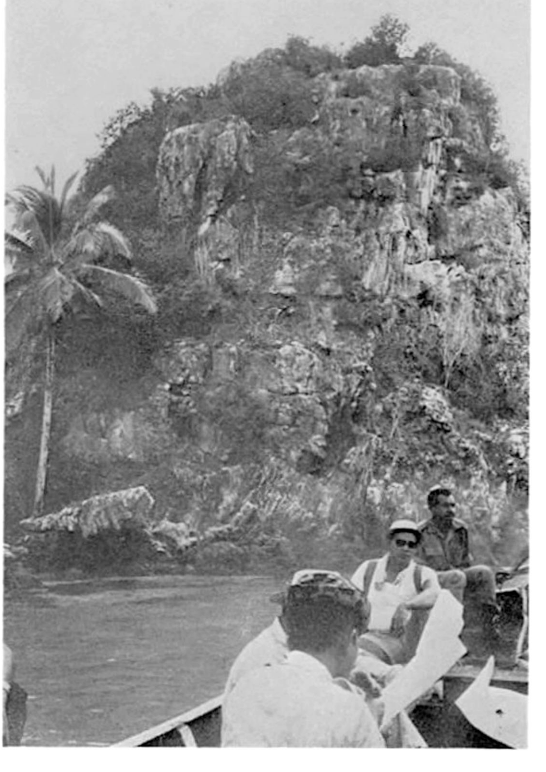
3a Granitic rock cut by basaltic dyke, Telok Birah, Tambelan Island. The piece of detached granite "rafted" into the dyke rock clearly shows that the latter is the younger.



3b Granite boulder with very thin basalt dykes, Tanjong Antu Tambelan Island. Note the dyke, 4 mm thick, meeting the thicker one by the compass (see text, description of UM6139).

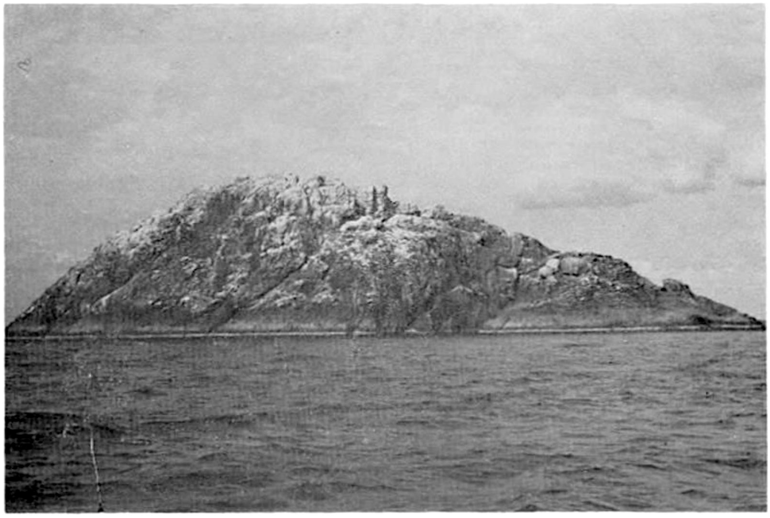
Plate IV-4

4a Banded dyke cutting older basic rocks, north coast of Tambelan Island.



4b Pulau Sahi, a rocky islet of chert off the west coast of Bunguran Island.

Plate IV-5



5a Batu Imung, an islet of brecciated chert off Pulau Laut.

5b Brecciated chert on Batu Imung.

Plate IV-6

6a The granite mountain, Gunong Ranai (1000 m), on Bunguran (Great Natuna) Island.

6b Basal conglomerate of the Natuna sandstone, Bunguran Island. Sharpstone cobble conglomerate with lenses of reddish brown sandstone.

Plate IV-7

7a Planar cross bedding in Natuna sandstone, northwest coast, Pulau Bunguran.

7b Geologists participating in the UNESCO/ECAFE training course, with members of the crew of RIJALANIDHI, and Indonesian officials on Bunguran Island, April 1969.

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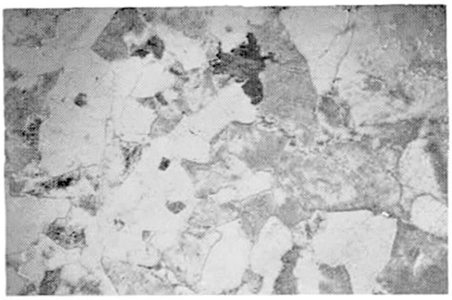
Plate IV–8. PHOTOMICROGRAPHS OF GRANITIC ROCKS FROM THE TAMBELAN AND BUNGURAN ISLANDS

Tambelan:	a and b	UM6125	alkali leucogranite
	c and d	UM6141	biotite granite
	e and f	UM6137	granophyric granodiorite porphyry;
	g	UM6144	fine-grained biotite granite:
Bunguran:	h	UM6155	two-mica adamellite

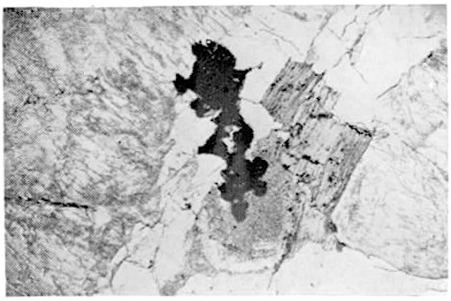
All $\times$ 20. PPL = plane polarized light;
XPL = crossed polarizers.

Plate IV-8



a PPL

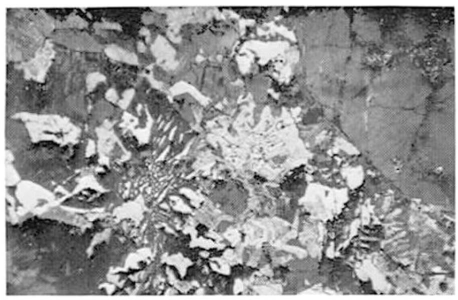
b XPL



c PPL

d XPL

e PPL



f XPL

g XPL

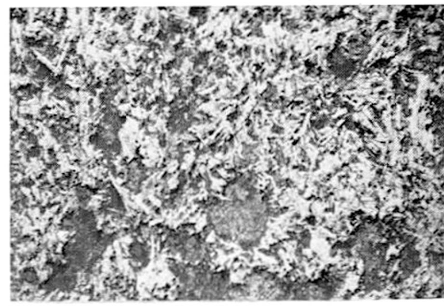
h XPL

Plate IV–9 VOLCANIC AND HYPABYSSAL ROCKS FROM THE TAMBELAN ISLANDS

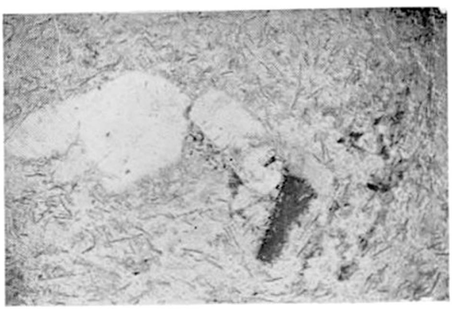
a UM6131 metamorphosed dolerite;
b UM6135 andesite;
c and d UM6134 siliceous vitreous lava or tuff;
e UM6136 altered ketabophyre (note epidote replacing feldspar phenocryst as dark squarish patch over centre);
f UM6146 andesitic dyke rock;
g and h UM6139 granite cut by thin basaltic dyke
A11 $\times$ 20 PPL = plane polarized light
XPL = crossed polarizers

Plate IV-9

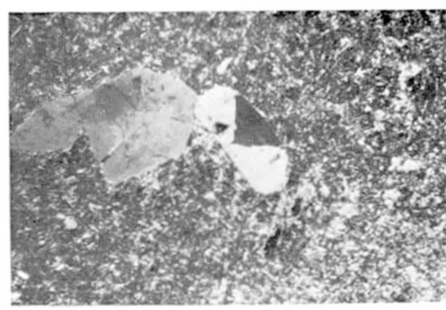
a XPL



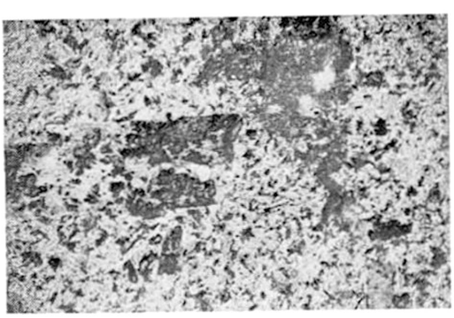
b PPL



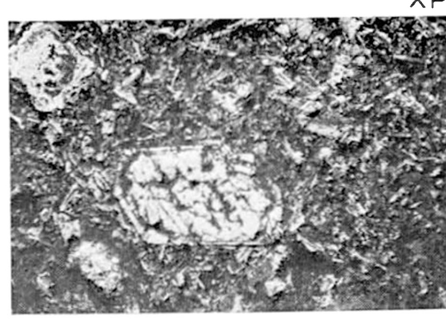
c PPL



d XPL



e PPL



f PPL

g PPL

h XPL

Plate IV–10 SEDIMENTARY ROCKS FROM THE BUNGURAN ISLANDS

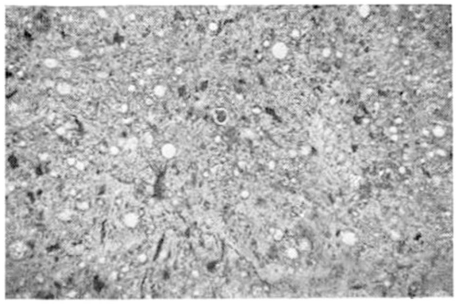
Bunguran beds: a UM6152 brecciated chert, Batu Imung;
b UM6150 radiolarian glassy tuff;
c UM6154 metamorphosed arkose

Natuna sandstone: d UM6160 chert-clast sandy conglomerate;
e and f UM6159 chert-clast sandy conglomerate;
g and h UM6163 feldspathic litharenite. The clear mottled patch near the centre of h is kaolinite

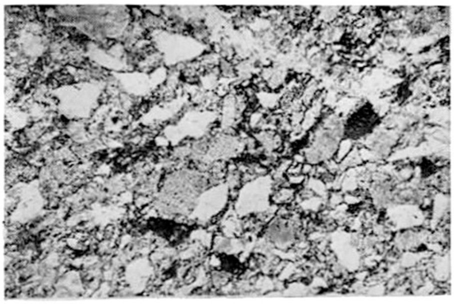
h $\times$ 55; others $\times$ 20
PPL = plane polarized light
XPL = crossed polarizers

Plate IV-10

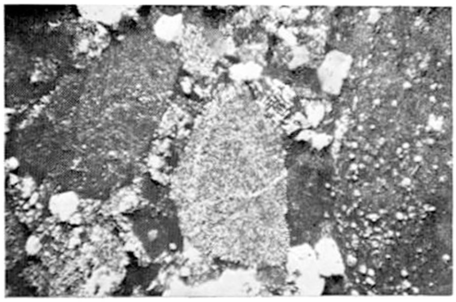
a PPL



b PPL

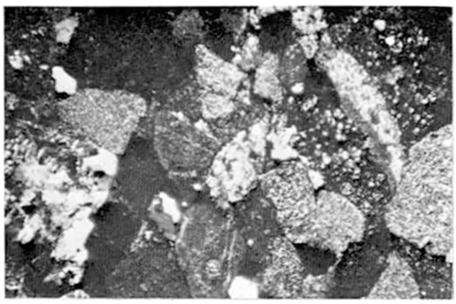


c PPL

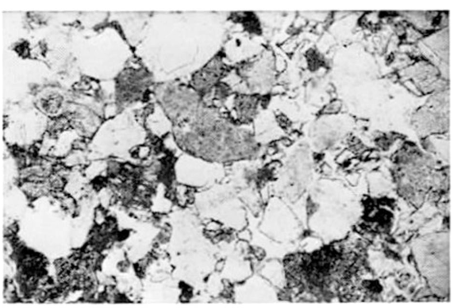


d XPL

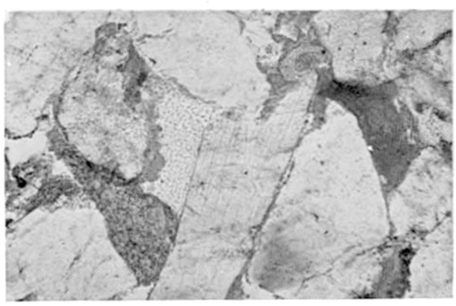
e PPL



f XPL



g PPL



h PPL

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V. REGIONAL GEOLOGY AND PETROLEUM PROSPECTS OF THE MARINE SHELVES OF EASTERN ASIA

(From document I&NR/PR. 4/15, submitted at Fourth ECAFE Petroleum Symposium, Canberra, 27 October-10 November 1969)

By

M. Mainguy, formerly of the Technical Secretariat of CCOP[1]

(with maps V-1 and V-2)

INTRODUCTION

This paper has been prepared as a contribution from the Technical Secretariat of the ECAFE Committee for Co-ordination of Joint Prospecting for Mineral Resources in Asian Offshore Areas (briefly known as Co-ordinating Committee for Offshore Prospecting, or CCOP). The data contained herein have been brought together by Maurice Mainguy, Special Adviser to CCOP from France and formerly attached to the Technical Secretariat of CCOP as Regional Adviser on Offshore Prospecting (Geology) for the ECAFE region, mainly from the results of offshore geophysical and other surveys conducted in the past two years through the medium of CCOP and from geologic studies of adjoining land areas made by staff of the Technical Secretariat of CCOP. The sources of the data include the preliminary results from offshore surveys conducted recently through the medium of CCOP, but not yet published, as well as unpublished data made available by organizations in the Federal Republic of Germany, the United Kingdom and the United States, and by oil companies of the French National Group, ERAP-ELF (ELF R. E. and SNPA). The compilation map of the Tertiary basins of the East Asian region, accompanying this paper, has been discussed with other Special Advisers of CCOP, mainly with Dr. H. Closs and Dr. K. O. Emery, and members of the Technical Secretariat of CCOP; much valuable information has also been gathered in the course of discussions with geologists of the organizations concerned with offshore prospecting in the member countries of CCOP.

It is unfortunate that the final geologic interpretation of the aeromagnetic surveys of the East China Sea and Yellow Sea conducted in 1968 and 1969 (Projects CCOP-1/IZ. 1 and CCOP-1/ROK. 2) and the results of sparker and magnetic profiling conducted in mid-1969 over the South China Sea and the Sunda Shelf (Project CCOP-1/IZ. 4) were not available in time to be taken into consideration in this report.

Although the conclusions include some considerations on a forecast of consumption and production of hydrocarbons in the ECAFE area, in order to emphasize the importance of offshore prospecting for oil and gas in eastern Asia, the paper is mainly concerned with defining the regional geologic framework of the East Asian shelf areas from the viewpoint of the petroleum geologist, and with the delineation of potential oil-bearing sedimentary basins.

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DELIMITATION OF THE AREA UNDER REVIEW

The area under review in this paper covers essentially the continental shelf adjoining the land areas of the member countries of CCOP, namely, in alphabetic order: Cambodia, Republic of China, Japan, Republic of Korea, Malaysia, Philippines, Thailand and the Republic of Viet-Nam. Reference is made also to the geology of Hong Kong, Brunei and the Republic of Singapore, as well as to other adjoining areas in eastern Asia, namely, the Sea of Japan up to the east coast of the Soviet Union, the shelf areas of Indonesia, the northern coast of Australia, and the Andaman Sea on the western coast of the Thai-Malay peninsula. Of course, surface geologic data on land provide the main clues to the interpretation of the geologic setting of the marine areas.

The lower limit of the continental shelf is generally considered as coinciding with the 200 metres (about 100 fathoms or 600 feet) bathymetric contour. This is by no means a clearcut and final delimitation, either from a geologic or from a legal viewpoint. The Geneva Convention of 1958 leaves the door open to an extension of the concept of the "continental shelf" down to the deepest zone where mineral exploitation is technically and economically feasible; on the other hand, emphasis has been put on several occasions on the geologic possibilities of hydrocarbon formation and accumulation in deeper parts of the oceans, and the petroleum prospects of the continental margin were described at the last annual meeting of the American Association of Petroleum Geologists (AAPG) held at Dallas in April 1969, by Dr. K. O. Emery (Emery, 1968), Dr. H. Hedberg, Prof. Tuzo Wilson and others. Preliminary exploration work, as well as exploratory drilling can readily be performed in deep waters, but the techniques for developing and producing oil and/or gas in the deeper waters beyond the edge of the shelf are still to be developed, and economic production is not yet feasible with present technology under waters deeper than 120 to 150 metres. In this paper, interest will be focussed on the continental shelf down to the 200-metre bathymetric contour, with some references to the possibilities in the deeper parts of the seas.

GEOLOGIC FRAMEWORK OF THE AREA

The geologic framework of the area, as shown in map V–1, is taken from the "Tectonic Map of Eurasia" edited by the Academy of Sciences of the USSR, but modified in some places. It is interpreted in terms of the theory of sea floor spreading, as expounded recently by Morgan (1968) and Le Pichon (1968), the practical aspect of which, from the viewpoint of oil prospects, has been revealed in several papers presented at the April 1969 meeting of AAPG.

The area under review is almost entirely included within the "Eurasian crustal block," as defined by Le Pichon. The eastern part of Indonesia belongs to the "Indo-Australian block." The "Pacific block" extends to the east of the Eurasian block. The boundaries between crustal blocks are ". . . the crests of the mid-ocean ridges, where crustal material may be added . . . and the active trenches and regions of active folding and thrusting, where crustal material may be lost or shortened . . ." (Le Pichon, 1968, p. 3661). The boundary between the Pacific block and the Eurasian and Indo-Australian blocks in the area studied is a region of active trenches, where compression occurs. This may not have been always the case, and Le Pichon (1968, p. 3691) assumes that ". . . the Pacific Ocean floor is now rotating away from North America, instead of being thrust below it along a trench system . . .". The change might have taken place during a period of quiescence in middle Cenozoic time. If so, it could be assumed that during late Mesozoic and early Cenozoic times, the eastern boundary of the Eurasian block was a zone of spreading, accompanied by acid to intermediate intrusions; this is the case in the Cretaceous of the eastern coast of China and Siberia, as well as in Korea and Japan.

The boundaries between the crustal blocks can be defined only on a broad scale. The continuity of the active trenches is not always apparent. Trenches may be partially filled in by sediments or interrupted by transverse faults. Smaller blocks, called "intermediate blocks," may be identified between the major ones; limited on both sides by deep trenches, the Philippines Sea is regarded as an "intermediate block." The structure of the area between Taiwan and Luzon is not clear; the two above-mentioned factors, partial filling of the trench and existence of transverse faults, may have combined their action to obscure the picture. There is no active trench along the north coast of New Guinea. The "three corners area" in eastern Indonesia, where the three crustal blocks meet together, is also rather complex; it might be considered as an "intermediate block," although its western edge is neither a ridge nor a trench. Morgan (1968, fig. 1, p. 1960) admits that "additional sub-blocks may be required . . ." in Asia. Big fracture zones, shown on map V–1, such as the fault of Hanoi and its southeastern extension, the Palawan graben as well as the Wonsan-Seoul rift, the Philippines rift and others, indicate the relative movements of the crustal blocks, either in the way of spreading, creating subsidence (many of the big deltas in the world are located on major fracture zones) or shortening, leading to developments of thrusts.

The cores of the Indo-Australian and Eurasian blocks are Proterozoic granitic shields around which the geosynclinal systems, and the orogenic belts to which they gave rise, are developed more or less concentrically. The late Proterozoic and Paleozoic systems are better developed on the western flank of the Eurasian block, and on the eastern flank of the Australian shield (Tasman geosyncline). Along the coastal areas of Asia, the sediments involved in these orogenies have undergone strong metamorphism and, consequently, they have very poor petroleum prospects, except in a few places; the case is different on the northern flank of the Australian shield. The Cimmerian orogenies have been accompanied by acid intrusives, which must have damaged any hydrocarbons which might have been originally present in their vicinity.

The Cenozoic (alpine) orogenic belt runs along the active trenches forming the boundaries between the crustal blocks. Miogeosynclinal and molasse-type basins of this period, as well as intracratonic basins folded and faulted by the remote action of the alpine orogeny, offer highly favourable environments; the Cenozoic basins will consequently offer the main, if not the only, target for oil and gas exploration in the east Asian offshore areas.

The deltas are of particular interest. The rivers flowing down from the Himalayas, which are among the largest in the world, carry a very high content of solid matter; these rivers, however, are very long and many of them deposit a large part of their solid load along their courses. The flow in the lower part of their courses may be extremely slow and only a small part of the load, consisting of the finest grade sediments which give rise to impervious rocks, reaches the sea; in some cases the sediments are trapped in interior basins. In eastern Asia, in streams like the Mekong River, only a very small solid load, composed almost solely of argillaceous matter, is carried in the lower part of the course. On the other hand, the Hoang Ho and the Yang Tze Kiang are the fourth largest and the largest contributors, respectively, of sediments to the oceans in the world. However, even short streams can bring down important loads of solid matter and develop effective deltaic systems; this may be the case for some streams in Borneo and it might also have been the case for streams running from the Fukien massif towards Taiwan during Miocene times.

The question of the supply of detrital material to provide suitable reservoir rocks is a crucial one. The main source for such material is found in the "granitic" shields, the acid to intermediate intrusives which have accompanied the Cimmerian orogeny, and the already winnowed sands and sandstones of the so-called "Indosinias" of south-east Asia. Good source areas for detrital material exist all along the coasts of eastern Asia, and could have supplied the nearby basins with suitable reservoir material. However, when a basin is too far from the source area, or is separated from the source area by deep sea troughs or trenches which act as traps for the coarser transported sediments, no clastic reservoir rock can be formed in such basins and their petroleum potential is consequently poor. The lack of sand could be compensated for by the presence of carbonate reservoirs, but true reefs are much less abundant in the Tertiary sequence of the western Pacific than they are in this region today. Moreover, the pinpointing of reefs in a given geologic environment is difficult; it involves the drilling of many dry holes and, at sea, this would be a very costly venture.

MAIN POTENTIALLY OIL-BEARING BASINS

As already pointed out, the most promising areas for oil and/or gas in eastern Asia are Cenozoic (mainly Neogene) basins. In several parts of the area under consideration, other parts of the stratigraphic sequence may be considered as possibly productive, and these will be specifically described.

Sea of Japan

The Sea of Japan is deep, especially in the northern half (Japan Sea Abyssal Plain). The southern part is not so deep, and its morphology is more complex. The continental shelf proper (i.e. down to 200 metres) is narrow along the coasts of Japan, Korea, and the USSR, except for isolated patches, and in the southern part of the Tsushima basin, in the northeastern extension of the Strait of Korea. According to a survey made by the "F.V. HUNT", and reported by Hilde *et al.* (1969) the Tsushima basin is filled in with more than 2,000 metres of sediments considered by the authors as "older than Pleistocene, and probably Miocene" in age.

According to the results of seismic surveys run along the eastern coast of south Korea as a part of a project assisted by ECAFE and with financial support from the United Nations Development Programme (Kim *et al.* 1967) Miocene sediments resting on upper Cretaceous or Paleogene volcanics along the east coast of Korea thicken rapidly eastward; they are in turn covered in places by Pleistocene basalt. They encroach over the land in a small basin near Ulsan, to the South, and more extensively in the Pohang basin, where shows of gas have been reported in drilling (Report of the Third ECAFE Symposium on Development of Petroleum Resources of Asia and the Far East, Tokyo, November 1965; Report of the Fifth session of CCOP, Tokyo, June 1968).

A narrow north-south channel connects the Tsushima basin with the basin of the northern abyssal plains which is probably filled in by turbidites 1,500 or more metres thick. Towards the north-east, a Neogene basin, which is a northeastern branch of the Tsushima basin, runs along the western coast of Japan. This basin is divided by two north-south ridges, the Oki island ridge to the west, and another one along the western flank of the "Fossa Magna" graben; the Toyama trough, which is supposed to deliver a great amount of the turbidites supplied to the abyssal plain basin, is probably a northern extension of this graben.

To the north of the "Fossa Magna" the known petroleum producing basins of Japan are located; although the reservoir rocks are good, the accumulations are rather small, and it might be difficult to find economically viable oil or gas fields in the offshore areas. The southern part (Tsushima basin) is wider and may be more promising both in Japanese and Korean waters. The Paleogene sediments of southwest Japan, as well as those of the Cretaceous of the Kyong Sang basin in southeast Korea may have acted as source beds, mainly for gas, which could have migrated into the reservoir rocks of the overlying Cenozoic. The possibilities of finding good reservoir rocks within the Cenozoic are excellent, since all source beds for coarse clastic sediments along the flanks of the basins are of acidic nature; the main drawback is that volcanic activity was going on during the Cenozoic, and the potentially productive sedimentary sequences are pierced in some places by acid to intermediate intrusives.

Yellow Sea and East China Sea

This area has been covered by aeromagnetic surveys flown in 1968 and 1969 by "Project MAGNET" and by the broad scale reconnaissance cruise of the "F. V. HUNT" in October-November 1968; both surveys were parts of a programme sponsored by CCOP. A provisional interpretation has been published by Emery *et al.* (1969). Recent sediments, the age of which will be discussed below, have filled two basins under the Yellow sea, and a long northeast-southwest trending basin in the East China sea; a sill running southwest-northeast from the south of Shanghai in mainland China to the southwestern tip of Korea separates the Yellow sea basins from the East China Sea basin; this sill is covered by about 800 to 1,000 metres of the above-mentioned "Recent" sediments. The basin of the East China Sea is connected toward the north-east with the Tsushima basin, referred to above, and the thickness of the Recent sediments is of the order of 1,000 metres in Korea Strait. The island of Tsushima acts as a north-south ridge, comparable to the Oki island ridge described in the previous paragraph. The basin deepens south-westward, and is probably several thousand metres deep off the northern end of the island of Taiwan.

In the coastal area of western Taiwan several refraction profiles were shot as a joint project between Japan and the Republic of China (Sato et al., 1969); the results demonstrated the existence of a very thick sedimentary section in part of the area and showed an abnormally high velocity in the Miocene section. To the south, the basin is limited by an east-west trending swell, extending from the Penghu (Pescadores) Islands to the Peikang shelf in west central Taiwan (Meng, 1968). This swell marks the position of a sharp change in the facies of the Neogene and, probably, according to the preliminary interpretation of the Project MAGNET survey, a change in structural attitude; it is certainly an important structural feature in relation to petroleum potential in this region.

The "recent" sediments, called "post deformational" or "third facies" in the above-mentioned report by Emery *et al.* (1969) are considered by the authors to be Neogene and Pleistocene. This is probably the case in the southwestern part of the basin of the East China Sea, and possibly also in the Tsushima basin, although it does not check very well with the known thickness of the same sequence along the eastern coast of Korea and in the Pohang basin.

On the other hand, the sediments filling the basins of the Yellow sea might represent only the Pleistocene, for the following reasons: (a) nearly 1,000 metres of Pleistocene sediments have been drilled in the Hoang Ho delta, in mainland China, without reaching the basement; (b) the thickness of the Pleistocene is probably greater under the sea than on land, and the "post-deformational" sediments amount to a maximum of 1,400 metres under the Yellow sea; (c) the time necessary for the deposition of the known thickness of the "post-deformational" sediments is estimated by the authors to be 150,000 years "if the entire river load has been deposited in it" (the Yellow sea basin), which is certainly not the case; this minimum has to be multiplied by an unknown factor but, assuming that only one tenth of the river load had been deposited in the Yellow sea, the necessary time for such sedimentation would be 1.5 million years, which corresponds to uppermost Pliocene; (d) the underlying sediments (pre-deformational, or "second facies") are considered to be rather old (Paleocene or Cretaceous) because of their acoustical properties: but it has been previously noted that the Miocene sediments of Taiwan are characterised by high velocities.

The "post-deformational" or third facies sediments rest unconformably either on "basement" (Cretaceous or older) or on an intermediate sequence which can be studied wherever the "third facies" is thin enough, namely in the Yellow Sea and in the northeastern part of the East China Sea. These older sediments are present in faulted, graben-like basins. They are considered as being of Paleogene age or older: in several places within the Yellow Sea, sediments of Paleogene age have been dredged by Emery and Niino (1967). The locations of the dredged samples do not check with the limits of the basins filled with "pre-deformational" (second facies) sediments. The island of Tsushima, on which Paleogene sediments are exposed, looks like a nose with a Paleogene or even Mesozoic core, plunging to the north. The existence of the "second facies" is not reported at the point where the southern extension of the axis of the Tsushima nose cuts across the nearest seismic line. It may be assumed that, at this location at least, the Paleogene is included in the seismic "basement"; the "second facies" could then be considered as representing the lower part of the Neogene sequence and the "third facies" as representing Upper Pliocene and Pleistocene. However, the arguments in favour of this interpretation are not strong enough to be considered as decisive, and a definite identification of the second and third facies will have to wait until drilling is undertaken.

The Neogene, including part of the early Pleistocene, is the most attractive part of the sedimentary sequence in this basin: a deltaic environment is considered as highly favourable to the formation and trapping of hydrocarbons, and the deltas of the Hoang Ho and the Yang Tze Kiang are among the biggest in the world: the Fukien-Reinan sill has created in the Yellow sea basins conditions for sedimentation in a reducing environment, thus enhancing the favourable conditions for generation of hydrocarbons. Sedimentation in the northeast part of the East China Sea basin has probably been under quite different conditions: the basin itself is shallower and is dissected into elongated sub-basins: this area was probably already a strait during Neogene times and strong currents might have existed: intrusives are rather abundant. These factors do not preclude the existence of hydrocarbon accumulations, but the environment is not favourable to the existence of very large ones: oil and gas fields of the western coast of Japan, north of the Fossa Magna, are of modest size: it may be different offshore along the southern part of the Japanese coast and along the Korean coast.

The basin becomes wider and deeper towards the southwest: the Miocene of Taiwan is gas bearing and no important intrusions are reported in this part of the stratigraphic column in Taiwan, except the Pleistocene Tatun volcano. The southern part of the East China Sea basin must then be considered as the most favourable part of the area as far as the Neogene is concerned. In Taiwan itself, as the sources of detrital material have shifted from west to east after the upheaval of the Central Range of Taiwan during early Pliocene time, the Pliocene sequence is poor in porous rocks: this is probably not the case farther north where the environment related to the Yangtze delta is prevailing and, whereas the sequence is probably thinner, it might be more homogeneous and may offer more favourable conditions within the Neogene sedimentary column.

The early Cenozoic sediments of southern Japan are coal bearing. They might have acted as sources for natural gas, as did the Carboniferous of the North Sea, which has generated gas which was trapped in the overlying porous media in the Lower Permian. It would appear that the quantities of gas likely to have been generated in the coal measures of Japan would be rather small. The Cretaceous is well exposed in the southern part of Korea and the southwestern part of Japan (the Cretaceous sequence of Hokkaido, which looks promising, is outside the area covered by this paper).

The facies of the Mesozoic in the "outer zone of southwest Japan" is typically marine and probably miogeosynclinal. In the "inner zone", it is similar to the facies of Korea and Manchuria, where it is considered to be non-marine; however, a few laboratory tests run at the Centre de Recherches du Pau (France) on the Cretaceous of the Kyong Sang (or Taegu) basin in southeast Korea, and of the Mokpo area in southwest Korea (Advisory Service Report to the Republic of Korea, by Maurice Mainguy, June 1969) may lead to a different interpretation. On the grounds of their geochemical characteristics, the Cretaceous sediments of the Kyong Sang basin may be attributed to a "restricted marine environment", the Cretaceous of the Mokpo area being "less marine" (but it may not be of the same age as the sequence in the Kyong Sang basin). The sediments of the Kyong Sang basin have some of the characteristics of source beds for gas, whereas the Cretaceous of Mokpo, containing oil shales of possibly lacustrine origin, looks less favourable. If these results are finally verified by more geochemical analyses, the sill delimiting the extension of the marine facies of the Cretaceous to the north-west would not coincide with the axial zone of Japan, but could be found along a southwest-northeast trending line located somewhere in the south part of the Korean peninsula; the Cretaceous sequence to the south-east of this line would be considered as a possible source of gas.

The only drawback to this possibility is the presence of acid intrusives piercing through the Cretaceous; from the laboratory tests referred to above, it can be assumed that the influence of metamorphism extends only for a short distance from the granitic plugs, but the abundance of intrusives has subdivided the Kyong Sang basin into many small sub-basins. The Cretaceous sequence is thick enough (several thousand metres) to have generated a notable amount of gas, which might have migrated upward into porous Tertiary beds, but the Cretaceous basin itself is not likely to contain very important accumulations.

The basin extending from north of Tsushima island to the Penghu-Peikang high in central Taiwan is more than 1,600 kilometres long and from 80 to 320 kilometres wide; its depth ranges from less than one thousand metres (according to the most conservative interpretation) under the sill of Korea Strait, to several thousand metres in the vicinity of Taiwan. The northeastern part of the basin is probably more affected by igneous intrusion than the central and southern parts. Significant indications of petroleum and some oil and gas fields are known in the vicinity. The most prospective part of the stratigraphic sequence is the late Cenozoic and early Pleistocene; older parts of the stratigraphic column are intruded and/or metamorphosed, but have the characteristics of source beds, mainly for gas. The adjacent basin of the Yellow sea is shallower, with its deepest part lying near the coast of mainland China; its interest depends on the interpretation given to the so-called "second facies." Its areal size is important and the facies (deltaic and/or restricted marine) is favourable to oil and gas generation and trapping.

South China Sea

Like the Sea of Japan and unlike the East China Sea, the South China Sea is deep; its marine geology is poorly known except along the northwestern coast of the island of Borneo. Seismic studies by the Oceanographic Institute of Nha Trang in Viet-Nam (Nguyen Hai, 1965) suggest that the sialic crust under its northeastern part is thin; the tectonic map of Eurasia represents it as being without a granitic layer. The southeastern part of the South China Sea, through which are scattered the numerous islands of the Spratly archipelago, is very poorly known, but it might be regarded as part of an ancient platform, separated from Palawan and Borneo by the so-called "Palawan graben", and filled in with prospective Cenozoic sediments, which are productive in Brunei. To the northeast, the Manila trench separates the South China Sea from the island of Luzon. The structure of northern Luzon, the Babuyan shelf and southern Taiwan, up to the Penghu-Peikang high, is not at all clear. The Neogene sediments of southern Taiwan consist mainly of a thick series of mudstones, probably of deep marine origin, although they could also be regarded as the sediments of a big estuary debouching in the open sea between the southern tip of Taiwan and the Taiwan Bank. The Taiwan Bank, from which bottom samples will be taken by oceanographic ships of the Republic of China, might represent either drowned basaltic islands similar to the Penghu islands, or deltaic sediments. The general picture of the area between southern Taiwan and the mainland is not unlike the coastal plains of the Si Kiang, around Canton, or the Rio de la Plata in South America, where a large estuary is masking a complex delta.

The continental shelf of mainland China between the Penghu Islands and Hainan is poorly known. The southern tip of Taiwan has undergone very recent tectonic movements, as Quaternary reefs are known to exist at elevations up to 200 metres. To the south-east of Hainan, the Paracels Islands also show the effects of recent tectonics, as the Quaternary reefoid and phosphatic limestones are folded in conspicuous anticlines, which have been studied by the Geological Survey of Viet-Nam (Bibliography of Viet-Nam, CCOP Technical Bulletin, vol. 1, 1968). The continental shelf is almost nonexistent along the eastern coast of Viet-Nam, which most probably represents a fault zone. Dredging in the gulf of Tonking (Emery and Niino, 1967) recovered a few samples containing Neogene fossils, but the sea bottom is mainly made of hard rock outcrop; the possibility for a deep Tertiary basin is remote but, according to some aeromagnetic data, a sedimentary basin pierced by intrusions may exist in the deeper part of the shelf, between Hainan and Hue, and extend offshore to the Paracels Islands and the Macclesfield Bank.

On the other hand, the basin of Hue and northeastern Laos is one of the few places where the Paleozoic limestones are not much altered by the action of metamorphism; some shows of oil have been reported either in the limestones or in the overlying "Indosinia" sandstones (The Technical Secretariat of CCOP 1968). However, owing to the strong tectonic events, it is not likely that significant oil or gas fields would be found at sea in the Paleozoic sequence; moreover, absolute age determinations made by Soviet and North Vietnamese geologists have indicated that the intrusives in Tonking are much younger than was formerly believed.

Sunda shelf

From the Gulf of Tonking to the west coast of the Thai-Malay peninsula, the-200 metre bathymetric contour, as far as it can be traced accurately, encompasses a big block of land and shallow seas; to the south lies the Sunda shelf proper, supporting the big and small islands of western Indonesia, and to the north the Indochina-Malay peninsula, deeply encroached by the sea in the Gulf of Thailand. The-200 m contour runs around the South China sea, approaches the north coast of Borneo in the vicinity of Brunei, extends along this coast and the northwestern coast of Palawan, turns around the north tip of Palawan and the Cuyo shelf, then follows the southeast coast of Palawan and the north coast of Borneo; from the Dent peninsula, it runs almost due south to the eastern tip of Java, follows the southwestern coast of Java, Sumatra and the Mentawi islands, then finally turns round the north tip of Sumatra and surrounds the sea of Andaman, leaving a rather large shelf on the west coast of the Thai-Malay peninsula.

The bulk of the area is a stable part of the Eurasian block, the southern and western edges belonging to the alpine geosyncline, from Java to Sumatra and the Mentawi Islands, and farther north to the Nicobar and Andaman islands and to the Arakan Yoma in Burma; however, the interpretation of Sumatra and Java as parts of a geosyncline is questioned by some authors. It is well known that the alpine geosynclinal area produces the greatest share of Asian oil and gas production, which is mainly confined to the central part of Sumatra. Several medium sized fields exist along the east coast of the island of Borneo, with good hopes for extension farther north, on the northeast coast; the localization of the oilfields around Brunei may be due to deltaic conditions.

The geology of the northern part of the Sunda shelf has been described in CCOP Technical Bulletin, vol. 1 and new data have been introduced from survey projects undertaken through the medium of CCOP; results obtained around Natuna island by a joint UNESCO-ECAFE training project (Recent advances in knowledge of the basic geology of the Sunda Shelf area, by John A. Katili, Indonesian Institute of Sciences,—Report of 6th session of CCOP, May 1969) are significant because they introduce a more optimistic view than that developed in the CCOP Technical Bulletin, vol. 1; at least several hundred metres of Recent (or late Cenozoic) sediments are reported to the southeast of Great Natuna Island. It is possible that this island, which was formerly regarded as a part of a continuous swell running from the Mekong delta to the southwestern tip of Borneo, has actually been an island for a long time, and this may hold true for other islands which were regarded as being parts of elongated arches or "highs".

The results of the work done by oil companies are, of course, still confidential; as far as they are known, (Petroleum offshore activities, by Soembarjono, Report of sixth session of CCOP, May 1969) they look consistent with the optimistic view just developed. In addition, a reconnaissance sparker and magnetic survey of the northern part of the Sunda shelf was made in July-August 1969 by the "F. V. HUNT," the results of which will certainly add considerably to the presently tentative picture of the geology of the area. Cenozoic basins are certainly present under the shallow seas of the Sunda shelf; their exact limits are not known, but they are probably more extensive than previously expected and productivity has already been proved in a small part of the shelf area.

However, the deltas of the Mekong and Menam (or Chao Phya) Rivers do not look like true "deltas"; the rivers themselves bring in a rather meagre amount of solids, and these solids are deposited in the forefront of the delta. Of the two characteristics of a delta, namely progradation and subsidence, these two "deltas" lack the second one. Near Ayudhya, 60 km northeast of Bangkok, recent alluvium (350~400 metres thick) rests directly on Paleozoic and/or granite in the Menam (Chao Phya) valley. In the region of Saigon and near Rach Gia, in the Mekong delta, the total thickness of alluvium is only in the order of 150 to 200 metres. Only one well, near Soc Trang, at the mouth of the Bassac, (southwest branch of the Mekong River) drilled through 450 metres of Recent alluvium without reaching basement. A preliminary interpretation of an aeromagnetic survey flown by Project MAGNET, and presented at the fifth session of CCOP at Tokyo, however, suggests the possibility of the existence of 2,500 metres of sediments in the Trans Bassac area; owing to the magnetic characteristics of some of the granites of the area, however, this interpretation is highly questionable.

In this area, the sediments of the Cimmerian "geosyncline" do not appear to be truly geosynclinal in facies. The Permian limestone, which has a considerable thickness in the north of Thailand, is of neritic and sometimes reefoid facies. The Triassic and Liassic consist of alternating marine shales and sandstones, sometimes referred to, perhaps incorrectly, as flysch. The facies grades to continental and the "Upper sandstones" are represented by red beds and sand or sandstones; the upper part of the marine series and the lower part of the redbeds interfinger in some places. The best reservoir rocks are probably to be found in the sandstones intercalated in the red-bed sequence; this sequence is intruded by acidic intrusives (called "granites" for the sake of simplicity) the age of which is still under discussion.

Originally, all the "granites" of the former French Indochina were considered by French geologists as Hercynian; their intrusive character through the post-Hercynian sequences was later recognized and two main stages of intrusion, one in the Triassic and one in Cretaceous time, have been identified. Incidentally, only the Cretaceous granites are tin bearing, except for the granite at Trengganu, in western Malaysia, which is Triassic. In northern Thailand, Cambodia and south-west Viet-Nam, most of the granites are probably Triassic; consequently, the post-Triassic sequences may not be affected too much by acidic intrusions, and prospects for hydrocarbons in the upper part of the Mesozoic may still exist in the areas where the bulk of the intrusives is Triassic, which is the case all around the Gulf of Thailand and probably also under the Gulf itself.

The upper part of the "Upper Sandstones" is missing over the Cambodian swell; on the northeastern flank of this swell near the Thai-Laos border, the uppermost part of this sequence, which is uppermost Cretaceous or Paleogene in age, is of lagoonal and evaporite facies. The same facies might also exist under the Gulf of Thailand. The Cenozoic sedimentary sequence may be rather complete and continuous under the Gulf of Thailand and perhaps also under the continental shelf off the eastern coast of the Malay peninsula.

The main part of the Gulf of Thailand, in the north, is probably separated from the remainder of the Sunda Shelf by the northeast-southwest trending Mui Bat Bong high which can be identified in the actual morphology of the sea bottom; it may also be silled by the southeastern extension of the Cambodian swell along the Con-Son-Natuna trend; according to unpublished seismic data, this swell is covered by more than 1,000 metres of young sediments and, as already mentioned, Con-Son and Natuna may already have been islands during the Cenozoic. The stratigraphic sequence becomes rapidly thicker towards the South China Sea to the east and this deep open sea basin is most probably in continuity with the producing basin of northwestern Borneo. An aeromagnetic profile (Isaacs, 1963) running from Singapore to Sarawak suggests the possible existence of only a narrow and shallow basin; seismic data to the east of Singapore indicate shallow pre-Tertiary "basement" (Cretaceous?) but this does not preclude the possibility that the delta of the Kapuas River develops into an offshore basin off the southwestern coast of Borneo, debouching into the open sea either between Animbas and Natuna Islands, or southeast of Natuna, or both.

To the south, however, the islands of Bangka and Billiton most probably separate the northern basin from the basin of the Java Sea, which has already been proved to be oil bearing, although the economic potential of the discovery has not yet been ascertained; it is also probable that the Java Sea basin is separated from the south Sumatra basin. These basins, as well as the narrow continental shelf of the eastern coast of Borneo, have very attractive potentialities. Late Cenozoic and early Pleistocene sequences are the most attractive targets of the northeastern offshore areas of Borneo.

The relationship between Borneo on the one hand and Palawan and the Sulu Archipelago on the other is highly conjectural. The axial range of Palawan seems to be the continuation of the central range of Sabah, but the geology of the Sulu and Pangutaran archipelagos is very poorly known, as these islands are covered by Quaternary volcanics and/or Recent sediments. Some Filipino geologists consider the Sulu Sea and its borderlands, Palawan Island and the Sulu archipelago, as a part of an old stable craton (Gervasio, 1968), which could be the north-east plunging nose of the Sunda shelf stable craton. Although the floor of the deep Sulu Sea is reported to have no granitic layer, this hypothesis seems quite reasonable. However, except for the northwest flank of the island of Palawan, which is probably the northeastern extension of the basin of northwestern Borneo, the oil and gas prospects of this area are almost completely unknown.

The Strait of Malacca and its extension into the Andaman Sea do not belong to the area reviewed in this paper. According to some seismic data, published and unpublished, the Sumatra basin extends, most probably interrupted from place to place by plunging noses and/or islands, into the Strait of Malacca and is connected through the Andaman Sea with the Burmese basin. From this, it would appear that the oil and gas prospects of the western coast of the Thai-Malay peninsula are far from negligible.

The hydrocarbon possibilities of the South China Sea and of the Sunda Shelf are in most cases confined to the late Cenozoic sequence. The early Cenozoic is yielding some production in southeast Borneo, and may elsewhere have some potential, for example in the Gulf of Thailand. Older parts of the sedimentary sequence are intruded by granitic plugs; the possibility of finding hydrocarbons in these parts of the sequence is remote, except in a few places. On the other hand, the areal extension of the potentially promising basins is certainly greater than was expected from the results of earlier surveys, and the petroleum prospects of these areas has been considerably enhanced.

Australian shelf

Within the area under review, only the eastern part of West Irian can be considered as part of the Australian shelf. Aru Island is the core of an old platform plunging eastward under the Arafura sea towards Frederick Hendrick Island on the south coast of West Irian. A Cenozoic basin is developed on both sides of this plunging nose. This basin becomes thicker and wider towards the east, where gas has been discovered in the Gulf of Papua and the land area to the north. Production has been obtained from the Miocene and the Cretaceous (Third Symposium on the Development of Petroleum Resources of Asia and the Far East, Tokyo, November 1965). South of the Aru nose the Cenozoic section becomes thinner and the prospects for oil and gas on the continental shelf of northwestern Australia lie in the Mesozoic and Paleozoic.

Several basins exist along the northern coast of New Guinea (East and West). They are rather poorly known, but some prospecting is being done on the Australian side. The continental shelf is quite narrow, and the prospects for offshore extensions looks poor.

Outer and intermediate zones

The areas lying along the limits between the three "crustal blocks" as defined in the introductory section on the geologic framework will now be briefly discussed. These are (a) the western limit of the Pacific block, from Hokkaido to West Irian, outlined by a series of deep trenches, (b) the intermediate zone between Taiwan and Luzon and (c) the "three corners" area, where the three blocks meet together. This last area covers the eastern part of Indonesia, east of Borneo, and includes the western part of West Irian, known as the Vogelkop.

The continental shelf in these intermediate zones is usually narrow as is the continental margin (slope and rise), so that the immediate prospects would seem to be rather poor. This also applies to any longer term prospect in the deeper seas. Moreover, these areas are generally separated from the continental masses, and consequently from the sources of acidic detrital material, by intervening deep seas or troughs in which this material would have been deposited. The volcanic rocks of these areas are mainly basic and therefore generally not a suitable source for reservoir rock materials. Conditions are better in some small areas, and new information could change this view but, according to present knowledge, only small and isolated accumulations of hydrocarbons could be expected.

Hokkaido to Taiwan: The eastern continental shelf of Japan is narrow, and the main oil and gas fields are found on the western side of the main island. Several late Cenozoic basins exist and one at least (Tokyo-Chiba basin) produces gas. The Ryukyu outer island arc is separated from the Asian mainland by the Okinawa trough. Elongated basins, partly filled with sedimentary material, have been described (Emery *et al.*, 1969) as well as sedimentary terraces. This environment does not look very promising.

The structural relationships of eastern Taiwan with the Ryukyu arc to the north, as well as with the Babuyan shelf to the south, are not clear. A sharp change in tectonic direction occurs towards the north of Taiwan. The basin of Ilan, on the northeastern coast, is roughly east-west, and may be the updip termination of the Okinawa basin; the central ridge has an east-west direction in its northernmost part, and then turns sharply towards the south. This well known change in direction is probably an effect of the Taiwan fracture zone (or Central Basin fault), which is evident in the sea bed morphology and runs northwest-southeast across the Philippines Sea. The rift and the eastern ridge of Taiwan represent the eugeosynclinal part of the geosyncline of Taiwan and their petroleum prospects are poor; no prospect seems to exist on the narrow continental shelf.

Southern Taiwan, Babuyan shelf and Northern Luzon: The southern half of Taiwan is different from the northern half. As already mentioned (Meng, 1969), the east-west trending Penghu-Peikang basement high may represent an old feature, the eastern half being masked by the north-south alignment of the central and eastern ridges; this east-west direction is again evident in the sea bed morphology east of Taiwan. The true relationship between the southern half of Taiwan and the adjacent areas might have been obscured by the recently superimposed north-south alignment. Whatever the structural relationships may be, the southern half of Taiwan has poor petroleum prospects owing to the argillaceous facies of almost the entire sequence of the Neogene in this area. The sedimentary basins of northern Luzon have also been prospected for oil and gas, and a small field was discovered in the north part of the Cagayan valley. The possibilities of extending this small production on the Babuyan shelf, which is scattered with basaltic islands, are remote.

Eastern and southeastern Philippines: The north-south alignment of the northern part of the island of Luzon allows it to be considered separately from the rest of the Philippines archipelago. It may be assumed that the faults bordering the Palawan graben extend towards the northeast; this northeastern extension would isolate the northern part of Luzon and run along the northwestern edge of the "Anzon block", a submarine high located northeast of the Philippines archipelago, which might have been earlier a part of Luzon. Under such an assumption, the Manila trench could be regarded as linking, before the assumed movement, the Ryukyu trench with the Philippines trench; northern Luzon and the Babuyan shelf would both have been moved southwesterly by the action of shear faults aligned in a northeast-southwest direction.

On the other hand, it has been assumed in an earlier section of this report that the "Sunda Shelf" was extending northeast to the Sulu Sea, considered by Filipino geologists as a "stable shelf", as well as to the adjacent islands (Palawan, and the Sulu and Pangutaran archipelagos). The Philippines island arc is moulded around this nosing of the northeastern tip of the Sunda Shelf and it is bordered to the northeast by the Philippines trench, which forms the boundary between the Eurasian block and the Philippine Sea intermediate block; the whole geosynclinal system, together with the late or post-geosynclinal molassic basins, develops along this rather narrow strip.

This situation is similar to that of Java and Sumatra, on the southwestern edge of the Eurasian block, along its limit with the Indo-Australian block. However, the oil and gas prospects do not look as good as those in Indonesia. The Philippines island arc is separated from the area of the stable shelf by deep seas. The most promising basin, the Visayan sea basin, is located northeast of the Sulu sea, and cannot be fed by detritus eroded from Borneo. The basement complex of the Philippines consists mainly of gabbro, andesites and schists, and it lacks acidic rocks.

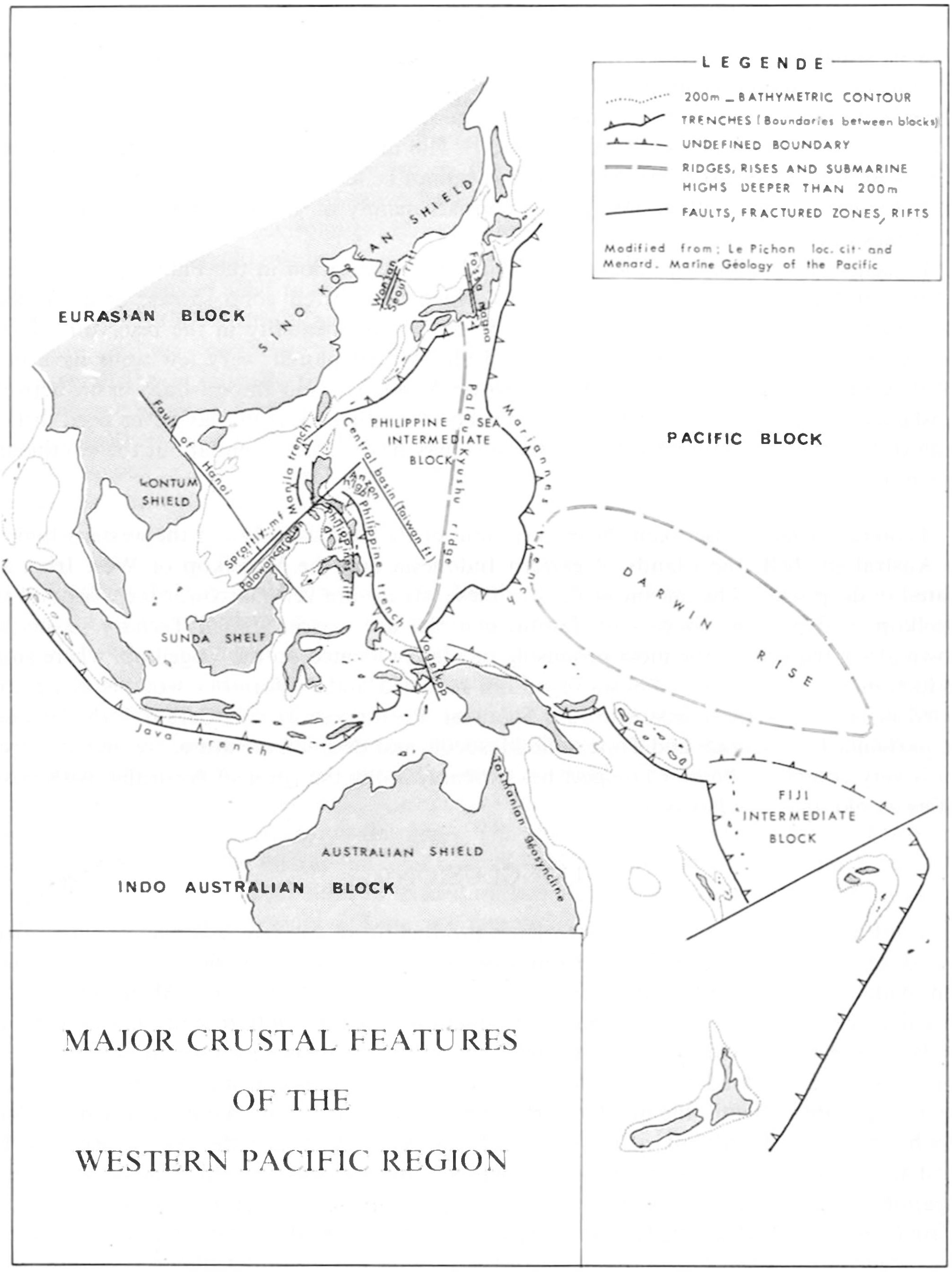
It seems that the main problem for oil and gas exploration in the Philippines is that of finding suitable reservoir rocks; many wells which have given good shows, or even small production, have been abandoned because of lack of permeability in the reservoir. However, several basins in this island arc are still almost unexplored; very few wells have been drilled in the basins of Davao and Cotabato on Mindanao and the offshore basin between the islands of Catanduanes and Polillo northeast of southern Luzon, has never been drilled. South of the island of Mindoro, the Cretaceous may have some potential but the continental shelf is very narrow.

Eastern Indonesia: Between the eastern limit of the Sunda Shelf and the western limit of the Australian shelf, the islands of eastern Indonesia and the Vogelkop of West Irian are located in deep seas. The marine shelves of these islands are very narrow, except around the Vogelkop, and possible sources of detrital material are scarce. Small Tertiary basins are known along the coasts, the most promising one being located on the Vogelkop, where small production was discovered. Shows of oil are reported and exploratory work is being conducted in several of these basins (South Sulawesi, Portuguese Timor, Ceram). In this area, and particularly on Ceram and Timor, the Mesozoic and Permian are attractive, but the structure is very complex; the best prospect lies probably along the coast of Australia, with possibilities as old as lower Paleozoic.

CONCLUSIONS

Until a few years ago, all the petroleum production of eastern Asia was obtained from oil and gas fields located on land. Even now, although several significant discoveries have been made at sea, the bulk of the production is still obtained from land. Moreover, the offshore discoveries are in areas adjacent to production on land. Only recently has oil exploration been directed to marine shelves bordering continental areas with little, if any, chance of production, and this kind of exploration has been very rewarding in some parts of the world. From Singapore to Seoul, the greater part of the coastal area of the Asian continent geologically has no potential for oil, as is the case also in Australia where the marine areas off the shield appear to be much more prospective than adjoining basins on land. The coastline from Singapore to Seoul, however, is bordered by a continental shelf covering more than a million square miles, within which the broad reconnaissance surveys made to date have already proved the existence of extensive deep sedimentary basins with attractive petroleum potential. It is too early to give any precise figures, but the percentage area of sedimentary basins detected on the East Asian shelf looks higher than the 35 to 40 per cent of known sedimentary basins on land. The assumed Neogene basin of the East China Sea alone, extending from Taiwan to the north of Tsushima, is as big as the Persian Gulf basin.

The hopes for new producing areas under the sea are great, but the greater part of the



Map V–1. Major crustal features of the western Pacific region.

most promising areas is under rather deep seas, and far from the coast. The cost of producing oil under such conditions is high and, to be competitive with the Middle East oil, the fields to be discovered must be very big in size, and the productivity of individual wells, which is the key factor in determining the economic value of an oil field, must be high; this factor itself is linked to the quality of the reservoir rocks. Some assumptions have been made in this review concerning this factor, but nothing can be ascertained in this respect except by drilling; even good looking structures with saturated reservoirs might eventually be dropped as uneconomic because of inadequate productivity. Taking into account also the cost of the production facilities, it must be realized that the gamble at sea is much more risky than on land, as the initial cost, and consequently the possible loss, would also be much higher.

There is some evidence for the possible presence of more gas than oil within the Neogene basins along the continental shelf of eastern Asia. Natural gas is of great value for industrially growing countries, but its production from offshore fields is even more costly than the production of oil and, owing to the rapid progress being made in the techniques of gas transportation, any gas field discovered in this area will have to compete also with the sources in the Middle East and Alaska.

The area reviewed in this paper produced in 1968 a total of 750,000 barrels (119,221 k*l*) of oil daily (bpd), of which 95 per cent came from Indonesia, Malaysia and Brunei; consumption of petroleum for this same area was 3,750,000 bpd (596,182 k*l*/day) of which 75 per cent was used in Japan. The rate of growth of consumption in the same area is expected to result in a three-fold increase within ten years (see: Forecasted Increases in Energy Consumption in the ECAFE Area, 1965–1975, ECAFE document E/CN. 11/TRADE/133, January 1969) which means a consumption or more than 11 million bpd (1.749 million k*l*) by 1978. Production in Indonesia is expected to increase notably but the development at Brunei is slowing down. The forecast for Indonesian production (Petroleum Intelligence Weekly, 12 May 1969) is 1.5 million bpd (238,475 k*l*) for 1972, including offshore oilfields still to be discovered. Not included in this review, but neighbouring the area concerned, Australia has a promising future and its production for 1970 will probably be close to 300,000 bpd (47,700 k*l*), as compared to consumption in 1968 in the order of 450,000 bpd (71,800 k*l*); with a rate of growth of nearly 10 per cent per year, the consumption by 1978 will be in the order of 1 million bpd (159,000 k*l*). It is not easy to forecast ten years ahead what the production in the area will be, even taking into account only the already known producing basins, but the discovery of new producing areas is greatly needed and efforts in this direction will certainly be rewarding.

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ADDITIONAL NOTES

1—ON ABSOLUTE DATATION OF INTRUSIVES AROUND THE GULF OF THAILAND—

A number of acidic intrusives (generally referred to as "granites") have been sampled for absolute age determination in the countries bordering the Gulf of Thailand. The results of these measures are not consistent. The results given by the K/Ar method are probably too recent: this method does not date the time of the first intrusion but probably some rejuvenation of an already intruded mass, whereas the results given by the Rb/Sr method are probably more reliable as an absolute datation of the intrusion. (See additional references). This remains controversial; however, it can be assumed as a working hypothesis that the intrusives on both coasts of the Valley of the Chao Phya and of the Gulf of Thailand (and probably also the intrusives which might exist under the Gulf of Thailand) are generally older than those to the N. E. and to the S. W. and that the upper part of the "Indosinias" are non metamorphosed and may be considered as possible target for oil and gas prospecting. In the Gulf of Thailand.

2—ON THE EXISTENCE OF GAS IN OKINAWA—

Several wells have been drilled on Okinawa Island. One of them, Naha 2, has given good indications of gas, which are probably of the same nature as the gas produced in Chiba and Niigata basins (gas dissolved in water: cf. Proceedings IInd Symposium of Petroleum Resources in the ECAFE area, Tokyo 1965). The data concerning the well Naha 2 are described in "Geological News" October 1969 (in Japanese). The existence of gas in the Neogene sequence of Okinawa is very encouraging factor for the neighbouring Neogene basins.

3—NORTHERN AUSTRALIA AND NEW GUINEA—

No reference is made in the text to the basins bordering the Australian continental block in northern Australia and New Guinea, but map N°2 has been amended according to the papers delivered by the Australian delegation to the IVth ECAFE Petroleum Symposium in Canberra and to informations received from the geological survey of Queensland in Brisbane. The most important are listed in the additional list of references.

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C. FAURE et H. FONTAINE:
Géochronologie du Viet-Nam méridional—Archives Géologiques du Viet-Nam—N° 12—Saigon Dec. 1969—A list of absolute age determination of intrusions in the Southern part of Viet-Nam.

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VI. A CONCEPTION OF THE EVOLUTION OF THE ISLAND OF TAIWAN AND ITS BEARING ON THE DEVELOPMENT OF THE NEOGENE SEDIMENTARY BASINS ON ITS WESTERN SIDE

(Presented orally at sixth session of CCOP)

By

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(with figures VI-1 to VI-16)

ABSTRACT

The island of Taiwan with its north-south structural trend resulting from late Cenozoic orogeny is situated between east-west structural trends both to the east and west of it. This is an important fact to be taken into consideration when studying the structural development of Taiwan.

The discovery of the east-west shallow basement "high" between the Peikang area and Penghu Island showed that the bulk of the Neogene sediments in Taiwan Strait and the western part of the island of Taiwan were deposited in deep basins to the north and south of it. The "Peikang-Penghu basement high," according the writer's conception, apparently acted as a tectonic dam during Miocene time. To the north of this basement high the sediments deposited are of continental shelf facies while to the south of it they are of continental slope facies.

The important orogenic movement which resulted in the dominantly north-south structural trend on the island of Taiwan gradually became stronger from Pliocene to Quaternary times whereas there is no definite evidence of any major orogenic movement before the Pliocene. In the pre-Pliocene time, therefore, it is probable that the southern end of the Ryukyu Arc was connected with east-west trending "Peikang-Penghu basement high" through the middle of the area where the island of Taiwan is now situated.

On the edge of the continent, the downward plunging of the sea floor may be taken as being the main cause for the development of a geosyncline. The major compression resulting from the movement of the oceanic block causes the major thrust plane to steepen and move inward so that the width of the geosyncline originally developed is shortened by the compression to make the proximal side rise, thrust or overthrust inward. Farther from the main uplift the compressive force gradually decreases to result in folding that dies out with distances. The cyclic process would stop after the readjustment of deep-seated material reaches equilibrium and this concludes the development of the geosyncline. The island of Taiwan must have came into existance in this manner.

STRUCTURAL TRENDS ON THE ISLAND OF TAIWAN AND OFFSHORE TO THE EAST AND WEST

Among the island arcs of the western Pacific an interesting phenomenon from the viewpoint of regional geologic structure is that the southern end of the NE–SW trending Ryukyu arc turns abruptly westward to meet the east coast of the island of Taiwan almost perpendicular to the main structural trends on that island (Meng, 1962). In the past, this strong bend has been considered only with respect to the connection between the tectonic trend of the island of Taiwan and the submarine topography eastward from Taiwan to the Ryukyu area (Fig. VI–1).

The results of the cruise of the R/V F. V. Hunt in the East China Sea and the Yellow Sea from 12 October to 29 November 1968 (Project CCOP–1/IZ. 3) confirmed that, to the east of the continental shelf of the East China Sea, the Okinawa Trough, the Ryukyu Folded Zone, and the Ryukyu Trench extend in parallel from the northeast towards the southwest to Miyako Island where their trend changes to westward and ends at the northern part of the east coast of Taiwan at right angles to the north-south trending geologic structure of the island of Taiwan (Emery, *et alia*, 1969). The writer considers that the sharp change in trend is due to the existence of a strike-slip fault between the two geologic structural trends (Fig. VI–2).

Gravity observations, seismic surveys and drilling data, have shown that there is Mesozoic and possibly Paleocene basement underneath the shallower part of the Peikang area in the central part of the coastal plain of western Taiwan (Meng, 1967). This basement is composed mainly of indurated, slightly hydrothermally altered quartz-porphyry, quartz-basalt, diabase, conglomerate, proto-quartzite, subgraywacke, lithic graywacke, arkose, feldspathic graywacke, siltstone, shale, and limestone (Chou, 1969 b; Lee, 1962). According to the results from drilling of the Tungliang Well TL–1 on the Penghu Islands in Taiwan Strait, the basement is shallower there than in western Taiwan (Chou, 1969 a). Based on the results of gravity survey, the writer considers that this Mesozoic basement exists at no great depth and extends from the middle part of the coastal plain in western Taiwan through the Penghu Channel to the Penghu Islands, and that it has an east-west trend (Meng, 1968). The preliminary results of an aeromagnetic survey made by the U.S. Naval Oceanographic Office's Project MAGNET in June 1968 (Project CCOP–1/ROC. 2) support the writer's belief that this ridge extends from east to west between Peikang and Penghu (Fig. VI–3).

Subsurface faults delineated by seismic survey in the Neogene sedimentary section, south of the "Peikang-Penghu basement high" strike mainly east-west and disappear eastward before reaching the foothills area, where the structural trends are generally north-south (Chang, 1964, 1965). The trends of the geologic structures discussed above may be summarized as follows (Fig. VI–4): (a) The structural trends shown on the surface of the island of Taiwan are mainly north-south; (b) the structural trend at the southwestern end of the Ryukyu arc is east-west; and (c) the axis of the basement ("Peikang-Penghu basement high") between the Peikang area and the Penghu Islands is nearly east-west or ESE-WNW. Consequently, the island of Taiwan with its north-south structural trend resulting from late Cenozoic orogeny is situated between east-west structural trends both to the east and west of it. This is an important fact to be taken into consideration when studying the structural development of Taiwan.

THE EAST-WEST PEIKANG-PENGHU BASEMENT HIGH

The discovery of the east-west shallow basement "high" between the Peikang area and Penghu Islands showed that the bulk of the Neogene sediments in Taiwan Strait and the western part of the island of Taiwan were deposited in deep basins to the north and south of it (Meng, 1968). The difference between the Miocene sediments in these two basins is quite marked. The northern basin contains sediments of deep and shallow marine facies with cyclic alternations of sandstone and shale, intercalated coal seams, and oil and natural gas

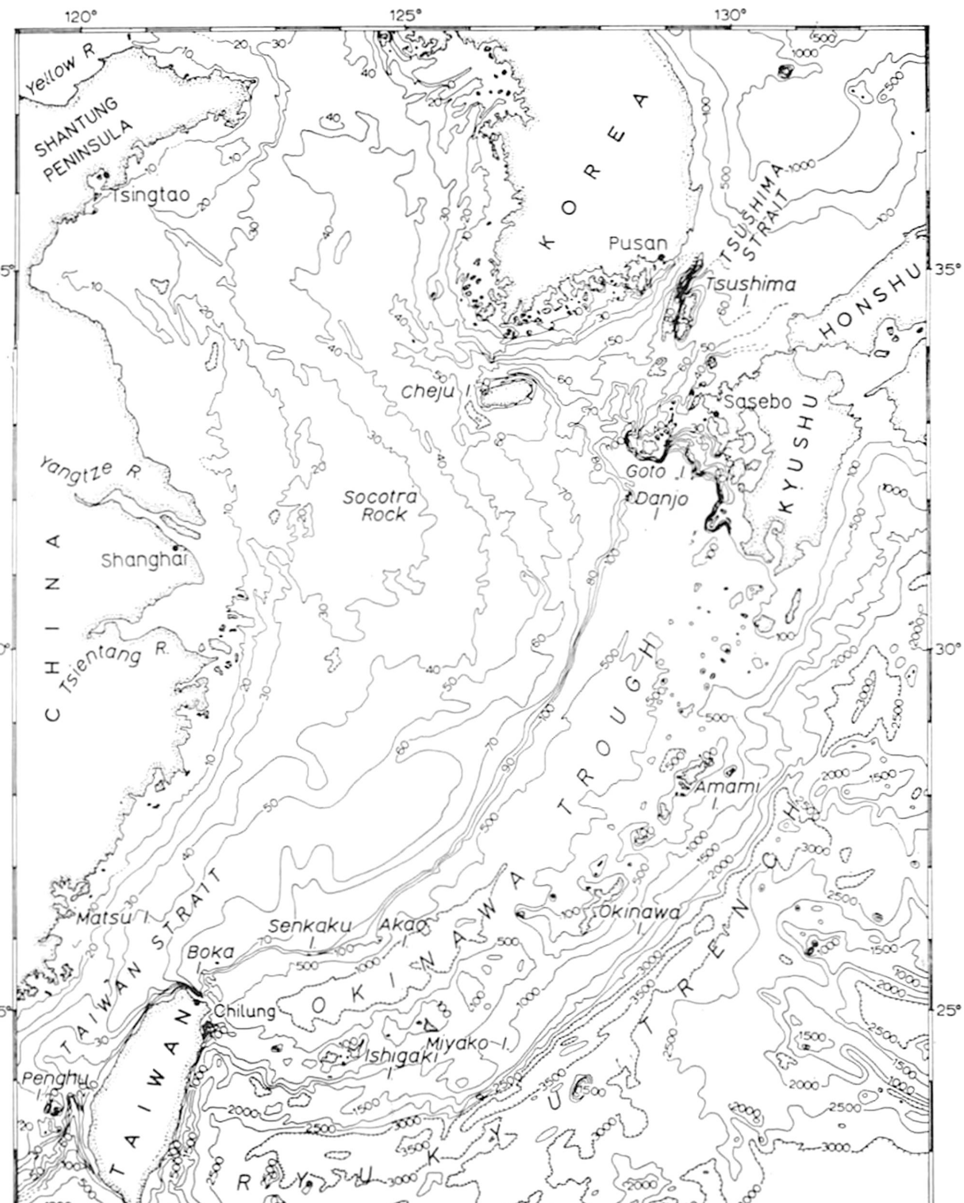

Figure VI– 1. Topography of the region of the Ryukyu Island Arc and the vicinity of the island of Taiwan (from a recent compilation by the U.S. Naval Oceanographic Office).

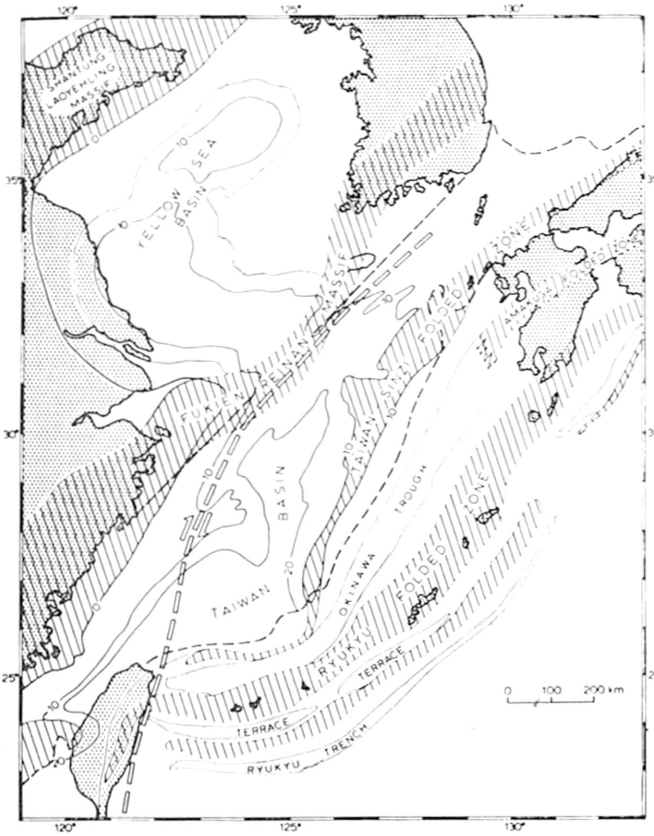

Figure VI– 2. Generalized pattern of ridges and troughs, and basins and trenches in the East China Sea and vicinity, based on the results of the cruise of R/V F. V. HUNT and previous information (taken from Fig. 17, ECAFE, *CCOP Tech. Bull.*, vol. 2, p. 40, 1969).

producing zones. The southern basin contains mainly silt and mud of deeper marine facies (Schreiber, 1968).

When Emery (1969) discussed the genesis of the continental shelf and the continental slope of the western Pacific, he considered the position of the "tectonic dam" as very important in relation to deposition of sediments in the sea. The coarser fraction of the sediments derived from the mainland would be deposited inside the dam while the finer fraction, mainly silt and mud, would be carried farther out by currents and deposited outside the dam. The outside of the dam often coincides with the position of the continental slope while the inside of the dam is readily filled up with sediments from the adjoining land mass and eventually becomes the continental shelf. According to this conception, the "Peikang-Penghu basement high" apparently acted as a tectonic dam during Miocene time. To the north of this basement

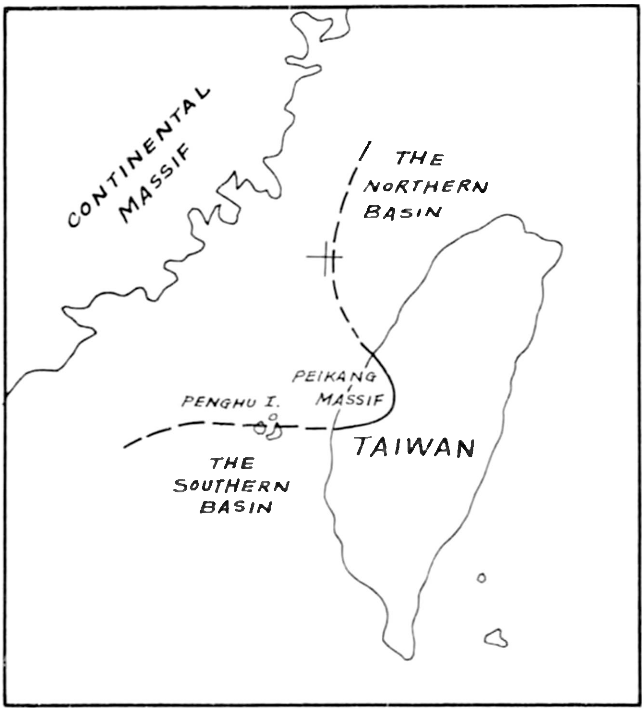

Figure VI–3. Presumed position of the "Peikang Penghu basement high" acting as a divide separating the northern and southern sedimentary basins of western Taiwan during Miocene time.

high, the sediments deposited are of continental shelf facies while to the south of it they are of continental slope facies (Fig. VI–4).

The east-west trend of the "Peikang-Penghu basement high" and the characteristics of Miocene sedimentation to the north and south of it are stressed because of their relation to the structural picture to the east and west of the island of Taiwan. According to structural and sedimentation data, the important orogenic movement which resulted in the dominantly north-south structural trend in the island of Taiwan gradually became stronger from Pliocene to Quaternary times whereas there is no definite evidence of any major orogenic movement before the Pliocene. In pre-Pliocene time, therefore, it is probable that the southern end of the Ryukyu Arc was connected with the east-west trending "Peikang-Penghu basement high" through the middle of the area where the island of Taiwan is now situated. To distinguish it from the present Ryukyu Arc, this pre-Pliocene connecting basement "high" is here termed the Old Ryukyu Arc (Fig. VI–5).

EFFECT OF THE OLD RYUKYU ARC ON SEDIMENTATION DURING THE MIOCENE

If the conception of the Old Ryukyu Arc is accepted, its role as a "tectonic dam" during Miocene time would explain the difference in facies of the sediments in the basins to the north and south of it. In the northern Miocene sedimentary basin, in north-western and northern

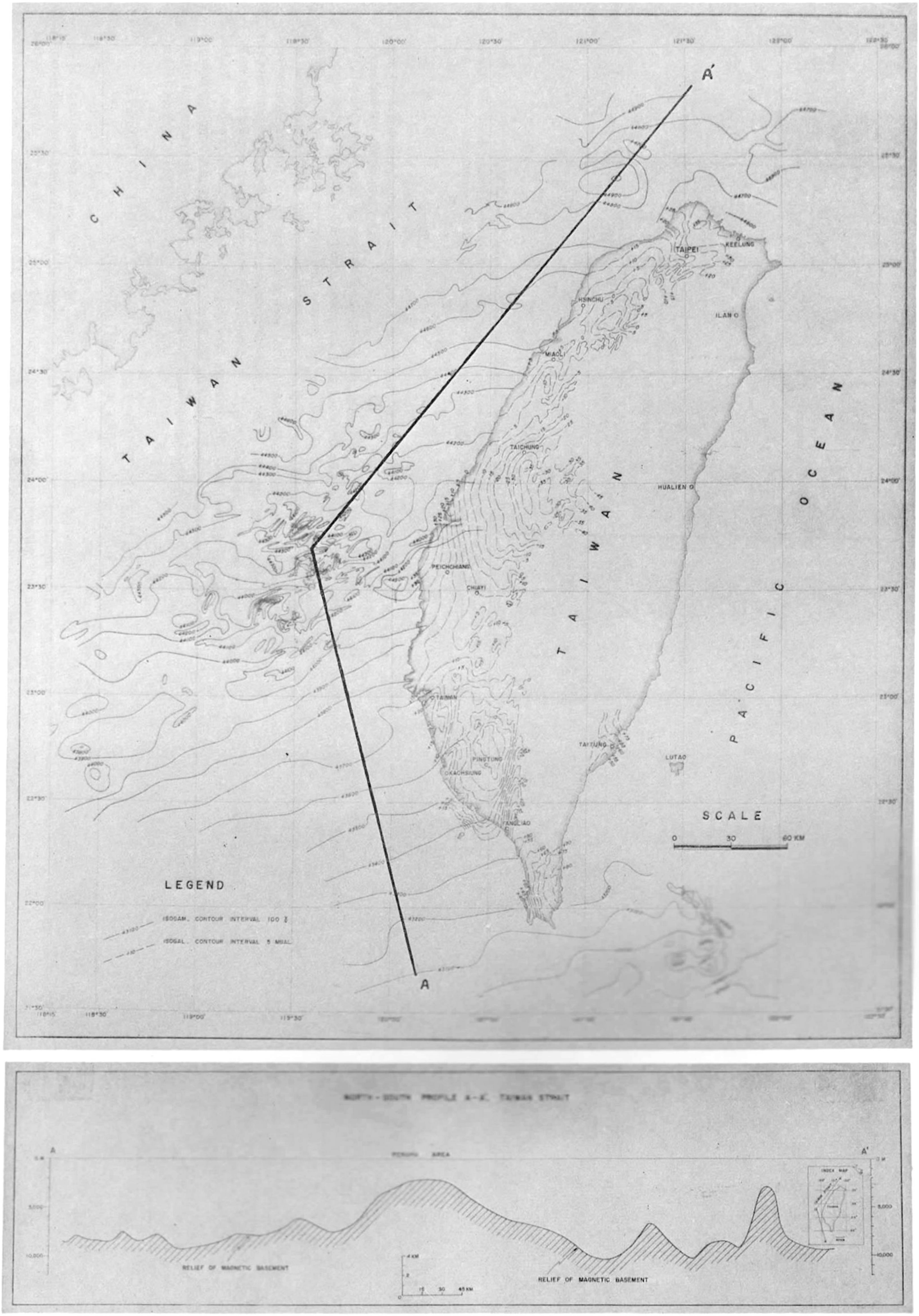

Figure VI-4. Compilation map showing total magnetic intensity in the eastern part of Taiwan Strait and Bouguer gravity anomalies of the western part of the island of Taiwan. The profile at the foot of the map shows total magnetic intensity along line A–A′, shown on the map.

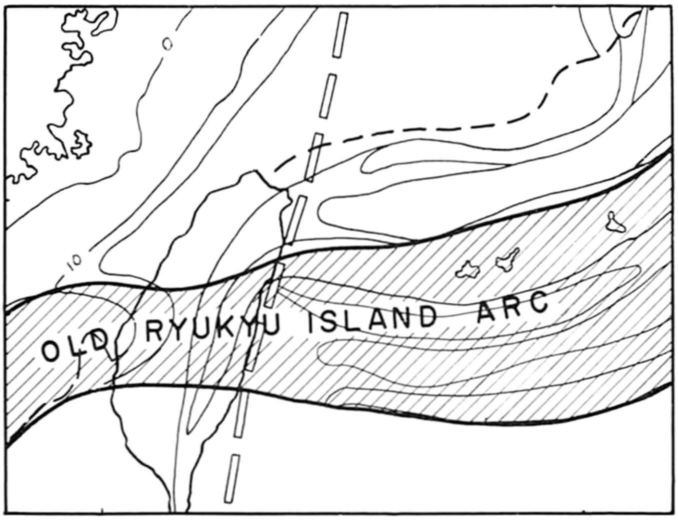

Figure VI– 5. Hypothetical position of the pre-Pliocene "Old Ryukyu Island Arc"

Taiwan, three cyclothems of marine sediments ranging in facies from deeper to shallowers, were deposited. When the water was deeper, silt and black shales were deposited and, as the water became shallower, well-sorted sands and coal seams were deposited.

The development of the three cyclothems from early to late Miocene time in the northern basin must have resulted from a greater subsidence rate in the area north of the tectonic dam than on the "Peikang-Penghu basement high", which was comparatively stable, and large volumes of sediments were deposited in it. According to the paleocurrent study of the Miocene formations in northern Taiwan (Chou, 1969 c), the Miocene currents in northern Taiwan originated from the north and north-west of the Peitou-Kuanyin Shelf and flowed southward and southeastward down the regional paleoslope. These currents would have been obstructed by the tectonic dam formed by the "Peikang-Penghu basement high." When the rate of subsidence of the northern sedimentary basin slightly exceeded the rate of deposition, the shaly and silty sediments were deposited in a deeper environment. When the rate of subsidence of the basin was equivalent to or less than the rate of deposition, the sedimentary basin would have been filled up by sediments consisting of coarser sandstones and autochthonous coal beds. Sedimentation in northern Taiwan was continuous during Miocene times as there is no evidence of unconformities in the whole of the Miocene sequence, but there was evidently some variation in its rate of subsidence.

The southern side of the "Peikang-Penghu basement high" during Miocene time was probably the margin of the continental shelf, which sloped down to a deep basin to the south. There is a hinge fault along this margin, the so-called Yichu Fault or Fault A, which can be inferred from the results of the aeromagnetic survey (see Section in Fig. VI–6). This fault, extending between Peikang and Tainan, is probably prolonged westwards to the south of the Penghu Islands and the Taiwan Bank. Movement along this fault caused the southern block to subside continuously at a greater rate than the rate of subsidence of the sedimentary basin north of the basement high consequently, a deeper water environment was developed to the south of it. The coarser sediments brought from the land mass to the northwest were deposited

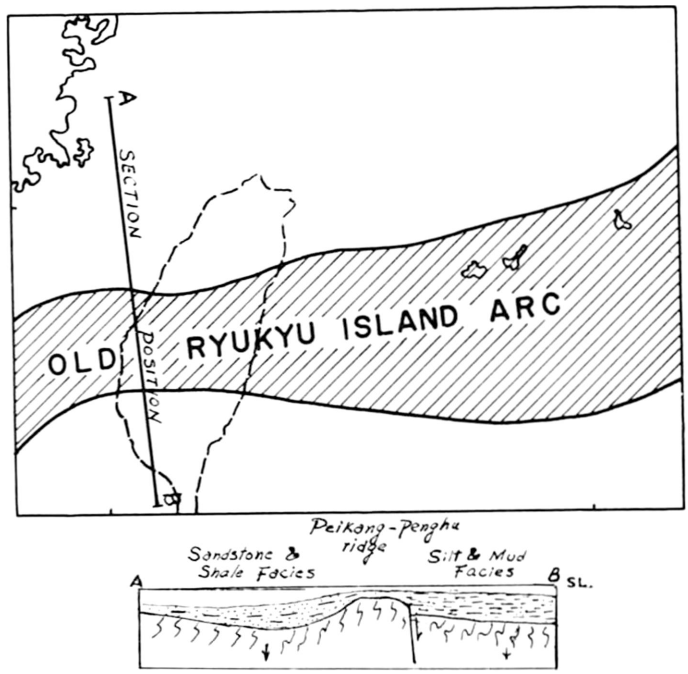

Figure VI– 6. Section and location map showing difference in facies of Miocene sediments north and south of the "Peikang-Penghu basement high" forming part of the Old Ryukyu Island Arc.

in the northern basin in a series of three cyclothems during Miocene time while some of the finer fractions, dominantly of clay with some silt, were carried by currents across the barrier and deposited in the deeper southern basin.

This submerged barrier, or "tectonic dam" was probably discontinuous and irregular in its topography, as is the present Ryukyu Arc. Some of the coarser sediments could have spilled over into parts of the southern basin through saddles in the barrier, intermingled with the greater bulk of fine fractions. This could account for the presence of some muddy sandstones in the Miocene sediments in the western foothills of southern Taiwan whereas the sediments farther to the west are almost entirely of mud or shale facies (Fig. VI–7).

The continuous subsidence of the northern sedimentary basin caused a relative uplift of the "Peikang-Penghu basement high" but the block to the south of the hinge fault subsided more rapidly. These opposing actions probably kept the ridge in a stable state, and a relatively thin flat-lying veneer of Cenozoic sediments was deposited on it.

Data obtained from wells drilled in the Peikang area show that the Cenozoic sediments are about 1,500 metres in thickness and that the sediments of Aquitanian age at the base of the sequence unconformably overlie the indurated formations of the Mesozoic basement. The Mesozoic rocks are quite different lithologically from those of Cenozoic age. The Mesozoic sandstones are relatively indurated, poorly sorted, feldspathic, siliceous, higher in apparent specific gravity, lower in effective porosity, and, in part, slightly hydrothermally altered (Chou, 1969 b); the sand grains are much less rounded than those of the Cenozoic sequence.

Matsumoto *et alia* (1965) studied the Aptian and Lower Cretaceous ammonite and mol-

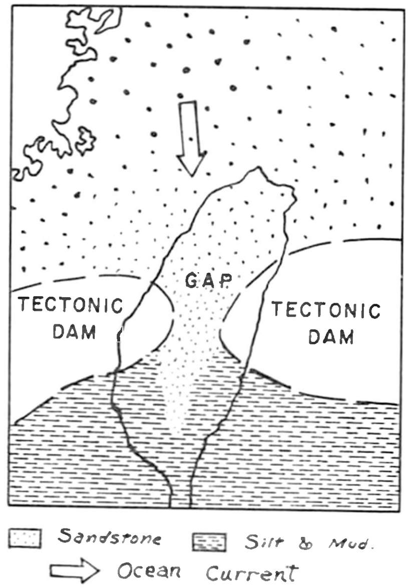

Figure VI- 7. Distribution of sedimentary facies in Miocene time north and south of the "tectonic dam" formed by the Old Ryukyu Island Arc and postulated position of saddle ("GAP") through which some coarser clastics spilled over to the south.

luscan fossils from the Mesozoic rocks of the two wells, PK–2 and PK–3. Huang (1963 and 1968) studied the planktonic foraminifera and found some Paleocene, planktonic foraminiferids in the basement section of the PK–3 well. The evidence from these fossils is reasonably complete but there has been difference of opinion concerning the age of the indurated series below the unconformity in this area. The writer considers that, when the northern sedimentary basin subsided, the deeper formations were crowded against the ridge to begin plastic flow, and the older formations of different ages were easily mixed. Therefore, parts of the Paleocene formations may be found mixed in with the Lower Cretaceous formations; the hydrothermal alteration in the indurated rocks may be attributed to plastic flow of deep seated material.

EVOLUTION OF THE ISLAND OF TAIWAN AFTER MIOCENE TIME

According to the conception outlined above, the Old Ryukyu Arc probably controlled the regional structure and the sedimentary environments in its vicinity during Miocene times. After the Miocene, the island of Taiwan was formed as a result of younger tectonic movements which gave rise to its present north-south structural trend. The source area of the sediments of Pliocene to Recent age was the Central Range in the east, and not from the land mass to the northwest, as was the case during Miocene time. The effects of the younger tectonic movements are described from the eastern side of Taiwan and across the Central Range to the Cenozoic sediments distributed in western Taiwan (Fig. VI–8).

1. The Coastal Range: The Coastal Range of eastern Taiwan is a longitudinal range extending from north to south, parallel and close to the Pacific Trench. The Longitudinal

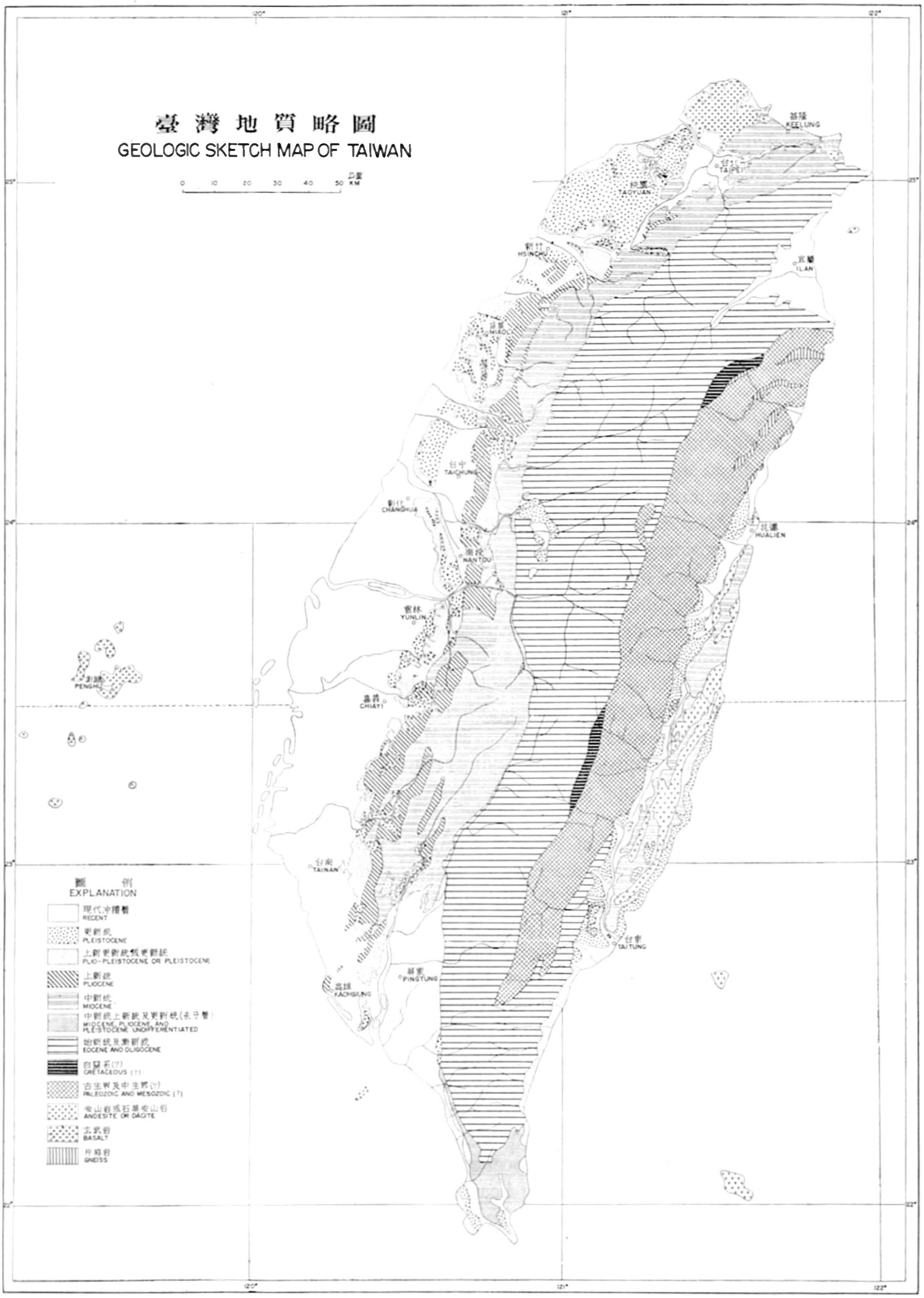

Figure VI– 8. Geologic sketch map of the island of Taiwan.

Valley west of the Coastal Range is parallel with it. The range consists of a structurally complex mixture of Neogene marine sedimentary formations and igneous rocks. Intermixed marine mudstone, ultrabasic igneous rocks, and derived rocks are distributed over a large area at the southern end of the Coastal Range; some geologists believe that these are of olithostrome origin. This longitudinal range has not yet been cut across by any large river and this indicates that the range was formed quite recently.

2. The Longitudinal Valley: The longitudinal valley between the Central Range and the Coastal Range is an eroded major thrust zone. Neogene sediments and igneous rocks are distributed along the eastern side of the valley, and the oldest metamorphic rocks of the Central Range along the west side of the valley. The great difference in geologic character and age along the two sides of valley indicates that large scale faulting must be responsible for this situation.

3. The metamorphic rocks of the Central Range: Between the fault in the Longitudinal Valley and the major longitudinal fault west of the Central Range which divides the indurated Paleogene rocks from the Neogene sediments in the west, is a belt of metamorphic rocks, the strike of which is generally north-south. This metamorphic complex of the Central Range is older and more intensely metamorphosed towards the east. The oldest beds, recognized as Permian, have become gneiss, sericite schist, green schist, and crystalline limestone. The undifferentiated Mesozoic may be as late as Cretaceous in age and the conglomerate is unconformably overlain by the Paleogene. All of the pre-Paleogene intensely metamorphosed complex is distributed in a narrow belt on the eastern flank of the Central Range. The less intensely metamorphosed Paleogene rocks to the west consist of Eocene quartzite and slate and Oligocene slightly altered black shale with interbeds of sandstone.

The whole of the metamorphic belt has suffered strong disturbance and is folded repeatedly and shattered by many faults so that it is very difficult to trace out a systematic structural pattern and the belt may be considered as having resulted from squeezing out of plastic material under intense pressure.

4. The Neogene sediments of western Taiwan: On the western slope of the Central Range, the indurated Paleogene rocks are in sharp contact with the unaltered Neogene sequence along the major longitudinal thrust fault which extends along the whole length of the island.

Lower Miocene formations are known only in surface outcrop, or where they have been penetrated by drilling, and their direct contact with older formations has not been found, except on the Peikang shelf where they rest unconformably on the Mesozoic basement. According to the sedimentary process deduced above, the Miocene sedimentary environment must have been controlled by the presence of the "Peikang-Penghu basement high."

The sedimentary conditions after the Miocene were evidently influenced by the continuous uplift of the Central Range. As already outlined above, this north-south trending structural unit rose from below and cut perpendicularly across the east-west trending Old Ryukyu Arc (Fig. VI–14). The Pliocene, Pleistocene and Recent sediments distributed in western Taiwan are clearly recognized as having been derived from the Central Range block in the east. These post-Miocene sediments become successively coarser and thicker, with the coarse conglomerate of the Pleistocene Toukoshan Formation being as thick as 2,000 metres, thus indicating that the rate of uplift of the Central Range was also becoming progressively greater. At the same time, the basin receiving the sediments also subsided and both of these factors led to an increasingly greater relative movement. The continuous rising and broadening of the Central Range block resulted in compression of the Neogene formations which caused them to rise up in the vicinity of the major thrust in the form of imbricated folding and multiple faults, but the folding decreased towards the west with the decrease of compressive force.

HOW THE ISLAND OF TAIWAN CAME INTO EXISTENCE

According to the sea floor spreading theory (Fig. VI–9), when the oceanic crust of the earth is affected by convection currents in the mantle, the sea floor diverges from the centre of the ocean and when it encounters the continental margin it flows downward. This divergence may not maintain a permanent direction because the convection current may change its course. The strong bends among the island arcs of the western Pacific resulted from difference in the direction of sea floor spreading.

Before Miocene time, the Old Ryukyu Arc must have been under the influence of a previous direction of sea floor spreading but, since the beginning of the Pliocene, the direction of spreading changed to bring about the north-south trending structure of the island of Taiwan.

The convergence of the sea floor usually occurs where the oceanic crust is in contact with the continental crust and the contact surface becomes a major fracture or fault. Gutenberg and Richter (1949) recognized the existence of such fractures from plotting the epicentres of earthquakes in various regions (Fig. VI–10). Hilde *et alia* (1969), from continuous seismic profiling, found that the oceanic crust crowds under the continental crust in the Sea of Japan (Fig. VI–11). On the edge of the continent, the convergence of the sea floor may be taken as being the main cause for the development of a geosyncline (Fig. VI–12).

The first factor to be considered is the initial movement along the major fracture on the edge of the continent. The oceanic crust can plunge beneath the continental crust along this major fault and at the same time strike-slip can take place along the fracture. Many examples of this dual movement may be cited from both sides of the Pacific (Fig. VI–13).

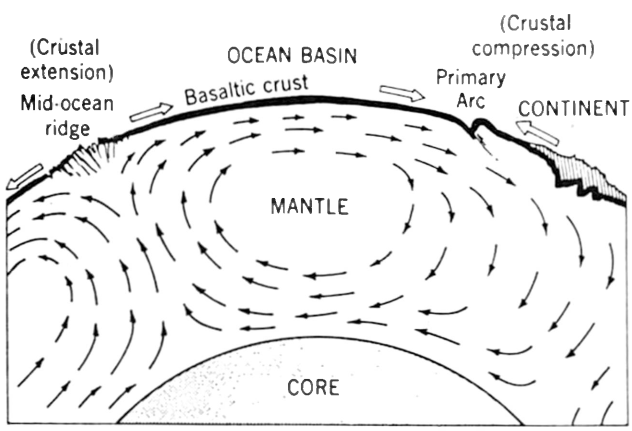

Figure VI– 9. Schematic diagram of a convection current system in the mantle and its relation to the mid-ocean ridge and the primary arc.

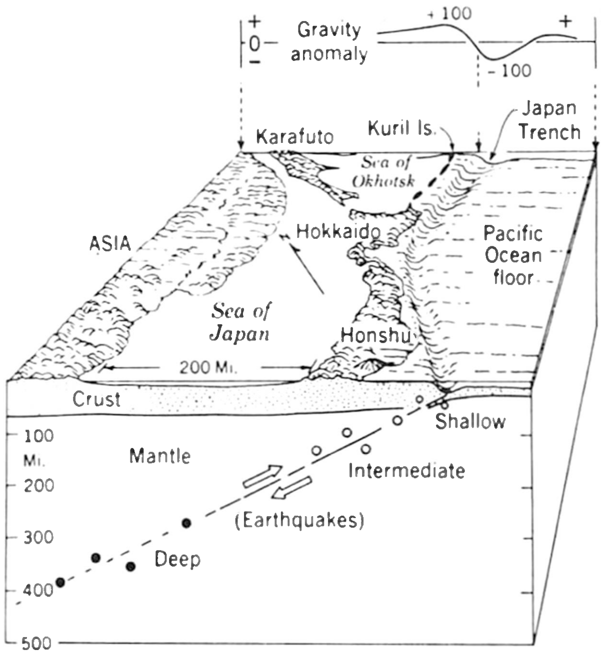

Figure VI-10. Block diagram of Japan-Kurile arc showing distribution of earthquake foci in the crust and mantle beneath. Based on data in Gutenberg and Richter, 1949.

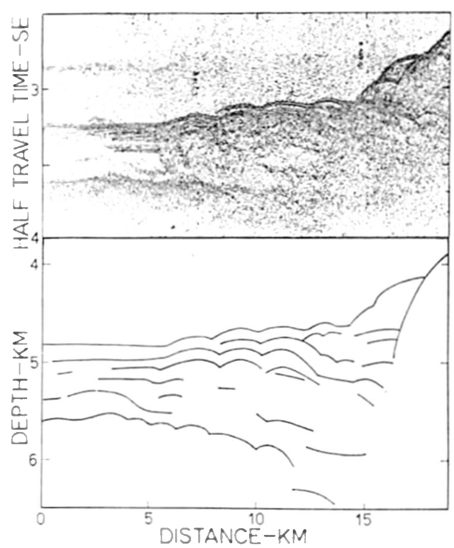

Figure VI-11. Continuous reflection profile, from Hilde *et al.* (1969), showing crowding of the oceanic crust under the continental crust in the Sea of Japan.

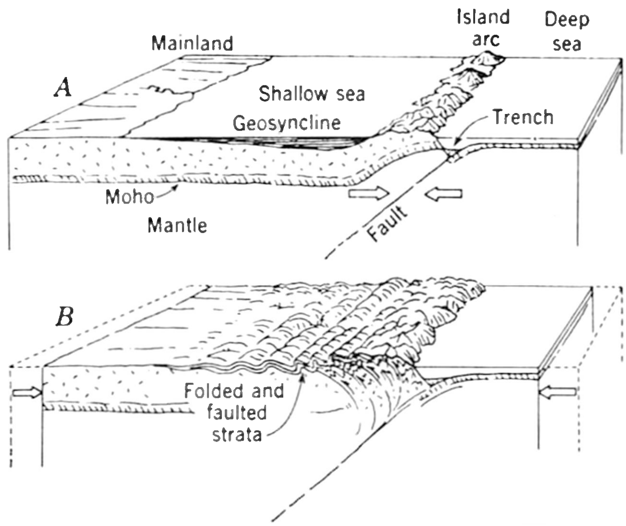

Figure VI–12. Block diagrams showing possible transformation of an island arc and its related geosyncline into a belt of intensely deformed rocks of the continental crust. From A. N. Strahler, Earth Science, p. 408, Fig. 22: 19.

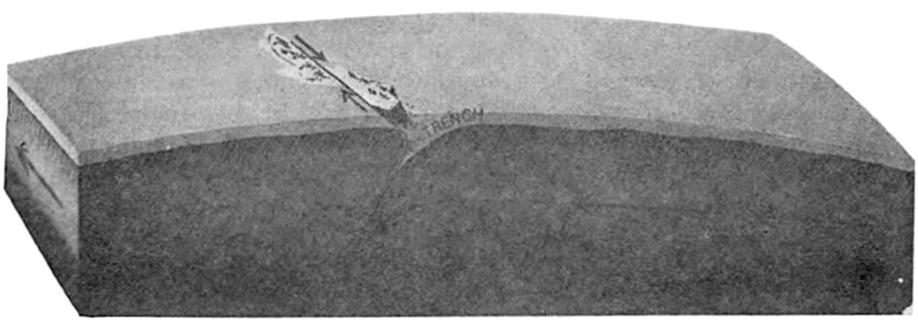

Figure VI–13. Block diagram showing suggested initial movement along a major fracture along the edge of a continental mass. The oceanic crust plunges beneath the continental crust along the fracture and strike-slip takes place along the fracture.

Long term crowding of the downthrown block towards the continent may cause the upthrown block to rise gradually and recede. The original low angle fracture becomes steeper as the crowding continues. The steepening of the thrust plane and the receding of the upthrown block would cause the outer margin of the upthrown block to rise. Further crowding would cause a depression inside the margin due to horizontal compression; this is the initial stage in the development of a geosyncline (Figs. VI–14 a, b).

Such movement of the downthrown block relative to the upthrown block continuing along the thrust plane would cause the outer margin of the upthrown block to emerge above sea level to become an island (or chain of islands) and the new born island would supply material for filling the geosyncline (Fig. VI–14c). As this geosyncline develops further, the horizontal compression from crowding causes the basement under the center of the geosyncline to be warped down, while the island continues to rise up to supply more eroded material which fills in the geosyncline and this additional load causes further downwarping of the basement.

If deep-seated material under the centre of the geosyncline does not shift aside, the bottom of the geosyncline cannot subside. In his discussion of the origin of geosynclines, Weeks (1940) emphasized that without sagging no graben or half graben can be developed. The writer thinks that when sagging reaches to a certain depth, deep-seated rocks begin plastic flow away from under the centre of the geosyncline to leave room for further subsidence of the geosyncline. Such plastic flow results in the second stage of geosynclinal development (Fig. VI–14d).

Since such orogeny on the continental margin takes place all along the major thrust, the plastic flow would be upward along the fracture which is the easiest outlet for release of pressure. Thus, on the outer margin of the new born geanticline the oldest and most intensely metamorphosed rocks are exposed; these may be considered as rocks which were originally deep seated under the centre of the geosyncline that have been later squeezed and brought to the surface by plastic flow, along the belt of strongest orogeny. During this last stage of development, the more the geosyncline sinks with accelerated rate as it receives sediments eroded from the rising geanticline, the more the geanticline rises at an accelerated rate as more metamorphic rocks are squeezed out. This cyclic movement causes increasing relative uplift and subsidence along the thrust plane in between the geanticline and the geosyncline.

The major compression resulting from the movement of the oceanic block causes the major thrust plane to steepen and move inward so that compression is in one direction. The width of the geosyncline originally developed is shortened by the compression to make the nearer side rise, thrust or overthrust inward. Farther from the main uplift the compressive force gradually decreases to result in folding that dies out with distance. The cyclic process would stop after the readjustment of deep-seated material reaches equilibrium and this concludes the development of the geosyncline. The island of Taiwan must have came into existence in this manner.

CONCLUSIONS

1. The tectonic features displayed on the island of Taiwan resulted mostly from orogenic movement after Miocene time, as shown in Fig. VI–16, the main features of which are as follows:

A: The Coastal Range, consisting mainly of sediments coming from the Pacific Ocean direction which extend to under the major thrust due to compression from sea floor spreading. It is only just east of the major thrust that such sediments are folded by compression into the

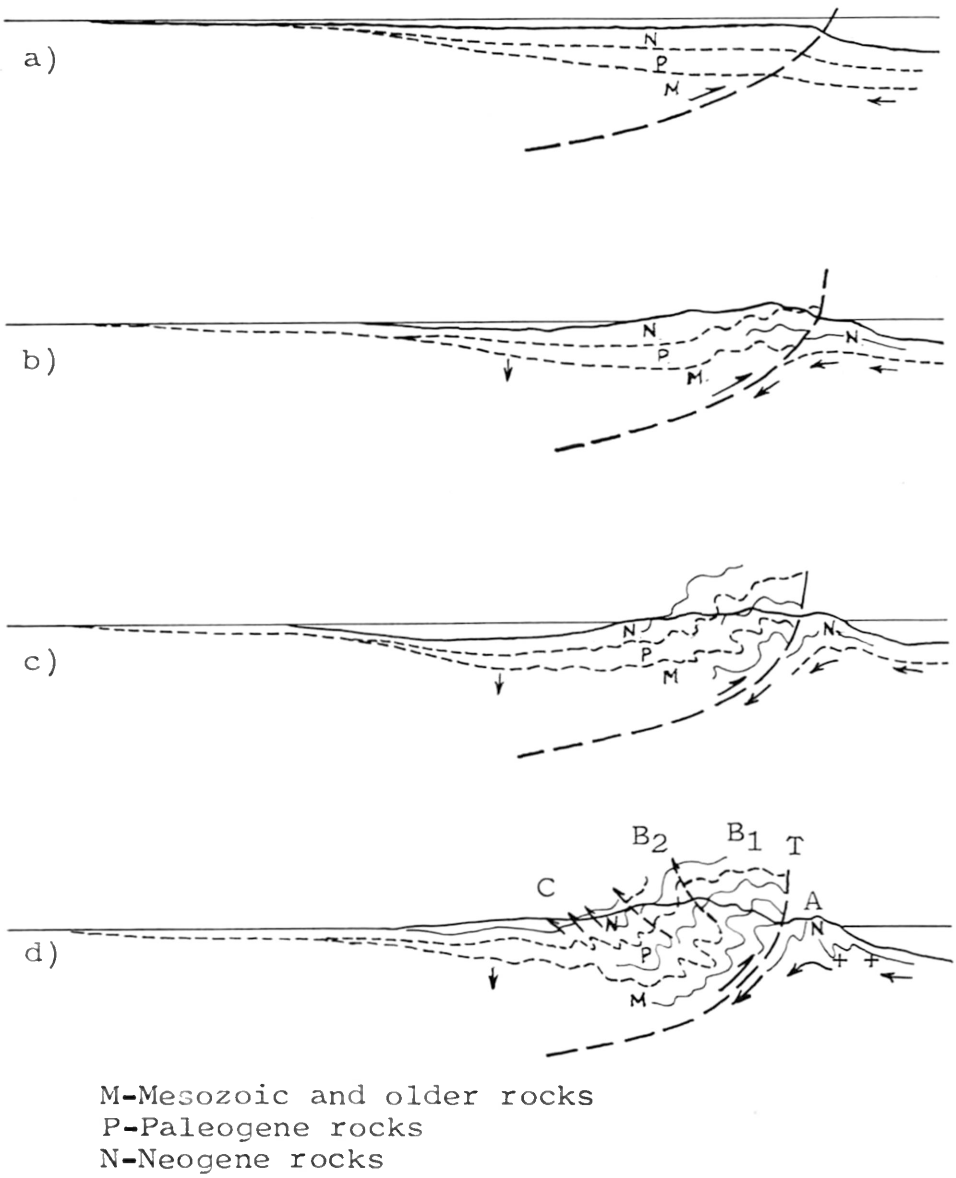

Figure VI-14. Sections showing stages in the development of a geosyncline along the continental margin: (a) The original position of the low-angle marginal thrust; (b) the steepening of the thrust plane as crowding continues; the upthrown block receded and initiated the development of a geosyncline on its continental side; (c) the outer margin of the upthrown block emerges as newborn islands which supply material for filling the geosyncline; and (d) horizontal compression from crowding causes downwarp of the basement below the geosynclinal basin while the island arc continues to emerge. (M, Mesozoic and older rocks; P, Paleogene rocks; N, Neogene sediments; for A, T, B_1, B_2 and C, see Fig. VI-16 and text).

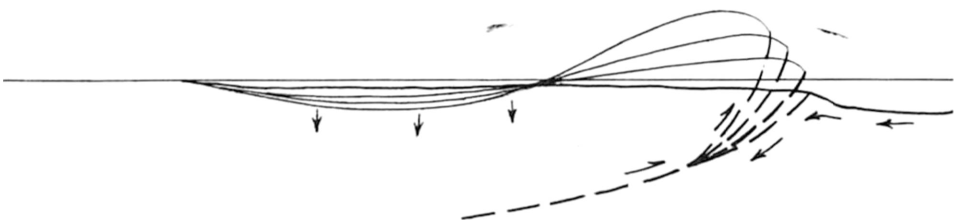

Figure VI-15. The cyclic movement of uplift and subsidence along the thrust plane in between the geanti-- cline and the geosvncline.

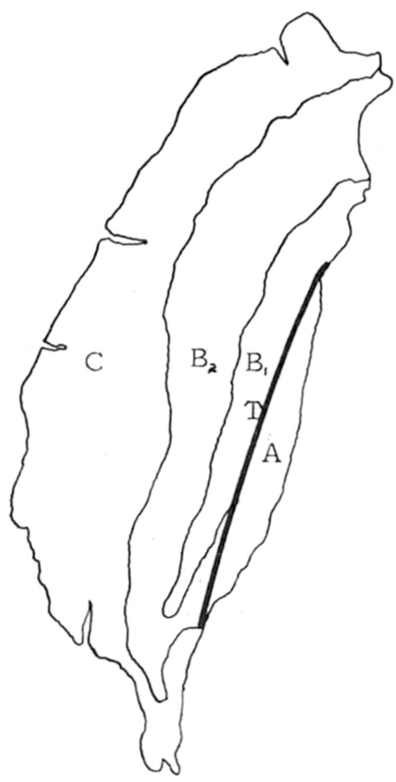

Figure VI-16. Main tectonic elements on the island of Taiwan resulting from orogenic movements after the end of Miocene time. For description of elements A, T, B_1, B_2 and C, see text.

Coastal Range in which the sediments are confused and mixed with various igneous rocks.

T: Major Thrust: Equivalent in position to the longitudinal valley the block west of this major thrust is forced by sea floor spreading to rise along the thrust plane and the block east of this major thrust, which includes the Coastal Range, plunges under along the thrust plane.

B_1: The eastern slope of the Central Range, the belt of complex pre-Paleogene intensely metamorphosed rocks, interpreted as deep seated material below the center of the geosyncline that was squeezed to come to the surface by plastic flow and was metamorphosed in the later stage of development of the geosyncline.

B_2: The west side of the Central Range, composed of a belt of slightly metamorphosed rocks, interpreted as deep seated material under the center of the geosyncline that was squeezed out in an earlier stage by plastic flow.

C: The west side of the island of Taiwan where the post-Miocene geosyncline is developed. Although the westward compression crumpled and shattered a belt close to the Central Range, farther west the folding is more gentle and favourable for bearing gas and oil.

2. The pre-Pliocene structures on the island of Taiwan are superimposed by the structures resulting from the younger orogenic movement but they may still be detected by geophysical surveys and well drilling.

3. The influence of the younger orogenic movement on the island of Taiwan extends westward but in Taiwan Strait it is already weak so that the structural trends probably represent the pre-Pliocene movement. Only further surveys can decide this question.

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VII. PLACER DEPOSITS OF DETRITAL HEAVY MINERALS IN KOREA

(Document CCOP/TAG(V)/17)

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(with figures VII-1 to VII-3 and tables VII-1 to VII-5)

ABSTRACT

Korean placer deposits generally can be divided into gold, monazite, ilmenite, silica sand and mixed heavy mineral placers; these are found in the six areas mostly distributed in western and southern coastal areas. These coastal areas are consisted mostly of Cretaceous or early Tertiary granite and Pre-Cambrian gneiss, in which east-west drainage systems are developed. The Geological Survey of Korea has summarized the data obtained from testing of more than 42 placer deposits, from 1958 to 1968, by Empiré drilling, reconnaissance surveys using hand augers, and by test pitting; however, it seems that at least half of these deposits still require further investigation. It is estimated that the total potential reserves of the placer minerals, including areas as yet unsurveyed, would be more than two or three times the present conservative estimates. Considering the lower labor cost, the cut-off grade could be lower than in foreign countries. Consequently, except for the heavy sands with high ilmenite content, the placers in Korea have some advantages because of their other more valuable mineral constituents so that, even if the grade is somewhat low, deposits containing approximately 1.5 per cent of heavy minerals could be profitably mined. At the present stage of the investigations, it would appear that 10 to 15 per cent of the 42 placer deposits already tested could be mined economically. Further detailed prospecting of the other placer deposits in Korea should be undertaken to up-grade their potential. Rational management of mining operations using modern methods, integrated management of mining, treatment and marketing, and introduction of chemical treatment to produce higher grade products for local and export markets, should make possible the successful exploitation of placer deposits in Korea, even though their grade may be lower than average in some cases.

INTRODUCTION

Some information on placer deposits of the Republic of Korea containing detrital heavy minerals has been submitted at previous sessions of CCOP (Kim, 1967; Geological Survey of Korea, 1968); these documents covered data collected by the Geological Survey of Korea in the period from 1958 to 1967. Since that time additional data have been obtained and this paper reviews the information available up to April 1969 concerning distribution, status

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Table VII–1. Distribution of placer deposits in each province of Korea, at the end of 1968; from data supplied by the Ministry of Commerce and Industry (1: Number of registered mine claims; 2: number of operating mine claims; 3: number of operating mines).

Kind of mineral	Placer gold			Placer iron			Placer tin			placer silicate			placer zircon			placer titanium			placer ceriumm			others, rare atom minerals		
province	1*	2*	3*	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Seoul	6	2	2																					
Kyungki-do	17	5		2						13	7	5				1			2			10	1	1
Kangwon-do	24	1	1	8	3	1				10	7	5				3			6			10	5	1
Chungbuk-do	3	1	1																					
Chungnam-do	53	2	2	1						33	7	2	5	5	1	3			24	6	2			
Chungnam-do	7									2	1	1				2	2	1				2		
Chunnam-do	15	2	2							39			18											
Kyungbuk-do	2			3																		7	7	4
Kyungnam-do	1									3	2	2				1								
Cheju-do				1												2			1					
Total	128	13	8	14	3	1	1			100	24	15	23	5	1	12	2	1	33	6	2	29	13	6

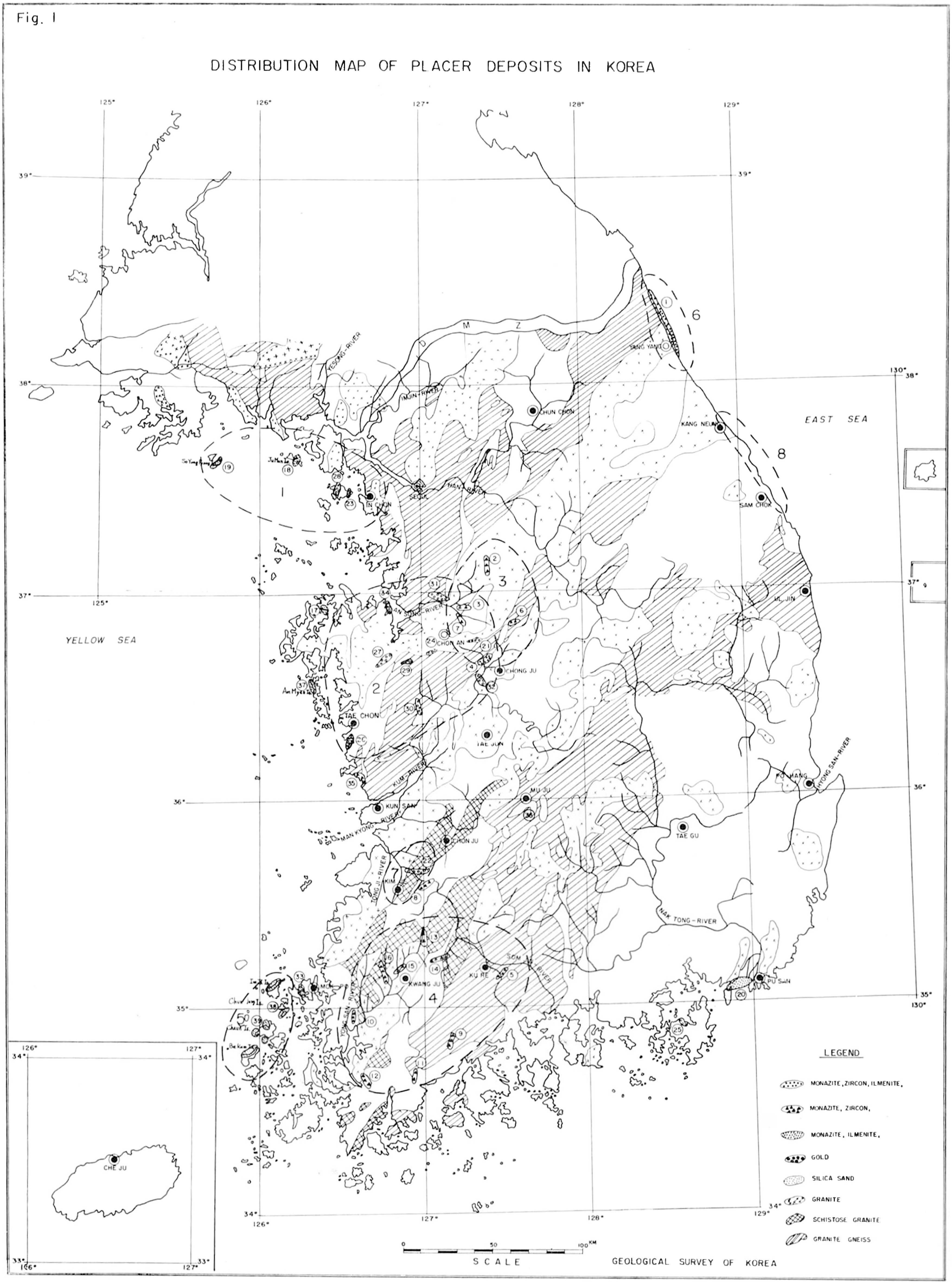

Figure VII–1. Source rock areas and location of main areas of placer deposits in the Republic of Korea.

of investigation, grade and reserves of the placer deposits, their present condition and problems involved in their development.

DISTRIBUTION OF PLACER DEPOSITS

The source rocks of the detrital heavy minerals found in the placer deposits consist of granite and granite-gneiss which are exposed over 60 per cent of the land area; granite exposures alone occupy 20 per cent of the total land area. The distribution of the source rocks is shown on figure VII–1. The granite-gneiss is of Precambrian age whereas the intrusive granites are Cretaceous or early Tertiary age; consequently, they have been subjected to weathering and erosion for long periods.

Rivers originating in the areas of source rocks follow the trends of the geologic structures and the streams meander through broad valleys in their lower courses, where banks of sand and gravel are deposited in the braided channel systems. The heavy minerals are sorted by current action and many kinds of placer deposits are formed, depending on the type of source rock in which the streams originate.

As shown in figure VII–1, most of the large rivers in Korea flow into the West (Yellow) Sea; these are named, from north to south, the Han, Ansong, Kum, Togjin and Yongsan Rivers. The larger streams in southeastern Korea, the Naktong and Somjin Rivers, flow into the Strait of Korea. On the eastern side of Korea, however, the granite and granite-gneiss source rocks are rare and the streams flowing into the East (Japan) Sea are much smaller as the main dividing range, the Taebaek Mountains, runs parallel to the east coast and only about 20 km inland from it. Accordingly, most of the placer deposits are distributed along the five large rivers and their tributaries on the western side of the Korean peninsula.

The placer deposits of Korea can be classified into the following four or five types according to the dominant minerals of potential economic value in them: gold, ilmenite, monazite, zircon and silica sand; in some cases, the deposit may be a composite of a few of the more important detrital heavy minerals, as in the case of the Kosong Beach monazite-ilmenite—zircon—magnetite deposit on the northern part of the east coast. As shown in figure VII–1, ilmenite placers are concentrated in Area 1, gold placers in Area 2, monazite in Areas 3 and 4, silica sand in Area 5 and composite placers in Area 6.

The number of mining claims registered for gold placers and silica sand, as shown in table VII–1, are 128 and 100, respectively; however, only about ten per cent of these (8 gold placers and 15 silica sand deposits) are being worked at present. In the case of other types of placers, the ratio of claims being worked to those registered is as follows: zircon, 2: 33; monazite, 1: 23; ilmenite, 1: 12; and magnetite, 1: 14. The low ratio of claims being worked may be attributed to poor grade of some deposits, low market price for product minerals, lack of technical ability and primitive working methods.

STATUS OF INVESTIGATION OF PLACER DEPOSITS

Methods of evaluation of placer deposits used by the Geological Survey of Korea up to the present time include Empire drilling, auger drilling and test-pitting. Most of the gold placers were investigated first by reconnaissance Empire drilling, followed by closer-spaced drilling if the results of the reconnaissance holes warranted it. On the other hand, most of the detrital heavy mineral deposits were evaluated by test-pitting except for a few of the more important deposits, as shown in table VII–2.

A new type of auger drill was donated to the Geological Survey of Korea by the Australian

Government in March 1969, as a result of the visit of the mining and treatment engineer (detrital heavy minerals) provided by that Government through the medium of CCOP. It has the advantage that it combines the mechanisms of the Empire drill, the core pumping method and the auger drill and it appears to be well adapted for investigation of placer deposits in Korea at less cost and time than is required by the methods formerly used.

RESERVES OF PLACER MINERALS

The estimated reserves of potentially economic minerals in 39 of the placer deposits in Korea are given in table 14–1 in the report of the fourth session of CCOP (Kim, 1967, facing page 98). The grade of the silica sand in deposit No. 38 shown in that table averages 87.2 per cent and in deposit No. 39 it ranges from 78.08 to 89.16 per cent. Similar data for three additional deposits are as follows:

Deposit No.:	40	41	42
Location:	Ungchun beach, S-Chung chong-do	Samchuk beach, Kongwon-do	Cheongju gold placer, Chung chong Buk-do
Geology:	Injection gneiss	Granite-gneiss, two-mica schist	Biotite granite, mica schist
Average thickness, alluvial sands:	+5 m	+5 m	+4.8 m
Average mineral content (grams per cubic metre)			
Monazite:	3,600	4,220	—
Zircon:	7,200	1,440	—
Ilmenite:	5,400	720	—
Magnetite:	—	10,800	—
Gold:	—	—	0.260
Estimated reserves (metric tons)			
Monazite:	4,812	18,024	—
Zircon:	9,625	4,506	—
Ilmenite:	7,219	9,763	—
Magnetite:	—	45,060	—
Gold:	—	—	(1,992 kg estimate)
Revised totals, Nos. 1—42:	Monazite, 171,358 mt; zircon, 85,215; ilmenite, 127,230; magnetite, 184,859.		

ECONOMIC CONSIDERATIONS

Placer gold

The minimum content of gold which can be profitably mined from placer deposits (the "cut-off grade") varies according to the size of the deposit and the topographic conditions; in foreign countries, large dredges can operate profitably on grades of 0.08~0.10 grains per cubic yard (0.104~0.13 grams per cubic metre). In Korea, deposits with a grade of 0.16 grams per cubic metre have been exploited by 6 cubic feet bucket-type dredge; this could be considered as the possible cut-off grade in Korea. Of the ten or more gold placers investigated by the Geological Survey of Korea, those at Seongnam, Kumje, Kumma-chon, and Cheongju could be considered as having economic potential, according to this standard. The total reserve of gold in these four deposits is estimated to be more than 8,000 kg.

Table VII-2. Status of investigation and evaluation of placer deposits in Korea.

May, 1969

Serial No.	Location	Date of Survey	Survey by	Kind of Ivestigation	Chemical analysis	Evaluation	Investigation Status
1	Kosong & Yang yang area, Kongwon-do	August 1963	Yoon, Suk Kyoo G.S.K. Hwang, In Chun Chang, Yun Hwan	Test Pit, 155 sites Empire drill 20 Holes	Have Total chemical analysis	Have data of relatively com plete or reliable evaluation	No need further invesrigation except for extended area
2	Jangho-won area, Ichon-gun, Kyonggi-do,	July 1963	G.S.K. Hwang, In Chun	Test Pit, 65 Sites	Have Total chemical analysis	Have partial evaluation	Need additional investigation
3	Soun & Miyang area, Ansong-gun, Kyonggi-do,	—	No. data Available	—	—	—	—
4	Yongdu-ri area, Chongwon-gun, S-Chung chong-do	July 1954	UNKRA, Robert B, Hall G.S.K. Roe, Hai Yong	Empire drill, 100 Holes	Partial chemical analysis	Have data of complete or reliable evaluation	No need further investigation
5	Kurae-gun area, S-Cholla-do	Oct. 1956	G.S.K. Yoon, Suk Kyoo Park, No. Young Kim, Young Sun	Test Pit, 16 Sites	No. chemical analysis	Have partial evaluation	No need further investigation
6	Jinchon Munbaek area, S-Chung chong-do	Nov. 1956	G.S.K. Yoon, Suk Kyoo Hwang, In Chun	Test Pit, 45 Sites	Partial chemical analysis	Have partial evaluation data	No need further investigation
				Test Pit, 60 Sites	Partial chemical analysis	Have data of complete or reliable's	No need further investigation
8	Euin area, Hongup-gun, N-Cholla-do	Nov. 1958	G.S.K. Hwang, In Chun Park, Byong Chul	Test Pit, 118 Sites	No chemical analysis	Have partial evaluation	No need further investigation
9	Bosong-gun area, S-Cholla-do	—	No data available	—	—	—	—
10	Yongsanpo area, Rachu-gun, S-Cholla-do	—	No data available	—	—	—	—
11	Apchon area, Kangchin-gun	—	No data available	—	—	—	—
12	Yongam-gun area, S-Cholla-do	August 1958	G.S.K. Hwang, In Chun Park, Byong Chul	Test Pit, 125 Sites	No chemical analysis	Have partial evaluation	No need further investigation
13	Tanyang-gun area, S-Cholla-do	—	No data available	—	—	—	—
14	Tanyang-gun area, S-Cholla-do	—	No data available	—	—	—	—
15	Kwangsan-gun area, S-Cholla-do	April 1957	G.S.K. Hwang, In Chun	Test Pit, 358 Sites	Total chemical analysis	Have data of complete or reliable evaluation	Need further investigation
16	Kwangsan-gun area, S-Cholla-do	April 1957	Moon, Jeong Uk Moon, Jeong Uk	Test Pit, 358 Sites	Total chemical analysis	Have data of complete or reliable evaluation	Need further investigation
17	Taesan area, Sosan-gun, S-Chung chong-do	Feb. 1966	G.S.K. Park, Byong Chul	Test Pit, 11 Sites	Partial chemical analysis	No evaluation data enough	No need further investigation
18	Chumun is, & Acha is., Kangwha-gun, Kyonggi-do	July 1959	G.S.K. Hwang, In Chun Kim, Ki Wan	Test Pit, 95 Sites	Total chemical analysis	Have partial evaluation data	No need Further investigation
19	So Yonpyong is., Kyonggi-do	—	No data available	—	—	—	—
20	Naktong delta area, S-Kyongsong-do	March 1962	G.S.K. Hwang, In Chun Kim Kyoo Bong	Empire drill, 48 Holes	No chemical analysis	Have partial evaluation data	No need further investigation
21	Songnam area, Chonwon-gun, S-Chung chong-do	June 1956	G.S.K. Hwang, In Chun Chai, Choung Il	Test Pit, 10 Sites Empire drill, 175 Holes	Partial chemical analysis	Have partial evaluation	Need further investigation partialy
22	Kumzae area, N-Cholla-do	Feb. 1962	G.S.K. Kim, Kyoo Bong Park, Byong Chul Koo, Moo Ok.	Empire drill, 137 Holes	No chemical analysis	Have partial evaluation	No need further investigation
23	Kwangmin area, Yonglong is., Kyonggi-do	Sep. 1962	G.S.K. Park, Byong Chul	Empire drill, 22 Holes	No chemical analysis	No evaluation data enough	No need further investigation
24	Baebang-myun area, Asan-gun, S-Chung chong-do	August 1965	G.S.K. Park, Byong Chul Shin, Jae Bong	Test Pit, 10 Sites Empire drill, 33 Holes	No chemical analysis	Nave partial evaluation	No need further investigation
25	Tockock area, Kojae-gun, S-Kyongsang-do	—	No data available	—	—	—	—
26	Chongso area, Boryong-gun, S-Chung chong-do	—	No data available	—	—	—	—
27	Kumsu-River, Hongsong-gun, S-Chung chong-do	March 1965	G.S.K. Park, Byong Chul Shin, Jae Bong	Empire drill 11 Holes	No chemical analysis	No evaluation data enough	No need further investigation
28	Byong area, Yongjong is Kyong gi-do	August 1963	G.S.K. Park, Byong Chul Cho, Ki Bong	Empire drill, 44 Holes	No chemical analysis	Have partial evaluation data	No need further investigation
29	Taeyang area, Yaesan-gun, S-Chung chong-do	April 1964	G.S.K. Park, Byong Chul	Empire drill 89 Holes	No chemical analysis	Have partial evaluation data	No need further investigation
30	Iin area, Kongchu-gun,	May 1964	G.S.K. Park, Byong Chul Sin, Jae Bong	Empire drill 61 Holes	No chemical analysis	Have partial evaluation data	No need further investigation
31	Pyongtaek area, Kyonggi-do	—	No data available	—	—	—	—
32	Chochiwon area, S-Chung chong-do	—	No data available	—	—	—	—
33	Muan area, S-Cholla-do	Oct. 1953 Dec. 1958	UNKRA R.B. Hall G.S.K. Kim, Won Jo Shang Ki Nam	Empire drill, 81 Holes	Total chemical analysis	Have data of complete or reliable evaluation	No need further investigation
34	Tangchin Beach area, S-Chung chong-do	July 1964	G.S.K. Park, Byong Chul Shin, Jae Bong Kim, Chul Min	Empire drill, 48 Holes	No chemical analysis	Have partial evaluation data	No need further investigation
35	Biin Beach area, S-Chung chong-do	—	No data available	—	—	—	—
36	Muju area, N-Cholla-do	—	No data available	—	—	—	—
37	Anmyen-do area, S-Chung chong-do	—	No data available	—	—	—	—
38	Chun jung-do area S-Cholla-do	—	No data available	—	—	—	—
39	Chaun do area, S-Cholla-do	—	No data available	—	—	—	—
40	Ung Chun beach area, S-Chung chong-do	April 1969	G.S.K. Yoon Keun Shin Lee Jeong Koo Han Boo Kap	Auger test, 78 Holes			
41	Sam Chuk beach area, Kangwon-do	April 1969	G.S.K. Lee Jeong Koo	Auger test, 19 Holes			
42	Cheong-Ju area, S-Chung chong-do	July 1968	G.S.K. Lee Jeong, Koo Kim, Byong Chun	Empire drill, 96 Holes	No chemical analysis	Have partial evaluation data	Need further investigation

Detrital heavy minerals

The cut-off grade for the detrital heavy minerals other than gold depends on many factors. The content of the more valuable among these minerals, their recoverability, conditions at the site of operations, the mining method used, type of treatment plant and market conditions are among the factors to be taken into consideration for establishing the cut-off grade for profitable exploitation of placer deposits in Korea.

In Natal, South Africa, a large scale plant, with capacity of 270 tons per hour of raw sand has been treating raw sand containing 1.5 per cent of heavy sand with an ilmenite content of 61 per cent; in this case the return per ton of raw sand treated is less than US$1.00.

Reliable surveys of the 20 detrital heavy mineral deposits in Korea show that four or five of them contain an average of more than 1.5 per cent of heavy concentrates, usually consisting of about 30–50 per cent of ilmenite, 30–40 per cent of monazite, 10–30 per cent of zircon and lesser quantities of other heavy minerals. If the value of the minerals in the raw sand is taken as being about US$1.00 per ton, the following conditions would need to be met for profitable operation in Korea: (1) Treatment of the raw sand must be at the rate of 30–50 tons per hour; (2) where sluice boxes are used, more than two sets, 50 metres long and 2 metres wide, should be installed; (3) if the Humphrey-spiral method, considered to be better than sluice boxes, is used, more than 50 sets of the Humphrey-spiral would be required; (4) a pinched sluice tpye of heavy sand dressing machine, developed recently in Australia, might prove to be more suitable for both beach sands and inland placers in Korea.

Treatment cost of the raw sand is a key point for economic operation of placer deposits and, in some foreign countries, it is reported to range between 15 and 25 cents (US) per ton, and the cost of treating the heavy sand concentrates should be in the range of US$2.50 ~ 3.50 per ton. A suitable flow-sheet system for treatment of the heavy sand concentrates must be selected on the basis of the character of the concentrates and some guidance for this is given in the report of the Australian mining and treatment engineer on his visit to Korea (document CCOP/TAG (V)/6). A representative example of a detrital heavy mineral placer deposit in Korea is examined to determine the cut-off grade and minimum treatment cost for profitable exploitation, as follows:

a: Content of heavy minerals in the raw sand is 1.5 per cent.

b: Assume 50 per cent of ilmenite, 30 per cent of monazite, 10 per cent of zircon and 10 per cent of magnetite in the heavy fraction as a standard content.

c: Then the value of marketable minerals contained in one ton of raw sand is $0.85.

d: If 100 per cent of the heavy fraction consists of ilmenite, the value becomes $0.30 per ton.

e: About 100 tons of raw sand would yield one ton of the heavy mineral concentrates assuming 75 per cent recoverability.

f: The value of 100 tons of raw sand is determined as follows:

(1) In the case of 100 per cent ilmenite in the heavy fraction:
value (dollars) = $0.30/M.T. × 75/100 (recoverability) × 100 M.T. = $22.50.

(2) In the case of standard content:
value (dollars) = $0.85/M.T. × 75/100 (recoverability) × 100 M.T. = $64.

g: Assume a cost of $2.50 to $3.50 per ton of heavy mineral concentrate for separating the heavy fraction into its marketable constituent minerals.

h: Assume transportation and packaging charges of $3.00 per ton of heavy mineral concentrate.

i: Assume overhead cost of management and miscellaneous expenses at the rate of $4.00

per ton of heavy mineral concentrate.

j: $g+h+i = \$10.00$

Therefore, when (j) is taken into account with (e) and (f), the minimum allowance cost for one ton of raw sand is as follows:

(1) In the case of heavy sand which contains 100 per cent of ilmenite:
$22.50–$10.00 = $12.50
$12.50÷100 (quantity of raw sand which contains 1 ton of recoverable heavy sand) = $0.125 per ton.
By the same process,

(2) In the case of the standard content:
($64–$10)÷100 = $0.54 per ton.

k: As mentioned previously, if the standard treatment cost per ton of raw sand is taken as $0.20, it is concluded that heavy sand of 1.5 per cent in grade could not be economically profitable in the case of a high content of ilmenite; however, in the case of standard content (b, above), the heavy sand of 1.5 per cent grade could be theoretically profitable.

The total cost per ton of heavy sand to get a final product would be calculated as $g+h+i+k$; $(\$3+\$3+\$4)+(\$0.2\times 100) = \$30.00$.

STATUS OF DEVELOPMENT OF PLACER DEPOSITS IN KOREA

Before the second World War, up to 1942, more than 30 dredges were operated in Korea for placer gold and the annual production was more than one ton in weight. Since 1945, only two gold placer deposits have been mined to produce a total of less than 600 kg during the period from 1954 to 1968.

Monazite has been the main detrital heavy mineral produced from placer deposits in Korea (see table VII–3). From 1951 to 1957, a period of increasing demand for monazite, the production in Korea totalled 4,000 to 5,000 M/T, all of which was exported to foreign countries. After that period the demand decreased sharply and prices fell; consequently, the

Table VII–3. Production of minerals from placer deposits in Korea

Minerals / Year	Placer gold (grams)	Iron sand	Monazite (M.T.)	Zircon (M.T.)	Ilmenite (M.T.)	Silica sand (M.T.)
1954	143,414		1,005			
1955	115,065		508			230
1956	82,044		184			250
1957	12,741		355			1,111
1958	62,014		322			3,844
1959	39,546					3,170
1960	916					
1961	10,423					
1962	8,974					
1963	925					16,393
1964	603		37			49,718
1965	215		10			34,008
1966	180			8		37,743
1967	43,958			5		43,958
1968	13,866		9	4	23	49,050
Totals:	534,884	0	2,430	17	23	239,475

production of placer minerals decreased and they could not be profitably exploited. In December 1968, the number of placer mines being worked in Korea totalled only 36. As shown in table VII–1, these include mines operating for silica sand (15), placer gold (8), zircon (2), iron sand (magnetite) (1), monazite (1), ilmenite (1) and six others for rare element heavy minerals.

The main reasons why placer deposits are not being actively developed in Korea at present appear to be: (a) insufficiency of detailed survey data needed for proper evaluation of the economic potential of the deposits; (b) lack of experience in modern methods of separation of the marketable heavy mineral constituents; (c) scarcity of capital and lack of knowledge of modern techniques by the mine owners; (d) difficulties in mechanizing the operations because of lack of experience; (e) the relatively small domestic market for detrital heavy minerals and the low prices for some of them, in the international market; and (f) the lack of local companies with sufficient experience to be able to operate an integrated organization combining systematic mining operations, mineral dressing and foreign marketing.

This situation must be solved and improved as soon as possible. Fortunately, some of the companies are now beginning to investigate an overall plan of management through the stages of systematic methods in mining, treatment and marketing, together with the introduction of new capital. Feasibility studies for the development of placer deposits also include the possibility of constructing chemical treatment plants for TiO_2, with monazite and zircon as secondary products.

One company, which considers the potential of gold placers in Korea to be very high, has planned to construct two or three dredges for working gold placers, at the rate of 3,000 metric tons per day. The first plant would be located in Asan Bay for extraction of gold from beach sands; the gold reserves of this area are estimated to be more than 20 tons.

At least three companies have planned to construct heavy sand treatment plants. One of these plants, already installed at Pusan city, is relatively well equipped and has a capacity of more than 30 MT/day; however, it requires further improvement in the automatic feeding systems and operating processes.

Tables VII–4 and 5 show the equipment available at the Pusan heavy mineral separation plant and the Seonghwan monazite treatment plant, respectively; figures VII–2 and VII–3 show the flow sheets for operations at the Chunan chemical leaching plant for treatment of monazite and the Chunan magnetic separator plant for separating the constituent detrital heavy minerals.

Table VII–4. Equipment at Pusan treatment plant, Republic of Korea

Name	Capacity	No. of set	Maker
1. Humphrey Spiral	42 M.T./hour	81	Australia
2. Dryer	10 per cent moisture base 2–3 M.T./hour	2	U.S. Carp. Co.
3. Electro-static Separator	5 M.T./hour 2 M.T./hour	1 1	U.S. Carp. Co. U.S. Carp. Co.
4. Roll type Magnetic Separator	5 M.T./hour	1	U.S. Carp. Co.
5. Air Table	1 M.T./hour	1	U.S.?
6. Cross Belt	1 M.T./hour	1	West German Hambolt
7. Drum Magnetic Separator	3 M.T./hour	1	West German Hambolt

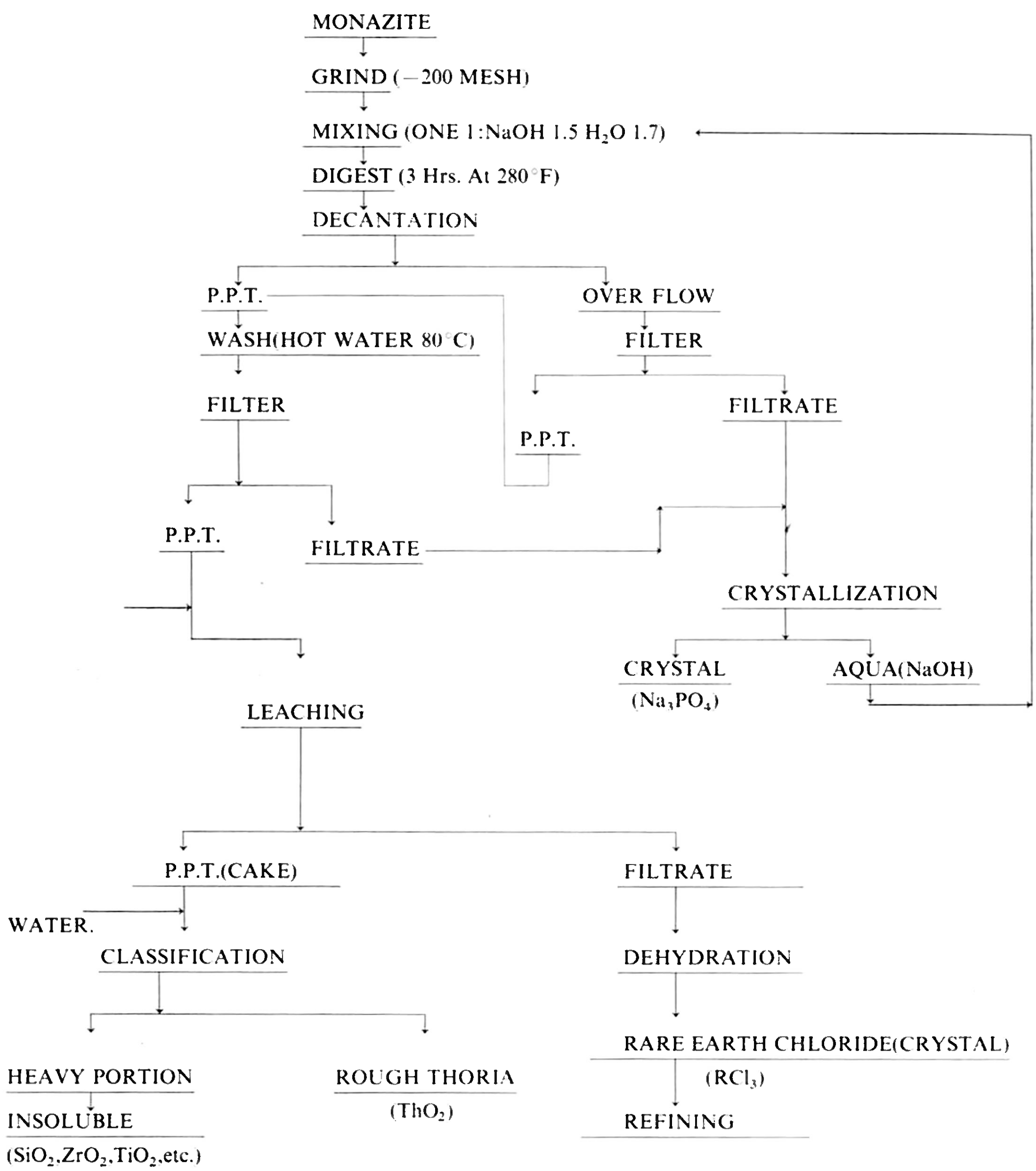

Figure VII–2. Flow sheet of Chunan chemical leaching plant, Republic of Korea.

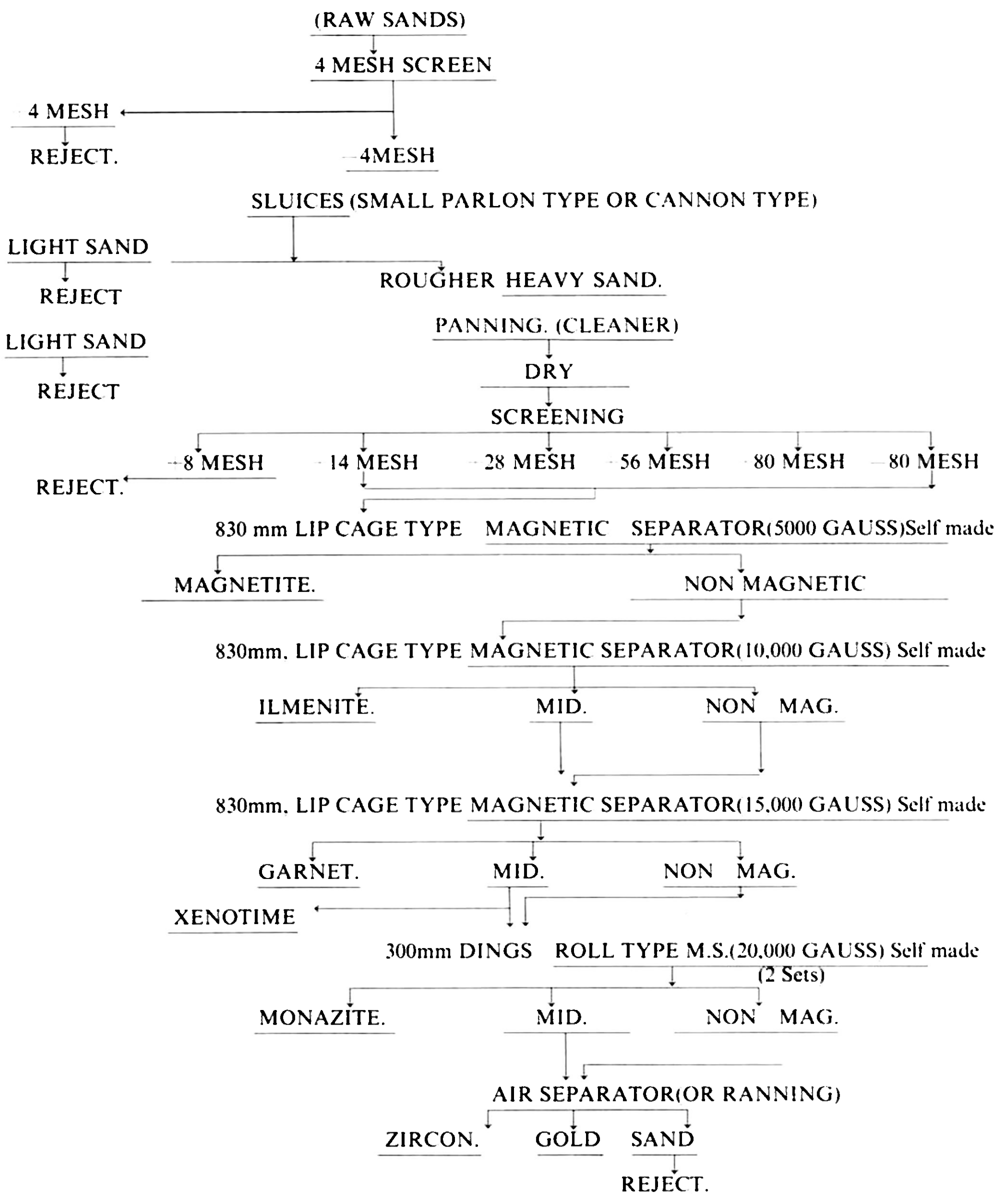

Figure VII–3. Flow sheet of Chunan magnetic separator plant, Republic of Korea.

Table VII-5. Ore dressing equipment at the Seonghwan monazite small treatment plant, Republic of Korea (Property of K.D. Co.)

Name	Capacity (MT/Day)	Unit	Q'ty	Remarks
Ding's magnetic separator	5	set	-2-	made in U.S.A.
Carp Co. magnetic separator	2	set	-1-	made in U.S.A.
High tension separator	2	set	-1-	made in U.S.A.
Humphrey's spiral separator	100	set	-7-	Australia

PLAN FOR RATIONAL DEVELOPMENT

There is no doubt that a plan for rational development is needed for the exploitation of what has not been developed actively to date and to overcome the local deficiencies outlined earlier; however, more time is needed to accomplish this.

Joint cooperation of technically qualified and experienced local personnel is needed, together with the import of the techniques necessary for the construction and operation of chemical treatment plants. The plan for rational development should include:

(a) Adequate detailed investigation for evaluation of the economic potential of placer deposits.

(b) Appropriate mining methods and sound management plans suited to the scale and character of Korean placer deposits must be developed.

(c) Mobile treatment plants should be used for working a number of smaller scale deposits.

(d) The owner of the enterprise should have all the technicians, skilled workers, equipment, and facilities needed for his operations.

(e) Account should be taken of the very competitive international market for detrital heavy minerals and long term contracts should be sought to ensure stability of the enterprise.

(f) Not only the high grade placer deposits but also the middle grade deposits should be exploited by attempting to construct chemical treatment plants as well as by cultivating and expanding domestic utilization, together with foreign markets.

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VIII. OCEANOGRAPHY AND LIMNOLOGY IN MAINLAND CHINA[1)]

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(with tables VIII-1 to VIII-3)

ABSTRACT

Since 1949 Mainland China has directed considerable research efforts towards the development of the fishing industry, the exploitation of aquatic resources, and environmental control and prediction. The scientific results of these efforts are reviewed under the general categories of marine biology, physical oceanography, chemical oceanography, marine geology, and limnology. Brief considerations are also given to research organizations in mainland China, and to their oceanographic publications in terms of journals, books, monographs, and translations.

INTRODUCTION

The present survey of oceanographic and limnological research in Mainland China is based on information extracted from some 450 issues of Chinese scientific journals published between 1949 and 1966[3)]. Although these journals provide a rather good coverage of the published literature, our study is necessarily limited in scope because of the incomplete availability of material and, what is probably more important, because military-oriented efforts are not reflected in the form of publications. Nevertheless, it is hoped that this article still can give a comprehensive account of the efforts and progress that have been made in China for this relatively new field of scientific endeavour.

Oceanographical and limnological research in China, though initiated in the nineteen thirties, was almost entirely interrupted by the nation's political situation and wars in the ensuing years. It was not until about 1956 that the Chinese were able to increase their research activities and start launching oceanographic programs on a national scale. Like other scientific research in the country, oceanography has been pursued for the purpose of developing production and is integrated with production practice. The early phases of research were mainly guided by three explicit goals: the development and exploitation of marine resources, the understanding and prediction of oceanic conditions, and the strengthening of national defense. Thus, research projects completed during the fifties were directed largely toward the development of fishery and aquaculture, the study of waves, tides, nearshore currents, and hydrochemistry of lakes and water reservoirs, and the prediction of environmental conditions for navigation and for marine, submarine, and anti-submarine warfare. With the advent of

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3) Since the fall of 1966 following the start of the Proletarian Cultural Revolution, scientific journals have been unavailable outside of China. However, whether a parallel stagnancy in research has occurred since then remains to be seen.

the present decade, a trend emphasizing the more fundamental aspects of research began to emerge and the number of publications also started to multiply. Reviewing the developments in the period 1949–1966, it is perhaps fair to comment that while Chinese oceanographic activities have so far been rather limited in scope, their approach has been systematic and their orientation well-defined. Furthermore, it is encouraging to learn that Chinese researchers are quite aware of activities outside the country.

RESEARCH ACTIVITIES ON OCEANOGRAPHY AND LIMNOLOGY IN MAINLAND CHINA

Like most other countries newly entering the scientific quest in oceanography, a major part of the mainland Chinese effort is devoted to marine biology. This is demonstrated by the statistics shown in Table VIII–1. Noteworthy are the dominance of publications in the biological discipline, and the rising interest in physical and chemical oceanography. Contributions in the fields of underwater acoustics, ocean engineering and marine geophysics are probably classified, and have not been included in the Table. However, it is felt that their inclusion probably would not alter significantly the picture presented here.

Table VIII–1. Percentage distribution of publications in the various oceanographic disciplines.

Discipline / %	biological	physical	chemical	geological	other[1]
1952–1960	74	5	3	7	11
1961–1966	64	10	10	6	10

1) This includes reviews, commentaries and articles related to instrumentation and analytical techniques, but excludes translations.

Marine Biology

Marine biological investigations have mainly been conducted in coastal waters on the taxonomy, classification and geographical and biomass distribution of the major flora and fauna, including planktonic foraminifera (Cheng and Cheng, 1963; 1964), radiolaria (Tchang and Tan, 1964; 1965), copepods (Chen and Zhang, 1965), cephalopods (Dong, 1963), mollusca (Tchang and Tsi, 1959; Tchang et al., 1963; Lin and Tchang, 1965), algae (Tseng and Chang, 1959a; 1959b; 1964, Shi and Chin, 1965), echnoids (Chang and Woo, 1957) and marine Cladocera (Cheng and Chen, 1966). One can discern a progressive trend in which emphasis has been shifting from classification to ecological studies, and from species description to the study of zoo- and phyto-geographic distribution and species (and sub-species) differentiation. A commendable measure adopted by the Chinese workers is their uniformity on certain experimental and result-reporting procedures (such as for species concentration), which greatly facilitates direct comparison of the outcome of different investigations (Planktology Division, 1959).

Survey and exploitation of marine resources, particularly of important food fishes, remain to be an area of primary interest. For example in 1959, a special group was established within the Institute of Oceanology of the Chinese Academy of Sciences (Academia Sinica) for the study of the yellow croakers (*Pseudosciaena polyactis* and *P. crocea*), (Wu, 1965; Chen and Yen, 1965), and subsequently a recommendation was made to postpone the fishing season to the fall and winter months so as to increase the catch (Luo, 1966). Besides the yellow croakers, the Japanese mackerel (*Pneumatophorus japonicus*). *Acetes chinensis*, and several other major food fishes were also intensively studied. Numerous investigations were made on fish parasites and fish diseases (Chen, 1956; Lee, 1963; Wen and Hui, 1963; Yin, *et al.*, 1963; Long and Lee, 1964), as well as on the effects of pollution upon the hydrobiological and physico-chemical conditions of rivers (Lu, *et al.*, 1963). Parallel to these fish-related studies are efforts toward the promotion of economically important faunal forms such as *Mytilus* spp. (Cai, 1963), *Porphyra* spp. and *Ostrea* spp. (Tchang *et al.*, 1959), and the control of pernicious forms like *Teredo* spp. and the various fouling organisms (especially the barnacles, Lou and Liu, 1958; Wu and Cai, 1963; Li, 1965).

A notable contribution from the Chinese is the study on the experimental ecology and biochemistry of marine algal flora. Methods for the growth and development of *Laminaria japonica* Aresch have been devised (Fang and Li, 1964; Fang et al., 1965; Fang and Li, 1965), and based on a series of cultivation and transplantation experiments performed on this species along the Chekiang coast (Tseng, 1957; Tseng, *et al.*, 1963), commercial production has been made possible since 1958. Extensive analytical work has been carried out on 681 species of marine algal flora found in the Chinese coastal region (Tseng and Chang, 1962). Extraction of algin from one of the species (*Sargassum pallidium*) which occurs abundantly along the north China coast has been very thoroughly investigated during the period 1952–1955 (Tseng *et al.*, 1962; Ji and Shi, 1962; Ji and Zhang, 1962), and in 1957, an algin factory using *Sargassum* as raw material was established in the city of Tsingtao. The cultivation of cellular algae to provide food for the larvae of invertebrates also met with considerable success.

More basic and theoretical aspects of marine biology have been given close attention only since the present decade. Two examples are the work on the comparative biochemistry of marine bioluminescence (Hsueh, 1964) and the use of C^{14} technique in the investigation of primary plankton productivity.

Physical Oceanography

Research in physical oceanography comprises about one-tenth of the total published output. Theoretically, considerations have been given to the prediction of large-scale tidal waves (You and Tseng, 1959; Chen, 1965), wind wave spectrum (Wang, 1964) drift and upwelling currents (Li and Wang, 1965) and wind driven waves in a semi-closed region of the sea (used as a first order model for the Gulf of Pohai) (Y.D. Ho, *et al.*, 1959). Observationally, detailed measurements were made on the formation and properties of the Yellow Sea cold water mass, which is exceedingly stable and exists year round off the Chinese coast (C.P. Ho, *et al.*, 1959). Quantitative treatment using T–S diagrams has been developed for the analysis of shallow water masses (Xi, *et al.*, 1965) and applied to such problems as the mixing processes of the Yangtze diluted water in the East China Sea and the distribution of the Yellow Sea cold water mass (Mao, 1963; Mao, *et al.*, 1964). Other more significant studies include the relationship between sea surface temperature and general circulation (Lü, *et al.*, 1964), and the characteristics of air-sea energy exchanges in the North Pacific during 1959 which had a direct bearing on the drought that hit the Chinese mainland in that particular year (Chen and Zhang, 1964). Based on the data collected during 1956–1961 by Japanese workers, an analysis was made on the distribution and variation of volume transport and surface velocity of the Kuroshio and their relation to bottom topography (Kwan, 1964). It was concluded that the magnitudes of velocity and transport are proportional to the frictional slope of the sea surface, and that while the Kuroshio has greater annual and secular variations of strength compared to the Gulf Stream, its axis (located near the shelf break) is more stable. In addition, it was found the velocity, transport, and the presence of a countercurrent on the eastward side are all strongly influenced by the bottom topography.

Aside from the activities outlined above, it is conceivable that a sizable portion of the research effort, particularly in the fields of physical and acoustical oceanography, was classified. For instance, even in the published literature, the exact locations where certain measurements were made sometimes are not specified. A review article (You and Qiu, 1964) indicates that studies have been made on sound scattering at sonic frequencies, short and long period internal waves and their propagation, environmental noise, microstructure and temporal fluctuations of temperature, salinity and sound velocity, and on the deep and shallow sound channels and their seasonal variation and relation to the structure of the water masses in the East China Sea.

Chemical Oceanography

Published work in the field of chemical oceanography and limnology is still rather scanty; the few reports that were encountered are mostly confined to the period after 1960. Apart from developing analytical techniques, determinations of the distribution of isotopes (Zhang, *et al.*, 1959) and the seasonal variation of temperature, salinity, oxygen and nutrient elements were made, notably in lakes and fresh water reservoirs. Signs of a beginning interest in subjects of a less routine nature are found in such articles as on the physico-chemical processes of silicate in estuaries (Li, *et al.*, 1964) and on the problem of the oxygen maximum observed during the summer months in the China Sea (Gu, 1966). Geochemical studies on elements occurring in sea water have been made (Koo, 1965), but as yet, no chemical investigations on bottom sediments have been reported.

Marine Geology

A study of the continental shelf was made by a group in the Institute of Oceanology during 1958–1962. Based on this study and results of previous work by Russian, U.S., and Japanese investigators, Fan and Ching (1959) and Ching (1963) published two charts showing the bathymetry (contour interval 10 m) and sediment distribution of the continental shelf off the Chinese coast. Two sedimentary units have been distinguished. Deposits of the inner shelf consist mainly of recent river-transported material characterized by low $CaCO_3$ and foraminiferal contents and well-sorted sand layers. The outer shelf deposits are relatively rich in $CaCO_3$ ($>20\%$) and foraminifera ($1{,}000 \sim 10{,}000$/gm sediment), and low in organic matter ($<0.5\%$). These sediments, to which a Holocene age has been ascribed, are generally phosphatized and glauconized. Other studies show that there were large sea level fluctuations during the Quaternary along the coast of China (Jen, 1965), and that the Pohai Strait was formed during Late Pleistocene or early Holocene (Jin and Zeng, 1964). Considerable work has also been done on the morphological development of estuaries and deltas (notably those of the Yangtze, e.g., Chen, 1957, and the Chien Tang Chiang, Chien *et al.*, 1964) and on the source, mineral composition, and transport processes of sediment loads in the major rivers of the country.

Limnology

Limnological research in mainland China began to be systematized and organized in 1958, with the establishment of a Limnology Division in the Geographical Institute of the Chinese Academy of Sciences. Reorganization in 1961 placed the Division under the Nanking Geographical Institute. With extensive co-operation from several universities in the country, the Division launched large-scale surveys of some 12 lakes (such as Taiho and Lake Tungting) along the Yangtze valley (Shih, 1964). These surveys include studies in geomorphology, hydrology, water level, sediment load, biological conditions (e.g., the abundance and seasonal variations of planktons, benthos, aquatic vascular plants and fishes), and physical and chemical properties of lake water (e.g. temperature, transparency, pH, alkalinity, contents of dissolved oxygen and nutrient salts. See for instance, Chu and Yang, 1959; Ley, *et al.*, 1963). Recommendations were often made on the initiation or improvement of acquaculture, irrigation, and fish-production and management. Similar surveys have been extended to dam-reservoirs (e.g. Tsao, 1959; Huang, 1964; Shu, 1964), as well as to lakes in remote areas like Inner Mongolia, Yunnan Plateau (Ley, *et al.*, 1963), Tsinghai (Liu, 1959) and Tibet (Jao, 1964). The Nanking Geographical Institute also operates in Yishin (a city in the Kiangsu province) a limnological laboratory equipped with a 100 m^2 and a 20 m^2 evaporation pool for time-series observations.

RESEARCH ORGANIZATIONS

A major portion of oceanographic research in mainland China is under the direction of the Chinese Academy of Sciences conducted in a number of research institutes, the most active among which is the Institute of Oceanology located in the city of Tsingtao, which runs several research stations along the coast. Other parallel organizations include the East China Institute of Oceanology, South China Sea Institute of Oceanology, and the Institutes of Marine Biology, Hydrobiology, Biology and Zoology. Also involved in certain aspects of marine and lake studies are the Institutes of Geology, Geophysics and Geography which are subordinated to the Ministry of Geology. The general pattern for the various organizational units at the national and local levels has been outlined by Orleans (1967) but the detailed picture of the management and direction of the various research institutions remains unclear. About 73% of the published oceanographical and limnological literature during 1949–1966 was contributed by the Academy. Nineteen percent came from institutions of higher education, notably the Shantung College of Oceanography, Shantung University, Wuhan College of Fisheries, Wuhan University, Amoy University, Shanghai College of Fisheries, Sun Yat-Sen University, Peking University, Nanking University, East China College of Water Conservancy, Harbin Fisheries University, and Hunghu University. The balance of 8% was made up by contributions from research institutes under the Chinese Ministry of Fisheries and from local government laboratories in the coastal provinces of Kwangtung, Fukian, Chekiang, Kiangsu and Shantung. Cooperation between the universities and the Academy research institutes and the industry is evident from the authorship and its affiliations indicated in publications.

CHINESE OCEANOGRAPHIC PUBLICATIONS

A close look at the published literature reveals that Chinese researchers do have reasonable access to foreign works in spite of the adversity in communication. About one quarter of the authors quote references to within two years of the date of publication of their papers, and literature from the English-speaking world is very well represented (Table VIII–2).

Table VIII–2. Distribution by language of references quoted by Chinese authors.

Language	English	Chinese	Russian	Japanese	French	German	Other[1]
%	55	18	11	5	5	4	2

1) Spanish, Italian, Swedish and Latin.

One characteristic of Chinese journals in the early period is the large number of articles written by Soviet scientists. These articles, which sometimes comprised as much as 40% of the printed pages, were often in the form of research policy recommendations or suggestions for research activities (e.g., Bogorov, 1957; Samoilov, 1958). There were also a number of joint Sino-Soviet expeditions (Gurjanova *et al.*, 1958; Chen, 1963). After 1960, however, Russian contributions sharply declined, a fact which we interpret as indications of rising Chinese activities as well as of deteriorating political relationship between the two nations.

There are five major publications in oceanography and limnology in mainland China (Table VIII–3). They all furnish foreign language abstracts, of which English is used most frequently (70%), followed by Russian (25%), French and German. The leading journal in the field (*Oceanologia et Limnologia Sinica*) has in addition foreign language figure and table captions. Such a usage, if adopted universally, would certainly render the Chinese literature more informative to the western reader.

Table VIII–3. Major Chinese oceanographic journals.

[1]Journal	Edited by	Publisher	First Published	Freq. of Publication
(a)	Chinese Society of Oceanography and Limnology	Science Publ. House, Peking	1957	Quarterly
(b)	Institute of Oceanology, Chinese Acad. of Sciences	Science Publ. House, Peking	1962	Semi-annual
(c)	Institute of Hydrobiology Chinese Acad. of Sciences	Science Publ. House, Peking	1956	Quarterly
(d)	Institute of Marine Biology Chinese Acad. of Sciences	Science Publ. House, Peking	1957	Annual
(e)	Institute of Oceanology, Chinese Acad. of Sciences	Science Publ. House, Peking	1959	Annual

[1](a) Oceanologia et Limnologia (Hai Yang Yü Hu Chao)
(b) Studia Marina Sinica (Hai Yang K'o Hsüeh Chi K'an)
(c) Acta Hydrobiologica Sinica (Shui Sheng Sheng Wu Hsüeh Chi K'an)
(d) Bulletin of the Institute of Marine Biology, Chinese Academy of Sciences (Chung Kuo K'o Hsüeh Yüan Hai Yang Sheng Wu Yen Chiu Suo T'sung K'an).
(e) Bulletin of the Institute of Oceanology, Chinese Academy of Sciences (Chung Kuo K'o Hsüeh Yüan Hai Yang Yen Chiu Suo T'sung K'an).

Papers dealing with the marine sciences are also found throughout publications specializing in other fields. The more important of these are listed below:

(1) Acta Zoologica Sinica (Tung Wu Hsüeh Pao)
(2) Acta Botanica Sinica (Chih Wu Hsüeh Pao)
(3) Acta Geophysica Sinica (Ti Ch'iu Wu Li Hsüeh Pao)
(4) Acta Geologica Sinica (Ti Chih Hsüeh Pao)
(5) Acta Geographica Sinica (Ti Li Hsüeh Pao)
(6) Acta Meteorologica Sinica (Ch'i Hsiang Hsüeh Pao)
(7) Acta Biochemica Sinica (Shen Hua Hsüeh Pao)
(8) Scientia (K'o Hsüeh T'ung Pao)
(9) Chinese Journal of Biology (Sheng Wu Hsüeh T'ung Pao)
(10) Chinese Geological Review (Ti Chih Lun P'ing)
(11) Chinese Journal of Geological Sciences (Ti Chi K'o Hsüeh)
(12) Journal of Shantung University (Shantung Ta Hsüeh Hsüeh Pao)
(13) Journal of Amoy University (Hsia Men Ta Hsüeh Hsüeh Pao)
(14) Amoy Fisheries Journal (Hsia Men Shui Ch'an Hsüeh Pao).

The amount of research output in the form of monographs and books is rather difficult to assess. From the announcements of publishers appearing in journals, we estimate that at least a dozen treatises summarizing specific research results have been published since 1960. The following are a few examples:

(1) Principles of Ocean Currents. Edited by C. H. Chin, Science Publishing House (Peking), 465 pp., 1966.

(2) Marine Fishes of China. Edited by the Institute of Oceanology of the Chinese Academy of Sciences, Science Publishing House (Peking), 174 pp., 1964.

(3) General Planktology, T. K. Tseng, *et al.*, Science Publishing House (Peking), 1964.

(4) Fresh Water Pesciculture in China. Edited by the Committee on Fresh Water Pesciculture, Science Publishing House (Peking), 612 pp., 1961.

(5) Bivalve Mollusca of the South China Sea. Edited by the Invertibrate Section, Institute of Oceanology, Chinese Academy of Science, Science Publishing House, (Peking), 274 pp., 1960.

Book translation in mainland China appears to be quite active. The Chinese version of "The Oceans" by Sverdrup, Johnson, and Fleming was published just after the 1966 Red Guard upheaval. Translations of scientific articles appear regularly in the major journals, introducing new fields, new techniques and recent theories. Collections of translated papers pertaining to a particular subject (e.g., underwater acoustics, marine microbiology) are also available.

Chinese scientific literature is rather difficult to procure in the United States. So far there has been no official cultural exchange between the two countries, and library accessions in the U.S. are obtained only through private purchase (mostly from Hong Kong) and unofficial exchange. Since the fall of 1966, Communist China has either stopped or curtailed the export of her scientific publications, and no journal issues have become available outside the country.

With regard to Chinese oceanographical and limnological literature in the U.S., the Library of Congress certainly has the best (though by no means complete) collection. Other libraries which also have substantial holdings include the Yenching Institute of Harvard University, the Hoover Institution of Stanford University, and the libraries of the Massachusetts Institute of Technology, Cornell University, and the University of California at Berkeley.

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中國大陸的海洋學和湖沼學

摘　　要

自一九四九年以來，中國大陸海洋學和湖沼學的發展以促進生產爲目的．其研究工作多以發展漁業，開發天然資源和改良環境預報爲標．文中把這些研究工作的科學成果分類爲海洋生物，海洋物理，水化學，海洋地質和湖沼學等，逐一討論．此外對中國大陸的研究組織及當海洋學有關的刊物（如科學期刊，書籍，專文，和譯本等）亦有簡短的論述．

IX. FORAMINIFERA IN THE BOTTOM SEDIMENTS OFF THE SOUTHWESTERN COAST OF KOREA

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(with figures IX-1 to IX-3, plates IX-1 to IX-3 and table IX-1)

ABSTRACT

Bottom sediments off the southwestern coast of Korea, bounded by latitudes 34°00'N and 37°30'N and longitudes 124°00'E and 125°00'E were sampled in May, August and December 1969; dredged samples were taken from 53 sites and cored samples from 13 sites. No samples were obtained from dredging at site No. 3 and coring was unsuccessful at sites 4, 5, 6, 7 and 8. For study of the foraminifera, 12 dredged samples and 9 cored samples were processed; these were taken during the first cruise, using the ship, Baeggyeongho (380 tons). The bottom sediments taken during the second and third cruises were also used to determine the colour and grain size of the bottom sediments for inclusion in the present paper. In the bottom sediments examined for their content of foraminifera, 14 species belonging to 6 genera of planktonic foraminifera and 124 species belonging to 57 genera of benthonic foraminifera have been identified.

INTRODUCTION

Bottom sediments of the Yellow Sea, off the southwestern coast of Korea, were sampled by geologists of the Geological Survey of Korea during three cruises made in 1969. Thirteen samples were taken by dredging and coring, from the survey vessel **Baeggyeong-ho** (380 tons), during 10 days from 10 May 1969. On this first cruise, bottom sampling, temperature measuring, and water sampling for salt content were undertaken; no bottom sediment could be obtained by dredging at site No. 3. Sea bottom coring was tried for the first time in Korea, using the Niino-type core sampler; at the thirteen sites sampled, no cores could be obtained from Nos. 4, 5, 6, 7 and 8; at sites 2, 3 and 10, the cores recovered were about 0.5 metre long, and at sites 1, 9, 11, 12 and 13, about one metre long. The data obtained from site 13, near Busan, is not dealt with in this paper.

Portions of the dredged and cored samples, weighing 50 and 30 grams respectively, were washed to separate the foraminifera. Time did not permit the writers to analyze the whole sequence of each core, and only the lowest parts of the cores were washed and analyzed; results of further studies will be presented in other papers.

Participants in the studies conducted on the first cruise of the Baeggyeong-ho were: Professor Bong Kyun Kim, Mr. Sungwoo Kim, Mr. Jae Du Kim and Mr. Hyun Il Choi of the Geological Survey of Korea; Kyu Baek Um, Assistant Professor, Department of Botany, Seoul National University; Jong Hwan Han, Assistant, Department of Geology, Seoul

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National University; and Soon Dok Chang, Professor of the Busan College of Fisheries. Mr. Sungwoo Kim, Mr. Jae Du Kim and Mr. Hyun Il Choi, participated in the second cruise made in the middle of August by the **Hanrasan-ho** (80 tons) and 21 dredged samples were obtained. Mr. Sungwoo Kim and Mr. Jae Du Kim went on the third cruise in the middle part of December, using the same ship, and 19 dredged samples were taken. The samples obtained from the second and third cruises have not yet been examined for their foraminiferal content because of the limited time available. Sampling sites are shown in fig. IX–1.

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TOPOGRAPHY AND REGIONAL GEOLOGY

The islands and adjoining mainland

The southwestern coast of Korea is a typical rias-type coast line. In the southwestern part of the Korean Peninsula, mountain ranges such as the Charyeong, Noryeong, and Sobaeg diverge from the Taebaeg range, which lies parallel to and near the east coast of the peninsula, to form groups of archipelagos by submergence of their southwestward extensions. The islands are believed to have been part of the main peninsula prior to submergence or inundation by post-glacial melting.

These northeast-southwest trending ranges become progressively lower and more mature in topographic relief towards the south-west and, near their southwestern extremities, a comparatively wide coastal plain is developed, except for some hilly watersheds. Meandering rivers flow across the coastal plain and carry sediments into the Yellow Sea. The Imjin-gang and the Han-gang flow into Inchon Bay, some smaller rivers into Asan Bay, the Geum-gang flows by Gunsan City and the Yeongsan-gang through Mogppo City.

The Imjin-gang drains areas made up of crystalline schists, granites and basalts. The Han-gang, the largest river which flows into the Yellow Sea, has its source in regions where granite gneisses, crystalline schists and granites are exposed and its lower course passes over a large eroded granite batholith. The drainage system of the Yeongsan-gang, which covers the southwestern part of the peninsula, has its source is granitic areas, passes through Mesozoic sediments in its middle part and schistose granite in its lower course.

The Precambrian crystalline schists and granite gneisses and the Mesozoic granites, which have a general southwesterly trend, are the main rocks exposed in the drainage areas of the rivers. As these rocks weather readily, rather rapid deposition of sediments derived from them could be expected on the floor of the Yellow Sea.

In the central part of the west side of the peninsula, from Daecheon to Gunsan City, Daedong System of Jurassic age is found together with the older rocks and the Mesozoic granite. In the Hampyeong Plain in the western part of South Jeonra Province the Jurassic sediments of the Sinra Series are widely distributed; these consist of tuffs, conglomerates, sandstones and shales which are also easily weathered and eroded.

Results obtained by Niino and Emery (1967) indicate that the sea floor around the archipelagos and farther offshore is covered mainly by muddy sediments, but new information obtained from the present bottom sampling programme has provided more detail, as shown in fig. IX–2. The geology of most of the islands off the southwest coast is similar to that of the adjoining mainland, but islands in Muan-gun are mostly composed of porphyry with studded porphyrite, and Mesozoic tuff and black shale. Soheugsan-do, the island farthest from the mainland, is composed mainly of acidic or intermediate volcanic flows and Daeheugsan-do, situated to the northeast, consists of metamorphic sediments (Yeoncheon System?), including quartzite, quartz schist, mica schist and phyllite. Hong-do, the island to the west of Daeheugsan-do, is made up of sediments believed to be of Mesozoic age. One of the remarkable features of the archipelago and the adjoining mainland is that no Tertiary sediments, marine or non-marine, have been found.

The sea floor

The area sampled lies between 34°00′ and 37°00′ north latitudes and 124°00′ and 126°-00′ east longitudes. In this area few islands are found except some belonging to the southern archipelago, the islands of the Gyeogyeol, and some near Inchon Harbour.

The depths at the 52 sampling sites were surveyed by echo sounding; fig. IX–1 is a contour map of the sea floor based on these soundings. Some data published by the Republic of Korea Hydrographic Office in 1966 were also used. The map shows some notable topographic relief in the area offshore from Mogpo City but elsewhere there is a fairly general slope towards the west.

The bottom samples can be classified into four groups, namely, sand, muddy sand, sandy mud and mud, distributed in that order from north to south in the form of a bow with the convex side to the south, as shown on fig. IX–2. The sandy floor is found between 124°15′ and 125°30′ east longitudes to the north of 35°30′N. latitude, and the southernmost part of the sandy floor is 140 km from the mainland coast of Korea. From this "nose" of sandy sea floor the bottom sediments gradually decrease in grain size to the south, south-east and south-west to the area between 34°30′ and 35°00′ north latitudes, which is covered by muddy sediments.

The sandy sediments are dominantly grayish olive green, light olive gray and moderate olive brown in colour. The muddy sand is gray in the west, but it becomes brown or greenish towards the mainland. The muddy part is olive gray in colour near the land, but is dark greenish-gray farther offshore. In general, the bottom sediments are grey in colour in the west, but grade into brown or green with an olive tint towards the east, whereas in the north they are olive gray and they grade into greyish-green towards the south.

The organic content of the bottom sediments decreases as the grain size of the sediments increases. It is a notable fact that very few foraminifera are found in the area of sandy bottom shown on fig. IX–2. The organic content and number of foraminifera increase somewhat in the muddy sand, but they increase sharply in the areas of sandy mud and mud bottoms. Shell fragments, diatoms, ostracodes, spines of echinoids, fish teeth, and other organic remains are common in the areas of muddy bottom.

Many rock fragments were dredged from site 21; they are obviously fragments of sedimentary rocks, judging from the stratification and detrital grains found in them, but no foraminifera were detected in them. At site 3, a small amount of rock fragments were obtained; they have almost the same texture as those from site 21, but they contain shell fragments, although again no foraminifera were found. These may be marine sediments of Ter-

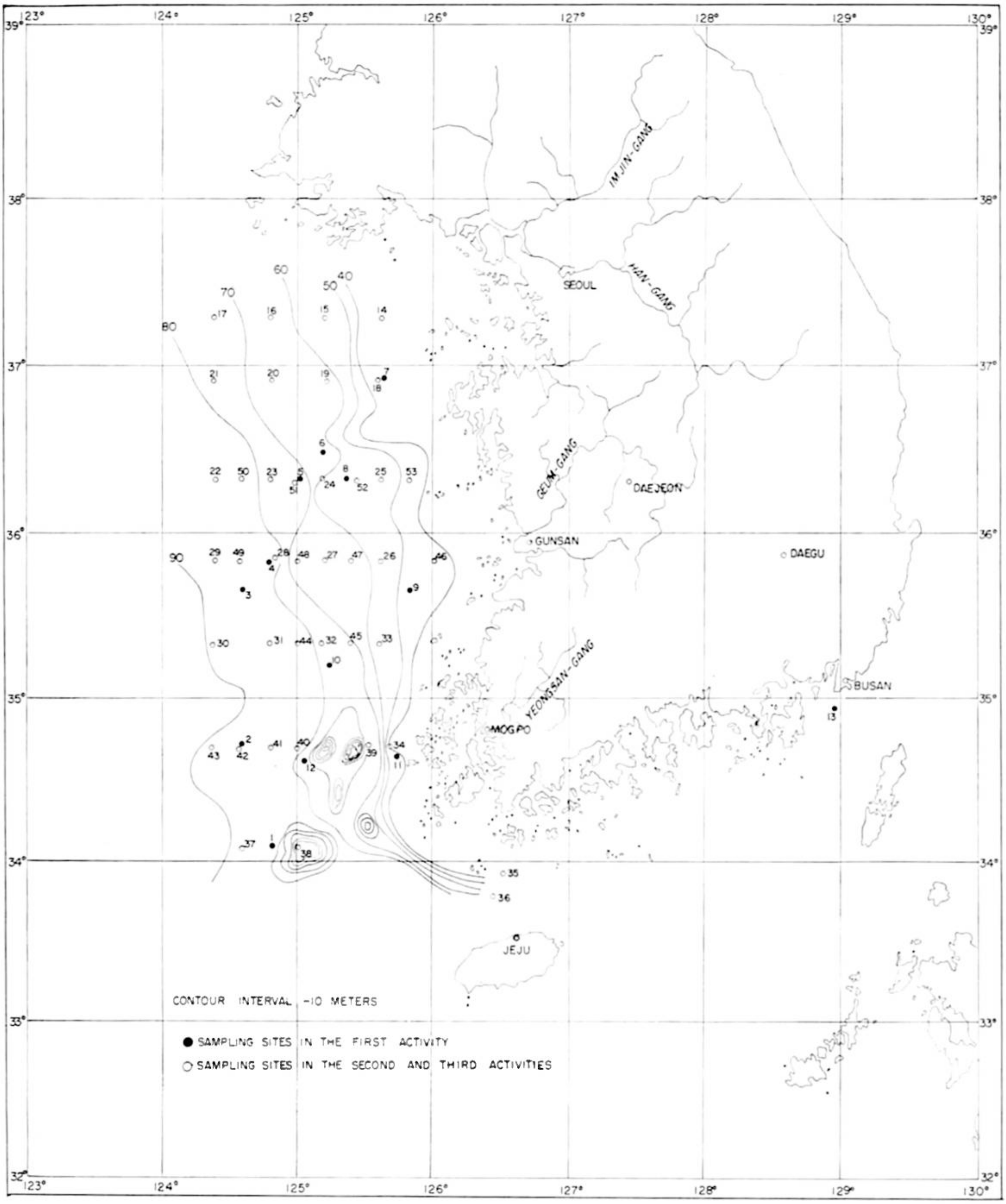


Figure IX–1. Contour map of the sea floor off the southwestern coast of Korea

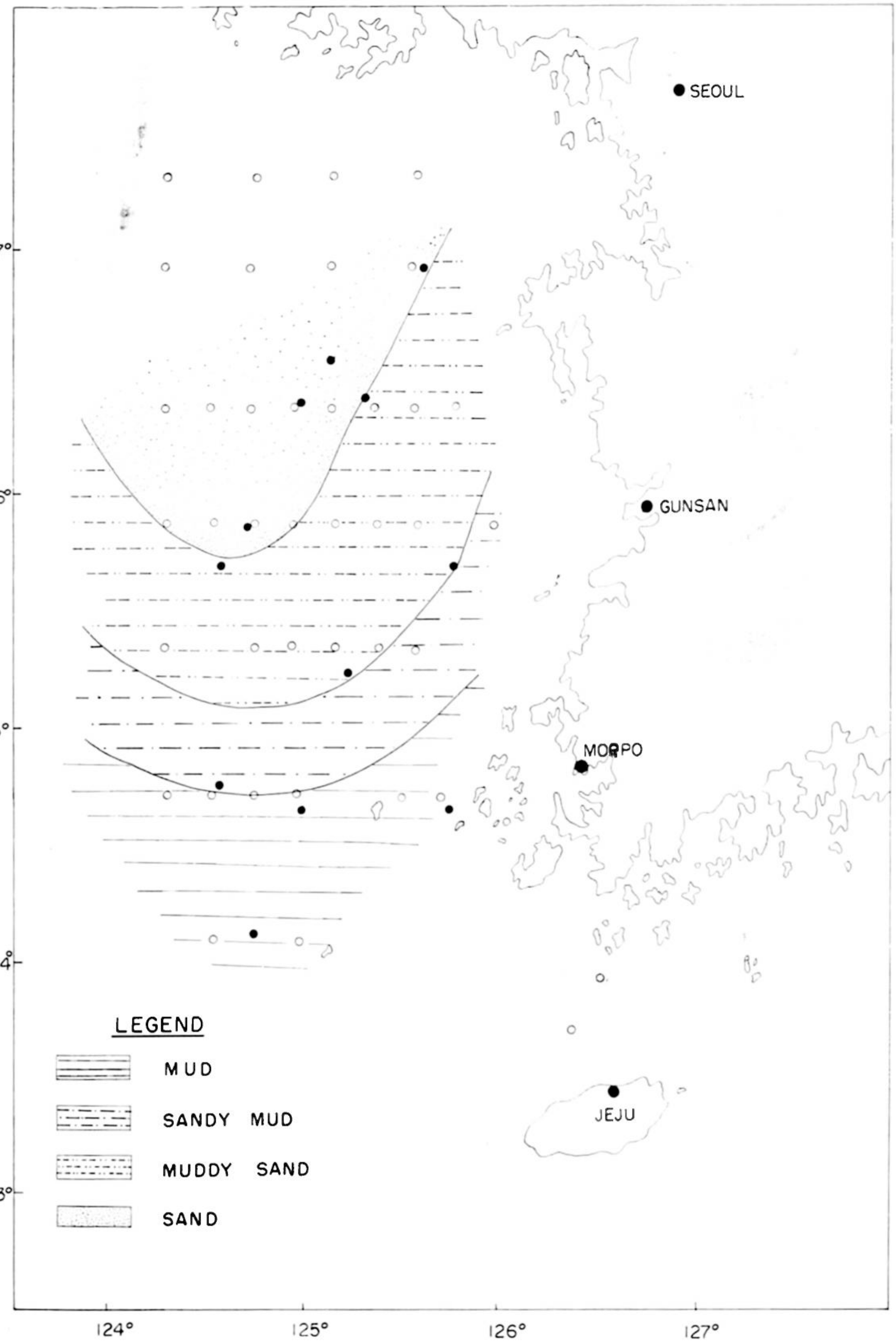


Figure IX–2. Sediment chart of the Yellow Sea off the southwestern coast of Korea, showing the zonal distribution of the bottom sediments tiary age. These two sites are very far from the mainland and from islands, and are in depths of more than 80 metres. It may be assumed that the fragments might have been derived from submarine outcrops of Tertiary rocks.

OCEANOGRAPHY

During the offshore operations in May, the surface temperature of the Yellow Sea in the north of 35°00′ north latitude was 9.3°C ~ 11.8°C, and the temperature near the bottom was 5.4°C ~ 7.3°C; the salt content of the sea water was found to be 32.5 per mille from the surface to the bottom. The surface temperature of the sea between 35°00′ and 36°00′ north latitudes averages 13°C, and the bottom temperature, 6.5°C; the salt content of the surface water averages 32.6 per mille and 33 per mille near the bottom, giving a difference of 0.4 per mille. Between 34°00′ and 35°00′ north latitudes, the temperature of the surface water averaged 13°C, and 10°C near the bottom; the salt content was 33.5 per mille from surface to bottom. These measurements show that both the water temperature and salt content increase gradually towards the south. In this study, the measurements of temperature and salt content were taken at intervals of 10 metres from surface to sea bottom.

Niino and Emery (1967) have shown that the Kuroshio current, with high temperature and salinity, would make its way northwards up to the Gulf of Pohai in summer, through the area under consideration, but it would not reach it, and cold water of low temperature and low salinity would pass through the offshore area near the Korean mainland from north to south to reach the Korean Strait. As this study was conducted in the middle part of May, it was too early for the Kuroshio current to reach the southwestern offshore area where the sea water still had a lower temperature and lower salinity.

FAUNAL ANALYSIS

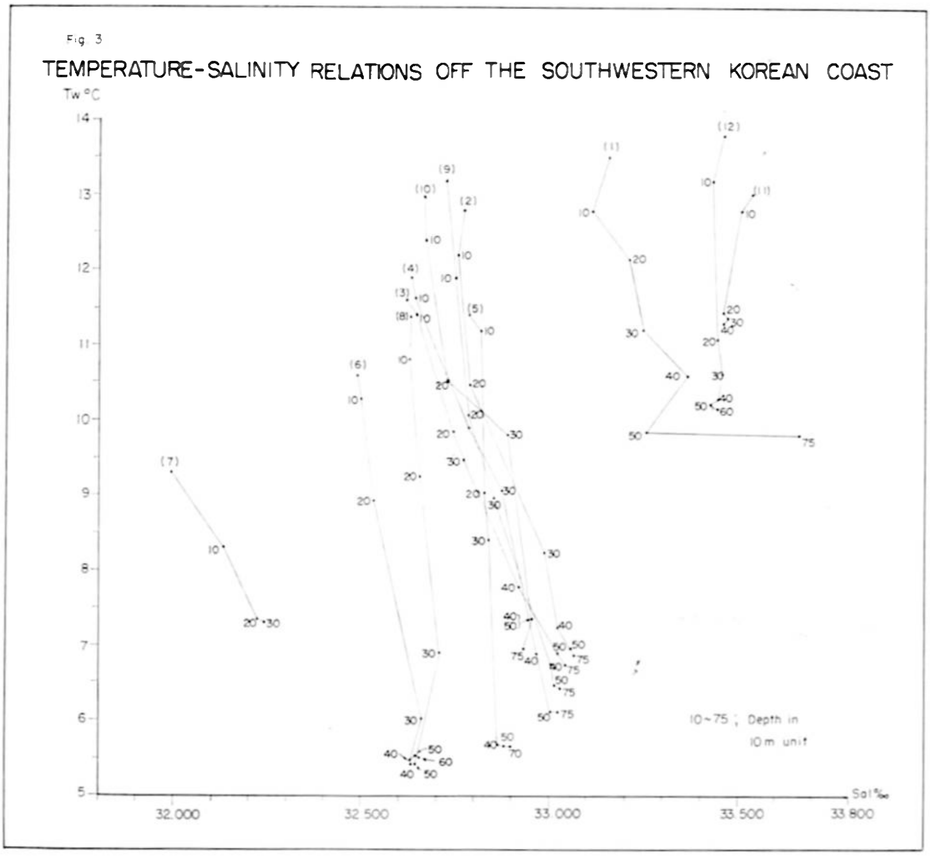
Twelve dredged samples and seven cored samples, obtained during the first cruise, were studied for foraminifera; the writers had time to study only the lowermost parts of the cores, and the upper parts will be processed in the near future. All the wet dredged samples, each of 50 grams, were washed and dried. Dredged sediments from sites 1, 2, 11 and 12 contained a small amount of foraminifera, and all of them were picked out; the other samples contained many foraminifera and about one-fourth of them were picked out for study. The cored samples, each of 30 grams taken from the lowest part of each core, were washed and dried, and the foraminifera were picked out in the same manner as for the dredged samples.

The results are shown in Table IX–1; 124 benthonic species belonging to 57 genera, and 14 planktonic species belonging to six genera have been identified. The frequency of occurrence of each species in the samples is expressed as follows: More than 20 individuals, abundant; 10 to 20 individuals, common; 5 to 10, few; less than 5, rare.

Planktonic foraminifera

As is evident from Table IX–1, it is noteworthy that planktonic foraminifera are found in the dredged samples only from sites 1, 2, 10, 11 and 12, all of which are situated to the south of 35°30′ north latitude, whereas all the cored samples, obtained from nine sites extending up to 36°00′ north latitude, contain planktonic foraminifera. The sandy sediments in both the dredged and cored samples are devoid of planktonic foraminifera, and their frequency increases as the bottom sediments become muddier.

As seen from the list, *Globigerionoides* is the most abundant genus, and *G. sacculifer*



(1)	lat. 35°20.1′N—long. 124°35.6′E May 1969	(7)	lat. 36°55.5′N—long. 125°37.9′E May 1969
(2)	lat. 34°43.0′N—long. 124°35.6′E May 1969	(8)	lat. 36°23.0′N—long. 125°20.2′E May 1969
(3)	lat. 35°20.1′N—long. 124°35.6′E May 1969	(9)	lat. 35°40.9′N—long. 124°49.5′E May 1969
(4)	lat. 35°51.3′N—long. 124°47.8′E May 1969	(10)	lat. 35°12.7′N—long. 125°13.9′E May 1969
(5)	lat. 36°19.8′N—long. 125°00.0′E May 1969	(11)	lat. 34°39.4′N—long. 125°42.8′E May 1969
(6)	lat. 36°43.8′N—long. 125°10.8′E May 1969	(12)	lat. 34°05.7′N—long. 125°37.8′E May 1969

Figure IX-3. Temperature-salinity relations off the southwestern coast of Korea

and *G. ruber* are the more frequently occurring species obtained from the dredge samples at sites 1, 2, 10, 11 and 12. On the other hand, *Globigerina* is the dominant genus present in the cored samples, and the following species have been identified:

Species	Site Numbers
Globigerina bulloides d'Orbigny	9
G. falconensis Blow	9
G. pachyderma (Ehrenberg)	1, 2, 9, 10
G. quinqueloba (Natland)	1, 9, 10
G. sp.	2, 9, 10, 11

G. pachyderma, a typical cold water species, and the temperate species, *G. bulloides*, occur together at site 9. The individuals of all the species are dwarfish in size, in both the dredged samples and in those from the lowest part of the core. This dwarfish tendency, which is seen in the foraminifera in the samples from about 0.5~0.6 metre below the sea floor, seems to indicate a somewhat colder climatic condition at the time of deposition of the sediments, influenced by a cold sea current.

At some dredged sites south of 35°00′ north latitude the following tropical or subtropical planktonic species are abundant: *Golobigerinoides* spp. at sites 1, 2, 10, 11, 12 and *Pulleniatina obliquiloculata* (Parker & Jones) at site 1. This suggests that the sea in this area is under the influence of the warm Kuroshio current which comes up in the summer seasons. On the other hand, some typically cold water species are found together with the warm water species, as follows: *Globigerina pachyderma* (Ehrenberg) at sites 1, 2, 11, 12 and *Globoquadrina dutertrei* (d'Orbigny) at sites 1, 2, 11. This would indicate that the area is also affected by a cold water current during the winter seasons.

In spite of the fact that planktonic foraminifera are floating organisms, they were not found in the samples from sites north of 35°N. latitude. It may be inferred that the sea water north of this latitude contains much harmful suspended materials and the lower temperature and salinity may also affect their distribution.

Benthonic foraminifera

Arenaceous forms are an important component of the benthonic assemblages of the area; this was also found to be the case by W. Polski (1959) who investigated samples from the northern part of the Yellow Sea. Arenaceous forms found in the samples comprise 16 species belonging to 11 genera, as follows:

Species	*Site Numbers* ( ) *Cored samples*
Ammobaculites sp.	1 (1)
Ammomassilina alveoliniformis (Millett)	1, 11, 12, (1)
Clavulina serventyi (Chapman & Parr)	1 (1)
Eggerella advena (Cushman)	1, 5, 11 (3)
Gaudryina sp.	1, 11, (1)
Haplophragmoides sp.	11 (3)
Reophax scorpiurus Montfort	4, 5 (3)
R. tubulata (Rhumbler)	1 (3)
Sigmoilina sp.	1 (1)
Sorosphaera confusa (Montfort)	1, 4 (1)
Textularia articulata (d'Orbigny)	1, 10, 12 (1)
T. conica d'Orbigny	1, 11
T. secasensis Lalicker & McCulloch	11
Trochammina inflata (Montagu)	2, 12
T. sp.	1, 11 (1)

Five species of arenaceous foraminifera belonging to four genera are present in the samples from sites 3, 4 and 5, which are all sandy. Samples from sites 1, 2 and 10, consisting of sandy mud or muddy sand, contain a more varied assemblage of 12 species belonging to 10 genera. From the muddy sediments at sites 11 and 12, nine species belonging to five genera of arenaceous forms were found. Polski (1959) considered that arenaceous foraminifera would not be found in muddy bottom sediments like those in the offshore area of south-western Korea, but this now appears to have been disproved.

Porcellaneous foraminifera are represented mainly by the genus *Quinqueloculina*. *Q. lamarckiana* is the dominant species, but the other species are badly preserved or dwarfed and could not be specifically identified. *Q. lamarckiana* occurs only in the muddy bottom samples such as those from sites 1, 2, 11 and 12; both dredged and cored samples from sites 11 and

12 contain abundant *Q. lamarckiana.* Some specimens of *Q. seminula* and other species were found only in samples from muddy bottom. *Triloculina tricarinata, T. trigonula* and *T.* sp. are found at the same sites as *Quinqueloculina.*

The hyaline forms are represented by species of *Ammonia, Cibicides, Elphidium, Hanzawaia* and *Bolivina. Ammonia beccarii* occurs abundantly at all except dredge sites 6, 7 and 8 and core sites 9, 11 and 12. *A. takanabensis* is next in abundance to *A. beccarii. Cibicides lobatulus* and *C. pseudoungerianus* are commonly found at sites 1, 2, 5, 10, 11 and 12. *Elphidium crispum* is also numerous in muddy bottom samples. *Hanzawaia nipponica* occurs abundantly in all the core samples except No. 12 and in all the dredged samples except those consisting of sand. *Uvigerina, Valvulineria, Lagena, Pyrgo,* and a few other genera are found in the area sampled.

The benthonic forms become rarer or are even absent, as is the case with the planktonic forms, towards the north and as the sand content increases. This tendency has been pointed out already by one of the writers, Prof. B. K. Kim (1965), who explained this as being due to rapid accumulation of sand, and low salinity and temperature of the water, but more detailed study will be needed to prove this.

CONCLUSIONS

1. The bottom sediments off the southwestern coast of Korea are sandy in the north, and areas of muddy sand, sandy mud and mud are distributed in that order towards the south, south-east and south-west of the area of sandy bottom north of 36° north latitude.

2. The colour of the bottom sediments changes from olive green or brown to gray towards the west from the Korean coast, and gradually from brown to olive green to gray from north to south.

3. The content of organic matter and foraminifera increases with the increase of mud content in the bottom sediments. The area of sandy bottom contains few foraminifera.

4. The sea floor to the west of the southwestern corner of the Korean peninsula has relatively high topographic relief whereas elsewhere in the area surveyed it slopes very gently westwards with a gradient generally of less than one metre per kilometre.

5. Abundant fragments of sedimentary rock were dredged from site 21 and a small amount from site 3. No foraminifera were detected in the rock fragments, but shell fragments were present in the rocks at site 3 which suggests that the rock fragments might be of Tertiary age.

6. Fourteen species belonging to six genera of planktonic foraminifera and 124 species belonging to 57 genera of benthonic forms were identified; the planktonic forms were found only to the south of 35°30′ north latitude in dredged samples but were found as far north as 36° north latitude in the lower parts of the cores.

7. As the specimens of foraminifera found in the lowest part of the cores are dwarfed, the environment of deposition of the sediments at 0.5～1 metre below the present sea floor seems to be different from that of the present time.

8. The most common species of benthonic foraminifera in the area studied are *Ammonia beccarii* and *Hanzawaia nipponica.* These forms occur at all depths and in all types of bottom sediments except where the bottom sediment is pure sand.

9. Sixteen species of arenaceous foraminifera belonging to 11 genera were identified; these are rather widespread and constitute an important element of the benthonic assemblage.

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Table IX-1. Assemblages of Foraminifera from the Yellow Sea off the southwestern coast of Korea

Genus & Species	Dredged samples											Cored samples						
	1	2	4	5	6	7	8	9	10	11	12	1	2	3	9	10	11	12
Benthonic Foraminifera																		
Ammobaculites sp.												•						
Ammomassilina alveoliniformis (Millett)	•											/						
Ammonia beccarii (Linnaeus)	•									•	/	○	/	○		/		
Ammonia beccarii aomoriensis Asano	○	○	○	○				○	○	○	×							
Ammonia inflata (Sequenza)										•								
Ammonia japonica (Hada)											×						/	
Ammonia nipponica (Asano)																	/	
Ammonia cf. *papillosa* Brady																	•	
Ammonia takanabensis (Ishizaki)									○	○	○			/		×	○	•
Ammonia sp. (A)	•	•		•								•	•	•	○			
Ammonia sp. (B)		×									•				/	/		
Anomalina sp.									•								/	
Asterononion umbiliculatum Uchio								•	•	×	×					•	×	
Asterononion sp.	•											•		/		•		
Bolivina compacta Sidebotrom										•								
Bolivina pacifica Cushman & McCulloch	•										•	•						
Bolivina pseudodifformis Asano																		•
Bolivina robusta Brady	○										•	○					○	×
Bolivina seminuda Cushman															•			
Bolivina spinescens Cushman	•											/			•			
Bolivina sp.																	•	
Buccella frigida (Cushman)	•									/	•	•			×	○	○	
Beccella frigidus calidus Cushman & Cole										×								
Buccella sp.										•							•	
Bulimina aculeata d'Orbigny	/	•		•						/	/	×		/			/	
Bulimina marginata d'Orbigny	•													/	•	•		
Bulimina sp.															•			
Cancris auriculus (Fichtel & Moll)	/								/	○	•	/					/	
Cibicides aknerianus (d'Orbigny)									•									
Cibicides lobatulus (Walker & Jocob)	○			•					•	○	○	○			×	/		/
Cibicides pseudoungerianus (Cushman)	○									○	○	○					○	
Cibicides cf. *refulgens* (Montfort)										/								
Cibicides sp.										/		○						
Clavulina serventyi (Chapman & Parr)	•											•						
Cribrogloborotalia sp.										•								
Cribrostomoides sp.	•											•						
Dentalina setanaensis Asano	•	•	•	•							•			/				
Discammina compressa (Goës)			/															
Discorbinella isabelleana (d'Orbigny)										/							•	
Discorbinella bradyi (Cushman)	/									/		/					•	
Discorbinella sp.															•			
Eggerella advena (Cushman)	•			•						•				/				
Elphidium advenum (Cushman)										○					○		×	/
Elphidium crispum (Linnaeus)	○	○				•				○	•	○				/		
Elphidium etigoense Husezima & Maruhasi	/	•	•	•					•			/	•					
Elphidium jenseni (Cushman)	/									/	/	/			/	•	•	
Elphidium subarcticum Cushman																○		
Elphidium subincertum Asano															○			
Elphidium sp.									•						•			
Epistominella naraensis (Kuwano)		•												/				
Eponides sp.	/								•		×	/						
Fissurina marginata (Montagu)	/	•								/	•	×	•			/		
Fissurina cf. *orbignyana* Seguenza				•												/		
Florilus japonicum (Asano)	○	•								•	•	/	/					•
Florilus sp. (A)	/									•	•	/						
Florilus sp. (B)		•											•					
Gaudryina sp.	×									•		×						
Globocassidulina depressa Asano & Nakamura										•								
Globocassidulina subglobosa (Brady)		•								•				/				
Globocassidulina sp.															•			
Guttulina sadoensis (Cushman & Ozawa)																	•	
Gyroidina sp.																•		
Hanzawaia nipponica Asano	○	×	•	/					/	○	○	○	×	•	/	/	/	
Hanzawaia sp.									/						/			
Haplophragmoides sp.										•				/				
Lagena apiopleura Loeblich & Tappan										•								
Lagena elongata (Ehrenberg)		•								•			•					
Lagena hispidula Cushman	•																	
Lagena pliocenica Cushman & Gray	•																	
Lagena sulcata spicata Cushman & McCulloch	•																	
Lagena sp.																•		/
Lenticulina lucida (Cushman)	/													/				
Lenticulina nicobarensis (Schwager)										/								
Lenticulina orbicularis (d'Orbigny)	/	•		•								/						
Lenticulina sp. (A)	/									•		/					•	
Lenticulina sp. (B)																•	•	
Marginulina sp.																	•	
Melonis nicobarense (Cushman)	/							•	•	/	×	○	/	•			×	/
Nodosaria subraphana Asano		•							•	•			•					
Nodosaria vertebralis (Batsch)	•							•										
Nonion scaphum (Fichtel & Moll)										•								
Nonionella miocenica stella (Cushman & Moyer)	•		/	/				•										
Oridorsalis umbonatus (Reuss)	•																	
Oolina hexagona (Williamson)										•						•		
Oolina melo d'Orbigny																/		
Oolina catenulata Williamson										•								
Oolina sp.									•	/								
Pararotalia ozawai (Asano)										/								•
Planulina sp.										•								
Porosorotalia makiyamae (Chiji)	○									○	•	×			•	/		•
Pseudorotalia gaimardii (d'Orbigny)	•	/							•	○	○							•
Pullenia quinqueloba Reuss	•									•	•							
Pyrgo subsphaerica (d'Orbigny)	•											•					•	
Quinqueloculina contorta d'Orbigny										/								
Quinqueloculina elongata Natland										/								•
Quinqueloculina hasimotoi Asano										/								
Quinqueloculina lamarckiana d'Orbigny	/	•								○	○	/	•				○	○
Quinqueloculina seminula (Linnaeus)											•							
Quinqueloculina sp. (A)	•									•								
Quinqueloculina sp. (B)										•								
Quinqueloculina sp. (C)										×								
Quinqueloculina sp. (D)										•								
Reophax scorpiurus Montfort			/	•										/				
Reophax tubulata (Rhumbler)	•													/				
Sigmomorphina sp.	○									/	/	○			/	•		
Sigmoilopsis schlumbergeri (Silvestri)	•											/						
Siphonis bradyana Cushman	•											•						
Siphogenerina rephanus (Parker & Jones)										/	○							
Sorosphaera confusa (Montfort)	/		•									/						
Textularia articulata d'Orbigny	•								•		•							
Textularia conica d'Orbigny	•									•								
Triloculia secasensis Lalicker & McCulloch										/								
Triloculina tricarinata d'Orbigny	/									/	•	/						
Triloculina trigonula (Lamarck)	/	•								•		/	•					
Triloculina sp.										•								
Trochammina inflata (Montagu)	•									•		•						
Trochammina sp.		•									•						•	
Uvigerina proboscidea Schwager										•								
Valvulineria japonica Asano										•							•	•
Valvulineria nipponica Ischizaki										•					○			
Valvulineria sp.										•								
Planktonic Foraminifera																		
Globigerina bulloides d'Orbigny										•					○			
Globigerina falconensis Blow															•			
Globigerina pachyderma (Ehrenberg)	/	/								•	•	/	/		/	/		
Globigerina quinqueloba Natland										•	×	/			×	/		
Globigerina sp.	•									•	/		/		×	/	/	
Globigerinita bradyi Wiessner											•						•	
Globigerinoides conglobatus (Brady)															×			
Globigerinoides ruber (d'Orbigny)	×								•	○	•	×						
Globigerinoides sacculifer (Brady)	•	•							•	•	•	•	•				○	
Globigerinoides trilobus (Reuss)																		
Globoquadrina dutertrei (d'Orbigny)	×	•								/		/		/				/
Pulleniatina obliquiloculata (Barker & Jones)	•											•						
Turborotalia subcretaces (Lomnicki)										/								×
Turborotalia sp.															•		•	

abundant; ○ common; × few; / rare; •

EXPLANATION OF PLATE IX-1

Figures

1a–b *Clavulina serventyi* (Chapman & Parr) × 30
dredged sample, 1. cored sample, 1.: Hypotype (DGSU coll. cat. 00130)

2a–b *Cribrostomoides* sp. × 70
dredged sample, 1. cored sample. 1.: Hypotype (DGSU coll. cat. 00131)

3 *Sorosphaera confusa* (Montfort) × 49
dredged samples, 1, 4. cored sample, 1.: Hypotype (DGSU coll. cat. 00132)

4 *P Rreophax tubulata* (Rhumbler) × 35
dredged sample, 1. cored sample. 3.: Hypotype (DGSU coll. cat. 00133)

5a–b *Trochammina inflata* (Montagu) × 95
dredged samples 2, 12. Hypotype (DGSU call. cat 00134)

6a–c *Sigmailopsis schlumbergeri* (Silvestri) × 55
dredged sample, 1. cored sample 1.: Hypotype (DGSU coll. cat. 00135)

7a–b Quinqueloculina lamarckiana d'Orbigny × 38
dredged sample, 1, 2, 11, 12 cored sample 1, 2, 11, 12: Hypotype (DGSU coll. cat. 00136)

8a–c *Quinqueloculina* sp. A × 90
dredged samples, 1, 11 Hypotype (DGSU call. cat. 00137)

9a–b *Triloculina tricarinata* d'Orbigny × 78
dredged samples, 1, 11, 12. cored sample, 1 Hypotype (DGSU call. cat. 00138)

10 *Lagena pliocenica* Cushman Gray × 44
dredged sample, 1: Hypotype (DGSU call. cat. 00139)

11a–b *Lenticulina orbicularis* (d'Orbigny) × 34
dredged samples., 1, 2, 5. cored sample, 1: Hypotype (DGSU coll. cat. 00140)

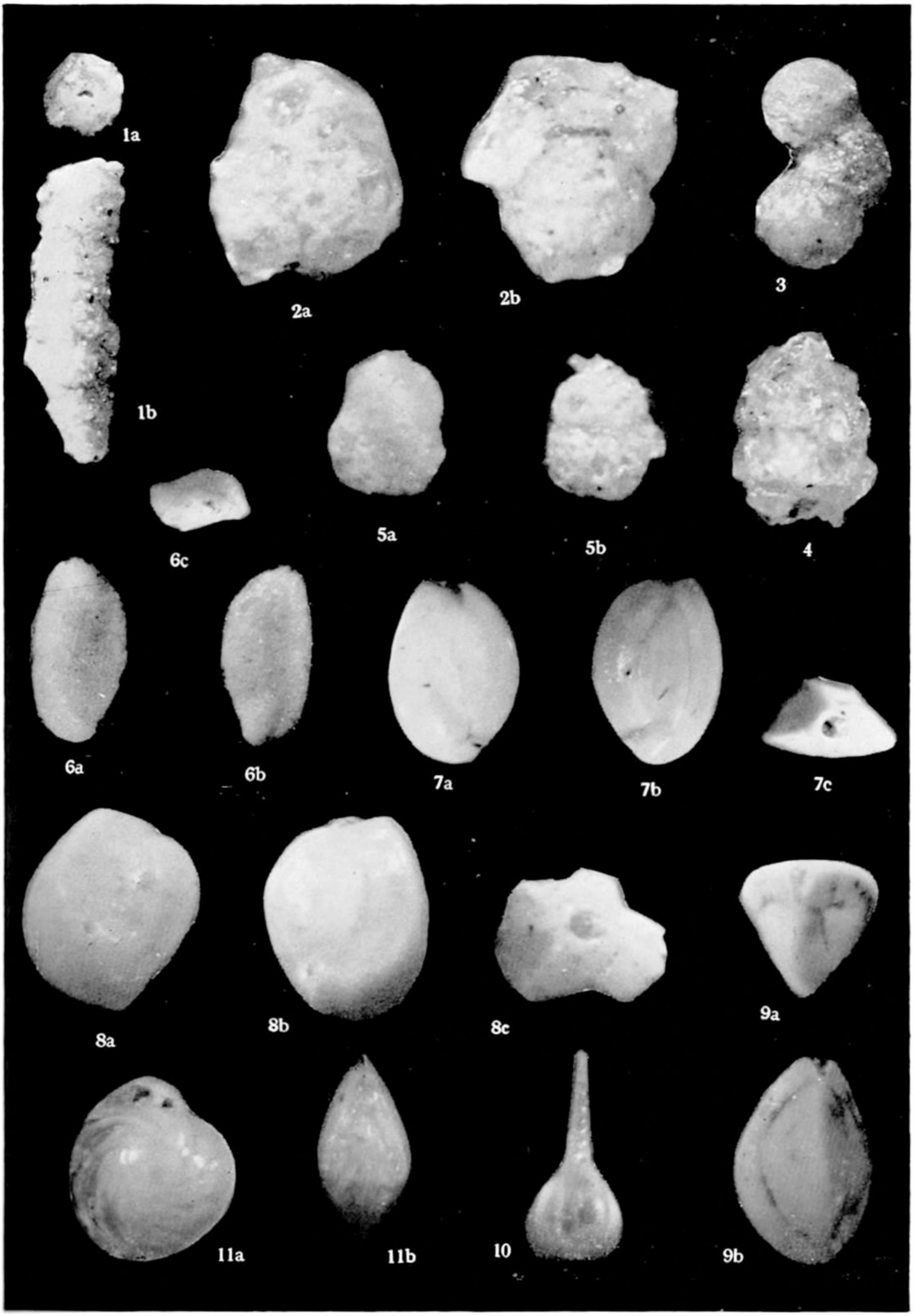

Plate IX-1. Foraminifera offshore from the southwestern coast of Korea.

EXPLANATION OF PLATE IX-2

Figures

1 *Nodosaria vertebralis* (Batsch) × 20
dredged samples, 1, 9, Hypotype (DGSU call. cat. 00141)

2a–b *Bulimina aculeata* d'Orbigny × 45
dredged samples, 1, 2, 5, 11, 12. cored samples, 1, 3, 11: Hypotype (DGSU coll. cat. 00142)

3 *Bolivina robusta* (Brady) × 63
dredged sampls 1, 11, 12. cored samples 1, 11, 12. Hypotype (DGSU call. cat. 00143)

4a–b *Uvigerina proboscidea* Schwager × 68
dredged sample, 11, cored sample 11: Hypotype (DGSU call, cat. 00144)

5a–c *Hanzawaia nipponica* Asano × 24
dredged samples 1, 2, 4, 5, 10, 11, 12. cored samples 1, 2, 3, 9, 10, 11, Hypotype (DGSU call. cat. 00145)

6a–c *Ammonia* sp. A × 30
dredged samples, 1, 2, 5, cored samples 1, 2, 3, 9: Hypotype (DGSU call. cat. 00146)

7a–c *Pseudorotalia gaimardii* (d'Orbigny) × 20
dredged samples, 1, 2, 10, 11, 12. cored sample 12: Hypotype (DGSU call. cat. 00147)

8a–c *Porosorotalia makiyamae* (Chiji) × 50
dredged samples, 1, 11, 12. cored samples, 1, 9, 10, 12: Hypotype (DGSU call. cat. 00148)

9a–c *Cancris auriculus* (Filchtel & Moll) × 40
dredged samples, 1, 10, 11, 12 cored samples, 1, 11, Hypotype (DGSU call. cat. 00149)

10a–c *Siphonina bradyana* Cushman × 47
dredged sample, 1, cored sample, 1: Hypotype (DGSU call. cat. 00150)

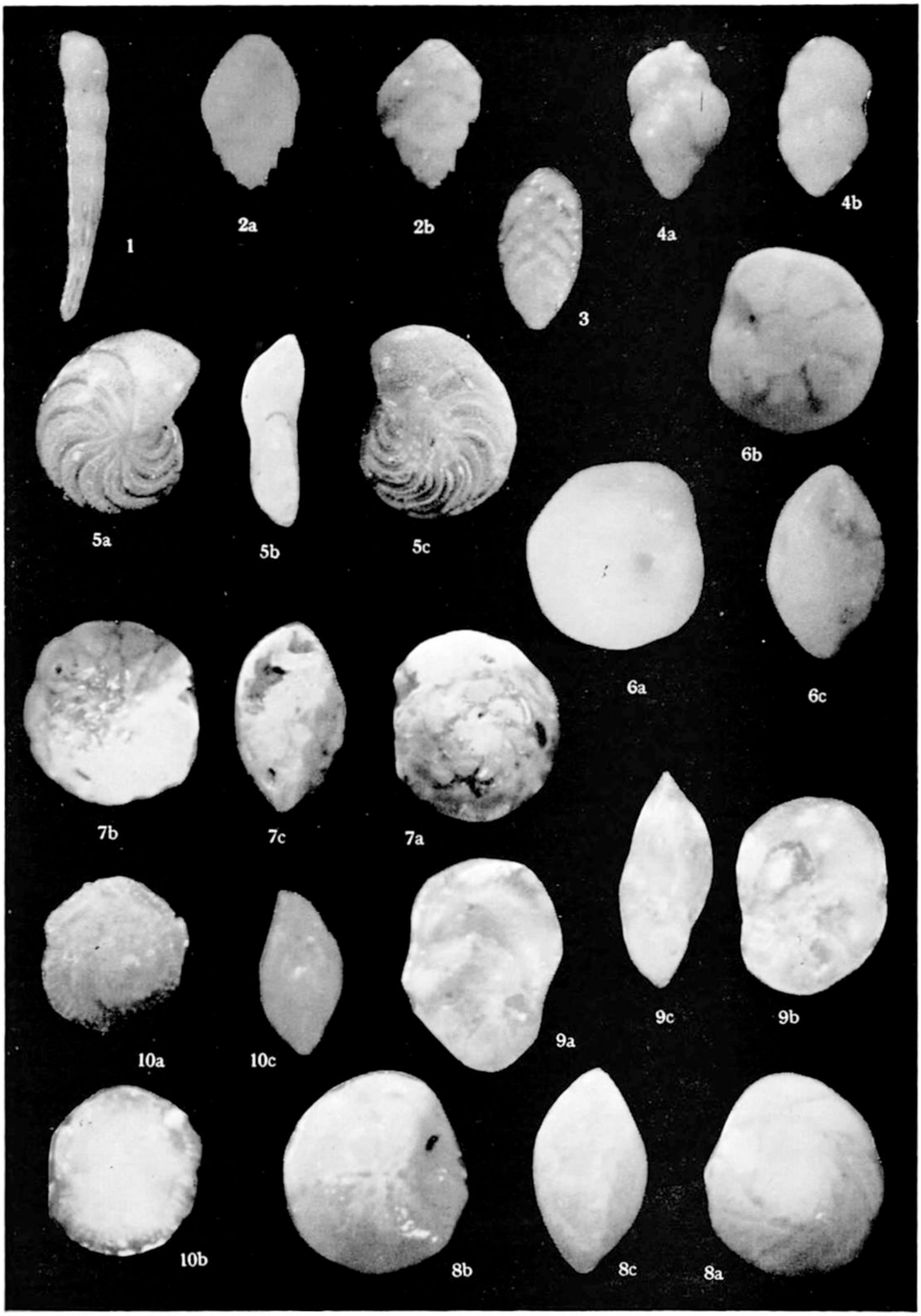

Plate IX-2. Foraminifera offshore from the southwestern coast of Korea.

EXPLANATION OF PLATE IX-3

Figures

1a–c *Globigerinabulloides* d'Orbigny × 48
dregded sample, 11, cored sample, 9, Hypotype (DGSU call cat. 00151)

2a–c *Glabigerina pachyderma* (Ehrenberg) × 60
dredged samples, 1, 2, 11, 12. cored samples. 1, 2, 9, 10: Hypotype (DGSU coll. cat. 00152)

3a–c *Globigerina quinqueloba* Natland × 68
dredged samples, 11, 12, cored samples, 1, 9, 10

4a–c *Globigerinoides ruber* (d'Orbigny) × 46
dredged samples, 1, 10, 11, 12 cored sample, 1, Hypotype (DGSU coll. cat. 00153)

5a–c *Globigerinoides sacculifer* (Brady) × 51
dredged samples 1, 2, 10, 11. 12 cored samples, 1, 2, 11 Hypotype (DGSU coll. cat. 00154)

6a–c *Globaquedrina dutertrei* (d'Orbigny) × 48
dredged samples, 1, 2, 11. cored samples, 1, 3, 12: Hypotype (DGSU coll. cat. 00155)

7a–c *Turborotalia subcretacea* (Lomnicki) × 48
dredged samples 11 cored sample, 12: Hypotype (DGSU coll. cat. 00156)

8 *Pulleniatina obliquiloculata* (Parker & Jones) × 44
dredged sample, 1 cored sample, 1: Hypotype (DGSU coll. cat. 00157)

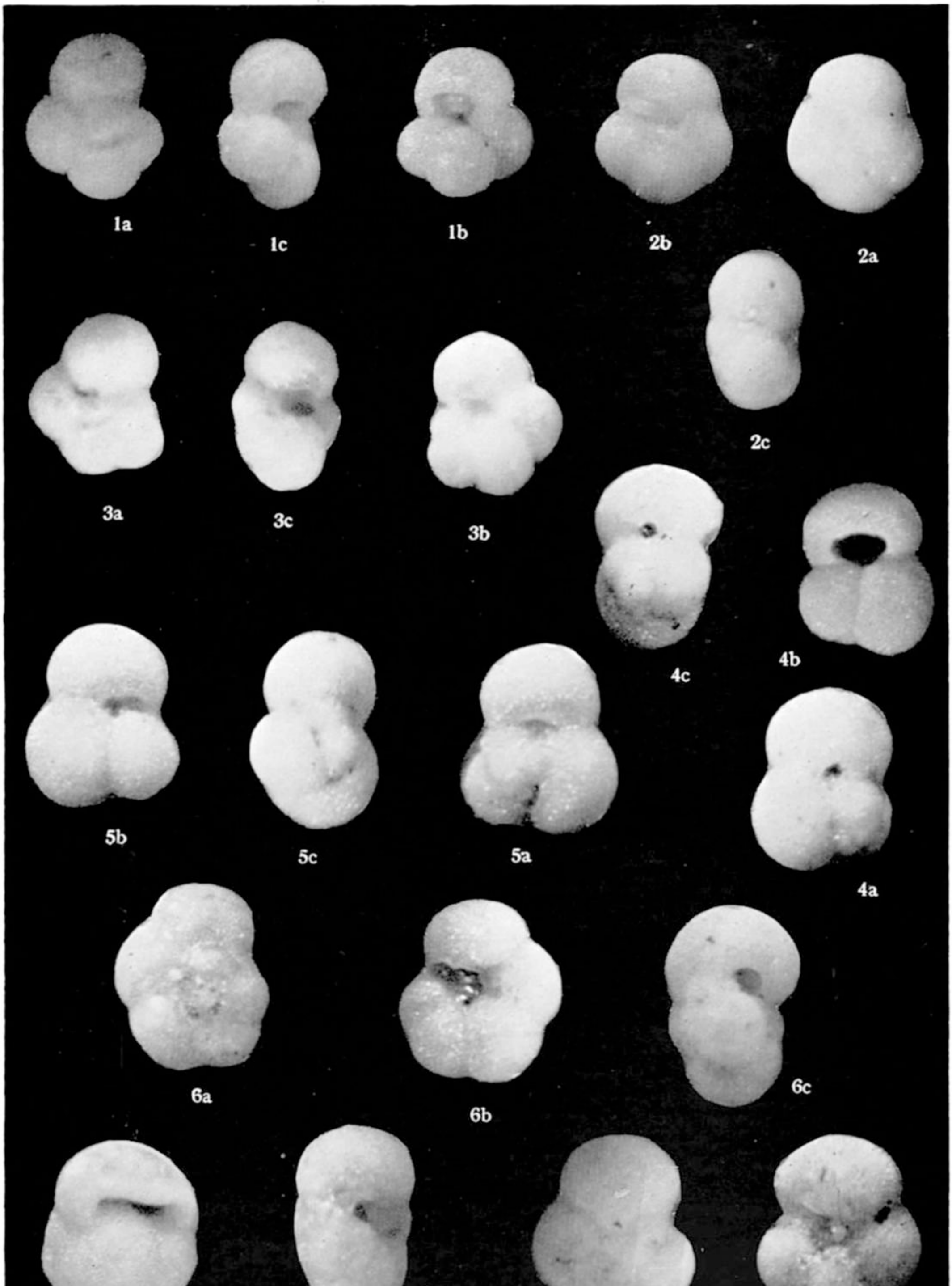

Plate IX–3. Foraminifera offshore from the southwestern coast of Korea.

Annexed 1 Map

to

Regional Geology and Petroleum Prospects of the marine shelves of Eastern Asia

By

M. Mainguy

CCOP Secretariat

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